

APEX CALCULUS FOR MA 301
Version 3.0

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14: VECTOR ANALYSIS

In previous chapters we have explored a relationship between vectors and integration. Our most tangible result: if $\vec{v}(t)$ is a vector-valued velocity function of a moving object, then integrating $\vec{v}(t)$ from $t = a$ to $t = b$ gives the displacement of that object over that time interval.

This chapter explores completely different relationships between vectors and integration. These relationships will enable us to compute the work done by a magnetic field in moving an object along a path and how much air moves through an oddly-shaped screen in space, among other things.

Our upcoming work with integration will benefit from a review. We are not concerned here with techniques of integration, but rather what an integral “does” and how that relates to the notation we use to describe it.

Integration Review

Recall from Section ?? that when R is a region in the x - y plane, $\iint_R dA$ gives the area of the region R . The integral symbols are “elongated esses” meaning “sum” and dA represents “a small amount of area.” Taken together, $\iint_R dA$ means “sum up, over R , small amounts of area.” This sum then gives the total area of R . We use two integral symbols since R is a two-dimensional region.

Now let $z = f(x, y)$ represent a surface. The double integral $\iint_R f(x, y) dA$ means “sum up, over R , function values (heights) given by f times small amounts of area.” Since “height \times area = volume,” we are summing small amounts of volume over R , giving the total signed volume under the surface $z = f(x, y)$ and above the x - y plane.

This notation does not directly inform us *how* to evaluate the double integrals to find an area or a volume. With additional work, we recognize that a small amount of area dA can be measured as the area of a small rectangle, with one side length a small change in x and the other side length a small change in y . That is, $dA = dx dy$ or $dA = dy dx$. We could also compute a small amount of area by thinking in terms of polar coordinates, where $dA = r dr d\theta$. These understandings lead us to the iterated integrals we used in Chapter ??.

Let us back our review up farther. Note that $\int_1^3 dx = x|_1^3 = 3 - 1 = 2$. We have simply measured the length of the interval $[1, 3]$. We could rewrite the above integral using syntax similar to the double integral syntax above:

$$\int_1^3 dx = \int_I dx, \quad \text{where } I = [1, 3].$$

We interpret “ $\int_I dx$ ” as meaning “sum up, over the interval I , small changes in x .” A change in x is a length along the x -axis, so we are adding up along I small

lengths, giving the total length of I .

We could also write $\int_1^3 f(x) dx$ as $\int_I f(x) dx$, interpreted as “sum up, over I , heights given by $y = f(x)$ times small changes in x .” Since “height \times length = area,” we are summing up areas and finding the total signed area between $y = f(x)$ and the x -axis.

This method of referring to the process of integration can be very powerful. It is the core of our notion of the Riemann Sum. When faced with a quantity to compute, if one can think of a way to approximate its value through a sum, the one is well on their way to constructing an integral (or, double or triple integral) that computes the desired quantity. We will demonstrate this process throughout this chapter, starting with the next section.

14.1 Introduction to Line Integrals

We first used integration to find “area under a curve.” In this section, we learn to do this (again), but in a different context.

Consider the surface and curve shown in Figure 14.1(a). The surface is given by $f(x, y) = 1 - \cos(x) \sin(y)$. The dashed curve lies in the x - y plane and is the familiar $y = x^2$ parabola from $-1 \leq x \leq 1$; we’ll call this curve C . The curve drawn with a solid line in the graph is the curve in space that lies on our surface with x and y values that lie on C .

The question we want to answer is this: what is the area that lies below the curve drawn with the solid line? In other words, what is the area of the region above C and under the surface f ? This region is shown in Figure 14.1(b).

We suspect the answer can be found using an integral, but before trying to figure out what that integral is, let us first try to approximate its value.

In Figure 14.1(c), four rectangles have been drawn over the curve C . The bottom corners of each rectangle lie on C , and each rectangle has a height given by the function $f(x, y)$ for some (x, y) pair along C between the rectangle’s bottom corners.

As we know how to find the area of each rectangle, we are able to approximate the area above C and under f . Clearly, our approximation will be *an approximation*. The heights of the rectangles do not match exactly with the surface f , nor does the base of each rectangle follow perfectly the path of C .

In typical calculus fashion, our approximation can be improved by using more rectangles. The sum of the areas of these rectangles gives an approximate value of the true area above C and under f . As the area of each rectangle is “height \times width”, we assert that the

$$\text{area above } C \approx \sum (\text{heights} \times \text{widths}).$$

When first learning of the integral, and approximating areas with “heights \times

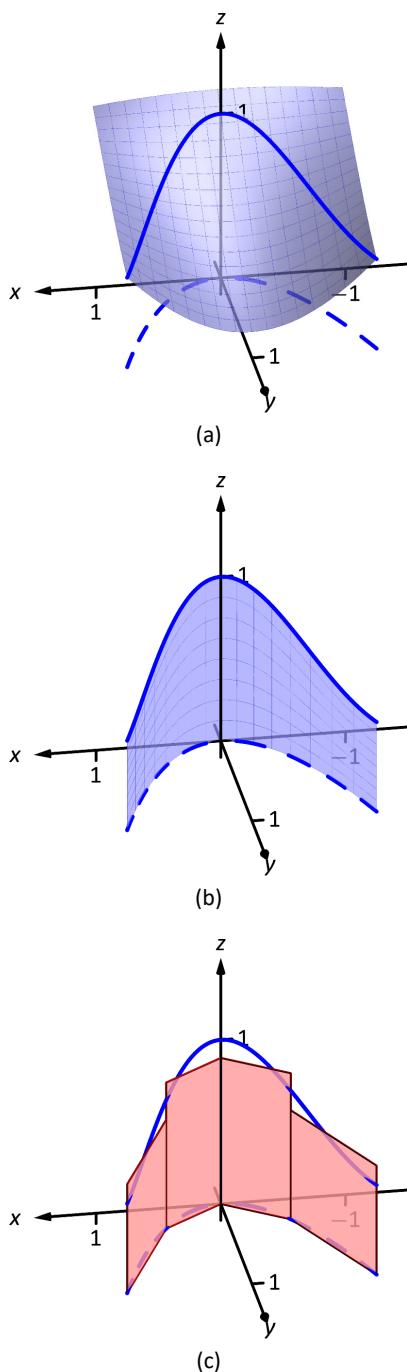


Figure 14.1: Finding area under a curve in space.

Notes:

"widths", the width was a small change in x : dx . That will not suffice in this context. Rather, each width of a rectangle is actually approximating the arc length of a small portion of C . In Section ??, we used s to represent the arc-length parameter of a curve. A small amount of arc length will thus be represented by ds .

The height of each rectangle will be determined in some way by the surface f . If we parametrize C by s , an s -value corresponds to an (x, y) pair that lies on the parabola C . Since f is a function of x and y , and x and y are functions of s , we can say that f is a function of s . Given a value s , we can compute $f(s)$ and find a height. Thus

$$\begin{aligned} \text{area under } f \text{ and above } C &\approx \sum (\text{heights} \times \text{widths}); \\ \text{area under } f \text{ and above } C &= \lim_{||\Delta s|| \rightarrow 0} \sum f(c_i) \Delta s_i \\ &= \int_C f(s) \, ds. \end{aligned} \quad (14.1)$$

Here we have introduce a new notation, the integral symbol with a subscript of C . It is reminiscent of our usage of \iint_R . Using the train of thought found in the Integration Review preceding this section, we interpret " $\int_C f(s) \, ds$ " as meaning "sum up, along a curve C , function values $f(s) \times$ small arc lengths." It is understood here that s represents the arc-length parameter.

All this leads us to a definition. The integral found in Equation 14.1 is called a **line integral**. We formally define it below, but note that the definition is very abstract. On one hand, one is apt to say "the defintion makes sense," while on the other, one is equally apt to say "but I don't know what I'm supposed to do with this definition." We'll address that after the definition, and actually find an answer to the area problem we posed at the beginning of this section.

Definition 0 Line Integral Over Scalar Field

Let C be a smooth curve parametrized by s , the arc-length parameter, and let f be a continuous function of s . A **line integral** is an integral of the form

$$\int_C f(s) \, ds = \lim_{||\Delta s|| \rightarrow 0} \sum_{i=1}^n f(c_i) \Delta s_i,$$

where $s_1 < s_2 < \dots < s_n$ is any partition of the s -interval over which C is defined, c_i is any value in the i^{th} subinterval, Δs_i is the width of the i^{th} subinterval, and $||\Delta s||$ is the length of the longest subinterval in the partition.

Note: Definition 0 uses the term **scalar field** which has not yet been defined. Its meaning is discussed in the paragraph preceding Definition 5 when it is compared to a **vector field**.

Notes:

When C is a **closed** curve, i.e., a curve that ends at the same point at which it starts, we use

$$\oint_C f(s) \, ds \quad \text{instead of} \quad \int_C f(s) \, ds.$$

The definition of the line integral does not specify whether C is a curve in the plane or space (or hyperspace), as the definition holds regardless. For now, we'll assume C lies in the x - y plane.

This definition of the line integral doesn't really say anything new. If C is a curve and s is the arc-length parameter of C on $a \leq s \leq b$, then

$$\int_C f(s) \, ds = \int_a^b f(s) \, ds.$$

The real difference with this integral from the standard " $\int_a^b f(x) \, dx$ " we used in the past is that of context. Our previous integrals naturally summed up values over an interval on the x -axis, whereas now we are summing up values over a curve. If we can parametrize the curve with the arc-length parameter, we can evaluate the line integral just as before.

The trouble here is that we have generally avoided direct use of the arc-length parameter s in the past as it is usually difficult to use. We continue that methodology here.

Given a curve C , find a parametrization of C : $x = g(t)$ and $y = h(t)$, for continuous functions g and h , where $a \leq t \leq b$. We can represent this parametrization with a vector-valued function, $\vec{r}(t) = \langle g(t), h(t) \rangle$.

In Section ??, we defined the arc-length parameter in Equation ?? as

$$s(t) = \int_0^t \|\vec{r}'(u)\| \, du.$$

By the Fundamental Theorem of Calculus, $ds = \|\vec{r}'(t)\| dt$. We can substitute the right hand side of this equation for ds in the line integral definition.

We can view f as being a function of x and y since it is a function of s . Thus $f(s) = f(x, y) = f(g(t), h(t))$. This gives us a concrete way to evaluate a line integral:

$$\int_C f(s) \, ds = \int_a^b f(g(t), h(t)) \|\vec{r}'(t)\| \, dt.$$

We write this as a Key Idea, along with its three-dimensional analogue, followed by an example where we finally evaluate an integral and find an area.

Notes:

Key Idea 0 Evaluating a Line Integral

- Let C be a curve parametrized by $\vec{r}(t) = \langle g(t), h(t) \rangle$, $a \leq t \leq b$, where g and h are continuously differentiable, and let $z = f(x, y)$. Then

$$\int_C f(s) ds = \int_a^b f(g(t), h(t)) \|\vec{r}'(t)\| dt.$$

- Let C be a curve parametrized by $\vec{r}(t) = \langle g(t), h(t), k(t) \rangle$, $a \leq t \leq b$, where g, h and k are continuously differentiable, and let $w = f(x, y, z)$. Then

$$\int_C f(s) ds = \int_a^b f(g(t), h(t), k(t)) \|\vec{r}'(t)\| dt.$$

To be clear, the first point of Key Idea 0 can be used to find the area under a surface $z = f(x, y)$ and above a curve C .

Let's finally do an example where we actually compute an area.

Example 0 Evaluating a line integral: area under a surface over a curve.

Find the area under the surface $f(x, y) = \cos(x) + \sin(y) + 2$ over the curve C , which is the segment of the line $y = 2x + 1$ on $-1 \leq x \leq 1$, as shown in Figure 14.2.

SOLUTION Our first step is to represent C with a vector-valued function. Since C is a simple line, and we have an explicit relationship between y and x (namely, that $y = 2x + 1$), we can let $x = t$, $y = 2t + 1$, and write $\vec{r}(t) = \langle t, 2t + 1 \rangle$ for $-1 \leq t \leq 1$.

We find the values of f over C as $f(x, y) = f(t, 2t + 1) = \cos(t) + \sin(2t + 1) + 2$. We also need $\|\vec{r}'(t)\|$; with $\vec{r}'(t) = \langle 1, 2 \rangle$, we have $\|\vec{r}'(t)\| = \sqrt{5}$. Thus $ds = \sqrt{5} dt$.

The area we seek is

$$\begin{aligned} \int_C f(s) ds &= \int_{-1}^1 (\cos(t) + \sin(2t + 1) + 2) \sqrt{5} dt \\ &= \sqrt{5} \left(\sin(t) - \frac{1}{2} \cos(2t + 1) + 2t \right) \Big|_{-1}^1 \\ &\approx 14.418 \text{ units}^2. \end{aligned}$$

We will practice setting up and evaluating a line integral in another example,

Notes:

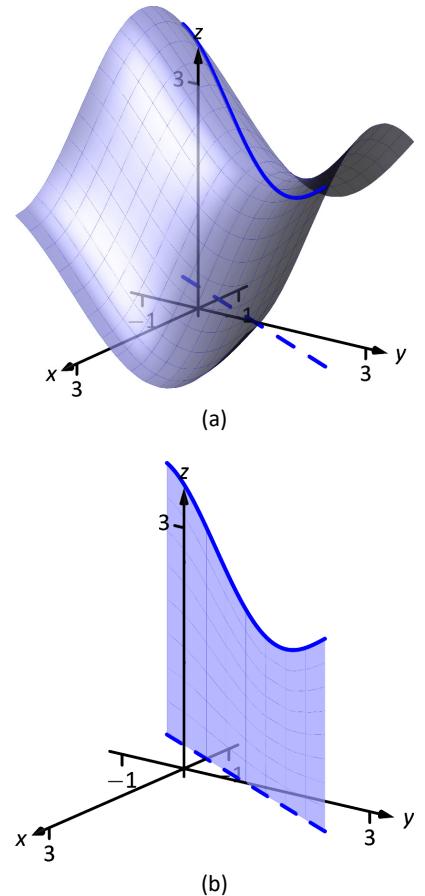


Figure 14.2: Finding area under a curve in Example 0.

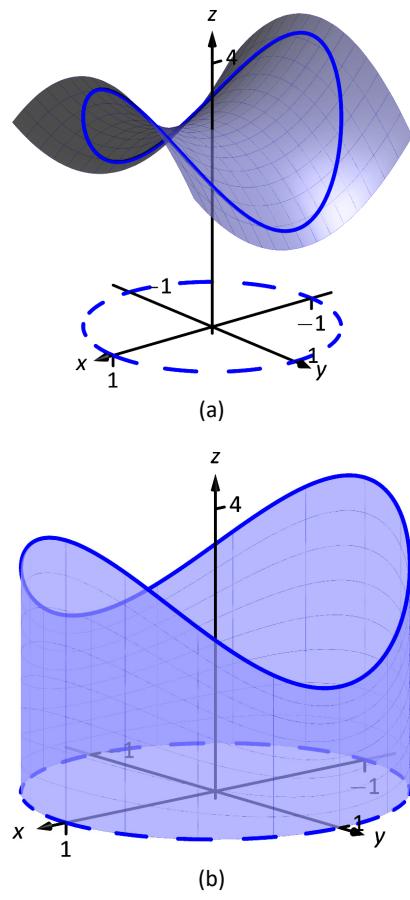


Figure 14.3: Finding area under a curve in Example 1.

then find the area described at the beginning of this section.

Example 1 Evaluating a line integral: area under a surface over a curve.

Find the area over the unit circle in the x - y plane and under the surface $f(x, y) = x^2 - y^2 + 3$, shown in Figure 14.3.

SOLUTION The curve C is the unit circle, which we will describe with the parametrization $\vec{r}(t) = \langle \cos t, \sin t \rangle$ for $0 \leq t \leq 2\pi$. We find $\|\vec{r}'(t)\| = 1$, so $ds = 1dt$.

We find the values of f over C as $f(x, y) = f(\cos t, \sin t) = \cos^2 t - \sin^2 t + 3$. Thus the area we seek is (note the use of the $\oint f(s) ds$ notation):

$$\begin{aligned} \oint_C f(s) ds &= \int_0^{2\pi} (\cos^2 t - \sin^2 t + 3) dt \\ &= 6\pi. \end{aligned}$$

(Note: we may have approximated this answer from the start. The unit circle has a circumference of 2π , and we may have guessed that due to the apparent symmetry of our surface, the average height of the surface is 3.)

We now consider the example that introduced this section.

Example 2 Evaluating a line integral: area under a surface over a curve.

Find the area under $f(x, y) = 1 - \cos(x) \sin(y)$ and over the parabola $y = x^2$, from $-1 \leq x \leq 1$.

SOLUTION We parametrize our curve C as $\vec{r}(t) = \langle t, t^2 \rangle$ for $-1 \leq t \leq 1$; we find $\|\vec{r}'(t)\| = \sqrt{1 + 4t^2}$, so $ds = \sqrt{1 + t^2} dt$.

Replacing x and y with their respective functions of t , we have $f(x, y) = f(t, t^2) = 1 - \cos(t) \sin(t^2)$. Thus the area under f and over C is found to be

$$\int_C f(s) ds = \int_{-1}^1 (1 - \cos(t) \sin(t^2)) \sqrt{1 + t^2} dt.$$

This integral is impossible to evaluate using the techniques developed in this text. We resort to a numerical approximation; accurate to two places after the decimal, we find the area is

$$= 2.17.$$

Notes:

We give one more example of finding area.

Example 3 Evaluating a line integral: area under a curve in space.

Find the area above the x - y plane and below the helix parametrized by $\vec{r}(t) = \langle \cos t, 2 \sin t, t/\pi \rangle$, for $0 \leq t \leq 2\pi$, as shown in Figure 14.4.

SOLUTION Note how this problem is different than the previous examples: here, the height is not given by a surface, but by the curve itself.

We use the given vector-valued function $\vec{r}(t)$ to determine the curve C in the x - y plane by simply using the first two components of $\vec{r}(t)$: $\vec{c}(t) = \langle \cos t, 2 \sin t \rangle$. Thus $ds = \|\vec{c}'(t)\| dt = \sqrt{\sin^2 t + 4 \cos^2 t} dt \approx 9.69$,

The height is not found by evaluating a surface over C , but rather it is given directly by the third component of $\vec{r}(t)$: t/π . Thus

$$\oint_C f(s) ds = \int_0^{2\pi} \frac{t}{\pi} \sqrt{\sin^2 t + 4 \cos^2 t} dt \approx 9.69,$$

where the approximation was obtained using numerical methods.

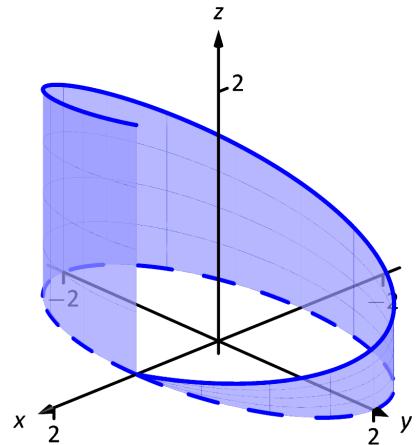


Figure 14.4: Finding area under a curve in Example 3.

Properties of Line Integrals

Many properties of line integrals can be inferred from general integration properties. For instance, if k is a scalar, then $\int_C k f(s) ds = k \int_C f(s) ds$.

One property in particular of line integrals is worth noting. If C is a curve composed of subcurves C_1 and C_2 , where they share only one point in common (see Figure 14.5(a)), then the line integral over C is the sum of the line integrals over C_1 and C_2 :

$$\int_C f(s) ds = \int_{C_1} f(s) ds + \int_{C_2} f(s) ds.$$

This property allows us to evaluate line integrals over some curves C that are not smooth. Note how in Figure 14.5(b) the curve is not smooth at D , so by our definition of the line integral we cannot evaluate $\int_C f(s) ds$. However, one can evaluate line integrals over C_1 and C_2 and their sum will be the desired quantity.

A curve C that is composed of two or more smooth curves is said to be **piecewise smooth**. In this chapter, any statement that is made about smooth curves also holds for piecewise smooth curves.

We state these properties as a theorem.

Notes:

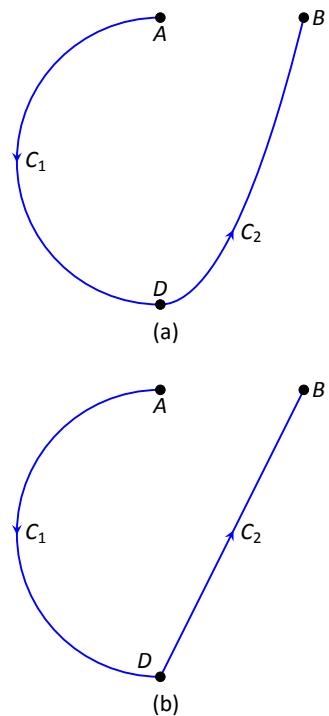


Figure 14.5: Illustrating properties of line integrals.

Theorem 0 Properties of Line Integrals Over Scalar Fields

Let C be a smooth curve parametrized by the arc-length parameter s , let f and g be continuous functions of s , and let k_1 and k_2 be scalars. Then:

$$1. \int_C (k_1 f(s) + k_2 g(s)) \, ds = k_1 \int_C f(s) \, ds + k_2 \int_C g(s) \, ds.$$

2. Let C be piecewise smooth, composed of smooth components C_1 and C_2 . Then

$$\int_C f(s) \, ds = \int_{C_1} f(s) \, ds + \int_{C_2} f(s) \, ds.$$

Mass and Center of Mass

We first learned integration as a method to find area under a curve, then later used integration to compute a variety of other quantities, such as arc length, volume, force, etc. In this section, we also introduced line integrals as a method to find area under a curve, and now we explore one more application.

Let a curve C (either in the plane or in space) represent a thin wire with variable density $\delta(s)$. We can approximate the mass of the wire by dividing the wire (i.e., the curve) into small segments and assume the density is constant across these small segments. The mass of each segment is density of the segment \times its length; by summing up the approximate mass of each segment we can approximate the total mass:

$$\text{Total Mass of Wire} = \sum \delta(s_i) \Delta s_i.$$

By taking the limit as the length of the segments approaches 0, we have the definition of the line integral as seen in Definition 0. When learning of the line integral, we let $f(s)$ represent a height; now we let $f(s) = \delta(s)$ represent a density.

We can extend this understanding of computing mass to also compute the center of mass of a thin wire. (As a reminder, the center of mass can be a useful piece of information as objects rotate about that center.) We give the relevant formulas in the next definition, followed by an example. Note the similarities between this definition and Definition ??, which gives similar properties of solids in space.

Notes:

Definition 1 Mass, Center of Mass of Thin Wire

Let a thin wire lie along a smooth curve C with continuous density function $\delta(s)$, where s is the arc length parameter.

1. The **mass** of the thin wire is $M = \int_C \delta(s) ds$.
2. The **moment about the y - z plane** is $M_{yz} = \int_C x\delta(s) ds$.
3. The **moment about the x - z plane** is $M_{xz} = \int_C y\delta(s) ds$.
4. The **moment about the x - y plane** is $M_{xy} = \int_C z\delta(s) ds$.
5. The **center of mass** of the wire is

$$(\bar{x}, \bar{y}, \bar{z}) = \left(\frac{M_{yz}}{M}, \frac{M_{xz}}{M}, \frac{M_{xy}}{M} \right).$$

Example 4 Evaluating a line integral: calculating mass.

A thin wire follows the path $\vec{r}(t) = \langle 1 + \cos t, 1 + \sin t, 1 + \sin(2t) \rangle$, $0 \leq t \leq 2\pi$. The density of the wire is determined by its position in space: $\delta(x, y, z) = y + z$ gm/cm. The wire is shown in Figure 14.6, where a light color indicates low density and a dark color represents high density. Find the mass and center of mass of the wire.

SOLUTION We compute the density of the wire as

$$\delta(x, y, z) = \delta(1 + \cos t, 1 + \sin t, 1 + \sin(2t)) = 2 + \sin t + \sin(2t).$$

We compute ds as

$$ds = \|\vec{r}'(t)\| dt = \sqrt{\sin^2 t + \cos^2 t + 4\cos^2(2t)} dt = \sqrt{1 + 4\cos^2(2t)} dt.$$

Thus the mass is

$$M = \int_C \delta(s) ds = \int_0^{2\pi} (2 + \sin t + \sin(2t)) \sqrt{1 + 4\cos^2(2t)} dt \approx 21.08 \text{ gm}.$$

Notes:

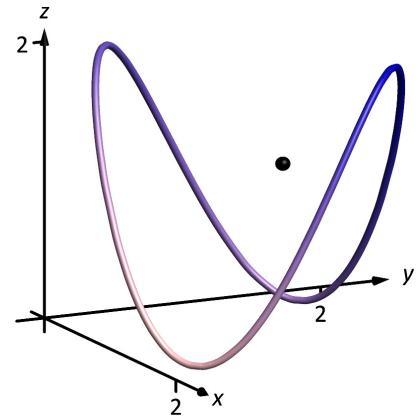


Figure 14.6: Finding the mass of a thin wire in Example 4.

We compute the moments about the coordinate planes:

$$M_{yz} = \oint_C x\delta(s) ds = \int_0^{2\pi} (1 + \cos t)(2 + \sin t + \sin(2t)) \sqrt{1 + 4\cos^2(2t)} dt \approx 21.08.$$

$$M_{xz} = \oint_C y\delta(s) ds = \int_0^{2\pi} (1 + \sin t)(2 + \sin t + \sin(2t)) \sqrt{1 + 4\cos^2(2t)} dt \approx 26.35$$

$$M_{xy} = \oint_C z\delta(s) ds = \int_0^{2\pi} (1 + \sin(2t))(2 + \sin t + \sin(2t)) \sqrt{1 + 4\cos^2(2t)} dt \approx 25.40$$

Thus the center of mass of the wire is located at

$$(\bar{x}, \bar{y}, \bar{z}) = \left(\frac{M_{yz}}{M}, \frac{M_{xz}}{M}, \frac{M_{xy}}{M} \right) \approx (1, 1.25, 1.20),$$

as indicated by the dot in Figure 14.6. Note how in this example, the curve C is “centered” about the point $(1, 1, 1)$, though the variable density of the wire pulls the center of mass out along the y and z axes.

We end this section with a callback to the Integration Review that preceded this section. A line integral looks like: $\int_C f(s) ds$. As stated before the definition of the line integral, this means “sum up, along a curve C , function values $f(s) \times$ small arc lengths.” When $f(s)$ represents a height, we have “height \times length = area.” When $f(s)$ is a density (and we use $\delta(s)$ by convention), we have “density (mass per unit length) \times length = mass.”

We’ll expand our uses for line integrals after the next section. First, we’ll investigate a new mathematical object, called a vector field.

Notes:

Exercises 14.1

Terms and Concepts

1. Explain how a line integral can be used to find the area under a curve.
2. How does the evaluation of a line integral given as $\int_C f(s) ds$ differ from a line integral given as $\oint_C f(s) ds$?
3. Why are most line integrals evaluated using Key Idea 0 instead of "directly" as $\int_C f(s) ds$?
4. Sketch a closed, piecewise smooth curve composed of three subcurves.

Problems

In Exercises 5 – 10, a planar curve C is given along with a surface f that is defined over C . Evaluate the line integral $\int_C f(s) ds$.

5. C is the line segment joining the points $(-2, -1)$ and $(1, 2)$; the surface is $f(x, y) = x^2 + y^2 + 2$.
6. C is the segment of $y = 3x + 2$ on $[1, 2]$; the surface is $f(x, y) = 5x + 2y$.
7. C is the circle with radius 2 centered at the point $(4, 2)$; the surface is $f(x, y) = 3x - y$.
8. C is the curve given by $\vec{r}(t) = \langle \cos t + t \sin t, \sin t - t \cos t \rangle$ on $[0, 2\pi]$; the surface is $f(x, y) = 5$.
9. C is the piecewise curve composed of the line segments that connect $(0, 1)$ to $(1, 1)$, then connect $(1, 1)$ to $(1, 0)$; the surface is $f(x, y) = x + y^2$.
10. C is the piecewise curve composed of the line segment joining the points $(0, 0)$ and $(1, 1)$, along with the quarter-circle parametrized by $\langle \cos t, -\sin t + 1 \rangle$ on $[0, \pi/2]$ (which

starts at the point $(1, 1)$ and ends at $(0, 0)$); the surface is $f(x, y) = x^2 + y^2$.

In Exercises 11 – 14, a planar curve C is given along with a surface f that is defined over C . Set up the line integral $\int_C f(s) ds$, then approximate its value using technology.

11. C is the portion of the parabola $y = 2x^2 + x + 1$ on $[0, 1]$; the surface is $f(x, y) = x^2 + 2y$.
12. C is the portion of the curve $y = \sin x$ on $[0, \pi]$; the surface is $f(x, y) = x$.
13. C is the ellipse given by $\vec{r}(t) = \langle 2 \cos t, \sin t \rangle$ on $[0, 2\pi]$; the surface is $f(x, y) = 10 - x^2 - y^2$.

14. C is the portion of $y = x^3$ on $[-1, 1]$; the surface is $f(x, y) = 2x + 3y + 5$.

In Exercises 15 – 18, a parametrized curve C in space is given. Find the area above the x - y plane that is under C .

15. C : $\vec{r}(t) = \langle 5t, t, t^2 \rangle$ for $1 \leq t \leq 2$.
16. C : $\vec{r}(t) = \langle \cos t, \sin t, \sin(2t) + 1 \rangle$ for $0 \leq t \leq 2\pi$.
17. C : $\vec{r}(t) = \langle 3 \cos t, 3 \sin t, t^2 \rangle$ for $0 \leq t \leq 2\pi$.
18. C : $\vec{r}(t) = \langle 3t, 4t, t \rangle$ for $0 \leq t \leq 1$.

In Exercises 19 – 20, a parametrized curve C is given that represents a thin wire with density δ . Find the mass and center of mass of the thin wire.

19. C : $\vec{r}(t) = \langle \cos t, \sin t, t \rangle$ for $0 \leq t \leq 4\pi$; $\delta(x, y, z) = z$.
20. C : $\vec{r}(t) = \langle t - t^2, t^2 - t^3, t^3 - t^4 \rangle$ for $0 \leq t \leq 1$; $\delta(x, y, z) = x + 2y + 2z$. Use technology to approximate the value of each integral.

14.2 Vector Fields

We have studied functions of two or three variables, where the input of such functions is a point (either a point in the plane or in space) and the output is a number.

We could also create functions where the input is a point (again, either in the plane or in space), but the output is a *vector*. For instance, we could create the following function: $\vec{F}(x, y) = \langle x + y, x - y \rangle$, where $\vec{F}(2, 3) = \langle 5, -1 \rangle$. We are to think of \vec{F} assigning the vector $\langle 5, -1 \rangle$ to the point $(2, 3)$; in some sense, the vector $\langle 5, -1 \rangle$ lies at the point $(2, 3)$.

Such functions are extremely useful in any context where magnitude and direction are important. For instance, we could create a function \vec{F} that represents the electromagnetic force exerted at a point by a electromagnetic field, or the velocity of air as it moves across an airfoil.

Because these functions are so important, we need to formally define them.

Definition 2 Vector Field

1. A **vector field in the plane** is a function $\vec{F}(x, y)$ whose domain is a subset of \mathbb{R}^2 and whose output is a two-dimensional vector:

$$\vec{F}(x, y) = \langle M(x, y), N(x, y) \rangle.$$

2. A **vector field in space** is a function $\vec{F}(x, y, z)$ whose domain is a subset of \mathbb{R}^3 and whose output is a three-dimensional vector:

$$\vec{F}(x, y, z) = \langle M(x, y, z), N(x, y, z), P(x, y, z) \rangle.$$

This definition may seem odd at first, as a special type of function is called a “field.” However, as the function determines a “field of vectors”, we can say the field is *defined by* the function, and thus the field *is* a function.

Visualizing vector fields helps cement this connection. When graphing a vector field in the plane, the general idea is to draw the vector $\vec{F}(x, y)$ at the point (x, y) . For instance, using $\vec{F}(x, y) = \langle x + y, x - y \rangle$ as before, at $(1, 1)$ we would draw $\langle 2, 0 \rangle$.

In Figure 14.7(a), one can see that the vector $\langle 2, 0 \rangle$ is drawn *starting from* the point $(1, 1)$. A total of 8 vectors are drawn, with the x - and y -values of $-1, 0, 1$. In many ways, the resulting graph is a mess; it is hard to tell what this field “looks like.”

In Figure 14.7(b), the same field is redrawn with each vector $\vec{F}(x, y)$ drawn *centered on* the point (x, y) . This makes for a better looking image, though the

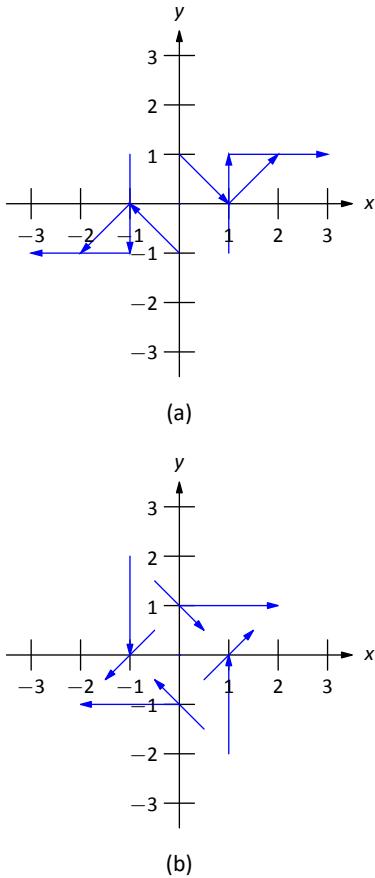


Figure 14.7: Demonstrating methods of graphing vector fields.

Notes:

long vectors can cause confusion: when one vector intersects another, the image looks cluttered.

A common way to address this problem is limit the length of each arrow, and represent long vectors with thick arrows, as done in Figure 14.8(a). Usually we do not use a graph of a vector field to determine exactly the magnitude of a particular vector. Rather, we are more concerned with the relative magnitudes of vectors: which are bigger than others? Thus limiting the length of the vectors is not problematic.

Drawing arrows with variable thickness is best done with technology; search the documentation of your favorite graphing program for terms like “vector fields” or “slope fields” to learn how. Technology obviously allows us to plot many vectors in a vector field nicely; in Figure 14.8(b), we see the same vector field drawn with many vectors, and finally get a clear picture of how this vector field behaves. (If this vector field represented the velocity of air moving across a flat surface, we could see that the air tends to move either to the upper-right or lower-left, and moves very slowly near the origin.)

We can similarly plot vector fields in space, as shown in Figure 14.9, though it is not often done. The plots get very busy very quickly, as there are lots of arrows drawn in a small amount of space. In Figure 14.9 the field $\vec{F} = \langle -y, x, z \rangle$ is graphed. If one could view the graph from above, one could see the arrows point in a circle about the z -axis. One should also note how the arrows far from the origin are larger than those close to the origin.

It is good practice to try to visualize certain vector fields in one’s head. For instance, consider a point mass at the origin and the vector field that represents the gravitational force exerted by the mass at any point in the room. The field would consist of arrows pointing toward the origin, increasing in size as they near the origin (as the gravitational pull is strongest near the point mass).

Vector Field Notation and Del Operator

Definition 2 defines a vector field \vec{F} using the notation

$$\vec{F}(x, y) = \langle M(x, y), N(x, y) \rangle \quad \text{and} \quad \vec{F}(x, y, z) = \langle M(x, y, z), N(x, y, z), P(x, y, z) \rangle.$$

That is, the components of \vec{F} are each functions of x and y (and also z in space). As done in other contexts, we will drop the “of x , y and z ” portions of the notation and refer to vector fields in the plane and in space as

$$\vec{F} = \langle M, N \rangle \quad \text{and} \quad \vec{F} = \langle M, N, P \rangle,$$

respectively, as this shorthand is quite convenient.

Another item of notation will become useful: the “del operator.” Recall in Section ?? how we used the symbol ∇ (pronounced “del”) to represent the

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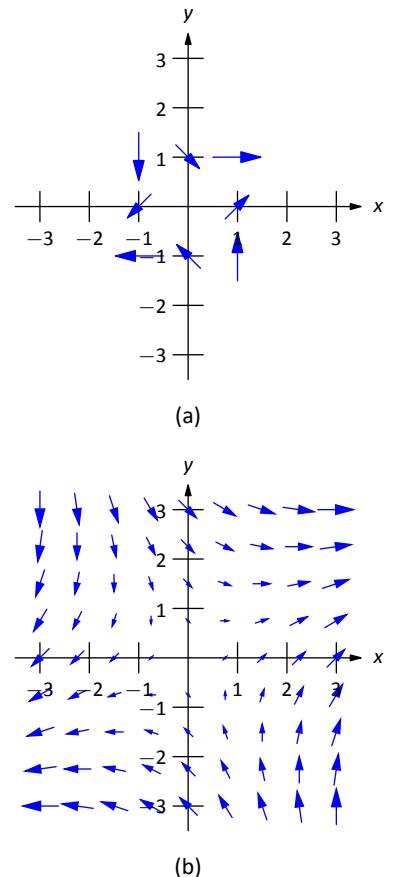


Figure 14.8: Demonstrating methods of graphing vector fields.

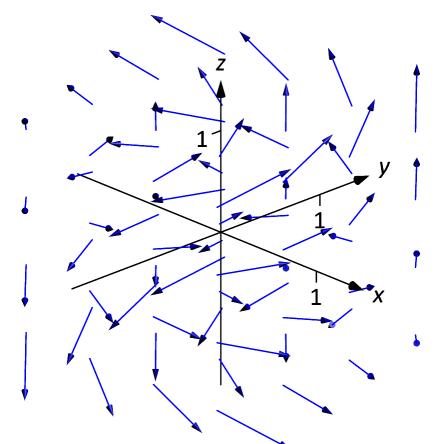


Figure 14.9: Graphing a vector field in space.

gradient of a function of two variables. That is, if $z = f(x, y)$, then “del f ” $= \nabla f = \langle f_x, f_y \rangle$.

We now define ∇ to be the “del operator.” It is a vector whose components are partial derivative operations.

$$\text{In the plane, } \nabla = \left\langle \frac{\partial}{\partial x}, \frac{\partial}{\partial y} \right\rangle; \text{ in space, } \nabla = \left\langle \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right\rangle.$$

Let $\vec{F} = \langle x + \sin y, y^2 + z, x^2 \rangle$. We can use vector operations and find the dot product of ∇ and \vec{F} :

$$\begin{aligned}\nabla \cdot \vec{F} &= \left\langle \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right\rangle \cdot \langle x + \sin y, y^2 + z, x^2 \rangle \\ &= \frac{\partial}{\partial x}(x + \sin y) + \frac{\partial}{\partial y}(y^2 + z) + \frac{\partial}{\partial z}(x^2) \\ &= 1 + 2y.\end{aligned}$$

We can also compute their cross products:

$$\begin{aligned}\nabla \times \vec{F} &= \left\langle \frac{\partial}{\partial y}(x^2) - \frac{\partial}{\partial z}(y^2 + z), \frac{\partial}{\partial z}(x + \sin y) - \frac{\partial}{\partial x}(x^2), \frac{\partial}{\partial x}(y^2 + z) - \frac{\partial}{\partial y}(x + \sin y) \right\rangle \\ &= \langle -1, -2x, -\cos y \rangle.\end{aligned}$$

We do not yet know why we would want to compute the above. However, as we next learn about properties of vector fields, we will see how these dot and cross products with the del operator are quite useful.

Divergence and Curl

Two properties of vector fields will prove themselves to be very important: divergence and curl. Each is a special “derivative” of a vector field; that is, each measures an instantaneous rate of change of a vector field.

If the vector field represents the velocity of a fluid or gas, then the **divergence** of the field is a measure of the “compressibility” of the fluid. If the divergence is negative at a point, it means that the fluid is compressing: more fluid is going into the point than is going out. If the divergence is positive, it means the fluid is expanding: more fluid is going out at that point than going in. A divergence of zero means the same amount of fluid is going in as is going out. If the divergence is zero at all points, we say the field is **incompressible**.

It turns out that the proper measure of divergence is simply $\nabla \cdot \vec{F}$, as stated in the following definition.

Notes:

Definition 3 Divergence of a Vector Field

The **divergence** of a vector field \vec{F} is

$$\operatorname{div} \vec{F} = \nabla \cdot \vec{F}.$$

- In the plane, with $\vec{F} = \langle M, N \rangle$, $\operatorname{div} \vec{F} = M_x + N_y$.
- In space, with $\vec{F} = \langle M, N, P \rangle$, $\operatorname{div} \vec{F} = M_x + N_y + P_z$.

Curl is a measure of the spinning action of the field. Let \vec{F} represent the flow of water over a flat surface. If a small round cork were held in place at a point in the water, would the water cause the cork to spin? No spin corresponds to zero curl; counterclockwise spin corresponds to positive curl and clockwise spin corresponds to negative curl.

In space, things are a bit more complicated. Again let \vec{F} represent the flow of water, and imagine suspending a tennis ball in one location in this flow. The water may cause the ball to spin along an axis. If so, the curl of the vector field is a *vector* (not a *scalar*, as before), parallel to the axis of rotation, following a right hand rule: when the thumb of one's right hand points in the direction of the curl, the ball will spin in the direction of the curling fingers of the hand.

In space, it turns out the proper measure of curl is $\nabla \times \vec{F}$, as stated in the following definition. To find the curl of a planar vector field $\vec{F} = \langle M, N \rangle$, embed it into space as $\vec{F} = \langle M, N, 0 \rangle$ and apply the cross product definition. Since M and N are functions of just x and y (and not z), all partial derivatives with respect to z become 0 and the result is simply $\langle 0, 0, N_x - M_y \rangle$. The third component is the measure of curl.

Definition 4 Curl of a Vector Field

- Let $\vec{F} = \langle M, N \rangle$ be a vector field in the plane. The **curl** of \vec{F} is $\operatorname{curl} \vec{F} = N_x - M_y$.
- Let $\vec{F} = \langle M, N, P \rangle$ be a vector field in space. The **curl** of \vec{F} is $\operatorname{curl} \vec{F} = \nabla \times \vec{F} = \langle P_y - N_z, M_z - P_x, N_x - M_y \rangle$.

We adopt the convention of referring to curl as $\nabla \times \vec{F}$, regardless of whether \vec{F} is a vector field in two or three dimensions.

We now practice computing these quantities.

Notes:

Example 5 Computing divergence and curl of planar vector fields

For each of the planar vector fields given below, view its graph and try to visually determine if its divergence and curl are 0. Then compute the divergence and curl.

1. $\vec{F} = \langle y, 0 \rangle$ (see Figure 14.10(a))
2. $\vec{F} = \langle -y, x \rangle$ (see Figure 14.10(b))
3. $\vec{F} = \langle x, y \rangle$ (see Figure 14.11(a))
4. $\vec{F} = \langle \cos y, \sin x \rangle$ (see Figure 14.11(b))

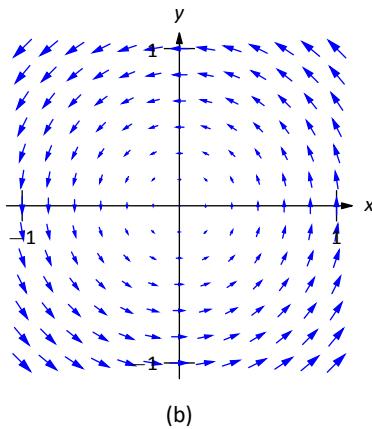
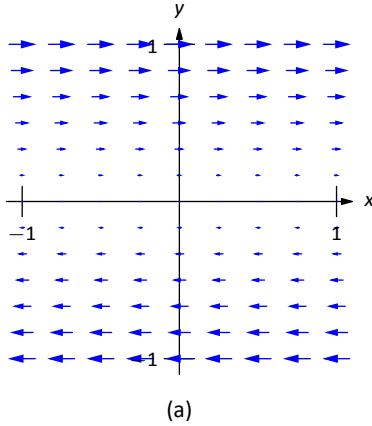


Figure 14.10: The vector fields in parts (a) and (b) in Example 5.

SOLUTION

1. The arrow sizes are constant along any horizontal line, so if one were to draw a small box anywhere on the graph, it would seem that the same amount of fluid would enter the box as exit. Therefore it seems the divergence is zero; it is, as

$$\operatorname{div} \vec{F} = \nabla \cdot \vec{F} = M_x + N_y = \frac{\partial}{\partial x}(y) + \frac{\partial}{\partial y}(0) = 0.$$

At any point on the x -axis, arrows above it move to the right and arrows below it move to the left, indicating that a cork placed on the axis would spin clockwise. A cork placed anywhere above the x -axis would have water above it moving to the right faster than the water below it, also creating a clockwise spin. A clockwise spin also appears to be created at points below the x -axis. Thus it seems the curl should be negative (and not zero). Indeed, it is:

$$\operatorname{curl} \vec{F} = \nabla \times \vec{F} = N_x - M_y = \frac{\partial}{\partial x}(0) - \frac{\partial}{\partial y}(y) = -1.$$

2. It appears that all vectors that lie on a circle of radius r , centered at the origin, have the same length (and indeed this is true). That implies that the divergence should be zero: draw any box on the graph, and any fluid coming in will lie along a circle that takes the same amount of fluid out. Indeed, the divergence is zero, as

$$\operatorname{div} \vec{F} = \nabla \cdot \vec{F} = M_x + N_y = \frac{\partial}{\partial x}(-y) + \frac{\partial}{\partial y}(x) = 0.$$

Clearly this field moves objects in a circle, but would it induce a cork to spin? It appears that yes, it would: place a cork anywhere in the flow, and

Notes:

the point of the cork closest to the origin would feel less flow than the point on the cork farthest from the origin, which would induce a counter-clockwise flow. Indeed, the curl is positive:

$$\operatorname{curl} \vec{F} = \nabla \times \vec{F} = N_x - M_y = \frac{\partial}{\partial x}(x) - \frac{\partial}{\partial y}(-y) = 1 - (-1) = 2.$$

Since the curl is constant, we conclude the induced spin is the same no matter where one is in this field.

3. At the origin, there are many arrows pointing out but no arrows pointing in. We conclude that at the origin, the divergence must be positive (and not zero). If one were to draw a box anywhere in the field, the edges farther from the origin would have larger arrows passing through them than the edges close to the origin, indicating that more is going from a point than going in. This indicates a positive (and not zero) divergence. This is correct:

$$\operatorname{div} \vec{F} = \nabla \cdot \vec{F} = M_x + N_y = \frac{\partial}{\partial x}(x) + \frac{\partial}{\partial y}(y) = 1 + 1 = 2.$$

One may find this curl to be harder to determine visually than previous examples. One might note that any arrow that induces a clockwise spin on a cork will have an equally sized arrow inducing a counterclockwise spin on the other side, indicating no spin and no curl. This is correct, as

$$\operatorname{curl} \vec{F} = \nabla \times \vec{F} = N_x - M_y = \frac{\partial}{\partial x}(y) - \frac{\partial}{\partial y}(x) = 0.$$

4. One might find this divergence hard to determine visually as large arrows appear in close proximity to small arrows, each pointing in different directions. Instead of trying to rationalize a guess, we compute the divergence:

$$\operatorname{div} \vec{F} = \nabla \cdot \vec{F} = M_x + N_y = \frac{\partial}{\partial x}(\cos y) + \frac{\partial}{\partial y}(\sin x) = 0.$$

Perhaps surprisingly, the divergence is 0.

Will all the loops of different directions in the field, one is apt to reason the curl is variable. Indeed, it is:

$$\operatorname{curl} \vec{F} = \nabla \times \vec{F} = N_x - M_y = \frac{\partial}{\partial x}(\sin x) - \frac{\partial}{\partial y}(\cos y) = \cos x + \sin y.$$

Depending on the values of x and y , the curl may be positive, negative, or zero.

Notes:

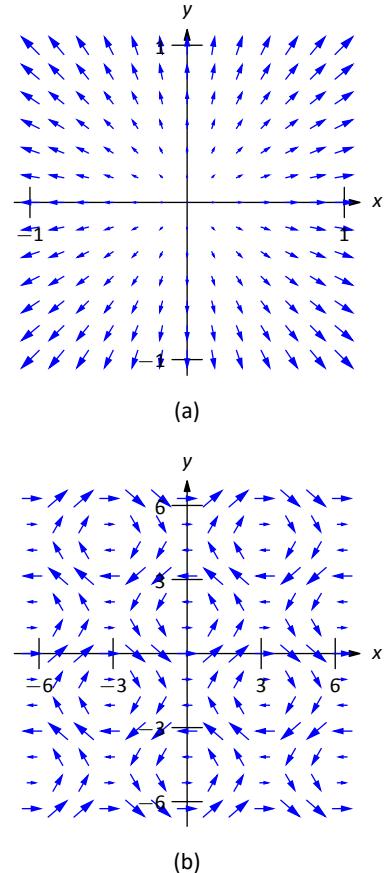


Figure 14.11: The vector fields in parts (c) and (d) in Example 5.

Example 6 Computing divergence and curl of vector fields in space

Compute the divergence and curl of each of the following vector fields.

$$1. \vec{F} = \langle x^2 + y + z, -x - z, x + y \rangle$$

$$2. \vec{F} = \langle e^{xy}, \sin(x + z), x^2 + y \rangle$$

SOLUTION We compute the divergence and curl of each field following the definitions.

$$1. \operatorname{div} \vec{F} = \nabla \cdot \vec{F} = M_x + N_y + P_z = 2x + 0 + 0 = 2x.$$

$$\begin{aligned} \operatorname{curl} \vec{F} &= \nabla \times \vec{F} = \langle P_y - N_z, M_z - P_x, N_x - M_y \rangle \\ &= \langle 1 - (-1), 1 - 1, -1 - (1) \rangle = \langle 2, 0, -2 \rangle. \end{aligned}$$

For this particular field, no matter the location in space, a spin is induced with axis parallel to $\langle 2, 0, -2 \rangle$.

$$2. \operatorname{div} \vec{F} = \nabla \cdot \vec{F} = M_x + N_y + P_z = ye^{xy} + 0 + 0 = ye^{xy}.$$

$$\begin{aligned} \operatorname{curl} \vec{F} &= \nabla \times \vec{F} = \langle P_y - N_z, M_z - P_x, N_x - M_y \rangle \\ &= \langle 1 - \cos(x + z), -2x, \cos(x + z) - xe^{xy} \rangle. \end{aligned}$$

Example 7 Creating a field representing gravitational force

The force of gravity between two objects is inversely proportional to the square of the distance between the objects. Locate a point mass at the origin. Create a vector field \vec{F} that represents the gravitational pull of the point mass at any point (x, y, z) . Find the divergence and curl of this field.

SOLUTION The point mass pulls toward the origin, so at (x, y, z) , the force will pull in the direction of $\langle -x, -y, -z \rangle$. To get the proper magnitude, it will be useful to find the unit vector in this direction. Dividing by its magnitude, we have

$$\vec{u} = \left\langle \frac{-x}{\sqrt{x^2 + y^2 + z^2}}, \frac{-y}{\sqrt{x^2 + y^2 + z^2}}, \frac{-z}{\sqrt{x^2 + y^2 + z^2}} \right\rangle.$$

The magnitude of the force is inversely proportional to the square of the distance between the two points. Letting k be the constant of proportionality, we have the magnitude as $\frac{k}{x^2 + y^2 + z^2}$. Multiplying this magnitude by the unit vector above, we have the desired vector field:

$$\vec{F} = \left\langle \frac{-kx}{(x^2 + y^2 + z^2)^{3/2}}, \frac{-ky}{(x^2 + y^2 + z^2)^{3/2}}, \frac{-kz}{(x^2 + y^2 + z^2)^{3/2}} \right\rangle.$$

Notes:

We leave it to the reader to confirm that $\operatorname{div} \vec{F} = 0$ and $\operatorname{curl} \vec{F} = \vec{0}$.

The analogous planar vector field is given in Figure 14.12. Note how all arrows point to the origin, and the magnitude gets very small when “far” from the origin.

A function $z = f(x, y)$ naturally induces a vector field, $\vec{F} = \nabla f = \langle f_x, f_y \rangle$. Given what we learned of the gradient in Section ??, we know that the vectors of \vec{F} point in the direction of greatest increase of f . Because of this, f is said to be the **potential function** of \vec{F} . Vector fields that are the gradient of potential functions will play an important role in the next section.

Example 8 A vector field that is the gradient of a potential function

Let $f(x, y) = 3 - x^2 - 2y^2$ and let $\vec{F} = \nabla f$. Graph \vec{F} , and find the divergence and curl of \vec{F} .

SOLUTION Given f , we find $\vec{F} = \nabla f = \langle -2x, -4y \rangle$. A graph of \vec{F} is given in Figure 14.13(a). In part (b) of the figure, the vector field is given along with a graph of the surface itself; one can see how each vector is pointing in the direction of “steepest uphill”, which, in this case, is not simply just “toward the origin.”

We leave it to the reader to confirm that $\operatorname{div} \vec{F} = -6$ and $\operatorname{curl} \vec{F} = 0$.

There are some important concepts visited in this section that will be revisited in subsequent sections and again at the very end of this chapter. One is: given a vector field \vec{F} , both $\operatorname{div} \vec{F}$ and $\operatorname{curl} \vec{F}$ are measures of rates of change of \vec{F} . The divergence measures how much the field spreads (diverges) at a point, and the curl measures how much the field twists (curls) at a point. Another important concept is this: given $z = f(x, y)$, the gradient ∇f is also a measure of a rate of change of f . We will see how the integrals of these rates of change produce meaningful results.

This section introduces the concept of a vector field. The next section “applies calculus” to vector fields. A common application is this: let \vec{F} be a vector field representing a force (hence it is called a “force field,” though this name has a decidedly comic-book feel) and let a particle move along a curve C under the influence of this force. What work is performed by the field on this particle? The solution lies in correctly applying the concepts of line integrals in the context of vector fields.

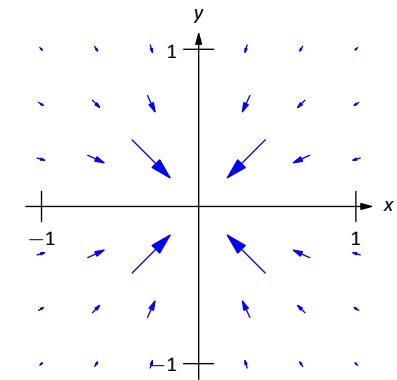
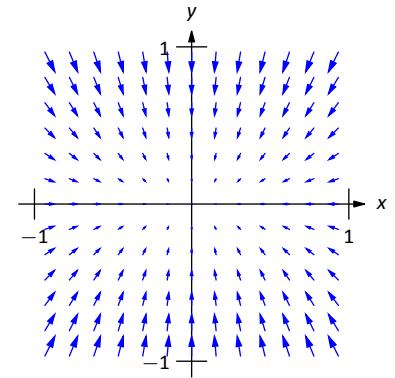
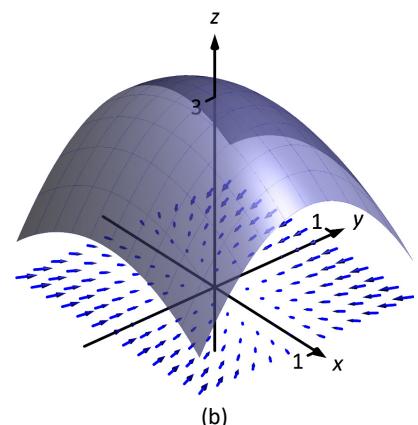


Figure 14.12: A vector field representing a planar gravitational force.



(a)



(b)

Figure 14.13: A graph of a function $z = f(x, y)$ and the vector field $\vec{F} = \nabla f$ in Example 8.

Notes:

Exercises 14.2

Terms and Concepts

1. Give two quantities that can be represented by a vector field in the plane or in space.
2. In your own words, describe what it means for a vector field to have a negative divergence at a point.
3. In your own words, describe what it means for a vector field to have a negative curl at a point.
4. The divergence of a vector field \vec{F} at a particular point is 0. Does this mean that \vec{F} is incompressible? Why/why not?

Problems

In Exercises 5 – 8, sketch the given vector field over the rectangle with opposing corners $(-2, -2)$ and $(2, 2)$, sketching one vector for every point with integer coordinates (i.e., at $(0, 0), (1, 2)$, etc.).

5. $\vec{F} = \langle x, 0 \rangle$

6. $\vec{F} = \langle 0, x \rangle$

7. $\vec{F} = \langle 1, -1 \rangle$

8. $\vec{F} = \langle y^2, 1 \rangle$

In Exercises 9 – 18, find the divergence and curl of the given vector field.

9. $\vec{F} = \langle x, y^2 \rangle$

10. $\vec{F} = \langle -y^2, x \rangle$

11. $\vec{F} = \langle \cos(xy), \sin(xy) \rangle$

12. $\vec{F} = \left\langle \frac{-2x}{(x^2 + y^2)^2}, \frac{-2y}{(x^2 + y^2)^2} \right\rangle$

13. $\vec{F} = \langle x + y, y + z, x + z \rangle$

14. $\vec{F} = \langle x^2 + z^2, x^2 + y^2, y^2 + z^2 \rangle$

15. $\vec{F} = \nabla f$, where $f(x, y) = \frac{1}{2}x^2 + \frac{1}{3}y^3$.

16. $\vec{F} = \nabla f$, where $f(x, y) = x^2y$.

17. $\vec{F} = \nabla f$, where $f(x, y, z) = x^2y + \sin z$.

18. $\vec{F} = \nabla f$, where $f(x, y, z) = \frac{1}{x^2 + y^2 + z^2}$.

14.3 Line Integrals over Vector Fields

Suppose a particle moves along a curve C under the influence of an electromagnetic force described by a vector field \vec{F} . Since a force is inducing motion, work is performed. How can we calculate how much work is performed?

Recall that when moving in a straight line, if \vec{F} represents a constant force and \vec{d} represents the direction and length of travel, then work is simply $W = \vec{F} \cdot \vec{d}$. However, we generally want to be able to calculate work even if \vec{F} is not constant and C is not a straight line.

As we have practiced many times before, we can calculate work by first approximating, then refining our approximation through a limit that leads to integration.

Assume as we did in Section 14.1 that C can be parametrized by the arc length parameter s . Over a short piece of the curve with length ds , the curve is approximately straight and our force is approximately constant. The straight-line direction of this short length of curve is given by \vec{T} , the unit tangent vector; let $\vec{d} = \vec{T} ds$, which gives the direction and magnitude of a small section of C . Thus work over this small section of C is $\vec{F} \cdot \vec{d} = \vec{F} \cdot \vec{T} ds$.

Summing up all the work over these small segments gives an approximation of the work performed. By taking the limit as ds goes to zero, and hence the number of segments approaches infinity, we can obtain the exact amount of work. Following the logic presented at the beginning of this chapter in the Integration Review, we see that

$$W = \int_C \vec{F} \cdot \vec{T} ds,$$

a line integral.

This line integral is beautiful in its simplicity, yet is not so useful in making actual computations (largely because the arc length parameter is so difficult to work with). To compute actual work, we need to parametrize C with another parameter t via a vector-valued function $\vec{r}(t)$. As stated in Section 14.1, $ds = \|\vec{r}'(t)\| dt$, and recall that $\vec{T} = \vec{r}'(t)/\|\vec{r}'(t)\|$. Thus

$$W = \int_C \vec{F} \cdot \vec{T} ds = \int_C \vec{F} \cdot \frac{\vec{r}'(t)}{\|\vec{r}'(t)\|} \|\vec{r}'(t)\| dt = \int_C \vec{F} \cdot \vec{r}'(t) dt = \int_C \vec{F} \cdot d\vec{r}, \quad (14.2)$$

where the final integral uses the differential $d\vec{r}$ for $\vec{r}'(t) dt$.

These integrals are known as **line integrals over vector fields**. By contrast, the line integrals we dealt with in Section 14.1 are sometimes referred to as **line integrals over scalar fields**. Just as a vector field is defined by a function that returns a vector, a scalar field is a function that returns a scalar, such as $z = f(x, y)$. We waited until now to introduce this terminology so we could contrast the concept with vector fields.

Notes:

We formally define this line integral, then give examples and applications.

Definition 5 Line Integral Over Vector Field

Let \vec{F} be a vector field with continuous components defined on a smooth curve C , parametrized by $\vec{r}(t)$, and let \vec{T} be the unit tangent vector of $\vec{r}(t)$. The **line integral over \vec{F} along C** is

$$\int_C \vec{F} \cdot d\vec{r} = \int_C \vec{F} \cdot \vec{T} ds.$$

In Definition 5, note how the dot product $\vec{F} \cdot \vec{T}$ is just a scalar. Therefore, this new line integral is really just a special kind of line integral found in Section 14.1; letting $f(s) = \vec{F}(s) \cdot \vec{T}(s)$, the right-hand side simply becomes $\int_C f(s) ds$, and we can use the techniques of that section to evaluate the integral. We combine those techniques, along with parts of Equation (14.2), to clearly state how to evaluate a line integral over a vector field in the following Key Idea.

Key Idea 1 Evaluating a Line Integral over a Vector Field

Let \vec{F} be a vector field with continuous components defined on a smooth curve C , parametrized by $\vec{r}(t)$, $a \leq t \leq b$, where \vec{r} is continuously differentiable. Then

$$\int_C \vec{F} \cdot \vec{T} ds = \int_C \vec{F} \cdot d\vec{r} = \int_a^b \vec{F}(\vec{r}(t)) \cdot \vec{r}'(t) dt.$$

An important concept implicit in this Key Idea: we can use any continuously differentiable parametrization $\vec{r}(t)$ of C that preserves the orientation of C : there isn't a "right" one. In practice, choose one that seems easy to work with.

Notation note: the above Definition and Key Idea implicitly evaluate \vec{F} along the curve C , which is parametrized by $\vec{r}(t)$. For instance, if $\vec{F} = \langle x + y, x - y \rangle$ and $\vec{r}(t) = \langle t^2, \cos t \rangle$, then evaluating \vec{F} along C means substituting the x - and y -components of $\vec{r}(t)$ in for x and y , respectively, in \vec{F} . Therefore, along C , $\vec{F} = \langle x + y, x - y \rangle = \langle t^2 + \cos t, t^2 - \cos t \rangle$. Since we are substituting the *output* of $\vec{r}(t)$ for the *input* of \vec{F} , we write this as $\vec{F}(\vec{r}(t))$. This is a slight abuse of notation as technically the input of \vec{F} is to be a *point*, not a *vector*, but this shorthand is useful.

We use an example to practice evaluating line integrals over vector fields.

Notes:

Example 9**Evaluating a line integral over a vector field: computing work**

Two particles move from $(0, 0)$ to $(1, 1)$ under the influence of the force field $\vec{F} = \langle x, x + y \rangle$. One particle follows C_1 , the line $y = x$; the other follows C_2 , the curve $y = x^4$, as shown in Figure 14.14. Force is measured in newtons and distance is measured in meters. Find the work performed by each particle.

SOLUTION To compute work, we need parametrize each path. We use $\vec{r}_1(t) = \langle t, t \rangle$ to parametrize $y = x$, and let $\vec{r}_2(t) = \langle t, t^4 \rangle$ parametrize $y = x^4$; for each, $0 \leq t \leq 1$.

Along the straight-line path, $\vec{F}(\vec{r}_1(t)) = \langle x, x + y \rangle = \langle t, t + t \rangle = \langle t, 2t \rangle$. We find $\vec{r}'_1(t) = \langle 1, 1 \rangle$. The integral that computes work is:

$$\begin{aligned}\int_{C_1} \vec{F} \cdot d\vec{r} &= \int_0^1 \langle t, 2t \rangle \cdot \langle 1, 1 \rangle \, dt \\ &= \int_0^1 3t \, dt \\ &= \frac{3}{2}t^2 \Big|_0^1 = 1.5 \text{ joules.}\end{aligned}$$

Along the curve $y = x^4$, $\vec{F}(\vec{r}_2(t)) = \langle x, x + y \rangle = \langle t, t + t^4 \rangle$. We find $\vec{r}'_2(t) = \langle 1, 1 + 4t^3 \rangle$. The work performed along this path is

$$\begin{aligned}\int_{C_2} \vec{F} \cdot d\vec{r} &= \int_0^1 \langle t, t + t^4 \rangle \cdot \langle 1, 1 + 4t^3 \rangle \, dt \\ &= \int_0^1 (t + 4t^4 + 4t^7) \, dt \\ &= \left(\frac{1}{2}t^2 + \frac{4}{5}t^5 + \frac{1}{2}t^8 \right) \Big|_0^1 = 1.8 \text{ joules.}\end{aligned}$$

Note how differing amounts of work are performed along the different paths. This should not be too surprising: the force is variable, one path is longer than the other, etc.

Example 10**Evaluating a line integral over a vector field: computing work**

Two particles move from $(-1, 1)$ to $(1, 1)$ under the influence of a force field $\vec{F} = \langle y, x \rangle$. One moves along the curve C_1 , the parabola defined by $y = 2x^2 - 1$. The other particle moves along the curve C_2 , the bottom half of the circle defined by $x^2 + (y - 1)^2 = 1$, as shown in Figure 14.15. Force is measured in pounds

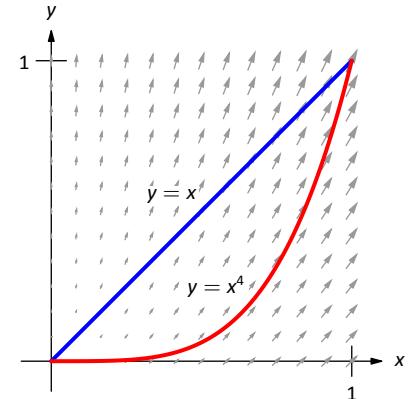


Figure 14.14: Paths through a vector field in Example 9.

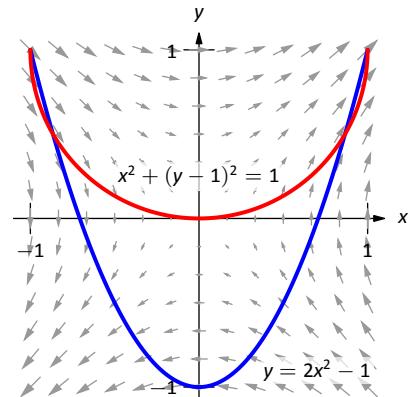


Figure 14.15: Paths through a vector field in Example 10.

Notes:

and distances are measured in feet. Find the work performed by moving each particle along its path.

SOLUTION We start by parametrizing C_1 : the parametrization $\vec{r}_1(t) = \langle t, 2t^2 - 1 \rangle$ is straightforward, giving $\vec{r}'_1 = \langle 1, 4t \rangle$. On C_1 , $\vec{F}(\vec{r}_1(t)) = \langle y, x \rangle = \langle 2t^2 - 1, t \rangle$.

Computing the work along C_1 , we have:

$$\begin{aligned}\int_{C_1} \vec{F} \cdot d\vec{r}_1 &= \int_{-1}^1 \langle 2t^2 - 1, t \rangle \cdot \langle 1, 4t \rangle dt \\ &= \int_{-1}^1 (2t^2 - 1 + 4t^2) dt = 2 \text{ ft-lbs.}\end{aligned}$$

For C_2 , it is probably simplest to parametrize the half circle using sine and cosine. Recall that $\vec{r}(t) = \langle \cos t, \sin t \rangle$ is a parametrization of the unit circle on $0 \leq t \leq 2\pi$; we add 1 to the second component to shift the circle up one unit, then restrict the domain to $\pi \leq t \leq 2\pi$ to obtain only the lower half, giving $\vec{r}_2(t) = \langle \cos t, \sin t + 1 \rangle$, $\pi \leq t \leq 2\pi$, and hence $\vec{r}'_2(t) = \langle -\sin t, \cos t \rangle$ and $\vec{F}(\vec{r}_2(t)) = \langle y, x \rangle = \langle \sin t + 1, \cos t \rangle$.

Computing the work along C_2 , we have:

$$\begin{aligned}\int_{C_2} \vec{F} \cdot d\vec{r}_2 &= \int_{\pi}^{2\pi} \langle \sin t + 1, \cos t \rangle \cdot \langle -\sin t, \cos t \rangle dt \\ &= \int_{\pi}^{2\pi} (-\sin^2 t - \sin t + \cos^2 t) dt = 2 \text{ ft-lbs.}\end{aligned}$$

Note how the work along C_1 and C_2 in this example is the same. We'll address why later in this section when *conservative fields* and *path independence* are discussed.

Properties of Line Integrals Over Vector Fields

Line integrals over vector fields share the same properties as line integrals over scalar fields, with one important distinction. The orientation of the curve C matters with line integrals over vector fields, whereas it did not matter with line integrals over scalar fields.

It is relatively easy to see why. Let C be the unit circle. The area under a surface over C is the same whether we traverse the circle in a clockwise or counterclockwise fashion, hence the line integral over a scalar field on C is the same irrespective of orientation. On the other hand, if we are computing work done by a force field, direction of travel definitely matters. Opposite directions create

Notes:

opposite signs when computing dot products, so traversing the circle in opposite directions will create line integrals that differ by a factor of -1 .

Theorem 1 Properties of Line Integrals Over Vector Fields

Let \vec{F} and \vec{G} be vector fields with continuous components defined on a smooth curve C , parametrized by $\vec{r}(t)$, and let k_1 and k_2 be scalars. Then:

$$1. \int_C (k_1 \vec{F} + k_2 \vec{G}) \cdot d\vec{r} = k_1 \int_C \vec{F} \cdot d\vec{r} + k_2 \int_C \vec{G} \cdot d\vec{r}.$$

2. Let C be piecewise smooth, composed of smooth components C_1 and C_2 . Then

$$\int_C \vec{F} \cdot d\vec{r} = \int_{C_1} \vec{F} \cdot d\vec{r} + \int_{C_2} \vec{F} \cdot d\vec{r}.$$

3. Let C^* be the curve C with opposite orientation, parametrized by \vec{r}^* . Then

$$\int_C \vec{F} \cdot d\vec{r} = - \int_{C^*} \vec{F} \cdot d\vec{r}^*.$$

We demonstrate using these properties in the following example.

Example 11 Using properties of line integrals over vector fields

Let $\vec{F} = \langle 3(y - 1/2), 1 \rangle$ and let C be the path that starts at $(0, 0)$, goes to $(1, 1)$ along the curve $y = x^3$, then returns to $(0, 0)$ along the line $y = x$, as shown in Figure 14.16. Evaluate $\oint_C \vec{F} \cdot d\vec{r}$.

SOLUTION As C is piecewise smooth, we break it into two components C_1 and C_2 , where C_1 follows the curve $y = x^3$ and C_2 follows the curve $y = x$.

We parametrize C_1 with $\vec{r}_1(t) = \langle t, t^3 \rangle$ on $0 \leq t \leq 1$, with $\vec{r}'_1(t) = \langle 1, 3t^2 \rangle$. We will use $\vec{F}(\vec{r}_1(t)) = \langle 3(t^3 - 1/2), 1 \rangle$.

While we always have unlimited ways in which to parametrize a curve, there are 2 “direct” methods to choose from when parametrizing C_2 . The parametrization $\vec{r}_2(t) = \langle t, t \rangle$, $0 \leq t \leq 1$ traces the correct line segment but with the wrong orientation. Using Property 3 of Theorem 1, we can use this parametrization and negate the result.

Another choice is to use the techniques of Section ?? to create the line with the orientation we desire. We wish to start at $(1, 1)$ and travel in the $\vec{d} = \langle -1, -1 \rangle$ direction for one length of \vec{d} , giving equation $\vec{r}(t) = \langle 1, 1 \rangle + t \langle -1, -1 \rangle = \langle 1 - t, 1 - t \rangle$ on $0 \leq t \leq 1$.

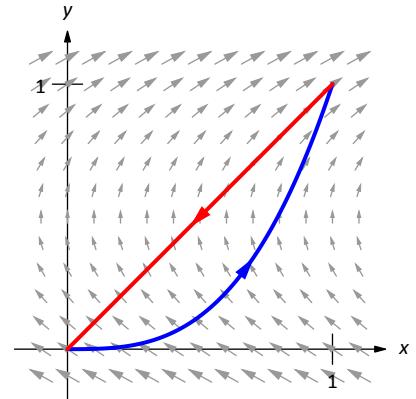


Figure 14.16: The vector field and curve in Example 11.

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Either choice is fine; we choose $\vec{r}_2(t)$ to practice using line integral properties. We find $\vec{r}'_2(t) = \langle 1, 1 \rangle$ and $\vec{F}(\vec{r}_2(t)) = \langle 3(t - 1/2), 1 \rangle$.

Evaluating the line integral (note how we subtract the integral over C_2 as the orientation of $\vec{r}_2(t)$ is opposite):

$$\begin{aligned}\oint_C \vec{F} \cdot d\vec{r} &= \int_{C_1} \vec{F} \cdot d\vec{r}_1 - \int_{C_2} \vec{F} \cdot d\vec{r}_2 \\ &= \int_0^1 \langle 3(t^3 - 1/2), 1 \rangle \cdot \langle 1, 3t^2 \rangle dt - \int_0^1 \langle 3(t - 1/2), 1 \rangle \cdot \langle 1, 1 \rangle dt \\ &= \int_0^1 (3t^3 + 3t^2 - 3/2) dt - \int_0^1 (3t - 1/2) dt \\ &= (1/4) - (1) \\ &= -3/4.\end{aligned}$$

If we interpret this integral as computing work, the negative work implies that the motion is mostly *against* the direction of the force, which seems plausible when we look at Figure 14.16.

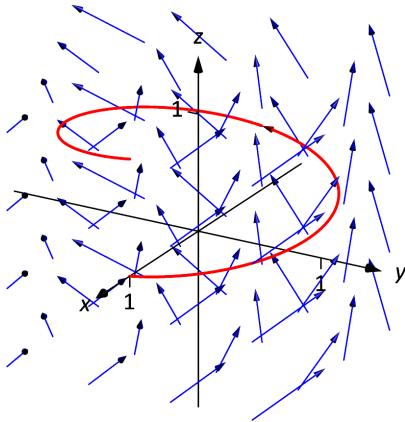


Figure 14.17: The graph of $\vec{r}(t)$ in Example 12.

Example 12 Evaluating a line integral over a vector field in space

Let $\vec{F} = \langle -y, x, 1 \rangle$, and let C be the portion of the helix given by $\vec{r}(t) = \langle \cos t, \sin t, t/(2\pi) \rangle$ on $[0, 2\pi]$, as shown in Figure 14.17. Evaluate $\int_C \vec{F} \cdot d\vec{r}$.

SOLUTION A parametrization is already given for C , so we just need to find $\vec{F}(\vec{r}(t))$ and $\vec{r}'(t)$.

We have $\vec{F}(\vec{r}(t)) = \langle -\sin t, \cos t, 1 \rangle$ and $\vec{r}'(t) = \langle -\sin t, \cos t, 1/(2\pi) \rangle$. Thus

$$\begin{aligned}\int_C \vec{F} \cdot d\vec{r} &= \int_0^{2\pi} \langle -\sin t, \cos t, 1 \rangle \cdot \langle -\sin t, \cos t, 1/(2\pi) \rangle dt \\ &= \int_0^{2\pi} \left(\sin^2 t + \cos^2 t + \frac{1}{2\pi} \right) dt \\ &= 2\pi + 1 \approx 7.28.\end{aligned}$$

The Fundamental Theorem of Line Integrals

We are preparing to make important statements about the value of certain line integrals over special vector fields. Before we can do that, we need to define some terms that describe the domains over which a vector field is defined.

A region in the plane is **connected** if any two points in the region can be joined by a piecewise smooth curve that lies entirely in the region. In Figure

Notes:

14.18, sets R_1 and R_2 are connected; set R_3 is not connected, though it is composed of two connected subregions.

A region is **simply connected** if every simple closed curve that lies entirely in the region can be continuously deformed (shrunk) to a single point without leaving the region. (A curve is **simple** if it does not cross itself.) In Figure 14.18, only set R_1 is simply connected. Region R_2 is not simple as any closed curve that goes around the “hole” in R_2 cannot be continuously shrunk to a single point. As R_3 is not even connected, it cannot be simply connected, though again it consists of two simply connected subregions.

We have applied these terms to regions of the plane, but they can be extended intuitively to regions in space (and hyperspace). In Figure 14.19(a), the sphere (at left) and the sphere with a subsphere removed (at right) are both simply connected. Any simple closed path that lies entirely within these domains can be continuously deformed into a single point. In Figure 14.19(b), neither domain is simply connected. A left, the sphere has a hole that extends its length and the pictured closed path cannot be deformed to a point. At right, two paths are illustrated on the torus that cannot be shrunk to a point.

We will use the terms connected and simply connected in subsequent definitions and theorems.

Recall how in Example 10 particles moved from $A = (-1, 1)$ to $B = (1, 1)$ along two different paths, wherein the same amount of work was performed along each path. It turns out that regardless of the choice of path from A to B , the amount of work performed under the field $\vec{F} = \langle y, x \rangle$ is the same. Since our expectation is that differing amounts of work are performed along different paths, we give such special fields a name.

Definition 6 Conservative Field, Path Independent

Let \vec{F} be a vector field defined on an open, connected domain D in the plane or in space containing points A and B . If the line integral $\int_C \vec{F} \cdot d\vec{r}$ has the same value for all choices of paths C starting at A and ending at B , then

- \vec{F} is a **conservative field** and
- The line integral $\int_C \vec{F} \cdot d\vec{r}$ is **path independent** and can be written as

$$\int_C \vec{F} \cdot d\vec{r} = \int_A^B \vec{F} \cdot d\vec{r}.$$

When \vec{F} is a conservative field, the line integral from points A to B is sometimes written as $\int_A^B \vec{F} \cdot d\vec{r}$ to emphasize the independence of its value from the

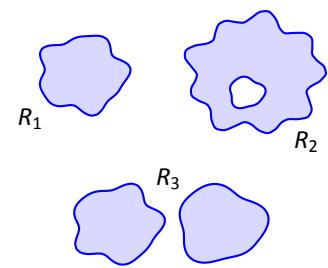


Figure 14.18: R_1 is simply connected; R_2 is connected, but not simply connected; R_3 is not connected.

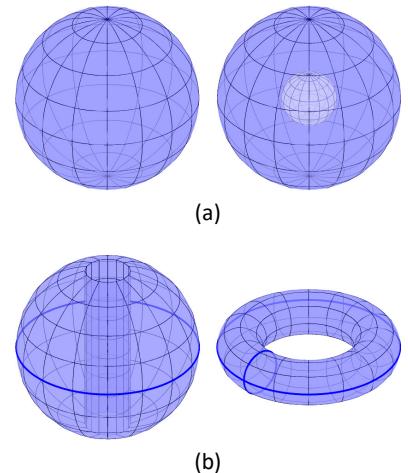


Figure 14.19: The domains in (a) are simply connected, while the domains in (b) are not.

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choice of path; all that matters are the beginning and ending points of the path.

How can we tell if a field is conservative? To show a field \vec{F} is conservative using the definition, we need to show that *all* line integrals from points A to B have the same value. It is equivalent to show that *all* line integrals over closed paths C are 0. Each of these tasks are generally nontrivial.

There is a simpler method. Consider the surface defined by $z = f(x, y) = xy$. We can compute the gradient of this function: $\nabla f = \langle f_x, f_y \rangle = \langle y, x \rangle$. Note that this is the field from Example 10, which we have claimed is conservative. We will soon give a theorem that states that a field \vec{F} is conservative if, and only if, it is the gradient of some scalar function f . To show \vec{F} is conservative, we need to determine whether or not $\vec{F} = \nabla f$ for some function f . (We'll later see that there is a yet simpler method). To recognize the special relationship between \vec{F} and f in this situation, f is given a name.

Definition 7 Potential Function

Let f be a function defined on a open domain D in the plane or in space (i.e., $z = f(x, y)$ or $w = f(x, y, z)$) and let $\vec{F} = \nabla f$, the gradient of f . Then f is a **potential function** of \vec{F} .

We now state the Fundamental Theorem of Line Integrals, which connects conservative fields and path independence to fields with potential functions.

Theorem 2 Fundamental Theorem of Line Integrals

Let \vec{F} be a vector field whose components are continuous on an open, connected domain D in the plane or in space.

1. \vec{F} is conservative if and only if there exists a differentiable function f such that $\vec{F} = \nabla f$.
2. If \vec{F} is conservative, then given any points A and B in D ,

$$\int_A^B \vec{F} \cdot d\vec{r} = f(B) - f(A).$$

Once again considering Example 10, we have $A = (-1, 1)$ and $B = (1, 1)$ and $\vec{F} = \langle y, x \rangle$. In that example, we evaluated two line integrals from A to B and found the value of each was 2. Note that $f(x, y) = xy$ is a potential function for

Notes:

\vec{F} . Following the Fundamental Theorem of Line Integrals, consider $f(B) - f(A)$:

$$f(B) - f(A) = f(1, 1) - f(-1, 1) = 1 - (-1) = 2,$$

the same value given by the line integrals.

We practice using this theorem again in the next example.

Example 13 Using the Fundamental Theorem of Line Integrals

Let $\vec{F} = \langle 3x^2y + 2x, x^3 + 1 \rangle$, $A = (0, 1)$ and $B = (1, 4)$. Use the first part of the Fundamental Theorem of Line Integrals to show that \vec{F} is conservative, then choose any path from A to B and confirm the second part of the theorem.

SOLUTION To show \vec{F} is conservative, we need to find $z = f(x, y)$ such that $\vec{F} = \nabla f = \langle f_x, f_y \rangle$. That is, we need to find f such that $f_x = 3x^2y + 2x$ and $f_y = x^3 + 1$. As all we know about f are its partial derivatives, we recover f by integration:

$$\int \frac{\partial f}{\partial x} dx = f(x, y) + C(y).$$

Note how the constant of integration is more than “just a constant”: it is anything that acts as a constant when taking a derivative with respect to x . Any function that is a function of y (containing no x 's) acts as a constant when deriving with respect to x .

Integrating f_x in this example gives:

$$\int \frac{\partial f}{\partial x} dx = \int (3x^2y + 2x) dx = x^3y + x^2 + C(y).$$

Likewise, integrating f_y with respect to y gives:

$$\int \frac{\partial f}{\partial y} dy = \int (x^3 + 1) dy = x^3y + y + C(x).$$

These two results should be equal with appropriate choices of $C(x)$ and $C(y)$:

$$x^3y + x^2 + C(y) = x^3y + y + C(x) \Rightarrow C(x) = x^2 \text{ and } C(y) = y.$$

We find $f(x, y) = x^3y + x^2 + y$, a potential function of \vec{F} . (If \vec{F} were not conservative, no choice of $C(x)$ and $C(y)$ would give equality.)

By the Fundamental Theorem of Line Integrals, regardless of the path from A to B ,

$$\begin{aligned} \int_A^B \vec{F} \cdot d\vec{r} &= f(B) - f(A) \\ &= f(1, 4) - f(0, 1) \\ &= 9 - 1 = 8. \end{aligned}$$

Notes:

To illustrate the validity of the Fundamental Theorem, we pick a path from A to B . The line between these two points would be simple to construct; we choose a slightly more complicated path by choosing the parabola $y = x^2 + 2x + 1$. This leads to the parametrization $\vec{r}(t) = \langle t, t^2 + 2t + 1 \rangle$, $0 \leq t \leq 1$, with $\vec{r}'(t) = \langle 1, 2t + 2 \rangle$. Thus

$$\begin{aligned}\int_C \vec{F} \cdot d\vec{r} &= \int_C \vec{F}(\vec{r}(t)) \cdot \vec{r}'(t) dt \\ &= \int_0^1 \langle 3(t)(t^2 + 2t + 1) + 2t, t^3 + 1 \rangle \cdot \langle 1, 2t + 2 \rangle dt \\ &= \int_0^1 (5t^4 + 8t^3 + 3t^2 + 4t + 2) dt \\ &= (t^5 + 2t^4 + t^3 + 2t^2 + 2t) \Big|_0^1 \\ &= 8,\end{aligned}$$

which matches our previous result.

The Fundamental Theorem of Line Integrals states that we can determine whether or not \vec{F} is conservative by determining whether or not \vec{F} has a potential function. This can be difficult. A simpler method exists if the domain of \vec{F} is simply connected (not just connected as needed in the Fundamental Theorem of Line Integrals), which is a reasonable requirement. We state this simpler method as a theorem.

Theorem 3 Curl of Conservative Fields

Let \vec{F} be a vector field whose components are continuous on an open, simply connected domain D in the plane or in space. Then \vec{F} is conservative if and only if $\text{curl } \vec{F} = 0$ or $\vec{0}$, respectively.

In Example 13, we showed that $\vec{F} = \langle 3x^2y + 2x, x^3 + 1 \rangle$ is conservative by finding a potential function for \vec{F} . Using the above theorem, we can show that \vec{F} is conservative much more easily by computing its curl:

$$\text{curl } \vec{F} = N_x - M_y = 3x^2 - 3x^2 = 0.$$

Notes:

Exercises 14.3

Terms and Concepts

1. T/F: In practice, the evaluation of line integrals over vector fields involves computing the magnitude of a vector-valued function.
2. Let $\vec{F}(x, y)$ be a vector field in the plane and let $\vec{r}(t)$ be a two-dimensional vector-valued function. Why is " $\vec{F}(\vec{r}(t))$ " an "abuse of notation"?
3. T/F: The orientation of a curve C matters when computing a line integral over a vector field.
4. T/F: The orientation of a curve C matters when computing a line integral over a scalar field.
5. Under "reasonable conditions," if $\operatorname{curl} \vec{F} = \vec{0}$, what can we conclude about the vector field \vec{F} ?
6. Let \vec{F} be a conservative field and let C be a closed curve. Why are we able to conclude that $\oint_C \vec{F} \cdot d\vec{r} = 0$?

Problems

In Exercises 7 – 12, a vector field \vec{F} and a curve C are given.

Evaluate $\int_C \vec{F} \cdot d\vec{r}$.

7. $\vec{F} = \langle y, y^2 \rangle$; C is the line segment from $(0, 0)$ to $(3, 1)$.
8. $\vec{F} = \langle x, x + y \rangle$; C is the portion of the parabola $y = x^2$ from $(0, 0)$ to $(1, 1)$.
9. $\vec{F} = \langle y, x \rangle$; C is the top half of the unit circle, beginning at $(1, 0)$ and ending at $(-1, 0)$.
10. $\vec{F} = \langle xy, x \rangle$; C is the portion of the curve $y = x^3$ on $-1 \leq x \leq 1$.
11. $\vec{F} = \langle z, x^2, y \rangle$; C is the line segment from $(1, 2, 3)$ to $(4, 3, 2)$.
12. $\vec{F} = \langle y + z, x + z, x + y \rangle$; C is the helix $\vec{r}(t) = \langle \cos t, \sin t, t/(2\pi) \rangle$ on $0 \leq t \leq 2\pi$.

In Exercises 13 – 16, find the work performed by the force field \vec{F} moving a particle along the path C .

13. $\vec{F} = \langle y, x^2 \rangle \text{ N}$; C is the segment of the line $y = x$ from $(0, 0)$ to $(1, 1)$, where distances are measured in meters.
14. $\vec{F} = \langle y, x^2 \rangle \text{ N}$; C is the portion of $y = \sqrt{x}$ from $(0, 0)$ to $(1, 1)$, where distances are measured in meters.
15. $\vec{F} = \langle 2xy, x^2, 1 \rangle \text{ lbs}$; C is the path from $(0, 0, 0)$ to $(2, 4, 8)$ via $\vec{r}(t) = \langle t, t^2, t^3 \rangle$ on $0 \leq t \leq 2$, where distance are measured in feet.
16. $\vec{F} = \langle 2xy, x^2, 1 \rangle \text{ lbs}$; C is the path from $(0, 0, 0)$ to $(2, 4, 8)$ via $\vec{r}(t) = \langle t, 2t, 4t \rangle$ on $0 \leq t \leq 2$, where distance are measured in feet.

In Exercises 17 – 20, a conservative vector field \vec{F} and a curve C are given.

1. Find a potential function f for \vec{F} .
2. Compute $\operatorname{curl} \vec{F}$.
3. Evaluate $\int_C \vec{F} \cdot d\vec{r}$ directly, i.e., using Key Idea 1.
4. Evaluate $\int_C \vec{F} \cdot d\vec{r}$ using the Fundamental Theorem of Line Integrals.
17. $\vec{F} = \langle y + 1, x \rangle$, C is the line segment from $(0, 1)$ to $(1, 0)$.
18. $\vec{F} = \langle 2x + y, 2y + x \rangle$, C is curve parametrized by $\vec{r}(t) = \langle t^2 - t, t^3 - t \rangle$ on $0 \leq t \leq 1$.
19. $\vec{F} = \langle 2xyz, x^2z, x^2y \rangle$, C is curve parametrized by $\vec{r}(t) = \langle 2t + 1, 3t - 1, t \rangle$ on $0 \leq t \leq 2$.
20. $\vec{F} = \langle 2x, 2y, 2z \rangle$, C is curve parametrized by $\vec{r}(t) = \langle \cos t, \sin t, \sin(2t) \rangle$ on $0 \leq t \leq 2\pi$.
21. Prove part of Theorem 3: let $\vec{F} = \langle M, N, P \rangle$ be a conservative vector field. Show that $\operatorname{curl} \vec{F} = 0$.

14.4 Flow, Flux, Green's Theorem and the Divergence Theorem

Flow and Flux

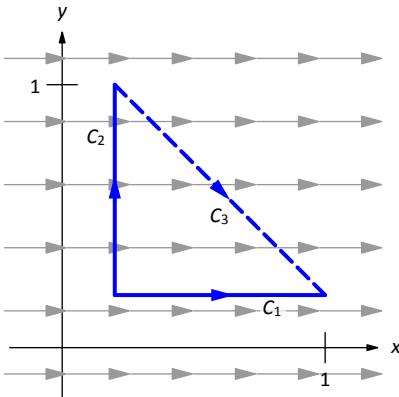


Figure 14.20: Illustrating the principles of flow and flux.

Line integrals over vector fields have the natural interpretation of computing work when \vec{F} represents a force field. It is also common to use vector fields to represent velocities. In these cases, the line integral $\int_C \vec{F} \cdot d\vec{r}$ is said to represent **flow**.

Let the vector field $\vec{F} = \langle 1, 0 \rangle$ represent the velocity of water as it moves across a smooth surface, depicted in Figure 14.20. A line integral over C will compute “how much water is moving *along* the path C .”

In the figure, “all” of the water above C_1 is moving along that curve, whereas “none” of the water above C_2 is moving along that curve (the curve and the flow of water are at right angles to each other). Because C_3 has nonzero horizontal and vertical components, “some” of the water above that curve is moving along the curve.

When C is a closed curve, we call flow **circulation**, represented by $\oint_C \vec{F} \cdot d\vec{r}$.

The “opposite” of flow is **flux**, a measure of “how much water is moving *across* the path C .” If a curve represents a filter in flowing water, flux measures how much water will pass through the filter. Considering again Figure 14.20, we see that a screen along C_1 will not filter any water as no water passes across that curve. Because of the nature of this field, C_2 and C_3 each filter the same amount of water per second.

The terms “flow” and “flux” are used apart from velocity fields, too. Flow is measured by $\int_C \vec{F} \cdot d\vec{r}$, which is the same as $\int_C \vec{F} \cdot \vec{T} ds$ by Definition 5. That is, flow is a summation of the amount of \vec{F} that is *tangent* to the curve C .

By contrast, flux is a summation of the amount of \vec{F} that is *orthogonal* to the direction of travel. To capture this orthogonal amount of \vec{F} , we use $\int_C \vec{F} \cdot \vec{n} ds$ to measure flux, where \vec{n} is a unit vector orthogonal to the curve C . (Later, we’ll measure flux across surfaces, too. For example, in physics it is useful to measure the amount of a magnetic field that passes through a surface.)

How is \vec{n} determined? We’ll later see that if C is a closed curve, we’ll want \vec{n} to point to the outside of the curve (measuring how much is “going out”). We’ll also adopt the convention that closed curves should be traversed counterclockwise.

(If C is a complicated closed curve, it can be difficult to determine what “counterclockwise” means. Consider Figure 14.21. Seeing the curve as a whole, we know which way “counterclockwise” is. If we zoom in on point A , one might incorrectly choose to traverse the path in the wrong direction. So we offer this definition: *a closed curve is being traversed counterclockwise if the outside is to the right of the path and the inside is to the left.*)

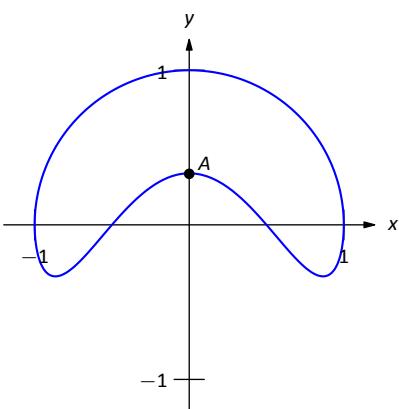


Figure 14.21: Determining “counterclockwise” is not always simple without a good definition.

Notes:

When a curve C is traversed counterclockwise by $\vec{r}(t) = \langle f(t), g(t) \rangle$, we rotate \vec{T} clockwise 90° to obtain \vec{n} :

$$\vec{T} = \frac{\langle f'(t), g'(t) \rangle}{\| \vec{r}'(t) \|} \Rightarrow \vec{n} = \frac{\langle g'(t), -f'(t) \rangle}{\| \vec{r}'(t) \|}.$$

Letting $\vec{F} = \langle M, N \rangle$, we calculate flux as:

$$\begin{aligned} \int_C \vec{F} \cdot \vec{n} \, ds &= \int_C \vec{F} \cdot \frac{\langle g'(t), -f'(t) \rangle}{\| \vec{r}'(t) \|} \| \vec{r}'(t) \| \, dt \\ &= \int_C \langle M, N \rangle \cdot \langle g'(t), -f'(t) \rangle \, dt \\ &= \int_C (M g'(t) - N f'(t)) \, dt \\ &= \int_C M g'(t) \, dt - \int_C N f'(t) \, dt. \end{aligned}$$

As the x and y components of $\vec{r}(t)$ are $f(t)$ and $g(t)$ respectively, the differentials of x and y are $dx = f'(t)dt$ and $dy = g'(t)dt$. We can then write the above integrals as:

$$= \int_C M \, dy - \int_C N \, dx.$$

This is often written as one integral (not incorrectly, though somewhat confusingly, as this one integral has two “d’s”):

$$= \int_C M \, dy - N \, dx.$$

We summarize the above in the following definition.

Notes:

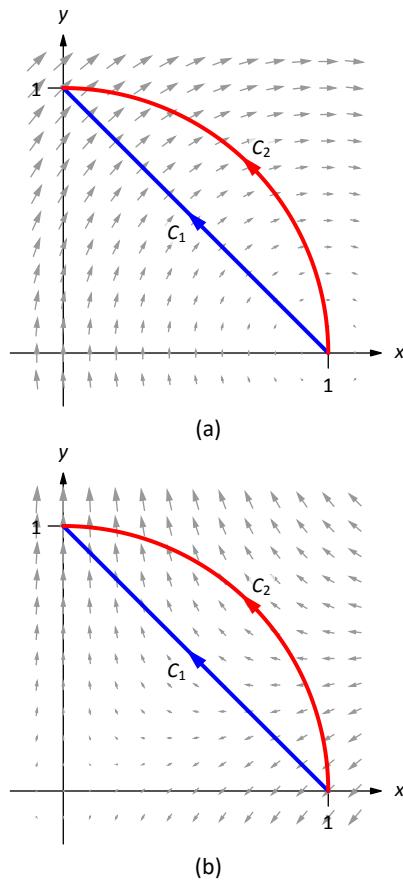


Figure 14.22: Illustrating the curves and vector fields in Example 14. In (a) the vector field is \vec{F}_1 , and in (b) the vector field is \vec{F}_2 .

Definition 8 Flow, Flux

Let $\vec{F} = \langle M, N \rangle$ be a vector field with continuous components defined on a smooth curve C , parametrized by $\vec{r}(t) = \langle f(t), g(t) \rangle$, let \vec{T} be the unit tangent vector of $\vec{r}(t)$, and let \vec{n} be the clockwise 90° degree rotation of \vec{T} .

- The **flow** of \vec{F} over C is

$$\int_C \vec{F} \cdot \vec{T} ds = \int_C \vec{F} \cdot d\vec{r}.$$

- The **flux** of \vec{F} over C is

$$\int_C \vec{F} \cdot \vec{n} ds = \int_C M dy - N dx = \int_C (Mg'(t) - Nf'(t)) dt.$$

This definition of flow also holds for curves in space, though it does not make sense to measure “flux across a curve” in space.

Measuring flow is essentially the same as finding work performed by a force as done in the previous examples. Therefore we practice finding only flux in the following example.

Example 14 Finding flux across curves in the plane

Curves C_1 and C_2 each start at $(1, 0)$ and end at $(0, 1)$, where C_1 follows the line $y = 1 - x$ and C_2 follows the unit circle, as shown in Figure 14.22. Find the flux across both curves for the vector fields $\vec{F}_1 = \langle y, -x + 1 \rangle$ and $\vec{F}_2 = \langle -x, 2y - x \rangle$.

SOLUTION We begin by finding parametrizations of C_1 and C_2 . As done in Example 11, parametrize C_1 by creating the line that starts at $(1, 0)$ and moves in the $\langle -1, 1 \rangle$ direction: $\vec{r}_1(t) = \langle 1, 0 \rangle + t \langle -1, 1 \rangle = \langle 1 - t, t \rangle$, for $0 \leq t \leq 1$. We parametrize C_2 with the familiar $\vec{r}_2(t) = \langle \cos t, \sin t \rangle$ on $0 \leq t \leq \pi/2$. For reference later, we give each function and its derivative below:

$$\vec{r}_1(t) = \langle 1 - t, t \rangle, \quad \vec{r}'_1(t) = \langle -1, 1 \rangle.$$

$$\vec{r}_2(t) = \langle \cos t, \sin t \rangle, \quad \vec{r}'_2(t) = \langle -\sin t, \cos t \rangle.$$

When $\vec{F} = \vec{F}_1 = \langle y, -x + 1 \rangle$ (as shown in Figure 14.22(a)), over C_1 we have $M = y$ and $N = -x + 1 = -(1-t) + 1 = t$. Using Definition 8, we compute

Notes:

the flux:

$$\begin{aligned}\int_{C_1} \vec{F} \cdot \vec{n} \, ds &= \int_{C_1} (Mg'(t) - Nf'(t)) \, dt \\ &= \int_0^1 (t(1) - t(-1)) \, dt \\ &= \int_0^1 2t \, dt \\ &= 1.\end{aligned}$$

Over C_2 , we have $M = y = \sin t$ and $N = -x + 1 = 1 - \cos t$. Thus the flux across C_2 is:

$$\begin{aligned}\int_{C_1} \vec{F} \cdot \vec{n} \, ds &= \int_{C_1} (Mg'(t) - Nf'(t)) \, dt \\ &= \int_0^{\pi/2} ((\sin t)(\cos t) - (1 - \cos t)(-\sin t)) \, dt \\ &= \int_0^{\pi/2} \sin t \, dt \\ &= 1.\end{aligned}$$

Notice how the flux was the same across both curves. This won't hold true when we change the vector field.

When $\vec{F} = \vec{F}_2 = \langle -x, 2y - x \rangle$ (as shown in Figure 14.22(b)), over C_1 we have $M = -x = t - 1$ and $N = 2y - x = 2t - (1 - t) = 3t - 1$. Computing the flux across C_1 :

$$\begin{aligned}\int_{C_1} \vec{F} \cdot \vec{n} \, ds &= \int_{C_1} (Mg'(t) - Nf'(t)) \, dt \\ &= \int_0^1 ((t - 1)(1) - (3t - 1)(-1)) \, dt \\ &= \int_0^1 (4t - 2) \, dt \\ &= 0.\end{aligned}$$

Over C_2 , we have $M = -x = -\cos t$ and $N = 2y - x = 2\sin t - \cos t$. Thus the

Notes:

flux across C_2 is:

$$\begin{aligned}\int_{C_1} \vec{F} \cdot \vec{n} \, ds &= \int_{C_1} (Mg'(t) - Nf'(t)) \, dt \\ &= \int_0^{\pi/2} ((-\cos t)(\cos t) - (2\sin t - \cos t)(-\sin t)) \, dt \\ &= \int_0^{\pi/2} (2\sin^2 t - \sin t \cos t - \cos^2 t) \, dt \\ &= \pi/4 - 1/2 \approx 0.285.\end{aligned}$$

We analyze the results of this example below.

In Example 14, we saw that the flux across the two curves was the same when the vector field was $\vec{F}_1 = \langle y, -x + 1 \rangle$. This is not a coincidence. We show why they are equal in Example 19. In short, the reason is this: the divergence of \vec{F}_1 is 0, and when $\operatorname{div} \vec{F} = 0$, the flux across any two paths with common beginning and ending points will be the same.

We also saw in the example that the flux across C_1 was 0 when the field was $\vec{F}_2 = \langle -x, 2y - x \rangle$. Flux measures “how much” of the field crosses the path from left to right (following the conventions established before). Positive flux means most of the field is crossing from left to right; negative flux means most of the field is crossing from right to left; zero flux means the same amount crosses from left to right as from right to left. When we consider Figure 14.22(b), it seems plausible that the same amount of \vec{F}_2 was crossing C_1 from left to right as from right to left.

Green’s Theorem

There is an important connection between the circulation around a closed region R and the curl of the vector field inside of R , as well as a connection between the flux across the boundary of R and the divergence of the field inside R . These connections are described by Green’s Theorem and the Divergence Theorem, respectively. We’ll explore each in turn.

Green’s Theorem states “the counterclockwise circulation around a closed region R is equal to the sum of the curls over R .”

Notes:

Theorem 4 Green's Theorem

Let R be a closed, bounded region of the plane whose boundary C is composed of finitely many smooth curves, let $\vec{r}(t)$ be a counterclockwise parametrization of C , and let $\vec{F} = \langle M, N \rangle$ where M_x and M_y are continuous over R . Then

$$\oint_C \vec{F} \cdot d\vec{r} = \iint_R \operatorname{curl} \vec{F} dA.$$

We'll explore Green's Theorem through an example.

Example 15 Confirming Green's Theorem

Let $\vec{F} = \langle -y, x^2 + 1 \rangle$ and let R be the region of the plane bounded by the triangle with vertices $(-1, 0)$, $(1, 0)$ and $(0, 2)$, shown in Figure 14.23. Verify Green's Theorem; that is, find the circulation of \vec{F} around the boundary of R and show that is equal to the double integral of $\operatorname{curl} \vec{F}$ over R .

SOLUTION The curve C that bounds R is composed of 3 lines. While we need to traverse the boundary of R in a counterclockwise fashion, we may start anywhere we choose. We arbitrarily choose to start at $(-1, 0)$, move to $(1, 0)$, etc., with each line parametrized by $\vec{r}_1(t)$, $\vec{r}_2(t)$ and $\vec{r}_3(t)$, respectively.

We leave it to the reader to confirm that the following parametrizations of the three lines are accurate:

$$\begin{aligned}\vec{r}_1(t) &= \langle 2t - 1, 0 \rangle, & \text{for } 0 \leq t \leq 1, & \text{with } \vec{r}'_1(t) = \langle 2, 0 \rangle, \\ \vec{r}_2(t) &= \langle 1 - t, 2t \rangle, & \text{for } 0 \leq t \leq 1, & \text{with } \vec{r}'_2(t) = \langle -1, 2 \rangle, \text{ and} \\ \vec{r}_3(t) &= \langle -t, 2 - 2t \rangle, & \text{for } 0 \leq t \leq 1, & \text{with } \vec{r}'_3(t) = \langle -1, -2 \rangle.\end{aligned}$$

The circulation around C is found by summing the flow along each of the sides of the triangle. We again leave it to the reader to confirm the following computations:

$$\begin{aligned}\int_{C_1} \vec{F} \cdot d\vec{r}_1 &= \int_0^1 \langle 0, (2t - 1)^2 + 1 \rangle \cdot \langle 2, 0 \rangle dt = 0, \\ \int_{C_2} \vec{F} \cdot d\vec{r}_2 &= \int_0^1 \langle -2t, (1 - t)^2 + 1 \rangle \cdot \langle -1, 2 \rangle dt = 11/3, \text{ and} \\ \int_{C_3} \vec{F} \cdot d\vec{r}_3 &= \int_0^1 \langle 2t - 2, t^2 + 1 \rangle \cdot \langle -1, -2 \rangle dt = -5/3.\end{aligned}$$

The circulation is the sum of the flows: 2.

We confirm Green's Theorem by computing $\iint_R \operatorname{curl} \vec{F} dA$. We find $\operatorname{curl} \vec{F} = 2x + 1$. The region R is bounded by the lines $y = 2x + 2$, $y = -2x + 2$ and $y = 0$.

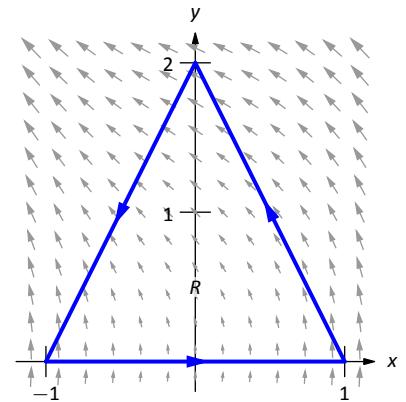


Figure 14.23: The vector field and planar region used in Example 15.

Notes:

Integrating with the order $dx dy$ is most straightforward, leading to

$$\int_0^2 \int_{y/2-1}^{1-y/2} (2x+1) dx dy = \int_0^2 (2-y) dy = 2,$$

which matches our previous measurement of circulation.

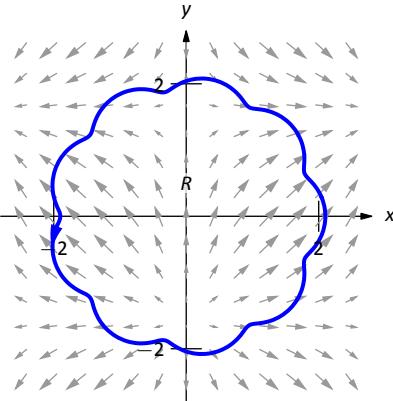


Figure 14.24: The vector field and planar region used in Example 16.

Example 16 Using Green's Theorem

Let $\vec{F} = \langle \sin x, \cos y \rangle$ and let R be the region enclosed by the curve C parametrized by $\vec{r}(t) = \langle 2 \cos t + \frac{1}{10} \cos(10t), 2 \sin t + \frac{1}{10} \sin(10t) \rangle$ on $0 \leq t \leq 2\pi$, as shown in Figure 14.24. Find the circulation around C .

SOLUTION Computing the circulation directly using the line integral looks difficult, as the integrand will include terms like $\sin(2 \cos t + \frac{1}{10} \cos(10t))$.

Green's Theorem states that $\oint_C \vec{F} \cdot d\vec{r} = \iint_R \text{curl } \vec{F} dA$; since $\text{curl } \vec{F} = 0$ in this example, the double integral is simply 0 and hence the circulation is 0.

Since $\text{curl } \vec{F} = 0$, we can conclude that the circulation is 0 in two ways. One method is to employ Green's Theorem as done above. The second way is to recognize that \vec{F} is a conservative field, hence there is a function $z = f(x, y)$ wherein $\vec{F} = \nabla f$. Let A be any point on the curve C ; since C is closed, we can say that C "begins" and "end" at A . By the Fundamental Theorem of Line Integrals, $\oint_C \vec{F} d\vec{r} = f(A) - f(A) = 0$.

One can use Green's Theorem to find the area of an enclosed region by integrating along its boundary. Let C be a closed curve, enclosing the region R , parametrized by $\vec{r}(t) = \langle f(t), g(t) \rangle$. We know the area of R is computed by the double integral $\iint_R dA$, where the integrand is 1. By creating a field \vec{F} where $\text{curl } \vec{F} = 1$, we can employ Green's Theorem to compute the area of R as $\oint_C \vec{F} \cdot d\vec{r}$.

One is free to choose any field \vec{F} to use as long as $\text{curl } \vec{F} = 1$. Common choices are $\vec{F} = \langle 0, x \rangle$, $\vec{F} = \langle -y, 0 \rangle$ and $\vec{F} = \langle -y/2, x/2 \rangle$. We demonstrate this below.

Example 17 Using Green's Theorem to find area

Let C be the closed curve parametrized by $\vec{r}(t) = \langle t - t^3, t^2 \rangle$ on $-1 \leq t \leq 1$, enclosing the region R , as shown in Figure 14.25. Find the area of R .

SOLUTION We can choose any field \vec{F} , as long as $\text{curl } \vec{F} = 1$. We choose $\vec{F} = \langle -y, 0 \rangle$. We also confirm (left to the reader) that $\vec{r}(t)$ traverses the region

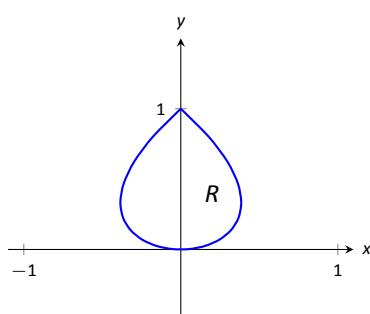


Figure 14.25: The region R , whose area is found in Example 17.

Notes:

R in a counterclockwise fashion. Thus

$$\begin{aligned}\text{Area of } R &= \iint_R dA \\ &= \oint_C \vec{F} \cdot d\vec{r} \\ &= \int_{-1}^1 \langle -t^2, 0 \rangle \cdot \langle 1 - 3t^2, 2t \rangle dt \\ &= \int_{-1}^1 (-t^2)(1 - 3t^2) dt \\ &= \frac{8}{15}.\end{aligned}$$

The Divergence Theorem

Green's Theorem makes a connection between the circulation around a closed region R and the sum of the curls over R . The Divergence Theorem makes a somewhat "opposite" connection: the total flux across the boundary of R is equal to the sum of the divergences over R .

Theorem 5 The Divergence Theorem (in the plane)

Let R be a closed, bounded region of the plane whose boundary C is composed of finitely many smooth curves, let $\vec{r}(t)$ be a counterclockwise parametrization of C , and let $\vec{F} = \langle M, N \rangle$ where M_x and N_y are continuous over R . Then

$$\oint_C \vec{F} \cdot \vec{n} ds = \iint_R \operatorname{div} \vec{F} dA.$$

Example 18 Confirming the Divergence Theorem

Let $\vec{F} = \langle x - y, x + y \rangle$, let C be the circle of radius 2 centered at the origin and define R to be the interior of that circle, as shown in Figure 14.26. Verify the Divergence Theorem; that is, find the flux across C and show it is equal to the double integral of $\operatorname{div} \vec{F}$ over R .

SOLUTION

We parametrize the circle in the usual way, with $\vec{r}(t) = \langle 2 \cos t, 2 \sin t \rangle$,

Notes:

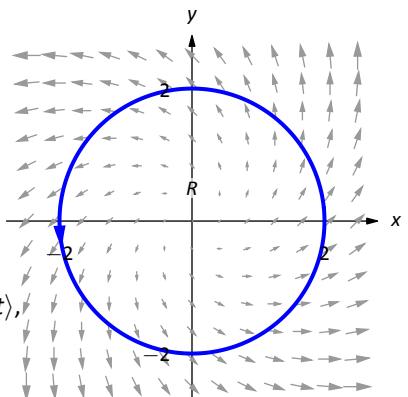


Figure 14.26: The region R used in Example 18.

$0 \leq t \leq 2\pi$. The flux across C is

$$\begin{aligned} \oint_C \vec{F} \cdot \vec{n} \, ds &= \oint_C (Mg'(t) - Nf'(t)) \, dt \\ &= \int_0^{2\pi} ((2 \cos t - 2 \sin t)(2 \cos t) - (2 \cos t + 2 \sin t)(-2 \sin t)) \, dt \\ &= \int_0^{2\pi} 4 \, dt = 8\pi. \end{aligned}$$

We compute the divergence of \vec{F} as $\operatorname{div} \vec{F} = M_x + N_y = 2$. Since the divergence is constant, we can compute the following double integral easily:

$$\iint_R \operatorname{div} \vec{F} \, dA = \iint_R 2 \, dA = 2 \iint_R \, dA = 2(\text{area of } R) = 8\pi,$$

which matches our previous result.

Example 19 Flux when $\operatorname{div} \vec{F} = 0$

Let \vec{F} be any field where $\operatorname{div} \vec{F} = 0$, and let C_1 and C_2 be any two nonintersecting paths, except that each begin at point A and end at point B (see Figure 14.27). Show why the flux across C_1 and C_2 is the same.

SOLUTION By referencing Figure 14.27, we see we can make a closed path C that combines C_1 with C_2 , where C_2 is traversed with its opposite orientation. We label the enclosed region R . Since $\operatorname{div} \vec{F} = 0$, the Divergence Theorem states that

$$\oint_C \vec{F} \cdot \vec{n} \, ds = \iint_R \operatorname{div} \vec{F} \, dA = \iint_R 0 \, dA = 0.$$

Using the properties and notation given in Theorem 1, consider:

$$\begin{aligned} 0 &= \oint_C \vec{F} \cdot \vec{n} \, ds \\ &= \int_{C_1} \vec{F} \cdot \vec{n} \, ds + \int_{C_2^*} \vec{F} \cdot \vec{n} \, ds \end{aligned}$$

(where C_2^* is the path C_2 traversed with opposite orientation)

$$= \int_{C_1} \vec{F} \cdot \vec{n} \, ds - \int_{C_2} \vec{F} \cdot \vec{n} \, ds.$$

$$\int_{C_2} \vec{F} \cdot \vec{n} \, ds = \int_{C_1} \vec{F} \cdot \vec{n} \, ds.$$

Thus the flux across each path is equal.

Notes:

Exercises 14.4

Terms and Concepts

1. Let \vec{F} be a vector field and let C be a curve. *Flow* is a measure of the amount of \vec{F} going C ; *flux* is a measure of the amount of \vec{F} going C .
2. What is circulation?
3. Green's Theorem states, informally, that the circulation around a closed curve that bounds a region R is equal to the sum of across R .
4. The Divergence Theorem states, informally, that the outward flux across a closed curve that bounds a region R is equal to the sum of across R .
5. Let \vec{F} be a vector field and let C_1 and C_2 be any nonintersecting paths except that each starts at point A and ends at point B . If = 0, then $\int_{C_1} \vec{F} \cdot \vec{T} ds = \int_{C_2} \vec{F} \cdot \vec{T} ds$.
6. Let \vec{F} be a vector field and let C_1 and C_2 be any nonintersecting paths except that each starts at point A and ends at point B . If = 0, then $\int_{C_1} \vec{F} \cdot \vec{n} ds = \int_{C_2} \vec{F} \cdot \vec{n} ds$.

Problems

In Exercises 7 – 12, a vector field \vec{F} and a curve C are given. Evaluate $\int_C \vec{F} \cdot \vec{n} ds$, the flux of \vec{F} over C .

7. $\vec{F} = \langle x + y, x - y \rangle$; C is the curve with initial and terminal points $(3, -2)$ and $(3, 2)$, respectively, parametrized by $\vec{r}(t) = \langle 3t^2, 2t \rangle$ on $-1 \leq t \leq 1$.
8. $\vec{F} = \langle x + y, x - y \rangle$; C is the curve with initial and terminal points $(3, -2)$ and $(3, 2)$, respectively, parametrized by $\vec{r}(t) = \langle 3, t \rangle$ on $-2 \leq t \leq 2$.
9. $\vec{F} = \langle x^2, y + 1 \rangle$; C is line segment from $(0, 0)$ to $(2, 4)$.
10. $\vec{F} = \langle x^2, y + 1 \rangle$; C is the portion of the parabola $y = x^2$ from $(0, 0)$ to $(2, 4)$.
11. $\vec{F} = \langle y, 0 \rangle$; C is the line segment from $(0, 0)$ to $(0, 1)$.
12. $\vec{F} = \langle y, 0 \rangle$; C is the line segment from $(0, 0)$ to $(1, 1)$.

In Exercises 13 – 16, a vector field \vec{F} and a closed curve C , enclosing a region R , are given. Verify Green's Theorem by evaluating $\oint_C \vec{F} \cdot d\vec{r}$ and $\iint_R \text{curl } \vec{F} dA$, showing they are equal.

13. $\vec{F} = \langle x - y, x + y \rangle$; C is the closed curve composed of the parabola $y = x^2$ on $0 \leq x \leq 2$ followed by the line segment from $(2, 4)$ to $(0, 0)$.

14. $\vec{F} = \langle -y, x \rangle$; C is the unit circle.

15. $\vec{F} = \langle 0, x^2 \rangle$; C the triangle with corners at $(0, 0)$, $(2, 0)$ and $(1, 1)$.

16. $\vec{F} = \langle x + y, 2x \rangle$; C the curve that starts at $(0, 1)$, follows the parabola $y = (x - 1)^2$ to $(3, 4)$, then follows a line back to $(0, 1)$.

In Exercises 17 – 20, a closed curve C enclosing a region R is given. Find the area of R by computing $\oint_C \vec{F} \cdot d\vec{r}$ for an appropriate choice of vector field \vec{F} .

17. C is the ellipse parametrized by $\vec{r}(t) = \langle 4 \cos t, 3 \sin t \rangle$ on $0 \leq t \leq 2\pi$.

18. C is the curve parametrized by $\vec{r}(t) = \langle \cos t, \sin(2t) \rangle$ on $-\pi/2 \leq t \leq \pi/2$.

19. C is the curve parametrized by $\vec{r}(t) = \langle \cos t, \sin(2t) \rangle$ on $0 \leq t \leq 2$.

20. C is the curve parametrized by $\vec{r}(t) = \langle 2 \cos t + \frac{1}{10} \cos(10t), 2 \sin t + \frac{1}{10} \sin(10t) \rangle$ on $0 \leq t \leq 2\pi$.

In Exercises 21 – 24, a vector field \vec{F} and a closed curve C , enclosing a region R , are given. Verify the Divergence Theorem by evaluating $\oint_C \vec{F} \cdot \vec{n} ds$ and $\iint_R \text{div } \vec{F} dA$, showing they are equal.

21. $\vec{F} = \langle x - y, x + y \rangle$; C is the closed curve composed of the parabola $y = x^2$ on $0 \leq x \leq 2$ followed by the line segment from $(2, 4)$ to $(0, 0)$.

22. $\vec{F} = \langle -y, x \rangle$; C is the unit circle.

23. $\vec{F} = \langle 0, y^2 \rangle$; C the triangle with corners at $(0, 0)$, $(2, 0)$ and $(1, 1)$.

24. $\vec{F} = \langle x^2/2, y^2/2 \rangle$; C the curve that starts at $(0, 1)$, follows the parabola $y = (x - 1)^2$ to $(3, 4)$, then follows a line back to $(0, 1)$.

14.5 Parametrized Surfaces and Surface Area

Thus far we have focused mostly on 2-dimensional vector fields, measuring flow and flux along/across curves in the plane. Both Green's Theorem and the Divergence Theorem make connections between planar regions and their boundaries. We now move our attention to 3-dimensional vector fields, considering both curves and surfaces in space.

Note: We use the letter S to denote Surface Area. This section begins a study into surfaces, and it is natural to label a surface with the letter "S". We distinguish a surface from its surface area by using a calligraphic S to denote a surface: \mathcal{S} . When writing this letter by hand, it may be useful to add serifs to the letter, such as: \mathfrak{S}

Note: A function is *one to one* on its domain if the function never repeats an output value over the domain. In the case of $\vec{r}(u, v)$, \vec{r} is one to one if $\vec{r}(u_1, v_1) \neq \vec{r}(u_2, v_2)$ for all points $(u_1, v_1) \neq (u_2, v_2)$ in the domain of \vec{r} .

Definition 9 Parametrized Surface

Let $\vec{r}(u, v) = \langle f(u, v), g(u, v), h(u, v) \rangle$ be a vector-valued function that is continuous and one to one on the interior of its domain R in the u - v plane. The set of all terminal points of \vec{r} (i.e., the *range* of \vec{r}) is the **surface** \mathcal{S} , and \vec{r} along with its domain R form a **parametrization** of \mathcal{S} .

This parametrization is **smooth** on R if \vec{r}_u and \vec{r}_v are continuous and $\vec{r}_u \times \vec{r}_v$ is never $\vec{0}$ on the interior of R .

Given a point (u_0, v_0) in the domain of a vector-valued function \vec{r} , the vectors $\vec{r}_u(u_0, v_0)$ and $\vec{r}_v(u_0, v_0)$ are tangent to the surface \mathcal{S} at $\vec{r}(u_0, v_0)$ (a proof of this is developed in the Exercise section). The definition of smoothness dictates that $\vec{r}_u \times \vec{r}_v \neq \vec{0}$; this ensures that neither \vec{r}_u nor \vec{r}_v are $\vec{0}$, nor are they ever parallel. Therefore smoothness guarantees that \vec{r}_u and \vec{r}_v determine a plane that is tangent to \mathcal{S} .

A surface \mathcal{S} is said to be **orientable** if a field of normal vectors can be defined on \mathcal{S} that vary continuously along \mathcal{S} . This definition may be hard to understand; it may help to know that orientable surfaces are often called "two sided." A sphere is an orientable surface, and one can easily envision an "inside" and "outside" of the sphere. A paraboloid is orientable, where again one can generally envision "inside" and "outside" sides (or "top" and "bottom" sides) to this surface. Just about every surface that one can imagine is orientable, and we'll assume all surfaces we deal with in this text are orientable.

It is enlightening to examine a classic non-orientable surface: the Möbius

Notes:

band, shown in Figure 14.28. Vectors normal to the surface are given, starting at the point indicated in the figure. These normal vectors “vary continuously” as they move along the surface. Letting each vector indicate the “top” side of the band, we can easily see near any vector which side is the “top”.

However, if as we progress along the band, we recognize that we are labeling “both sides” of the band as the top; in fact, there are not two “sides” to this band, but one. The Möbius band is a non-orientable surface.

We now practice parameterizing surfaces.

Example 20 Parameterizing a surface over a rectangle

Parametrize the surface $z = x^2 + 2y^2$ over the rectangular region R defined by $-3 \leq x \leq 3, -1 \leq y \leq 1$.

SOLUTION There is a straightforward way to parametrize a surface of the form $z = f(x, y)$ over a rectangular domain. We let $x = u$ and $y = v$, and let $\vec{r}(u, v) = \langle u, v, f(u, v) \rangle$. In this instance, we have $\vec{r}(u, v) = \langle u, v, u^2 + 2v^2 \rangle$, for $-3 \leq u \leq 3, -1 \leq v \leq 1$. This surface is graphed in Figure 14.29.

Example 21 Parameterizing a surface over a circular disk

Parametrize the surface $z = x^2 + 2y^2$ over the circular region R enclosed by the circle of radius 2 that is centered at the origin.

SOLUTION We can parametrize the circular boundary of R with the vector-valued function $\langle 2\cos u, 2\sin u \rangle$, where $0 \leq u \leq 2\pi$. We can obtain the interior of R by scaling this function by a variable amount, i.e., by multiplying by v : $\langle 2v\cos u, 2v\sin u \rangle$, where $0 \leq v \leq 1$.

It is important to understand the role of v in the above function. When $v = 1$, we get the boundary of R , a circle of radius 2. When $v = 0$, we simply get the point $(0, 0)$, the center of R (which can be thought of as a circle with radius of 0). When $v = 1/2$, we get the circle of radius 1 that is centered at the origin, which is the circle *halfway* between the boundary and the center.

Thus far, we have determined the x and y components of our parametrization of the surface: $x = 2v\cos u$ and $y = 2v\sin u$. We find the z component simply by using $z = f(x, y) = x^2 + 2y^2$:

$$z = (2v\cos u)^2 + 2(2v\sin u)^2 = 4v^2\cos^2 u + 8v^2\sin^2 u.$$

Thus $\vec{r}(u, v) = \langle 2v\cos u, 2v\sin u, 4v^2\cos^2 u + 8v^2\sin^2 u \rangle$, $0 \leq u \leq 2\pi, 0 \leq v \leq 1$, which is graphed in Figure 14.30. The way that this graphic was generated highlights how the surface was parametrized. When viewing from above, one can see lines emanating from the origin; these represent different values of u as u sweeps from an angle of 0 up to 2π . One can also see concentric circles, each

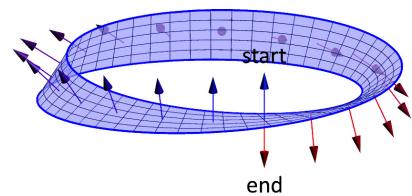


Figure 14.28: A Möbius band, a non-orientable surface.

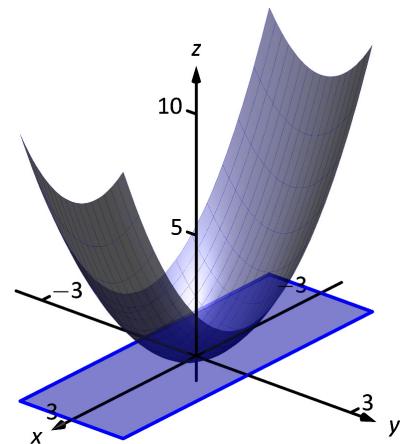


Figure 14.29: The surface parametrized in Example 20.

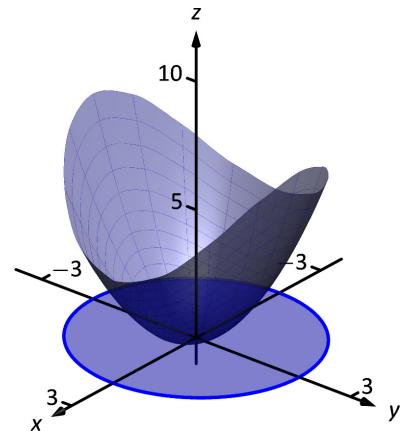


Figure 14.30: The surface parametrized in Example 21.

Notes:

corresponding to a different value of v .

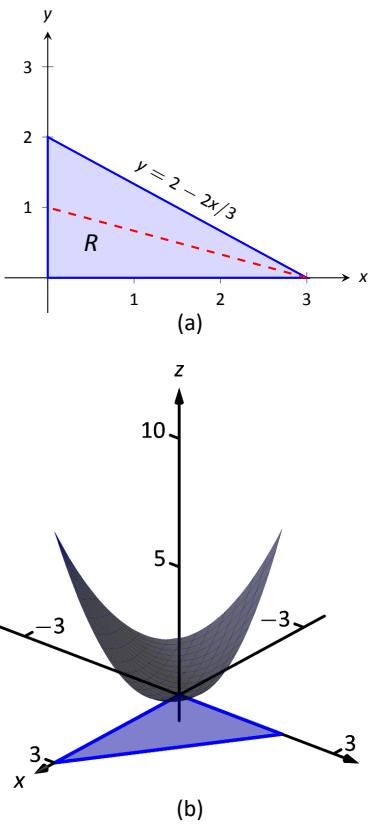


Figure 14.31: Part (a) shows a graph of the region R , and part (b) shows the surface over R , as defined in Example 22.

Examples 20 and 21 demonstrate an important principle when parameterizing surfaces given in the form $z = f(x, y)$ over a region R : if one can determine x and y in terms of u and v , then z follows directly as $z = f(x, y)$.

In the following two examples, we parametrize the same surface over triangular regions. Each will use v as a “scaling factor” as done in Example 21.

Example 22 Parameterizing a surface over a triangle

Parametrize the surface $z = x^2 + 2y^2$ over the triangular region R enclosed by the coordinate axes and the line $y = 2 - 2x/3$, as shown in Figure 14.31(a).

SOLUTION We may begin by letting $x = u$, $0 \leq u \leq 3$, and $y = 2 - 2u/3$. This gives only the line on the “upper” side of the triangle. To get all of the region R , we can once again scale y by a variable factor, v .

Still letting $x = u$, $0 \leq u \leq 3$, we let $y = v(2 - 2u/3)$, $0 \leq v \leq 1$. When $v = 0$, all y -values are 0, and we get the portion of the x -axis between $x = 0$ and $x = 3$. When $v = 1$, we get the upper side of the triangle. When $v = 1/2$, we get the line $y = 1/2(2 - 2u/3) = 1 - u/3$, which is the line “halfway up” the triangle, shown in the figure with a dashed line.

Letting $z = f(x, y) = x^2 + 2y^2$, we have $\vec{r}(u, v) = \langle u, v(2 - 2u/3), u^2 + 2(v(2 - 2u/3))^2 \rangle$, $0 \leq u \leq 3$, $0 \leq v \leq 1$. This surface is graphed in Figure 14.31(b). Again, when one looks from above, we can see the scaling effects of v : the series of lines that run to the point $(3, 0)$ each represent a different value of v .

Another common way to parametrize the surface is to begin with $y = u$, $0 \leq u \leq 2$. Solving the equation of the line $y = 2 - 2x/3$ for x , we have $x = 3 - 3y/2$, leading to using $x = v(3 - 3u/2)$, $0 \leq v \leq 1$. With $z = x^2 + 2y^2$, we have $\vec{r}(u, v) = \langle v(3 - 3u/2), u, (v(3 - 3u/2))^2 + 2u^2 \rangle$, $0 \leq u \leq 2$, $0 \leq v \leq 1$.

Example 23 Parameterizing a surface over a triangle

Parametrize the surface $z = x^2 + 2y^2$ over the triangular region R enclosed by the lines $y = 3 - 2x/3$, $y = 1$ and $x = 0$ as shown in Figure 14.32(a).

SOLUTION While the region R in this example is very similar to the region R in the previous example, and our method of parameterizing the surface is fundamentally the same, it will feel as though our answer is much different than before.

We begin with letting $x = u$, $0 \leq u \leq 3$. We may be tempted to let $y = v(3 - 2u/3)$, $0 \leq v \leq 1$, but this is incorrect. When $v = 1$, we obtain the upper line of the triangle as desired. However, when $v = 0$, the y -value is 0, which

Notes:

does not lie in the region R .

We will describe the general method of proceeding following this example. For now, consider $y = 1 + v(2 - 2u/3)$, $0 \leq v \leq 1$. Note that when $v = 1$, we have $y = 3 - 2u/3$, the upper line of the boundary of R . Also, when $v = 0$, we have $y = 1$, which is the lower boundary of R . With $z = x^2 + 2y^2$, we determine $\vec{r}(u, v) = \langle u, 1 + v(2 - 2u/3), u^2 + 2(1 + v(2 - 2u/3))^2 \rangle$, $0 \leq u \leq 3$, $0 \leq v \leq 1$.

The surface is graphed in Figure 14.32(b).

Given a surface of the form $z = f(x, y)$, one can often determine a parametrization of the surface over a region R in a manner similar to determining bounds of integration over a region R . Using the techniques of Section ??, suppose a region R can be described by $a \leq x \leq b$, $g_1(x) \leq y \leq g_2(x)$, i.e., the area of R can be found using the iterated integral

$$\int_a^b \int_{g_1(x)}^{g_2(x)} dy dx.$$

When parameterizing the surface, we can let $x = u$, $a \leq u \leq b$, and we can let $y = g_1(u) + v(g_2(u) - g_1(u))$, $0 \leq v \leq 1$. The parametrization of x is straightforward, but look closely at how y is determined. When $v = 0$, $y = g_1(u) = g_1(x)$. When $v = 1$, $y = g_2(u) = g_2(x)$.

As a specific example, consider the triangular region R from Example 23, shown in Figure 14.32(a). Using the techniques of Section ??, we can find the area of R as

$$\int_0^3 \int_1^{3-2x/3} dy dx.$$

Following the above discussion, we can set $x = u$, where $0 \leq u \leq 3$, and set $y = 1 + v(3 - 2u/3 - 1) = 1 + v(2 - 2u/3)$, $0 \leq v \leq 1$, as used in that example.

One can do a similar thing if R is bounded by $c \leq y \leq d$, $h_1(y) \leq x \leq h_2(y)$, but for the sake of simplicity we leave it to the reader to flesh out those details. The principles outlined above are given in the following Key Idea for reference.

Key Idea 2 Parameterizing Surfaces

Let a surface S be the portion of the graph of $z = f(x, y)$ that lies above a region R in the x - y plane. Let R be bounded by $a \leq x \leq b$, $g_1(x) \leq y \leq g_2(x)$, i.e., the area of R can be found using the iterated integral $\int_a^b \int_{g_1(x)}^{g_2(x)} dy dx$, and let $h(u, v) = g_1(u) + v(g_2(u) - g_1(u))$. S can be parametrized as

$$\vec{r}(u, v) = \langle u, h(u, v), f(u, h(u, v)) \rangle, \quad a \leq u \leq b, 0 \leq v \leq 1.$$

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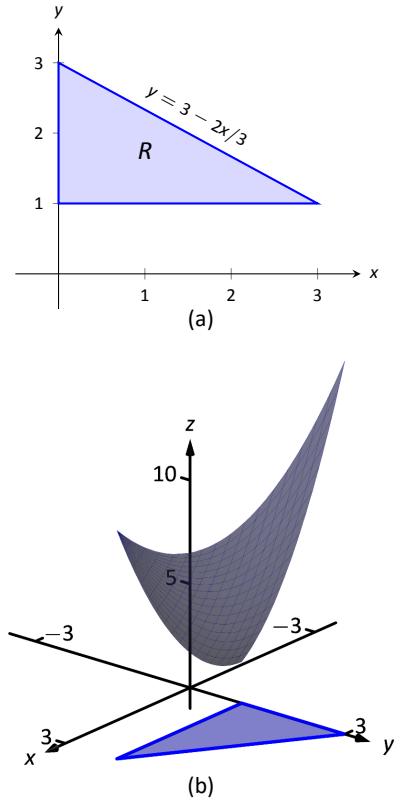


Figure 14.32: Part (a) shows a graph of the region R , and part (b) shows the surface over R , as defined in Example 23.

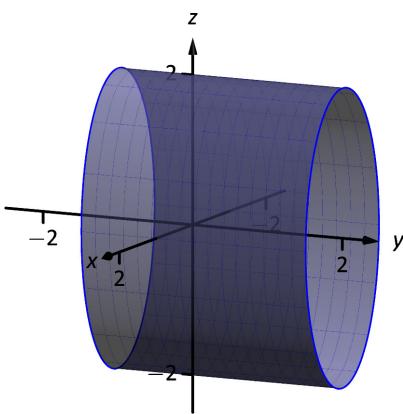


Figure 14.33: The cylinder parametrized in Example 24.

Example 24 Parameterizing a cylindrical surface

Find a parametrization of the cylinder $x^2 + z^2/4 = 1$, where $-1 \leq y \leq 2$, as shown in Figure 14.33.

SOLUTION The equation $x^2 + z^2/4 = 1$ can be envisioned to describe an ellipse in the x - z plane; as the equation lacks a y -term, the equation describes a cylinder (recall Definition ??) that extends without bound parallel to the y -axis. This ellipse has a vertical major axis of length 4, a horizontal minor axis of length 2, and is centered at the origin. We can parametrize this ellipse using sines and cosines; our parametrization can begin with

$$\vec{r}(u, v) = \langle \cos u, ???, 2 \sin u \rangle, \quad 0 \leq u \leq 2\pi,$$

where we still need to determine the y component.

While the cylinder $x^2 + z^2/4 = 1$ is satisfied by any y value, the problem states that all y values are to be between $y = -1$ and $y = 2$. Since the value of y does not depend at all on the values of x or z , we can use another variable, v , to describe y . Our final answer is

$$\vec{r}(u, v) = \langle \cos u, v, 2 \sin u \rangle, \quad 0 \leq u \leq 2\pi, \quad -1 \leq v \leq 2.$$

Example 25 Parameterizing an elliptic cone

Find a parametrization of the elliptic cone $z^2 = \frac{x^2}{4} + \frac{y^2}{9}$, where $-2 \leq z \leq 3$, as shown in Figure 14.34(a).

SOLUTION One way to parametrize this cone is to recognize that given a z value, the cross section of the cone at that z value is an ellipse with equation $\frac{x^2}{(2z)^2} + \frac{y^2}{(3z)^2} = 1$. We can let $z = v$, for $-2 \leq v \leq 3$ and then parametrize the above ellipses using sines, cosines and v .

We can parametrize the x component of our surface with $x = 2z \cos u$ and the y component with $y = 3z \sin u$, where $0 \leq u \leq 2\pi$. Putting all components together, we have

$$\vec{r}(u, v) = \langle 2v \cos u, 3v \sin u, v \rangle, \quad 0 \leq u \leq 2\pi, \quad -2 \leq v \leq 3.$$

When v takes on negative values, the radii of the cross-sectional ellipses become “negative,” which can lead to some surprising results. Consider Figure 14.34(b), where the cone is graphed for $0 \leq u \leq \pi$. Because v is negative below the x - y plane, the radii of the cross-sectional ellipses are negative, and the opposite side of the cone is sketched below the x - y plane.

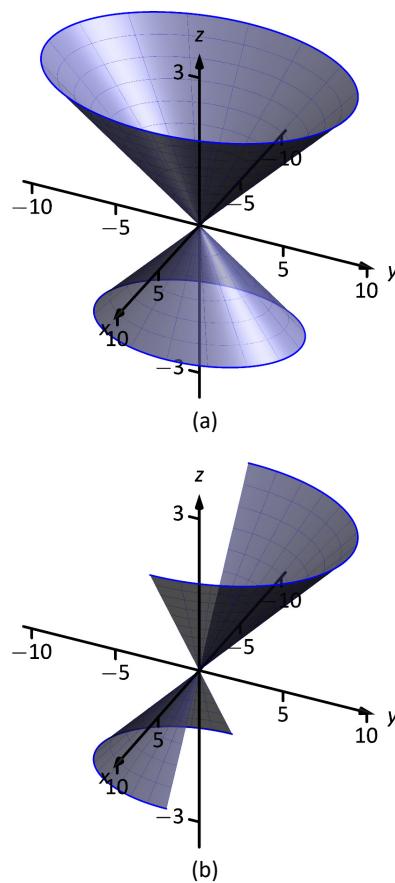


Figure 14.34: An elliptic cone in (a), drawn again in (b) with its domain restricted, as described in Example 25.

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Example 26 Parameterizing an ellipsoid

Find a parametrization of the ellipsoid $\frac{x^2}{25} + y^2 + \frac{z^2}{4} = 1$ as shown in Figure 14.35(a).

SOLUTION Recall Key Idea ?? from Section ??, which states that all unit vectors in space have the form $\langle \sin \theta \cos \varphi, \sin \theta \sin \varphi, \cos \theta \rangle$ for some angles θ and φ . If we choose our angles appropriately, this allows us to draw the unit sphere. To get an ellipsoid, we need only scale each component of the sphere appropriately.

The x -radius of the given ellipsoid is 5, the y -radius is 1 and the z -radius is 2. Substituting u for θ and v for φ , we have $\vec{r}(u, v) = \langle 5 \sin u \cos v, \sin u \sin v, 2 \cos u \rangle$, where we still need to determine the ranges of u and v .

Note how the x and y components of \vec{r} have $\cos v$ and $\sin v$ terms, respectively. This hints at the fact that ellipses are drawn parallel to the x - y plane as v varies, which implies we should have v range from 0 to 2π .

One may be tempted to let $0 \leq u \leq 2\pi$ as well, but note how the z component is $2 \cos u$. We only need $\cos u$ to take on values between -1 and 1 once, therefore we can restrict u to $0 \leq u \leq \pi$.

The final parametrization is thus

$$\vec{r}(u, v) = \langle 5 \sin u \cos v, \sin u \sin v, 2 \cos u \rangle, \quad 0 \leq u \leq \pi, \quad 0 \leq v \leq 2\pi.$$

In Figure 14.35(b), the ellipsoid is graphed on $\frac{\pi}{4} \leq u \leq \frac{2\pi}{3}$, $\frac{\pi}{4} \leq v \leq \frac{3\pi}{2}$ to demonstrate how each variable affects the surface.

Parametrization is a powerful way to represent surfaces. One of the advantages of the methods of parametrization described in this section is that the domain of $\vec{r}(u, v)$ is always a rectangle; that is, the bounds on u and v are constants. This will make some of our future computations easier to evaluate.

Just as we could parametrize curves in more than one way, there will always be multiple ways to parametrize a surface. Some ways will be more “natural” than others, but these other ways are not incorrect. Because technology is often readily available, it is often a good idea to check one’s work by graphing a parametrization of a surface to check if it indeed represents what it was intended to.

Surface Area

It will become important in the following sections to be able to compute the surface area of a surface S given a smooth parametrization $\vec{r}(u, v)$, $a \leq u \leq b$, $c \leq v \leq d$. Following the principles given in the integration review at the

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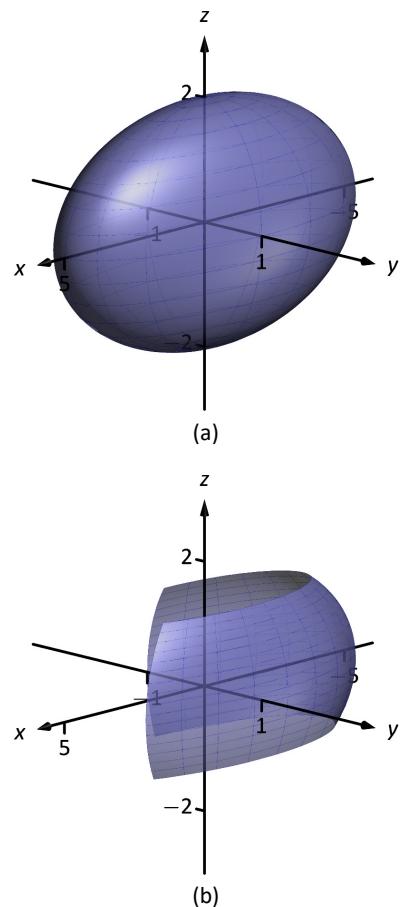


Figure 14.35: An ellipsoid in (a), drawn again in (b) with its domain restricted, as described in Example 26.

beginning of this chapter, we can say that

$$\text{Surface Area of } S = S = \iint_S dS,$$

where dS represents a small amount of surface area. That is, to compute total surface area S , add up lots of small amounts of surface area dS across the entire surface S . The key to finding surface area is knowing how to compute dS . We begin by approximating.

In Section ?? we used the area of a plane to approximate the surface area of a small portion of a surface. We will do the same here.

Let R be the region of the $u-v$ plane bounded by $a \leq u \leq b$, $c \leq v \leq d$ as shown in Figure 14.36(a). Partition R into rectangles of width $\Delta u = \frac{b-a}{n}$ and height $\Delta v = \frac{d-c}{n}$, for some n . Let $p = (u_0, v_0)$ be the lower left corner of some rectangle in the partition, and let m and q be neighboring corners as shown.

The point p maps to a point $P = \vec{r}(u_0, v_0)$ on the surface S , and the rectangle with corners p, m and q maps to some region (probably not rectangular) on the surface as shown in Figure 14.36(b), where $M = \vec{r}(m)$ and $Q = \vec{r}(q)$. We wish to approximate the surface area of this mapped region.

Let $\vec{u} = M - P$ and $\vec{v} = Q - P$. These two vectors form a parallelogram, illustrated in Figure 14.36(c), whose area *approximates* the surface area we seek. In this particular illustration, we can see that parallelogram does not particularly match well the region we wish to approximate, but that is acceptable; by increasing the number of partitions of R , Δu and Δv shrink and our approximations will become better.

From Section ?? we know the area of this parallelogram is $\| \vec{u} \times \vec{v} \|$. If we repeat this approximation process for each rectangle in the partition of R , we can sum the areas of all the parallelograms to get an approximation of the surface area S :

$$\text{Surface area of } S = S \approx \sum_{j=1}^n \sum_{i=1}^n \| \vec{u}_{i,j} \times \vec{v}_{i,j} \|,$$

where $\vec{u}_{i,j} = \vec{r}(u_i + \Delta u, v_j) - \vec{r}(u_i, v_j)$ and $\vec{v}_{i,j} = \vec{r}(u_i, v_j + \Delta v) - \vec{r}(u_i, v_j)$.

From our previous calculus experience, we expect that taking a limit as $n \rightarrow \infty$ will result in the exact surface area. However, the current form of the above double sum makes it difficult to realize what the result of that limit is. The following rewriting of the double summation will be helpful:

Notes:

$$\begin{aligned} & \sum_{j=1}^n \sum_{i=1}^n \| \vec{u}_{i,j} \times \vec{v}_{i,j} \| = \\ & \sum_{j=1}^n \sum_{i=1}^n \| (\vec{r}(u_i + \Delta u, v_j) - \vec{r}(u_i, v_j)) \times (\vec{r}(u_i, v_j + \Delta v) - \vec{r}(u_i, v_j)) \| = \\ & \sum_{j=1}^n \sum_{i=1}^n \left\| \frac{\vec{r}(u_i + \Delta u, v_j) - \vec{r}(u_i, v_j)}{\Delta u} \times \frac{\vec{r}(u_i, v_j + \Delta v) - \vec{r}(u_i, v_j)}{\Delta v} \right\| \Delta u \Delta v. \end{aligned}$$

We now take the limit as $n \rightarrow \infty$, forcing Δu and Δv to 0. As $\Delta u \rightarrow 0$,

$$\begin{aligned} \frac{\vec{r}(u_i + \Delta u, v_j) - \vec{r}(u_i, v_j)}{\Delta u} & \rightarrow \vec{r}_u(u_i, v_j) \quad \text{and} \\ \frac{\vec{r}(u_i, v_j + \Delta v) - \vec{r}(u_i, v_j)}{\Delta v} & \rightarrow \vec{r}_v(u_i, v_j). \end{aligned}$$

(This limit process also demonstrates that $\vec{r}_u(u, v)$ and $\vec{r}_v(u, v)$ are tangent to the surface S at $\vec{r}(u, v)$. We don't need this fact now, but it will be important in the next section.)

Thus, in the limit, the double sum leads to a double integral:

$$\lim_{n \rightarrow \infty} \sum_{j=1}^n \sum_{i=1}^n \| \vec{u}_{i,j} \times \vec{v}_{i,j} \| = \int_c^d \int_a^b \| \vec{r}_u \times \vec{r}_v \| \, du \, dv.$$

Theorem 6 Surface Area of Parametrically Defined Surfaces

Let $\vec{r}(u, v)$ be a smooth parametrization of a surface S over a region R of the u - v plane.

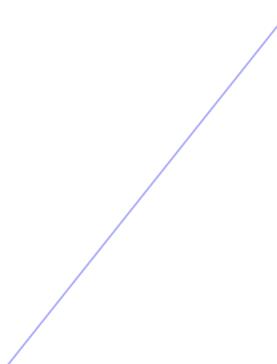
- The surface area differential dS is: $dS = \| \vec{r}_u \times \vec{r}_v \| \, dA$.
- The surface area S of S is

$$S = \iint_S dS = \iint_R \| \vec{r}_u \times \vec{r}_v \| \, dA.$$

Example 27 Finding the surface area of a parametrized surface

Using the parametrization found in Example 21, find the surface area of $z = x^2 + 2y^2$ over the circular disk of radius 2, centered at the origin.

Notes:



SOLUTION In Example 21, we parametrized the surface as $\vec{r}(u, v) = \langle 2v \cos u, 2v \sin u, 4v^2 \cos^2 u + 8v^2 \sin^2 u \rangle$, for $0 \leq u \leq 2\pi$, $0 \leq v \leq 1$. To find the surface area using Theorem 6, we need $\|\vec{r}_u \times \vec{r}_v\|$. We find:

$$\begin{aligned}\vec{r}_u &= \langle -2v \sin u, 2v \cos u, 8v^2 \cos u \sin u \rangle \\ \vec{r}_v &= \langle 2 \cos u, 2 \sin v, 8v \cos^2 u + 16v \sin^2 u \rangle \\ \vec{r}_u \times \vec{r}_v &= \langle 16v^2 \cos u, 32v^2 \sin u, -4v \rangle \\ \|\vec{r}_u \times \vec{r}_v\| &= \sqrt{256v^4 \cos^2 u + 1024v^4 \sin^2 u + 16v^2}.\end{aligned}$$

Thus the surface area is

$$\begin{aligned}s &= \iint_S dS = \iint_R \|\vec{r}_u \times \vec{r}_v\| dA \\ &= \int_0^1 \int_0^{2\pi} \sqrt{256v^4 \cos^2 u + 1024v^4 \sin^2 u + 16v^2} du dv \approx 53.59.\end{aligned}$$

There is a lot of tedious work in the above calculations and the final integral is nontrivial. The use of a computer-algebra system is highly recommended.

In Section 14.1, we recalled the arc length differential $ds = \|\vec{r}'(t)\| dt$. In subsequent sections, we used that differential, but in most applications the “ $\|\vec{r}'(t)\|$ ” part of the differential canceled out of the integrand (to our benefit, as integrating the square roots of functions is generally difficult). We will find a similar thing happens when we use the surface area differential dS in the following sections. That is, our main goal is not to be able to compute surface area; rather, surface area is tool to obtain other quantities that are more important and useful. In our applications, we will use dS , but most of the time the “ $\|\vec{r}_u \times \vec{r}_v\|$ ” part will cancel out of the integrand, making the subsequent integration easier to compute.

Notes:

Exercises 14.5

Terms and Concepts

- In your own words, describe what an orientable surface is.
- Give an example of a non-orientable surface.

Problems

In Exercises 3 – 4, parametrize the surface defined by the function $z = f(x, y)$ over each of the given regions R of the x - y plane.

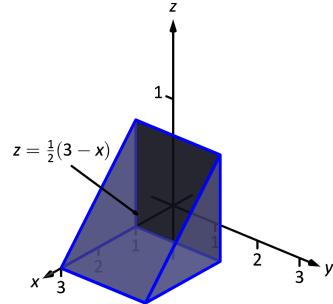
- $z = 3x^2y;$
 - R is the rectangle bounded by $-1 \leq x \leq 1$ and $0 \leq y \leq 2$.
 - R is the circle of radius 3, centered at $(1, 2)$.
 - R is the triangle with vertices $(0, 0)$, $(1, 0)$ and $(0, 2)$.
 - R is the region bounded by the x -axis and the graph of $y = 1 - x^2$.
- $z = 4x + 2y^2;$
 - R is the rectangle bounded by $1 \leq x \leq 4$ and $5 \leq y \leq 7$.
 - R is the ellipse with major axis of length 8 parallel to the x -axis, and minor axis of length 6 parallel to the y -axis, centered at the origin.
 - R is the triangle with vertices $(0, 0)$, $(2, 2)$ and $(0, 4)$.
 - R is the annulus bounded between the circles, centered at the origin, with radius 2 and radius 5.

In Exercises 5 – 8, a surface S in space is described that cannot be defined in terms of a function $z = f(x, y)$. Give a parametrization of S .

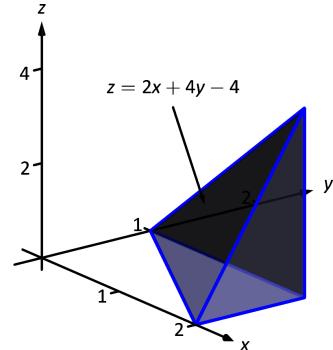
- S is the rectangle in space with corners at $(0, 0, 0)$, $(0, 2, 0)$, $(0, 2, 1)$ and $(0, 0, 1)$.
- S is the triangle in space with corners at $(1, 0, 0)$, $(1, 0, 1)$ and $(0, 0, 1)$.
- S is the ellipsoid $\frac{x^2}{9} + \frac{y^2}{4} + \frac{z^2}{16} = 1$.
- S is the elliptic cone $y^2 = x^2 + \frac{z^2}{16} = 1$, for $-1 \leq y \leq 5$.

In Exercises 9 – 16, a domain D in space is given. Parametrize each of the bounding surfaces of D .

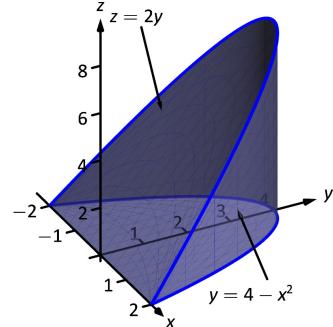
- D is the domain bounded by the planes $z = \frac{1}{2}(3-x)$, $x = 1$, $y = 0$, $y = 2$ and $z = 0$.



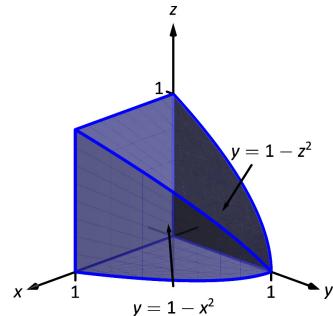
- D is the domain bounded by the planes $z = 2x + 4y - 4$, $x = 2$, $y = 1$ and $z = 0$.



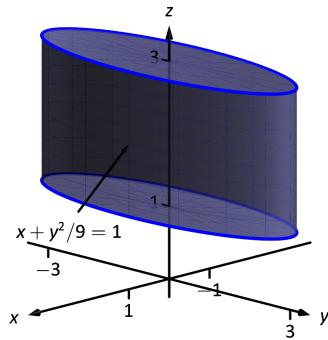
- D is the domain bounded by $z = 2y$, $y = 4 - x^2$ and $z = 0$.



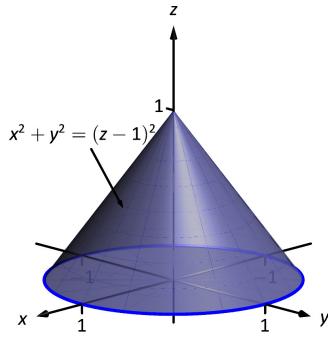
- D is the domain bounded by $y = 1 - z^2$, $y = 1 - x^2$, $x = 0$, $y = 0$ and $z = 0$.



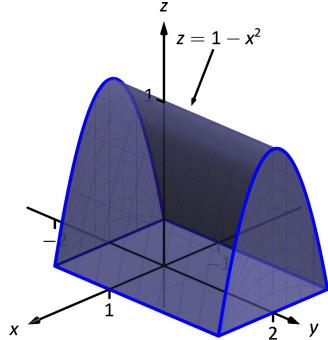
13. D is the domain bounded by the cylinder $x + y^2/9 = 1$ and the planes $z = 1$ and $z = 3$.



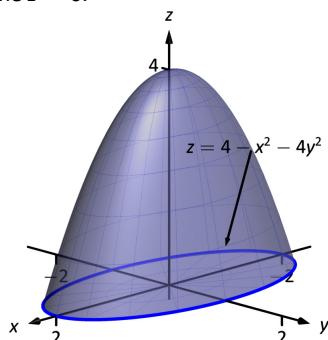
14. D is the domain bounded by the cone $x^2 + y^2 = (z - 1)^2$ and the plane $z = 0$.



15. D is the domain bounded by the cylinder $z = 1 - x^2$ and the planes $y = -1$, $y = 2$ and $z = 0$.



16. D is the domain bounded by the paraboloid $z = 4 - x^2 - 4y^2$ and the plane $z = 0$.



In Exercises 17 – 20, find the surface area S of the given surface \mathcal{S} . (The associated integrals are computable without the assistance of technology.)

17. \mathcal{S} is the plane $z = 2x + 3y$ over the rectangle $-1 \leq x \leq 1$, $2 \leq y \leq 3$.

18. \mathcal{S} is the plane $z = x + 2y$ over the triangle with vertices at $(0, 0)$, $(1, 0)$ and $(0, 1)$.

19. \mathcal{S} is the plane $z = x + y$ over the circular disk, centered at the origin, with radius 2.

20. \mathcal{S} is the plane $z = x + y$ over the annulus bounded by the circles, centered at the origin, with radius 1 and radius 2.

In Exercises 21 – 24, set up the double integral that finds the surface area S of the given surface \mathcal{S} , then use technology to approximate its value.

21. \mathcal{S} is the paraboloid $z = x^2 + y^2$ over the circular disk of radius 3 centered at the origin.

22. \mathcal{S} is the paraboloid $z = x^2 + y^2$ over the triangle with vertices at $(0, 0)$, $(0, 1)$ and $(1, 1)$.

23. \mathcal{S} is the plane $z = 5x - y$ over the region enclosed by the parabola $y = 1 - x^2$ and the x -axis.

24. \mathcal{S} is the hyperbolic paraboloid $z = x^2 - y^2$ over the circular disk of radius 1 centered at the origin.

14.6 Surface Integrals

Consider a smooth surface \mathcal{S} that represents a thin sheet of metal. How could we find the mass of this metallic object?

If the density of this object is constant, then we can find mass via “mass = density \times surface area,” and we could compute the surface area using the techniques of the previous section.

What if the density were not constant, but variable, described by a function $\delta(x, y, z)$? We can describe the mass using our general integration techniques as

$$\text{mass} = \iint_{\mathcal{S}} dm,$$

where dm represents “a little bit of mass.” That is, to find the total mass of the object, sum up lots of little masses over the surface.

How do we find the “little bit of mass” dm ? On a small portion of the surface with surface area ΔS , the density is approximately constant, hence $dm \approx \delta(x, y, z) \Delta S$. As we use limits to shrink the size of ΔS to 0, we get $dm = \delta(x, y, z) dS$; that is, a little bit of mass is equal to a density times a small amount of surface area. Thus the total mass of the thin sheet is

$$\text{mass} = \iint_{\mathcal{S}} \delta(x, y, z) dS. \quad (14.3)$$

To evaluate the above integral, we would seek $\vec{r}(u, v)$, a smooth parametrization of \mathcal{S} over a region R of the u - v plane. The density would become a function of u and v , and we would integrate $\iint_R \delta(u, v) \parallel \vec{r}_u \times \vec{r}_v \parallel dA$.

The integral in Equation (14.3) is a specific example of a more general construction defined below.

Definition 10 Surface Integral

Let $G(x, y, z)$ be a continuous function defined on a surface \mathcal{S} . The **surface integral of G on \mathcal{S}** is

$$\iint_{\mathcal{S}} G(x, y, z) dS.$$

Surface integrals can be used to measure a variety of quantities beyond mass. If $G(x, y, z)$ measures the static charge density at a point, then the surface integral will compute the total static charge of the sheet. If G measures the amount of fluid passing through a screen (represented by \mathcal{S}) at a point, then the surface integral gives the total amount of fluid going through the screen.

Notes:

Example 28 Finding the mass of a thin sheet

Find the mass of a thin sheet modeled by the plane $2x + y + z = 3$ over the triangular region of the x - y plane bounded by the coordinate axes and the line $y = 2 - 2x$, as shown in Figure 14.37, with density function $\delta(x, y, z) = x^2 + 5y + z$, where all distances are measured in cm and the density is given as gm/cm².

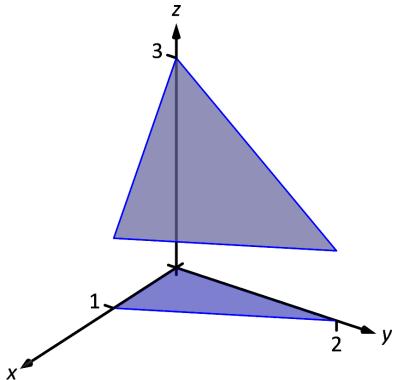


Figure 14.37: The surface whose mass is computed in Example 28.

SOLUTION We begin by parameterizing the planar surface \mathcal{S} . Using the techniques of the previous section, we can let $x = u$ and $y = v(2 - 2u)$, where $0 \leq u \leq 1$ and $0 \leq v \leq 1$. Solving for z in the equation of the plane, we have $z = 3 - 2x - y$, hence $z = 3 - 2u - v(2 - 2u)$, giving the parametrization $\vec{r}(u, v) = \langle u, v(2 - 2u), 3 - 2u - v(2 - 2u) \rangle$.

We need $dS = \|\vec{r}_u \times \vec{r}_v\| dA$, so we need to compute \vec{r}_u , \vec{r}_v and the norm of their cross product. We leave it to the reader to confirm the following:

$$\vec{r}_u = \langle 1, -2v, 2v - 2 \rangle, \quad \vec{r}_v = \langle 0, 2 - 2u, 2u - 2 \rangle,$$

$$\vec{r}_u \times \vec{r}_v = \langle 4 - 4u, 2 - 2u, 2 - 2u \rangle \quad \text{and} \quad \|\vec{r}_u \times \vec{r}_v\| = 2\sqrt{6}\sqrt{(u-1)^2}.$$

We need to be careful to not “simplify” $\|\vec{r}_u \times \vec{r}_v\| = 2\sqrt{6}\sqrt{(u-1)^2}$ as $2\sqrt{6}(u-1)$; rather, it is $2\sqrt{6}|u-1|$. In this example, u is bounded by $0 \leq u \leq 1$, and on this interval $|u-1| = 1-u$. Thus $dS = 2\sqrt{6}(1-u)dA$.

The density is given as a function of x , y and z , for which we’ll substitute the corresponding components of \vec{r} (with the slight abuse of notation that we used in previous sections):

$$\begin{aligned} \delta(x, y, z) &= \delta(\vec{r}(u, v)) \\ &= u^2 + 5v(2 - 2u) + 3 - 2u - v(2 - 2u) \\ &= u^2 - 8uv - 2u + 8v + 3. \end{aligned}$$

Thus the mass of the sheet is:

$$\begin{aligned} M &= \iint_{\mathcal{S}} dm \\ &= \iint_R \delta(\vec{r}(u, v)) \|\vec{r}_u \times \vec{r}_v\| dA \\ &= \int_0^1 \int_0^1 (u^2 - 8uv - 2u + 8v + 3)(2\sqrt{6}(1-u)) du dv \\ &= \frac{31}{\sqrt{6}} \approx 12.66 \text{ gm.} \end{aligned}$$



Notes:

Flux

Let a surface \mathcal{S} lie within a vector field \vec{F} . One is often interested in measuring the *flux* of \vec{F} across \mathcal{S} ; that is, measuring “how much of the vector field passes across \mathcal{S} .” For instance, if \vec{F} represents the velocity field of moving air and \mathcal{S} represents the shape of an air filter, the flux will measure how much air is passing through the filter per unit time.

As flux measures the amount of \vec{F} passing across \mathcal{S} , we need to find the “amount of \vec{F} orthogonal to \mathcal{S} .” Similar to our measure of flux in the plane, this is equal to $\vec{F} \cdot \vec{n}$, where \vec{n} is a unit vector normal to \mathcal{S} at a point. We now consider how to find \vec{n} .

Given a smooth parametrization $\vec{r}(u, v)$ of \mathcal{S} , the work in the previous section showing the development of our method of computing surface area also shows that $\vec{r}_u(u, v)$ and $\vec{r}_v(u, v)$ are tangent to \mathcal{S} at $\vec{r}(u, v)$. Thus $\vec{r}_u \times \vec{r}_v$ is orthogonal to \mathcal{S} , and we let

$$\vec{n} = \frac{\vec{r}_u \times \vec{r}_v}{\|\vec{r}_u \times \vec{r}_v\|},$$

which is a unit vector normal to \mathcal{S} at $\vec{r}(u, v)$.

The measurement of flux across a surface is a surface integral; that is, to measure total flux we sum the product of $\vec{F} \cdot \vec{n}$ times a small amount of surface area: $\vec{F} \cdot \vec{n} dS$.

A nice thing happens with the actual computation of flux: the $\|\vec{r}_u \times \vec{r}_v\|$ terms go away. Consider:

$$\begin{aligned} \text{Flux} &= \iint_{\mathcal{S}} \vec{F} \cdot \vec{n} dS \\ &= \iint_R \vec{F} \cdot \frac{\vec{r}_u \times \vec{r}_v}{\|\vec{r}_u \times \vec{r}_v\|} \|\vec{r}_u \times \vec{r}_v\| dA \\ &= \iint_R \vec{F} \cdot (\vec{r}_u \times \vec{r}_v) dA. \end{aligned}$$

The above only makes sense if \mathcal{S} is orientable; the normal vectors \vec{n} must vary continuously across \mathcal{S} . We assume that \vec{n} does vary continuously. (If the parametrization \vec{r} of \mathcal{S} is smooth, then our above definition of \vec{n} will vary continuously.)

Notes:

Definition 11 Flux over a surface

Let \vec{F} be a vector field with continuous components defined on an orientable surface S with normal vector \vec{n} . The **flux** of \vec{F} across S is

$$\text{Flux} = \iint_S \vec{F} \cdot \vec{n} dS.$$

If S is parametrized by $\vec{r}(u, v)$, which is smooth on its domain R , then

$$\text{Flux} = \iint_R \vec{F}(\vec{r}(u, v)) \cdot (\vec{r}_u \times \vec{r}_v) dA.$$

Since S is orientable, we adopt the convention of saying one passes from the “back” side of S to the “front” side when moving across the surface parallel to the direction of \vec{n} . Also, when S is closed, it is natural to speak of the regions of space “inside” and “outside” S . We also adopt the convention that when S is a closed surface, \vec{n} should point to the outside of S . If $\vec{n} = \vec{r}_u \times \vec{r}_v$ points inside S , use $\vec{n} = \vec{r}_v \times \vec{r}_u$ instead.

When the computation of flux is positive, it means that the field is moving from the back side of S to the front side; when flux is negative, it means the field is moving opposite the direction of \vec{n} , and is moving from the front of S to the back. When S is not closed, there is not a “right” and “wrong” direction in which \vec{n} should point, but one should be mindful of its direction to make full sense of the flux computation.

We demonstrate the computation of flux, and its interpretation, in the following examples.

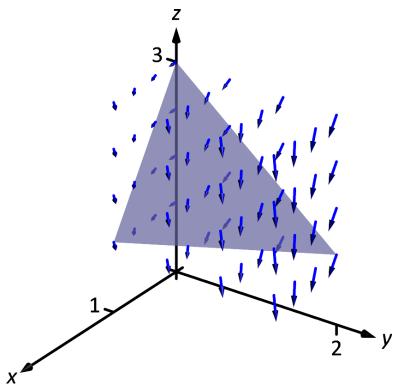


Figure 14.38: The surface and vector field used in Example 29.

Example 29 Finding flux across a surface

Let S be the surface given in Example 28; that is, let S be the surface parametrized by $\vec{r}(u, v) = \langle u, v(2 - 2u), 3 - 2u - v(2 - 2u) \rangle$ on $0 \leq u \leq 1$, $0 \leq v \leq 1$, and let $\vec{F} = \langle 1, x, -y \rangle$, as shown in Figure 14.38. Find the flux of \vec{F} across S .

SOLUTION Using our work from the previous example, we have $\vec{n} = \vec{r}_u \times \vec{r}_v = \langle 4 - 4u, 2 - 2u, 2 - 2u \rangle$. We also need $\vec{F}(\vec{r}(u, v)) = \langle 1, u, -v(2 - 2u) \rangle$.

Notes:

Thus the flux of \vec{F} across S is:

$$\begin{aligned}\text{Flux} &= \iint_S \vec{F} \cdot \vec{n} dS \\ &= \iint_R \langle 1, u, -v(2-2u) \rangle \cdot \langle 4-4u, 2-2u, 2-2u \rangle dA \\ &= \int_0^1 \int_0^1 (-4u^2v - 2u^2 + 8uv - 2u - 4v + 4) du dv \\ &= 5/3.\end{aligned}$$

To make full use of this numeric answer, we need to know the direction in which the field is passing across S . The graph in Figure 14.38 helps, but we need a method that is not dependent on a graph.

Pick a point (u, v) in the interior of R and consider $\vec{n}(u, v)$. For instance, choose $(1/2, 1/2)$ and look at $\vec{n}(1/2, 1/2) = \langle 2, 1, 1 \rangle / \sqrt{6}$. This vector has positive x , y and z components. Generally speaking, one has *some* idea of what the surface S looks like, as that surface is for some reason important. In our case, we know S is a plane with z -intercept of $z = 3$. Knowing \vec{n} and the flux measurement of positive $5/3$, we know that the field must be passing from “behind” S , i.e., the side the origin is on, to the “front” of S .

Example 30 Flux across surfaces with shared boundaries

Let S_1 be the unit disk in the x - y plane, and let S_2 be the paraboloid $z = 1 - x^2 - y^2$, for $z \geq 0$, as graphed in Figure 14.39. Note how these two surfaces each have the unit circle as a boundary.

Let $\vec{F}_1 = \langle 0, 0, 1 \rangle$ and $\vec{F}_2 = \langle 0, 0, z \rangle$. Using normal vectors for each surface that point “upward,” i.e., with a positive z -component, find the flux of each field across each surface.

SOLUTION We begin by parameterizing each surface.

The boundary of the unit disk in the x - y plane is the unit circle, which can be described with $\langle \cos u, \sin u, 0 \rangle$, $0 \leq u \leq 2\pi$. To obtain the interior of the circle as well, we can scale by v , giving

$$\vec{r}_1(u, v) = \langle v \cos u, v \sin u, 0 \rangle, \quad 0 \leq u \leq 2\pi \quad 0 \leq v \leq 1.$$

As the boundary of S_2 is also the unit circle, the x and y components of \vec{r}_2 will be the same as those of \vec{r}_1 ; we just need a different z component. With $z = 1 - x^2 - y^2$, we have

$$\vec{r}_2(u, v) = \langle v \cos u, v \sin u, 1 - v^2 \cos^2 u - v^2 \sin^2 u \rangle = \langle v \cos u, v \sin u, 1 - v^2 \rangle,$$

where $0 \leq u \leq 2\pi$ and $0 \leq v \leq 1$.

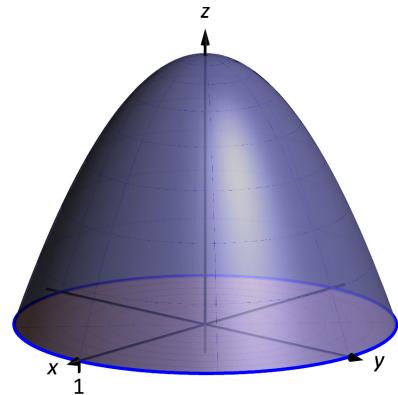


Figure 14.39: The surfaces used in Example 30.

Notes:

We now compute the normal vectors \vec{n}_1 and \vec{n}_2 .

For \vec{n}_1 : $\vec{r}_{1u} = \langle -v \sin u, v \cos u, 0 \rangle$, $\vec{r}_{1v} = \langle \cos u, \sin u, 0 \rangle$, so

$$\vec{n}_1 = \vec{r}_{1u} \times \vec{r}_{1v} = \langle 0, 0, -v \rangle.$$

As this vector has a negative z-component, we instead use

$$\vec{n}_1 = \vec{r}_{1v} \times \vec{r}_{1u} = \langle 0, 0, v \rangle.$$

Similarly, \vec{n}_2 : $\vec{r}_{2u} = \langle -v \sin u, v \cos u, 0 \rangle$, $\vec{r}_{2v} = \langle \cos u, \sin u, -2v \rangle$, so

$$\vec{n}_2 = \vec{r}_{2u} \times \vec{r}_{2v} = \langle -2v^2 \cos u, -2v^2 \sin u, -v \rangle.$$

Again, this normal vector has a negative z-component so we use

$$\vec{n}_2 = \vec{r}_{2v} \times \vec{r}_{2u} = \langle 2v^2 \cos u, 2v^2 \sin u, v \rangle.$$

We are now set to compute flux. Over field $\vec{F}_1 = \langle 0, 0, 1 \rangle$:

$$\begin{aligned} \text{Flux across } S_1 &= \iint_{S_1} \vec{F}_1 \cdot \vec{n}_1 \, dS \\ &= \iint_R \langle 0, 0, 1 \rangle \cdot \langle 0, 0, v \rangle \, dA \\ &= \int_0^1 \int_0^{2\pi} (v) \, du \, dv \\ &= \pi. \end{aligned}$$

$$\begin{aligned} \text{Flux across } S_2 &= \iint_{S_2} \vec{F}_1 \cdot \vec{n}_2 \, dS \\ &= \iint_R \langle 0, 0, 1 \rangle \cdot \langle 2v^2 \cos u, 2v^2 \sin u, v \rangle \, dA \\ &= \int_0^1 \int_0^{2\pi} (v) \, du \, dv \\ &= \pi. \end{aligned}$$

These two results are equal and positive. Each are positive because both normal vectors are pointing in the positive z-directions, as does \vec{F}_1 . As the field passes through each surface in the direction of their normal vectors, the flux is measured as positive.

We can also intuitively understand why the results are equal. Consider \vec{F}_1 to represent the flow of air, and let each surface represent a filter. Since \vec{F}_1 is

Notes:

constant, and moving “straight up,” it makes sense that all air passing through \mathcal{S}_1 also passes through \mathcal{S}_2 , and vice-versa.

If we treated the surfaces as creating one piecewise-smooth surface \mathcal{S} , we would find the total flux across \mathcal{S} by finding the flux across each piece, being sure that each normal vector pointed to the outside of the closed surface. Above, \vec{n}_1 does not point outside the surface, though \vec{n}_2 does. We would instead want to use $-\vec{n}_1$ in our computation. We would then find that the flux across \mathcal{S}_1 is $-\pi$, and hence the total flux across \mathcal{S} is $-\pi + \pi = 0$. (As 0 is a special number, we should wonder if this answer has special significance. It does, which is briefly discussed following this example and will be more fully developed in the next section.)

We now compute the flux across each surface with $\vec{F}_2 = \langle 0, 0, z \rangle$:

$$\text{Flux across } \mathcal{S}_1 = \iint_{\mathcal{S}_1} \vec{F}_2 \cdot \vec{n}_1 \, dS.$$

Over \mathcal{S}_1 , $\vec{F}_2 = \vec{F}_2(\vec{r}_2(u, v)) = \langle 0, 0, 0 \rangle$. Therefore,

$$\begin{aligned} &= \iint_R \langle 0, 0, 0 \rangle \cdot \langle 0, 0, v \rangle \, dA \\ &= \int_0^1 \int_0^{2\pi} (0) \, du \, dv \\ &= 0. \end{aligned}$$

$$\text{Flux across } \mathcal{S}_2 = \iint_{\mathcal{S}_2} \vec{F}_2 \cdot \vec{n}_2 \, dS.$$

Over \mathcal{S}_2 , $\vec{F}_2 = \vec{F}_2(\vec{r}_2(u, v)) = \langle 0, 0, 1 - v^2 \rangle$. Therefore,

$$\begin{aligned} &= \iint_R \langle 0, 0, 1 - v^2 \rangle \cdot \langle 2v^2 \cos u, 2v^2 \sin u, v \rangle \, dA \\ &= \int_0^1 \int_0^{2\pi} (v^3 - v) \, du \, dv \\ &= \pi/2. \end{aligned}$$

This time the measurements of flux differ. Over \mathcal{S}_1 , the field \vec{F}_2 is just $\vec{0}$, hence there is no flux. Over \mathcal{S}_2 , the flux is again positive as \vec{F}_2 points in the positive z direction over \mathcal{S}_2 , as does \vec{n}_2 .

Notes:

In the previous example, the surfaces S_1 and S_2 form a closed surface that is piecewise smooth. That the measurement of flux across each surface was the same for some fields (and not for others) is reminiscent of a result from Section 14.4, where we measured flux across curves. The quick answer to why the flux was the same when considering \vec{F}_1 is that $\operatorname{div} \vec{F}_1 = 0$. In the next section, we'll see the second part of the Divergence Theorem which will more fully explain this occurrence.

Notes:

Exercises 14.6

Terms and Concepts

- In the plane, flux is a measurement of how much of the vector field passes across a _____; in space, flux is a measurement of how much of the vector field passes across a _____.
- When computing flux, what does it mean when the result is a negative number?
- When \mathcal{S} is a closed surface, we choose the normal vector so that it points to the _____ of the surface.
- If \mathcal{S} is a plane, and \vec{F} is always parallel to \mathcal{S} , then the flux of \vec{F} across \mathcal{S} will be _____.

Problems

In Exercises 5 – 6, a surface \mathcal{S} that represents a thin sheet of material with density δ is given. Find the mass of each thin sheet.

- \mathcal{S} is the plane $f(x, y) = x + y$ on $-2 \leq x \leq 2, -3 \leq y \leq 3$, with $\delta(x, y, z) = z$.
- \mathcal{S} is the unit sphere, with $\delta(x, y, z) = x + y + z + 10$.

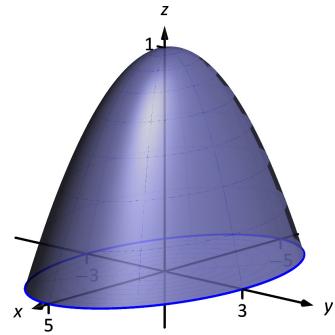
In Exercises 7 – 14, a surface \mathcal{S} and a vector field \vec{F} are given. Compute the flux of \vec{F} across \mathcal{S} . (If \mathcal{S} is not a closed surface, choose \vec{n} so that it has a positive z -component, unless otherwise indicated.)

- \mathcal{S} is the plane $f(x, y) = 3x + y$ on $0 \leq x \leq 1, 1 \leq y \leq 4$; $\vec{F} = \langle x^2, -z, 2y \rangle$.
- \mathcal{S} is the plane $f(x, y) = 8 - x - y$ over the triangle with vertices at $(0, 0), (1, 0)$ and $(1, 5)$; $\vec{F} = \langle 3, 1, 2 \rangle$.
- \mathcal{S} is the paraboloid $f(x, y) = x^2 + y^2$ over the unit disk; $\vec{F} = \langle 1, 0, 0 \rangle$.

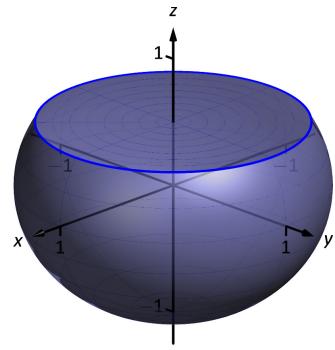
- \mathcal{S} is the unit sphere; $\vec{F} = \langle y - z, z - x, x - y \rangle$.
- \mathcal{S} is the square in space with corners at $(0, 0, 0), (1, 0, 0), (1, 0, 1)$ and $(0, 0, 1)$ (choose \vec{n} such that it has a positive y -component); $\vec{F} = \langle 0, -z, y \rangle$.

- \mathcal{S} is the disk in the y - z plane with radius 1, centered at $(0, 1, 1)$ (choose \vec{n} such that it has a positive x -component); $\vec{F} = \langle y, z, x \rangle$.

- \mathcal{S} is the closed surface composed of \mathcal{S}_1 , whose boundary is the ellipse in the x - y plane described by $\frac{x^2}{25} + \frac{y^2}{9} = 1$ and \mathcal{S}_2 , part of the elliptical paraboloid $f(x, y) = 1 - \frac{x^2}{25} - \frac{y^2}{9}$ (see graph); $\vec{F} = \langle 5, 2, 3 \rangle$.



- \mathcal{S} is the closed surface composed of \mathcal{S}_1 , part of the unit sphere and \mathcal{S}_2 , part of the plane $z = 1/2$ (see graph); $\vec{F} = \langle x, -y, z \rangle$.



14.7 The Divergence Theorem and Stokes' Theorem

The Divergence Theorem

Theorem 5 gives the Divergence Theorem in the plane, which states that the flux of a vector field across a closed *curve* equals the sum of the divergences over the region enclosed by the curve. Recall that the flux was measured via a line integral, and the sum of the divergences was measured through a double integral.

We now consider the three-dimensional version of the Divergence Theorem. It states, in words, that the flux across a closed *surface* equals the sum of the divergences over the domain enclosed by the surface. Since we are in space (versus the plane), we measure flux via a surface integral, and the sums of divergences will be measured through a triple integral.

Note: the term “outer unit normal vector” used in Theorem 7 means \vec{n} points to the outside of \mathcal{S} .

Theorem 7 The Divergence Theorem (in space)

Let D be a closed domain in space whose boundary is an orientable, piecewise smooth surface \mathcal{S} with outer unit normal vector \vec{n} , and let \vec{F} be a vector field whose components are differentiable on D . Then

$$\iint_{\mathcal{S}} \vec{F} \cdot \vec{n} dS = \iiint_D \operatorname{div} \vec{F} dV.$$

Example 31 Using the Divergence Theorem in space

Let D be the domain in space bounded by the planes $z = 0$ and $z = 2x$, along with the cylinder $x = 1 - y^2$, as graphed in Figure 14.40, let \mathcal{S} be the boundary of D , and let $\vec{F} = \langle x + y, y^2, 2z \rangle$.

Verify the Divergence Theorem by finding the total outward flux of \vec{F} across \mathcal{S} , and show this is equal to $\iiint_D \operatorname{div} \vec{F} dV$.

SOLUTION The surface \mathcal{S} is piecewise smooth, comprising surfaces \mathcal{S}_1 , which is part of the plane $z = 2x$, surface \mathcal{S}_2 , which is part of the cylinder $x = 1 - y^2$, and surface \mathcal{S}_3 , which is part of the plane $z = 0$. To find the total outward flux across \mathcal{S} , we need to compute the outward flux across each of these three surfaces.

We leave it to the reader to confirm that surfaces \mathcal{S}_1 , \mathcal{S}_2 and \mathcal{S}_3 can be pa-

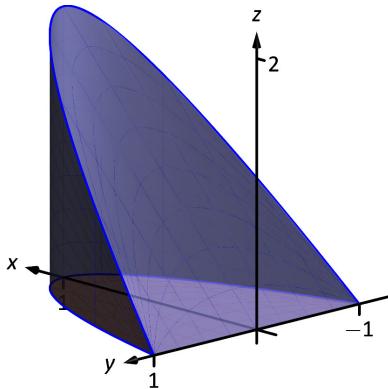


Figure 14.40: The surfaces used in Example 31.

Notes:

parameterized by \vec{r}_1 , \vec{r}_2 and \vec{r}_3 respectively as

$$\begin{aligned}\vec{r}_1(u, v) &= \langle v(1 - u^2), u, 2v(1 - u^2) \rangle, \\ \vec{r}_2(u, v) &= \langle (1 - u^2), u, 2v(1 - u^2) \rangle, \\ \vec{r}_3(u, v) &= \langle v(1 - u^2), u, 0 \rangle,\end{aligned}$$

where $-1 \leq u \leq 1$ and $0 \leq v \leq 1$ for all three functions.

We compute a unit normal vector \vec{n} for each as $\frac{\vec{r}_u \times \vec{r}_v}{\|\vec{r}_u \times \vec{r}_v\|}$, though recall that as we are integrating $\vec{F} \cdot \vec{n} dS$, we actually only use $\vec{r}_u \times \vec{r}_v$. Finally, in previous flux computations, it did not matter which direction \vec{n} pointed as long as we made note of its direction. When using the Divergence Theorem, we need \vec{n} to point to the outside of the closed surface, so in practice this means we'll either use $\vec{r}_u \times \vec{r}_v$ or $\vec{r}_v \times \vec{r}_u$, depending on which points outside of the closed surface \mathcal{S} .

We leave it to the reader to confirm the following cross products and integrations are correct.

For \mathcal{S}_1 , we need to use $\vec{r}_{1v} \times \vec{r}_{1u} = \langle 2(u^2 - 1), 0, 1 - u^2 \rangle$. (Note the z-component is nonnegative as $u \leq 1$, therefore this vector always points up, meaning to the outside, of \mathcal{S} .) The flux across \mathcal{S}_1 is:

$$\begin{aligned}\text{Flux across } \mathcal{S}_1: &= \iint_{\mathcal{S}_1} \vec{F} \cdot \vec{n}_1 dS \\ &= \int_0^1 \int_{-1}^1 \vec{F}(\vec{r}_1(u, v)) \cdot (\vec{r}_{1v} \times \vec{r}_{1u}) du dv \\ &= \int_0^1 \int_{-1}^1 \langle v(1 - u^2) + u, u^2, 4v(1 - u^2) \rangle \cdot \langle 2(u^2 - 1), 0, 1 - u^2 \rangle du dv \\ &= \int_0^1 \int_{-1}^1 (2u^4v + 2u^3 - 4u^2v - 2u + 2v) du dv \\ &= \frac{16}{15}.\end{aligned}$$

For \mathcal{S}_2 , we use $\vec{r}_{2u} \times \vec{r}_{2v} = \langle 2(1 - u^2), 4u(1 - u^2), 0 \rangle$. (Note the x-component is always nonnegative, meaning this vector points outside \mathcal{S} .) The flux across \mathcal{S}_2

Notes:

is:

$$\begin{aligned}
 \text{Flux across } S_2: &= \iint_{S_2} \vec{F} \cdot \vec{n}_2 \, dS \\
 &= \int_0^1 \int_{-1}^1 \vec{F}(\vec{r}_2(u, v)) \cdot (\vec{r}_{2u} \times \vec{r}_{2v}) \, du \, dv \\
 &= \int_0^1 \int_{-1}^1 \langle 1 - u^2 + u, u^2, 4v(1 - u^2) \rangle \cdot \langle 2(1 - u^2), 4u(1 - u^2), 0 \rangle \, du \, dv \\
 &= \int_0^1 \int_{-1}^1 (4u^5 - 2u^4 - 2u^3 + 4u^2 - 2u - 2) \, du \, dv \\
 &= \frac{32}{15}.
 \end{aligned}$$

For S_3 , we use $\vec{r}_{3u} \times \vec{r}_{3v} = \langle 0, 0, u^2 - 1 \rangle$. (Note the z-component is never positive, meaning this vector points down, outside of S .) The flux across S_3 is:

$$\begin{aligned}
 \text{Flux across } S_3: &= \iint_{S_3} \vec{F} \cdot \vec{n}_3 \, dS \\
 &= \int_0^1 \int_{-1}^1 \vec{F}(\vec{r}_3(u, v)) \cdot (\vec{r}_{3u} \times \vec{r}_{3v}) \, du \, dv \\
 &= \int_0^1 \int_{-1}^1 \langle v(1 - u^2) + u, u^2, 0 \rangle \cdot \langle 0, 0, u^2 - 1 \rangle \, du \, dv \\
 &= \int_0^1 \int_{-1}^1 0 \, du \, dv \\
 &= 0.
 \end{aligned}$$

Thus the total outward flux, measured by surface integrals across all three component surfaces of S , is $16/15 + 32/15 + 0 = 48/15 = 16/5 = 3.2$. We now find the total outward flux by integrating $\operatorname{div} \vec{F}$ over D .

Following the steps outlined in Section ??, we see the bounds of x , y and z can be set as (thinking “surface to surface, curve to curve, point to point”):

$$0 \leq z \leq 2x; \quad 0 \leq x \leq 1 - y^2; \quad -1 \leq y \leq 1.$$

With $\operatorname{div} \vec{F} = 1 + 2y + 2 = 2y + 3$, we find the total outward flux of \vec{F} over S as:

$$\text{Flux} = \iiint_D \operatorname{div} \vec{F} \, dV = \int_{-1}^1 \int_0^{1-y^2} \int_0^{2x} (2y + 3) \, dz \, dx \, dy = 16/5,$$

the same result we obtained previously.

Notes:

In Example 31 we see that the total outward flux of a vector field across a closed surface can be found two different ways because of the Divergence Theorem. One computation took far less work to obtain. In that particular case, since S was comprised of three separate surfaces, it was far simpler to compute one triple integral than three surface integrals (each of which required partial derivatives and a cross product). In practice, if outward flux needs to be measured, one would choose only one method. We will use both methods in this section simply to reinforce the truth of the Divergence Theorem.

We practice again in the following example.

Example 32 Using the Divergence Theorem in space

Let S be the surface formed by the paraboloid $z = 1 - x^2 - y^2$, $z \geq 0$, and the unit disk centered at the origin in the x - y plane, graphed in Figure 14.41, and let $\vec{F} = \langle 0, 0, z \rangle$. (This surface and vector field were used in Example 30.)

Verify the Divergence Theorem; find the total outward flux across S and evaluate the triple integral of $\operatorname{div} \vec{F}$, showing that these two quantities are equal.

SOLUTION We find the flux across S first. As S is piecewise-smooth, we decompose it into smooth components S_1 , the disk, and S_2 , the paraboloid, and find the flux across each.

In Example 30, we found the flux across S_1 is 0. We also found that the flux across S_2 is $\pi/2$. (In that example, the normal vector had a positive z component hence was an outer normal.) Thus the total outward flux is $0 + \pi/2 = \pi/2$.

We now compute $\iiint_D \operatorname{div} \vec{F} dV$. We can describe D as the domain bounded by (think “surface to surface, curve to curve, point to point”):

$$0 \leq z \leq 1 - x^2 - y^2, \quad -\sqrt{1-x^2} \leq y \leq \sqrt{1-x^2}, \quad -1 \leq x \leq 1.$$

This description of D is not very easy to integrate. With polar, we can do better. Let R represent the unit disk, which can be described in polar simply as r , where $0 \leq r \leq 1$ and $0 \leq \theta \leq 2\pi$. With $x = r \cos \theta$ and $y = r \sin \theta$, the surface S_2 becomes

$$z = 1 - x^2 - y^2 \Rightarrow 1 - (r \cos \theta)^2 - (r \sin \theta)^2 \Rightarrow 1 - r^2.$$

Thus D can be described as the domain bounded by:

$$0 \leq z \leq 1 - r^2, \quad 0 \leq r \leq 1, \quad 0 \leq \theta \leq 2\pi.$$

With $\operatorname{div} \vec{F} = 1$, we can integrate, recalling that $dV = r dz dr d\theta$:

$$\iiint_D \operatorname{div} \vec{F} dV = \int_0^{2\pi} \int_0^1 \int_0^{1-r^2} r dz dr d\theta = \frac{\pi}{2},$$

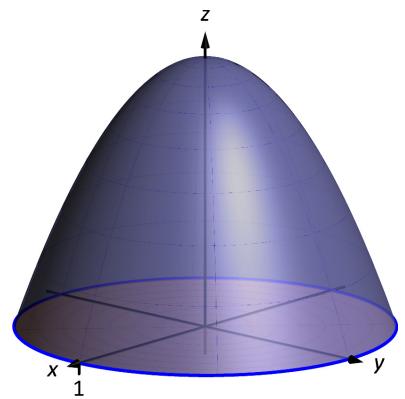


Figure 14.41: The surfaces used in Example 32.

Notes:

which matches our flux computation above.

Example 33 A “paradox” of the Divergence Theorem and Gauss’s Law

The magnitude of many physical quantities (such as light intensity or electromagnetic and gravitational forces) follow an “inverse square law”: the magnitude of the quantity at a point is inversely proportional to the square of the distance to the source of the quantity.

Let a point light source be placed at the origin and let \vec{F} be the vector field which describes the intensity and direction of the emanating light. At a point (x, y, z) , the unit vector describing the direction of the light passing through that point is $\langle x, y, z \rangle / \sqrt{x^2 + y^2 + z^2}$. As the intensity of light follows the inverse square law, the magnitude of \vec{F} at (x, y, z) is $k / (x^2 + y^2 + z^2)$ for some constant k . Taken together,

$$\vec{F}(x, y, z) = \frac{k}{(x^2 + y^2 + z^2)^{3/2}} \langle x, y, z \rangle.$$

Consider the cube, centered at the origin, with sides of length $2a$ for some $a > 0$ (hence corners of the cube lie at (a, a, a) , $(-a, -a, -a)$, etc., as shown in Figure 14.42). Find the flux across the six faces of the cube and compare this to $\iint_D \operatorname{div} \vec{F} dV$.

SOLUTION Let S_1 be the “top” face of the cube, which can be parametrized by $\vec{r}(u, v) = \langle u, v, a \rangle$ for $-a \leq u \leq a$, $-a \leq v \leq a$. We leave it to the reader to confirm that $\vec{r}_u \times \vec{r}_v = \langle 0, 0, 1 \rangle$, which points outside of the cube.

The flux across this face is:

$$\begin{aligned} \text{Flux} &= \iint_{S_1} \vec{F} \cdot \vec{n} dS \\ &= \int_{-a}^a \int_{-a}^a \vec{F}(\vec{r}(u, v)) \cdot (\vec{r}_u \times \vec{r}_v) du dv \\ &= \int_{-a}^a \int_{-a}^a \frac{k a}{(u^2 + v^2 + a^2)^{3/2}} du dv. \end{aligned}$$

This double integral is *not* trivial to compute, requiring multiple trigonometric substitutions. This example is not meant to stress integration techniques, so we leave it to the reader to confirm the result is

$$= \frac{2k\pi}{3}.$$

Note how the result is independent of a ; no matter the size of the cube, the flux through the top surface is always $2k\pi/3$.

Notes:

An argument of symmetry shows that the flux through each of the six faces is $2\pi/3$, thus the total flux through the faces of the cube is $6 \times 2k\pi/3 = 4k\pi$.

It takes a bit of algebra, but we can show that $\operatorname{div} \vec{F} = 0$. Thus the Divergence Theorem would seem to imply that the total flux through the faces of the cube should be

$$\text{Flux} = \iiint_D \operatorname{div} \vec{F} dV = \iiint_D 0 dV = 0,$$

but clearly this does not match the result from above. What went wrong?

Revisit the statement of the Divergence Theorem. One of the conditions is that the components of \vec{F} must be differentiable on the domain enclosed by the surface. In our case, \vec{F} is not differentiable at the origin – it is not even defined! As \vec{F} does not satisfy the conditions of the Divergence Theorem, it does not apply, and we cannot expect $\iint_S \vec{F} \cdot \vec{n} dA = \iiint_D \operatorname{div} \vec{F} dV$.

Since \vec{F} is differentiable everywhere except the origin, the Divergence Theorem does apply over any domain that does not include the origin. Let S_2 be any surface that encloses the cube used before, and let \hat{D} be the domain between the cube and S_2 ; note how \hat{D} does not include the origin and so the Divergence Theorem does apply over this domain. The total outward flux over \hat{D} is thus $\iint_{\hat{D}} \operatorname{div} \vec{F} dV = 0$, which means the amount of flux coming out of S_2 is the same as the amount of flux coming out of the cube. The conclusion: the flux across any surface enclosing the origin will be $4k\pi$.

This has an important consequence in electrodynamics. Let q be a point charge at the origin. The electric field generated by this point charge is

$$\vec{E} = \frac{q}{4\pi\epsilon_0} \frac{\langle x, y, z \rangle}{(x^2 + y^2 + z^2)^{3/2}},$$

i.e., it is \vec{F} with $k = q/(4\pi\epsilon_0)$, where ϵ_0 is a physical constant (the “permittivity of free space”). Gauss’s Law states that the outward flux of \vec{E} across any surface enclosing the origin is q/ϵ_0 .

Our interest in the Divergence Theorem is twofold. First, its truth alone is interesting: to study the behavior of a vector field across a closed surface, one can examine properties of that field within the surface. Secondly, it offers an alternative way of computing flux. When there are multiple methods of computing a desired quantity, one has power to select the easiest computation as illustrated next.

Example 34 Using the Divergence Theorem to compute flux

Let S be the cube bounded by the planes $x = \pm 1$, $y = \pm 1$, $z = \pm 1$, and let $\vec{F} = \langle x^2y, 2yz, x^2z^3 \rangle$. Compute the outward flux of \vec{F} over S .

Notes:

SOLUTION We compute $\operatorname{div} \vec{F} = 2xy + 2z + 3x^2z^2$. By the Divergence Theorem, the outward flux is the triple integral over the domain D enclosed by \mathcal{S} :

$$\text{Outward flux: } \int_{-1}^1 \int_{-1}^1 \int_{-1}^1 (2xy + 2z + 3x^2z^2) dz dy dx = \frac{8}{3}.$$

The direct flux computation requires six surface integrals, one for each face of the cube. The Divergence Theorem offers a much more simple computation.

Stokes' Theorem

Just as the spatial Divergence Theorem of this section is an extension of the planar Divergence Theorem, Stokes' Theorem is the spatial extension of Green's Theorem. Recall that Green's Theorem states that the circulation of a vector field around a closed curve in the plane is equal to the sum of the curl of the field over the region enclosed by the curve. Stokes' Theorem effectively makes the same statement: given a closed curve that lies on a surface \mathcal{S} , the circulation of a vector field around that curve is the same as the sum of "the curl of the field" across the enclosed surface. We use quotes around "the curl of the field" to signify that this statement is not quite correct, as we do not sum $\operatorname{curl} \vec{F}$, but $\operatorname{curl} \vec{F} \cdot \vec{n}$, where \vec{n} is a unit vector normal to \mathcal{S} . That is, we sum the portion of $\operatorname{curl} \vec{F}$ that is orthogonal to \mathcal{S} at a point.

Green's Theorem dictated that the curve was to be traversed counterclockwise when measuring circulation. Stokes' Theorem will follow a right hand rule: when the thumb of one's right hand points in the direction of \vec{n} , the path C will be traversed in the direction of the curling fingers of the hand (this is equivalent to traversing counterclockwise in the plane).

Theorem 8 Stokes' Theorem

Let \mathcal{S} be a piecewise smooth, orientable surface whose boundary is a piecewise smooth curve C , let \vec{n} be a unit vector normal to \mathcal{S} , let C be traversed with respect to \vec{n} according to the right hand rule, and let the components of \vec{F} have continuous first partial derivatives over \mathcal{S} . Then

$$\oint_C \vec{F} \cdot d\vec{r} = \iint_{\mathcal{S}} (\operatorname{curl} \vec{F}) \cdot \vec{n} dS.$$

In general, the best approach to evaluating the surface integral in Stokes' Theorem is to parametrize the surface \mathcal{S} with a function $\vec{r}(u, v)$. We can find a

Notes:

unit normal vector \vec{n} as

$$\vec{n} = \frac{\vec{r}_u \times \vec{r}_v}{\|\vec{r}_u \times \vec{r}_v\|}.$$

Since $dS = \|\vec{r}_u \times \vec{r}_v\| dA$, the surface integral in practice is evaluated as

$$\iint_S (\operatorname{curl} \vec{F}) \cdot (\vec{r}_u \times \vec{r}_v) dA,$$

where $\vec{r}_u \times \vec{r}_v$ may be replaced by $\vec{r}_v \times \vec{r}_u$ to properly match the direction of this vector with the orientation of the parameterization of C .

Example 35 Verifying Stokes' Theorem

Considering the planar surface $f(x, y) = 7 - 2x - 2y$, let C be the curve in space that lies on this surface above the circle of radius 1 and centered at $(1, 1)$ in the x - y plane, let S be the planar region enclosed by C , as illustrated in Figure 14.43, and let $\vec{F} = \langle x + y, 2y, y^2 \rangle$. Verify Stoke's Theorem by showing $\oint_C \vec{F} \cdot d\vec{r} = \iint_S (\operatorname{curl} \vec{F}) \cdot \vec{n} dS$.

SOLUTION We begin by parameterizing C and then find the circulation. A unit circle centered at $(1, 1)$ can be parametrized with $x = \cos t + 1$, $y = \sin t + 1$ on $0 \leq t \leq 2\pi$; to put this curve on the surface f , make the z component equal $f(x, y)$: $z = 7 - 2(\cos t + 1) - 2(\sin t + 1) = 3 - 2 \cos t - 2 \sin t$. All together, we parametrize C with $\vec{r}(t) = \langle \cos t + 1, \sin t + 1, 3 - 2 \cos t - 2 \sin t \rangle$.

The circulation of \vec{F} around C is

$$\begin{aligned} \oint_C \vec{F} \cdot d\vec{r} &= \int_0^{2\pi} \vec{F}(\vec{r}(t)) \cdot \vec{r}'(t) dt \\ &= \int_0^{2\pi} (2 \sin^3 t - 2 \cos t \sin^2 t + 3 \sin^2 t - 3 \cos t \sin t) dt \\ &= 3\pi. \end{aligned}$$

We now parametrize S . (We reuse the letter “ r ” for our surface as this is our custom.) Based on the parametrization of C above, we describe S with $\vec{r}(u, v) = \langle v \cos u + 1, v \sin u + 1, 3 - 2v \cos u - 2v \sin u \rangle$, where $0 \leq u \leq 2\pi$ and $0 \leq v \leq 1$.

We leave it to the reader to confirm that $\vec{r}_u \times \vec{r}_v = \langle 2v, 2v, v \rangle$. As $0 \leq v \leq 1$, this vector always has a non-negative z -component, which the right-hand rule requires given the orientation of C used above. We also leave it to the reader to confirm $\operatorname{curl} \vec{F} = \langle 2y, 0, -1 \rangle$.

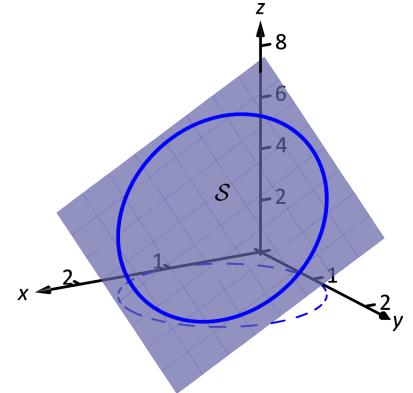


Figure 14.43: As given in Example 35, the surface S is the portion of the plane bounded by the curve.

Notes:

The surface integral of Stokes' Theorem is thus

$$\begin{aligned}\iint_S (\operatorname{curl} \vec{F}) \cdot \vec{n} dS &= \iint_S (\operatorname{curl} \vec{F}) \cdot (\vec{r}_u \times \vec{r}_v) dA \\ &= \int_0^1 \int_0^{2\pi} \langle 2v \sin u + 2, 0, -1 \rangle \cdot \langle 2v, 2v, v \rangle du dv \\ &= 3\pi,\end{aligned}$$

which matches our previous result.

One of the interesting results of Stokes' Theorem is that if two surfaces S_1 and S_2 share the same boundary, then $\iint_{S_1} (\operatorname{curl} \vec{F}) \cdot \vec{n} dS = \iint_{S_2} (\operatorname{curl} \vec{F}) \cdot \vec{n} dS$. That is, the value of these two surface integrals is somehow independent of the interior of the surface. We demonstrate this principle in the next example.

Example 36 Stokes' Theorem and surfaces that share a boundary

Let C be the curve given in Example 35 and note that it lies on the surface $z = 6 - x^2 - y^2$. Let S be the region of this surface bounded by C , and let $\vec{F} = \langle x + y, 2y, y^2 \rangle$ as in the previous example. Compute $\iint_S (\operatorname{curl} \vec{F}) \cdot \vec{n} dS$ to show it equals the result found in the previous example.

SOLUTION We begin by demonstrating that C lies on the surface $z = 6 - x^2 - y^2$. We can parametrize the x and y components of C with $x = \cos t + 1$, $y = \sin t + 1$ as before. Lifting these components to the surface f gives the z component as $z = 6 - x^2 - y^2 = 6 - (\cos t + 1)^2 - (\sin t + 1)^2 = 3 - 2 \cos t - 2 \sin t$, which is the same z component as found in Example 35. Thus the curve C lies on the surface $z = 6 - x^2 - y^2$, as illustrated in Figure 14.44.

Since C and \vec{F} are the same as in the previous example, we already know that $\oint_C \vec{F} \cdot d\vec{r} = 3\pi$. We confirm that this is also the value of $\iint_S (\operatorname{curl} \vec{F}) \cdot \vec{n} dS$.

We parametrize S with

$$\vec{r}(u, v) = \langle v \cos u + 1, v \sin u + 1, 6 - (v \cos u + 1)^2 - (v \sin u + 1)^2 \rangle,$$

where $0 \leq u \leq 2\pi$ and $0 \leq v \leq 1$, and leave it to the reader to confirm that

$$\vec{r}_u \times \vec{r}_v = \langle 2v(v \cos u + 1), 2v(v \sin u + 1), v \rangle,$$

which also conforms to the right-hand rule with regard to the orientation of C .

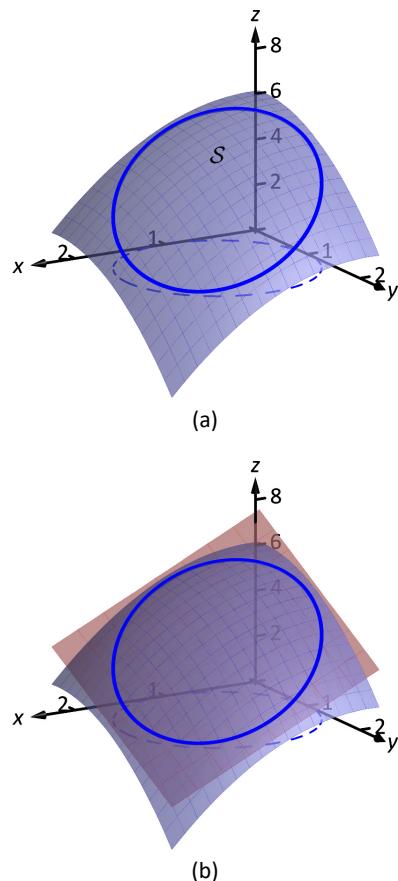


Figure 14.44: As given in Example 36, the surface S is the portion of the plane bounded by the curve.

Notes:

With $\operatorname{curl} \vec{F} = \langle 2y, 0, -1 \rangle$ as before, we have

$$\begin{aligned} \iint_S (\operatorname{curl} \vec{F}) \cdot \vec{n} \, dS &= \\ \int_0^1 \int_0^{2\pi} \langle 2v \sin u + 2, 0, -1 \rangle \cdot \langle 2v(v \cos u + 1), 2v(v \sin u + 1), v \rangle \, du \, dv &= \\ 3\pi. \end{aligned}$$

Even though the surfaces used in this example and in Example 35 are very different, because they share the same boundary, Stokes' Theorem guarantees they have equal “sum of curls” across their respective surfaces.

A Common Thread of Calculus

We have threefold interest in each of the major theorems of this chapter: the Fundamental Theorem of Line Integrals, Green's, Stokes' and the Divergence Theorems. First, we find the beauty of their truth interesting. Second, each provides two methods of computing a desired quantity, sometimes offering a simpler method of computation.

There is yet one more reason of interest in the major theorems of this chapter. These important theorems also all share an important principle with the Fundamental Theorem of Calculus, introduced in Chapter ??.

Revisit this fundamental theorem, adopting the notation used heavily in this chapter. Let I be the interval $[a, b]$ and let $y = F(x)$ be differentiable on I , with $F'(x) = f(x)$. The Fundamental Theorem of Calculus states that

$$\int_I f(x) \, dx = F(b) - F(a).$$

That is, the sum of the rates of change of a function F over an interval I can also be calculated with a certain sum of F itself on the boundary of I (in this case, at the points $x = a$ and $x = b$).

Each of the named theorems above can be expressed in similar terms. Consider the Fundamental Theorem of Line Integrals: given a function $z = f(x, y)$, the gradient ∇f is a type of rate of change of f . Given a curve C with initial and terminal points A and B , respectively, this fundamental theorem states that

$$\int_C \nabla f \cdot ds = f(B) - f(A),$$

where again the sum of a rate of change of f along a curve C can also be evaluated by a certain sum of f at the boundary of C (i.e., the points A and B).

Notes:

Green's Theorem is essentially a special case of Stokes' Theorem, so we consider just Stokes' Theorem here. Recalling that the curl of a vector field \vec{F} is a measure of a rate of change of \vec{F} , Stokes' Theorem states that over a surface S bounded by a closed curve C ,

$$\iint_S (\operatorname{curl} \vec{F}) \cdot \vec{n} dS = \oint_C \vec{F} \cdot d\vec{r},$$

i.e., the sum of a rate of change of \vec{F} can be calculated with a certain sum of \vec{F} itself over the boundary of S . In this case, the latter sum is also an infinite sum, requiring an integral.

Finally, the Divergence Theorems state that the sum of divergences of a vector field (another measure of a rate of change of \vec{F}) over a region can also be computed with a certain sum of \vec{F} over the boundary of that region. When the region is planar, the latter sum of \vec{F} is an integral; when the region is spatial, the latter sum of \vec{F} is a double integral.

The common thread among these theorems: the sum of a rate of change of a function over a region can be computed as another sum of the function itself on the boundary of the region. While very general, this is a very powerful and important statement.

Notes:

Exercises 14.7

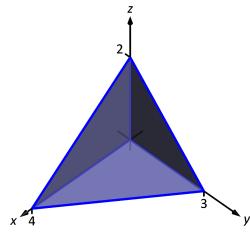
Terms and Concepts

- What are the differences between the Divergence Theorems of Section 14.4 and this section?
- What property of a vector field does the Divergence Theorem relate to flux?
- What property of a vector field does Stokes' Theorem relate to circulation?
- Stokes' Theorem is the spatial version of what other theorem?

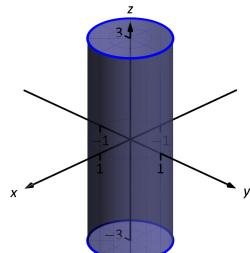
Problems

In Exercises 5 – 8, a closed surface S enclosing a domain D and a vector field \vec{F} are given. Verify the Divergence Theorem on S ; that is, show $\iint_S \vec{F} \cdot \vec{n} dS = \iiint_D \operatorname{div} \vec{F} dV$.

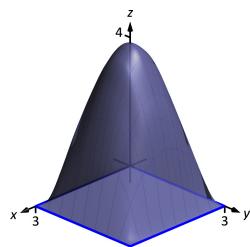
- S is the surface bounding the domain D enclosed by the plane $z = 2 - x/2 - 2y/3$ and the coordinate planes in the first octant; $\vec{F} = \langle x^2, y^2, x \rangle$.



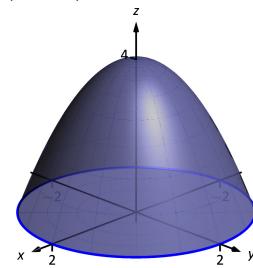
- S is the surface bounding the domain D enclosed by the cylinder $x^2 + y^2 = 1$ and the planes $z = -3$ and $z = 3$; $\vec{F} = \langle -x, y, z \rangle$.



- S is the surface bounding the domain D enclosed by $z = xy(3-x)(3-y)$ and the plane $z = 0$; $\vec{F} = \langle 3x, 4y, 5z+1 \rangle$.

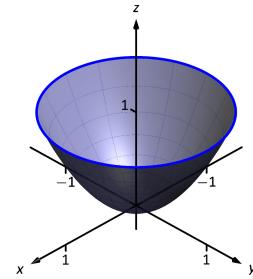


- S is the surface composed of S_1 , the paraboloid $z = 4 - x^2 - y^2$ for $z \geq 0$, and S_2 , the disk of radius 2 centered at the origin; $\vec{F} = \langle x, y, z^2 \rangle$.

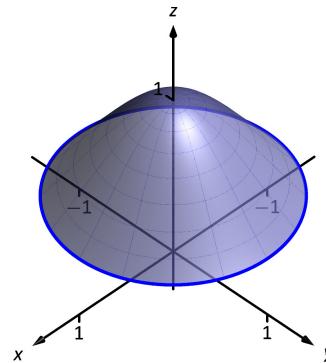


In Exercises 9 – 12, a closed curve C that is the boundary of a surface S is given along with a vector field \vec{F} . Verify Stokes' Theorem on C ; that is, show $\oint_C \vec{F} \cdot d\vec{r} = \iint_S (\operatorname{curl} \vec{F}) \cdot \vec{n} dS$.

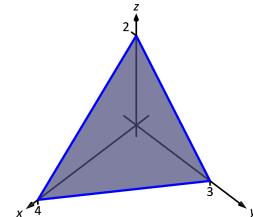
- C is the curve parametrized by $\vec{r}(t) = \langle \cos t, \sin t, 1 \rangle$ and S is the portion of $z = x^2 + y^2$ enclosed by C ; $\vec{F} = \langle z, -x, y \rangle$.



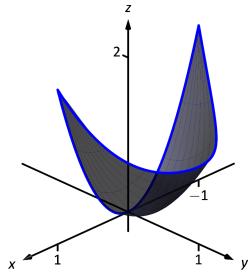
- C is the curve parametrized by $\vec{r}(t) = \langle \cos t, \sin t, e^{-t} \rangle$ and S is the portion of $z = e^{-x^2 - y^2}$ enclosed by C ; $\vec{F} = \langle -y, x, 1 \rangle$.



- C is the curve that follows the triangle with vertices at $(0, 0, 2), (4, 0, 0)$ and $(0, 3, 0)$, traversing the vertices in that order and returning to $(0, 0, 2)$, and S is the portion of the plane $z = 2 - x/2 - 2y/3$ enclosed by C ; $\vec{F} = \langle y, -z, y \rangle$.

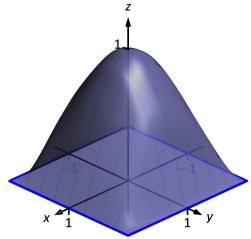


12. C is the curve whose x and y coordinates follow the parabola $y = 1 - x^2$ from $x = 1$ to $x = -1$, then follow the line from $(-1, 0)$ back to $(1, 0)$, where the z coordinates of C are determined by $f(x, y) = 2x^2 + y^2$, and \mathcal{S} is the portion of $z = 2x^2 + y^2$ enclosed by C ; $\vec{F} = \langle y^2 + z, x, x^2 - y \rangle$.

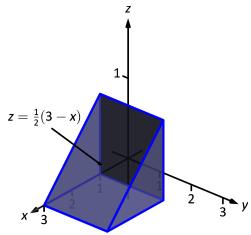


In Exercises 13 – 16, a closed surface \mathcal{S} and a vector field \vec{F} are given. Find the outward flux of \vec{F} over \mathcal{S} either through direct computation or through the Divergence Theorem.

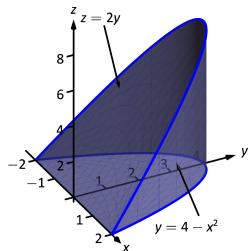
13. \mathcal{S} is the surface formed by the intersections of $z = 0$ and $z = (x^2 - 1)(y^2 - 1)$; $\vec{F} = \langle x^2 + 1, yz, xz^2 \rangle$.



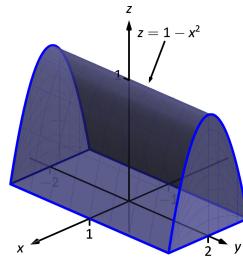
14. \mathcal{S} is the surface formed by the intersections of the planes $z = \frac{1}{2}(3 - x)$, $x = 1$, $y = 0$, $y = 2$ and $z = 0$; $\vec{F} = \langle x, y^2, z \rangle$.



15. \mathcal{S} is the surface formed by the intersections of the planes $z = 2y$, $y = 4 - x^2$ and $z = 0$; $\vec{F} = \langle xz, 0, xz \rangle$.

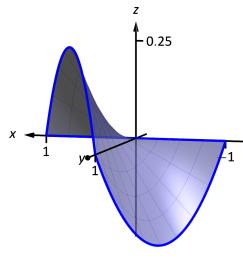


16. \mathcal{S} is the surface formed by the intersections of the cylinder $z = 1 - x^2$ and the planes $y = -2$, $y = 2$ and $z = 0$; $\vec{F} = \langle 0, y^3, 0 \rangle$.

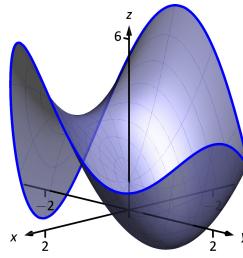


In Exercises 17 – 20, a closed curve C that is the boundary of a surface \mathcal{S} is given along with a vector field \vec{F} . Find the circulation of \vec{F} around C either through direct computation or through Stokes' Theorem.

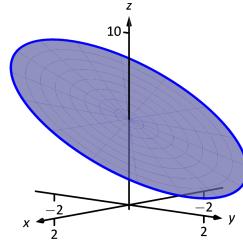
17. C is the curve whose x - and y -values are determined by the three sides of a triangle with vertices at $(-1, 0)$, $(1, 0)$ and $(0, 1)$, traversed in that order, and the z -values are determined by the function $z = xy$; $\vec{F} = \langle z - y^2, x, z \rangle$.



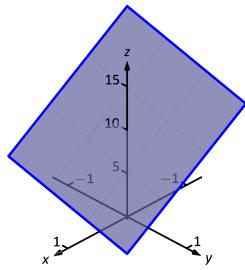
18. C is the curve whose x - and y -values are given by $\vec{r}(t) = \langle 2 \cos t, 2 \sin t \rangle$ and the z -values are determined by the function $z = x^2 + y^3 - 3y + 1$; $\vec{F} = \langle -y, x, z \rangle$.



19. C is the curve whose x - and y -values are given by $\vec{r}(t) = \langle \cos t, 3 \sin t \rangle$ and the z -values are determined by the function $z = 5 - 2x - y$; $\vec{F} = \langle -\frac{1}{3}y, 3x, \frac{2}{3}y - 3x \rangle$.



20. C is the curve whose x - and y -values are sides of the square with vertices at $(1, 1)$, $(-1, 1)$, $(-1, -1)$ and $(1, -1)$, traversed in that order, and the z -values are determined by the function $z = 10 - 5x - 2y$; $\vec{F} = \langle 5y^2, 2y^2, y^2 \rangle$.



Exercises 21 – 24 are designed to challenge your understanding and require no computation.

21. Let S be any closed surface enclosing a domain D . Consider $\vec{F}_1 = \langle x, 0, 0 \rangle$ and $\vec{F}_2 = \langle y, y^2, z - 2yz \rangle$.

These fields are clearly very different. Why is it that the total outward flux of each field across S is the same?

22. (a) Green's Theorem can be used to find the area of a region enclosed by a curve by evaluating a line integral with the appropriate choice of vector field \vec{F} . What condition on \vec{F} makes this possible?

- (b) Likewise, Stokes' Theorem can be used to find the surface area of a region enclosed by a curve in space by evaluating a line integral with the appropriate choice of vector field \vec{F} . What condition on \vec{F} makes this possible?

23. The Divergence Theorem establishes equality between a particular double integral and a particular triple integral. What types of circumstances would lead one to choose to evaluate the triple integral over the double integral?

24. Stokes' Theorem establishes equality between a particular line integral and a particular double integral. What types of circumstances would lead one to choose to evaluate the double integral over the line integral?

A: SOLUTIONS TO SELECTED PROBLEMS

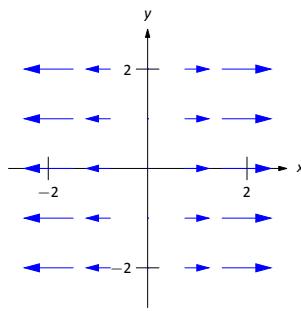
Chapter 14

Section 14.1

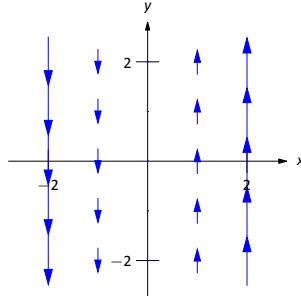
1. When C is a curve in the plane and f is a surface defined over C , then $\int_C f(s) ds$ describes the area under the spatial curve that lies on f , over C .
2. The evaluation is the same. The \oint notation signifies that the curve C is a closed curve, though the evaluation is the same.
3. The variable s denotes the arc-length parameter, which is generally difficult to use. The Key Idea allows one to parametrize a curve using another, ideally easier-to-use, parameter.
4. Answers will vary.
5. $12\sqrt{2}$
6. $41\sqrt{10}/2$
7. 40π
8. $10\pi^2$
9. Over the first subcurve of C , the line integral has a value of $3/2$; over the second subcurve, the line integral has a value of $4/3$. The total value of the line integral is thus $17/6$.
10. Over the first subcurve of C , the line integral has a value of $2\sqrt{2}/3$; over the second subcurve, the line integral has a value of $\pi - 2$. The total value of the line integral is thus $\pi + 2\sqrt{2}/3 - 2$.
11. $\int_0^1 (5t^2 + 2t + 2) \sqrt{(4t+1)^2 + 1} dt \approx 17.071$
12. $\int_0^\pi t \sqrt{1 + \cos^2 t} dt \approx 6.001$
13. $\oint_0^{2\pi} (10 - 4 \cos^2 t - \sin^2 t) \sqrt{\cos^2 t + 4 \sin^2 t} dt \approx 74.986$
14. $\int_{-1}^1 (3t^3 + 2t + 5) \sqrt{9t^4 + 1} dt \approx 15.479$
15. $7\sqrt{26}/3$
16. 2π
17. $8\pi^3$
18. $5/2$
19. $M = 8\sqrt{2}\pi^2$; center of mass is $(0, -1/(2\pi), 8\pi/3)$.
20. $M \approx 0.237$; center of mass is approximately $(0.173, 0.099, 0.065)$.

Section 14.2

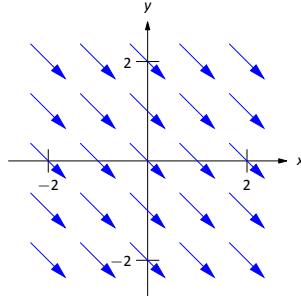
1. Answers will vary. Appropriate answers include velocities of moving particles (air, water, etc.); gravitational or electromagnetic forces.
2. Specific answers will vary, though should relate to the idea that "more of the vector field is moving into that point than out of that point."
3. Specific answers will vary, though should relate to the idea that the vector field is spinning clockwise at that point.
4. No; to be incompressible, the divergence needs to be 0 everywhere, not just at one point.
5. Correct answers should look similar to



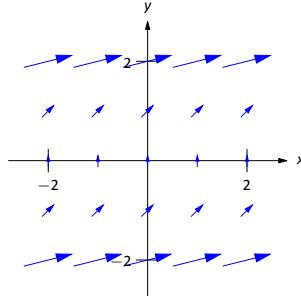
6. Correct answers should look similar to



7. Correct answers should look similar to



8. Correct answers should look similar to



9. $\operatorname{div} \vec{F} = 1 + 2y$
 $\operatorname{curl} \vec{F} = 0$
10. $\operatorname{div} \vec{F} = 0$
 $\operatorname{curl} \vec{F} = 1 + 2y$
11. $\operatorname{div} \vec{F} = x \cos(xy) - y \sin(xy)$
 $\operatorname{curl} \vec{F} = y \cos(xy) + x \sin(xy)$
12. $\operatorname{div} \vec{F} = \frac{4}{(x^2+y^2)^2}$
 $\operatorname{curl} \vec{F} = 0$
13. $\operatorname{div} \vec{F} = 3$
 $\operatorname{curl} \vec{F} = \langle -1, -1, -1 \rangle$

14. $\operatorname{div} \vec{F} = 2x + 2y + 2z$
 $\operatorname{curl} \vec{F} = \langle 2y, 2z, 2x \rangle$
15. $\operatorname{div} \vec{F} = 1 + 2y$
 $\operatorname{curl} \vec{F} = 0$
16. $\operatorname{div} \vec{F} = 2y$
 $\operatorname{curl} \vec{F} = 0$
17. $\operatorname{div} \vec{F} = 2y - \sin z$
 $\operatorname{curl} \vec{F} = \vec{0}$
18. $\operatorname{div} \vec{F} = \frac{2}{(x^2+y^2+z^2)^2}$
 $\operatorname{curl} \vec{F} = \vec{0}$

Section 14.3

1. False. It is true for line integrals over scalar fields, though.
2. The input of \vec{F} should be a point in the plane, not a two dimensional vector.
3. True.
4. False.
5. We can conclude that \vec{F} is conservative.
6. By the Fundamental Theorem of Line Integrals, since \vec{F} is conservative, $\oint_C \vec{F} \cdot d\vec{r} = f(B) - f(A)$, where f is a potential function for \vec{F} and A and B are the initial and terminal points of C , respectively. Since C is a closed curve, $A = B$, and hence $f(B) - f(A) = 0$.
7. 11/6. (One parametrization for C is $\vec{r}(t) = \langle 3t, t \rangle$ on $0 \leq t \leq 1$.)
8. 5/3. (One parametrization for C is $\vec{r}(t) = \langle t, t^2 \rangle$ on $0 \leq t \leq 1$.)
9. 0. (One parametrization for C is $\vec{r}(t) = \langle \cos t, \sin t \rangle$ on $0 \leq t \leq \pi$.)
10. 2/5. (One parametrization for C is $\vec{r}(t) = \langle t, t^3 \rangle$ on $-1 \leq t \leq 1$.)
11. 12. (One parametrization for C is $\vec{r}(t) = \langle 1, 2, 3 \rangle + t\langle 3, 1, -1 \rangle$ on $0 \leq t \leq 1$.)
12. 1.
13. 5/6 joules. (One parametrization for C is $\vec{r}(t) = \langle t, t \rangle$ on $0 \leq t \leq 1$.)
14. 13/15 joules. (One parametrization for C is $\vec{r}(t) = \langle t, \sqrt{t} \rangle$ on $0 \leq t \leq 1$.)
15. 24 ft-lbs.
16. 24 ft-lbs.
17. (a) $f(x, y) = xy + x$
(b) $\operatorname{curl} \vec{F} = 0$.
(c) 1. (One parametrization for C is $\vec{r}(t) = \langle t, -1t \rangle$ on $0 \leq t \leq 1$.)
(d) 1 (with $A = (0, 1)$ and $B = (1, 0)$, $f(B) - f(A) = 1$.)
18. (a) $f(x, y) = x^2 + xy + y^2$
(b) $\operatorname{curl} \vec{F} = 0$.
(c) 0.
(d) 0 (with $A = (0, 0)$ and $B = (0, 0)$, $f(B) - f(A) = 0$.)
19. (a) $f(x, y) = x^2yz$
(b) $\operatorname{curl} \vec{F} = \vec{0}$.
(c) 250.
(d) 250 (with $A = (1, -1, 0)$ and $B = (5, 5, 2)$, $f(B) - f(A) = 250$.)
20. (a) $f(x, y) = x^2 + y^2 + z^2$

- (b) $\operatorname{curl} \vec{F} = \vec{0}$.
(c) 0.
(d) 0 (with $A = (1, 0, 0)$ and $B = (1, 0, 0)$, $f(B) - f(A) = 250$.)
21. Since \vec{F} is conservative, it is the gradient of some potential function. That is, $\nabla f = \langle f_x, f_y, f_z \rangle = \vec{F} = \langle M, N, P \rangle$. In particular, $M = f_x$, $N = f_y$ and $P = f_z$. Note that $\operatorname{curl} \vec{F} = \langle P_y - N_z, M_z - P_x, N_x - M_y \rangle = \langle f_{zy} - f_{yz}, f_{xz} - f_{zx}, f_{yx} - f_{xy} \rangle$, which, by Theorem ??, is $\langle 0, 0, 0 \rangle$.

Section 14.4

1. along, across
2. It is the measure of flow around the entirety of a closed curve C .
3. the curl of \vec{F} , or $\operatorname{curl} \vec{F}$
4. the divergence of \vec{F} , or $\operatorname{div} \vec{F}$
5. $\operatorname{curl} \vec{F}$
6. $\operatorname{div} \vec{F}$
7. 12
8. 12
9. $-2/3$
10. $10/3$
11. $1/2$
12. $1/2$
13. The line integral $\oint_C \vec{F} \cdot d\vec{r}$, over the parabola, is $38/3$; over the line, it is -10 . The total line integral is thus $38/3 - 10 = 8/3$. The double integral of $\operatorname{curl} \vec{F} = 2$ over R also has value $8/3$.
14. Both the line integral and double integral have value of 2π .
15. Three line integrals need to be computed to compute $\oint_C \vec{F} \cdot d\vec{r}$. It does not matter which corner one starts from first, but be sure to proceed around the triangle in a counterclockwise fashion. From $(0, 0)$ to $(2, 0)$, the line integral has a value of 0. From $(2, 0)$ to $(1, 1)$ the integral has a value of $7/3$. From $(1, 1)$ to $(0, 0)$ the line integral has a value of $-1/3$. Total value is 2. The double integral of $\operatorname{curl} \vec{F}$ over R also has value 2.
16. Two line integrals need to be computed to compute $\oint_C \vec{F} \cdot d\vec{r}$. Along the parabola, the line integral has value 25.5. Along the line, the line integral has value -21 . Together, the total value is 4.5. The double integral of $\operatorname{curl} \vec{F}$ over R also has value 4.5.
17. Any choice of \vec{F} is appropriate as long as $\operatorname{curl} \vec{F} = 1$. When $\vec{F} = \langle -y/2, x/2 \rangle$, the integrand of the line integral is simply 6. The area of R is 12π .
18. Any choice of \vec{F} is appropriate as long as $\operatorname{curl} \vec{F} = 1$. The choices of $\vec{F} = \langle -y, 0 \rangle$ and $\langle 0, x \rangle$ each lead to reasonable integrands. The area of R is $4/3$.
19. Any choice of \vec{F} is appropriate as long as $\operatorname{curl} \vec{F} = 1$. The choices of $\vec{F} = \langle -y, 0 \rangle$, $\langle 0, x \rangle$ and $\langle -y/2, x/2 \rangle$ each lead to reasonable integrands. The area of R is $16/15$.
20. Any choice of \vec{F} is appropriate as long as $\operatorname{curl} \vec{F} = 1$. The choice of $\vec{F} = \langle -y/2, x/2 \rangle$ leads to a reasonable integrand after simplification. The area of R is $41\pi/10$.
21. The line integral $\oint_C \vec{F} \cdot \vec{n} ds$, over the parabola, is $-22/3$; over the line, it is 10. The total line integral is thus $-22/3 + 10 = 8/3$. The double integral of $\operatorname{div} \vec{F} = 2$ over R also has value $8/3$.
22. Both the line integral and double integral have value of 0.

23. Three line integrals need to be computed to compute $\oint_C \vec{F} \cdot \vec{n} ds$. It does not matter which corner one starts from first, but be sure to proceed around the triangle in a counterclockwise fashion. From $(0, 0)$ to $(2, 0)$, the line integral has a value of 0. From $(2, 0)$ to $(1, 1)$ the integral has a value of $1/3$. From $(1, 1)$ to $(0, 0)$ the line integral has a value of $1/3$. Total value is $2/3$. The double integral of $\operatorname{div} \vec{F}$ over R also has value $2/3$.

24. Two line integrals need to be computed to compute $\oint_C \vec{F} \cdot \vec{n} ds$. Along the parabola, the line integral has value $159/20$. Along the line, the line integral has value 6. Together, the total value is $279/20$. The double integral of $\operatorname{div} \vec{F}$ over R also has value $279/20$.

Section 14.5

 - Answers will vary, though generally should meaningfully include terms like "two sided".
 - Many possible answers exist; the one given by the book is the Möbius band.
 - (a) $\vec{r}(u, v) = \langle u, v, 3u^2v \rangle$ on $-1 \leq u \leq 1, 0 \leq v \leq 2$.
 (b) $\vec{r}(u, v) = \langle 3v \cos u + 1, 3v \sin u + 2, 3(3v \cos u + 1)^2(3v \sin u + 2) \rangle$, on $0 \leq u \leq 2\pi, 0 \leq v \leq 1$.
 (c) $\vec{r}(u, v) = \langle u, v(2 - 2u), 3u^2v(2 - 2u) \rangle$ on $0 \leq u, v \leq 1$.
 (d) $\vec{r}(u, v) = \langle u, v(1 - u^2), 3u^2v(1 - u^2) \rangle$ on $-1 \leq u \leq 1, 0 \leq v \leq 1$.
 - (a) $\vec{r}(u, v) = \langle u, v, 4u + 2u^2 \rangle$ on $1 \leq u \leq 4, 5 \leq v \leq 7$.
 (b) $\vec{r}(u, v) = \langle 4v \cos u, 3v \sin u, 16v \cos u + 2(3v \sin u)^2 \rangle$, on $0 \leq u \leq 2\pi, 0 \leq v \leq 1$.
 (c) $\vec{r}(u, v) = \langle u, u + v(4 - 2u), 4u + 2(u + v(4 - 2u))^2 \rangle$ on $0 \leq u \leq 2, 0 \leq v \leq 1$.
 (d) $\vec{r}(u, v) = \langle v \cos u, v \sin u, 4v \cos u + 2(v \sin u)^2 \rangle$ on $0 \leq u \leq 2\pi, 2 \leq v \leq 5$.
 - $\vec{r}(u, v) = \langle 0, u, v \rangle$ with $0 \leq u \leq 2, 0 \leq v \leq 1$.
 - $\vec{r}(u, v) = \langle u, 0, 1 - u + vu \rangle$ with $0 \leq u \leq 1, 0 \leq v \leq 1$.
 - $\vec{r}(u, v) = \langle 3 \sin u \cos v, 2 \sin u \sin v, 4 \cos u \rangle$ with $0 \leq u \leq \pi, 0 \leq v \leq 2\pi$.
 - Answers may vary; one solution is $\vec{r}(u, v) = \langle v \cos u, v, 4v \sin u \rangle$ with $0 \leq u \leq 2\pi, -1 \leq v \leq 5$.
 - Answers may vary.
 For $z = \frac{1}{2}(3 - x)$: $\vec{r}(u, v) = \langle u, v, \frac{1}{2}(3 - u) \rangle$, with $1 \leq u \leq 3$ and $0 \leq v \leq 2$.
 For $x = 1$: $\vec{r}(u, v) = \langle 0, u, v \rangle$, with $0 \leq u \leq 2, 0 \leq v \leq 1$.
 For $y = 0$: $\vec{r}(u, v) = \langle u, 0, v/2(3 - u) \rangle$, with $1 \leq u \leq 3, 0 \leq v \leq 1$.
 For $y = 2$: $\vec{r}(u, v) = \langle u, 2, v/2(3 - u) \rangle$, with $1 \leq u \leq 3, 0 \leq v \leq 1$.
 For $z = 0$: $\vec{r}(u, v) = \langle u, v, 0 \rangle$, with $1 \leq u \leq 3, 0 \leq v \leq 2$
 - Answers may vary.
 For $z = 2x + 4y - 4$:
 $\vec{r}(u, v) = \langle u, 1 - u/2 + uv/2, 2u + 4(1 - u/2 + uv/2) - 4 \rangle$, with $0 \leq u \leq 2, 0 \leq v \leq 1$.
 For $x = 2$: $\vec{r}(u, v) = \langle 2, u, 4uv \rangle$, with $0 \leq u \leq 1, 0 \leq v \leq 1$.
 For $y = 1$: $\vec{r}(u, v) = \langle u, 1, 2uv \rangle$, with $0 \leq u \leq 2, 0 \leq v \leq 1$.
 For $z = 0$: $\vec{r}(u, v) = \langle u, 1 - u/2 + uv/2, 0 \rangle$, with $0 \leq u \leq 2, 0 \leq v \leq 1$
 - Answers may vary.
 For $z = 2y$: $\vec{r}(u, v) = \langle u, v(4 - u^2), 2v(4 - u^2) \rangle$ with $-2 \leq u \leq 2$ and $0 \leq v \leq 1$.
 For $y = 4 - x^2$: $\vec{r}(u, v) = \langle u, 4 - u^2, 2v(4 - u^2) \rangle$ with $-2 \leq u \leq 2$ and $0 \leq v \leq 1$.
 For $z = 0$: $\vec{r}(u, v) = \langle u, v(4 - u^2), 0 \rangle$ with $-2 \leq u \leq 2$ and $0 \leq v \leq 1$.
 - Answers may vary.
 For $x + y^2/9 = 1$: $\vec{r}(u, v) = \langle \cos u, 3 \sin u, v \rangle$ with $0 \leq u \leq 2\pi$ and $1 \leq v \leq 3$.
 For $z = 1$: $\vec{r}(u, v) = \langle v \cos u, 3v \sin u, 1 \rangle$ with $0 \leq u \leq 2\pi$ and $0 \leq v \leq 1$.
 For $z = 3$: $\vec{r}(u, v) = \langle v \cos u, 3v \sin u, 3 \rangle$ with $0 \leq u \leq 2\pi$ and $0 \leq v \leq 1$.
 - Answers may vary.
 For $x^2 + y^2 = (z - 1)^2$: $\vec{r}(u, v) = \langle v \cos u, v \sin u, 1 - v \rangle$ with $0 \leq u \leq 2\pi$ and $0 \leq v \leq 1$.
 For $z = 0$: $\vec{r}(u, v) = \langle v \cos u, v \sin u, 0 \rangle$ with $0 \leq u \leq 2\pi$ and $0 \leq v \leq 1$.
 - Answers may vary.
 For $z = 1 - x^2$: $\vec{r}(u, v) = \langle u, v, 1 - u^2 \rangle$ with $-1 \leq u \leq 1$ and $-1 \leq v \leq 2$.
 For $y = -1$: $\vec{r}(u, v) = \langle u, -1, v(1 - u^2) \rangle$ with $-1 \leq u \leq 1$ and $0 \leq v \leq 1$.
 For $y = 2$: $\vec{r}(u, v) = \langle u, 2, v(1 - u^2) \rangle$ with $-1 \leq u \leq 1$ and $0 \leq v \leq 1$.
 For $z = 0$: $\vec{r}(u, v) = \langle u, v, 0 \rangle$ with $-1 \leq u \leq 1$ and $-1 \leq v \leq 2$.
 - Answers may vary.
 For $z = 4 - x^2 - 4y^2$:
 $\vec{r}(u, v) = \langle 2v \cos u, v \sin u, 4 - (2v \cos u)^2 - 4(v \sin u)^2 \rangle$ with $0 \leq u \leq 2\pi$ and $0 \leq v \leq 1$.
 For $z = 0$: $\vec{r}(u, v) = \langle 2v \cos u, v \sin u, 0 \rangle$ with $0 \leq u \leq 2\pi$ and $0 \leq v \leq 1$.
 - $S = 2\sqrt{14}$.
 - $S = \sqrt{6}/2$.
 - $S = 4\sqrt{3}\pi$.
 - $S = 3\sqrt{3}\pi$.
 - $S = \int_0^3 \int_0^{2\pi} \sqrt{v^2 + 4v^4} du dv = (37\sqrt{37} - 1)\pi/6 \approx 117.319$.
 - $S = \int_0^1 \int_0^1 \sqrt{v^2 + 4u^2v^2 + 4v^4} du dv \approx 0.931$.
 - $S = \int_0^1 \int_{-1}^1 \sqrt{(5u^2 - 2uv - 5)^2 + u^4 + (1 - u^2)^2} du dv \approx 7.084$.
 - $S = \int_0^1 \int_0^{2\pi} \sqrt{v^2 + 4v^4} du dv = (5\sqrt{5} - 1)\pi/6 \approx 5.330$.

Section 14.6

 - curve; surface
 - Answers will vary; in general, it means that more of the vector field passes through the surface opposite the direction of the normal vector than in the same direction of the normal vector.
 - outside
 - 0.
 - $240\sqrt{3}$
 - 40π

Section 14.6

- curve; surface
 - Answers will vary; in general, it means that more of the vector field passes through the surface opposite the direction of the normal vector than in the same direction of the normal vector.
 - outside
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 - $240\sqrt{3}$
 - 40π

7. 24
 8. 15
 9. 0
 10. 0
 11. $-1/2$
 12. π
 13. 0; the flux over S_1 is -45π and the flux over S_2 is 45π .
 14. $9\pi/8$; the flux over S_1 is $3\pi/4$ (use
 $\vec{r}(u, v) = \langle \sin u \cos v, \sin u \sin v, \cos u \rangle$ on $\pi/3 \leq u \leq \pi$,
 $0 \leq v \leq 2\pi$) and the flux over S_2 is $3\pi/8$ (use
 $\vec{r}(u, v) = \langle v\sqrt{3} \cos(u)/2, v\sqrt{3} \sin(u)/2, 1/2 \rangle$ for $0 \leq u \leq 2\pi$,
 $0 \leq v \leq 1$.

Section 14.7

1. Answers will vary; in Section 14.4, the Divergence Theorem connects outward flux over a closed curve in the plane to the divergence of the vector field, whereas in this section the Divergence Theorem connects outward flux over a closed surface in space to the divergence of the vector field.
 2. Divergence.
 3. Curl.
 4. Green's Theorem.
 5. Outward flux across the plane $z = 2 - x/2 - 2y/3$ is 14; across the plane $z = 0$ the outward flux is -8 ; across the planes $x = 0$ and $y = 0$ the outward flux is 0.
 Total outward flux: 14.

$$\iint_D \operatorname{div} \vec{F} dV = \int_0^4 \int_0^{3-3x/4} \int_0^{2-x/2-2y/3} (2x + 2y) dz dy dx = 14.$$

 6. Outward flux across the cylinder $x^2 + y^2 = 1$ is 0; across the plane $z = 3$ the outward flux is 3π ; across the plane $z = -3$ the outward flux is 3π .
 Total outward flux: 6π .

$$\iint_D \operatorname{div} \vec{F} dV = \int_0^{2\pi} \int_0^1 \int_{-3}^3 r dz dr d\theta = 6\pi.$$

 7. Outward flux across the surface $z = xy(3-x)(3-y)$ is 252; across the plane $z = 0$ the outward flux is -9 .
 Total outward flux: 243.

$$\iint_D \operatorname{div} \vec{F} dV = \int_0^3 \int_0^3 \int_0^{xy(3-x)(3-y)} 12 dz dy dx = 243.$$

 8. Outward flux across the paraboloid is $112\pi/3$; across the disk the outward flux is 0.
 Total outward flux: $112\pi/3$.

$$\iint_D \operatorname{div} \vec{F} dV = \int_0^{2\pi} \int_0^2 \int_0^{4-r^2} (2z + 2)r dz dr d\theta = 112\pi/3.$$
9. Circulation on C : $\oint_C \vec{F} \cdot d\vec{r} = \pi$

$$\iint_S (\operatorname{curl} \vec{F}) \cdot \vec{n} dS = \pi.$$
10. Circulation on C : $\oint_C \vec{F} \cdot d\vec{r} = \pi$

$$\iint_S (\operatorname{curl} \vec{F}) \cdot \vec{n} dS = \pi.$$
11. Circulation on C : The flow along the line from $(0, 0, 2)$ to $(4, 0, 0)$ is 0; from $(4, 0, 0)$ to $(0, 3, 0)$ it is -6 , and from $(0, 3, 0)$ to $(0, 0, 2)$ it is 6. The total circulation is $0 + (-6) + 6 = 0$.

$$\iint_S (\operatorname{curl} \vec{F}) \cdot \vec{n} dS = \iint_S 0 dS = 0.$$
12. Circulation on C : The flow along the parabola is $-32/15$; the flow along the line is $4/3$. The total circulation is $4/3 - 32/15 = -4/5$.

$$\iint_S (\operatorname{curl} \vec{F}) \cdot \vec{n} dS = -4/5.$$
13. 128/225
 14. 8
 15. $8192/105 \approx 78.019$
 16. $64/3$
 17. $5/3$
 18. 8π
 19. 23π
 20. 0
 21. Each field has a divergence of 1; by the Divergence Theorem, the total outward flux across S is $\iint_D 1 dS$ for each field.
 22. (a) $\operatorname{curl} \vec{F} = 1$.
 (b) $\operatorname{curl} \vec{F} \cdot \vec{n} = 1$, where \vec{n} is a unit vector normal to S .
 23. Answers will vary. Often the closed surface S is composed of several smooth surfaces. To measure total outward flux, this may require evaluating multiple double integrals. Each double integral requires the parametrization of a surface and the computation of the cross product of partial derivatives. One triple integral may require less work, especially as the divergence of a vector field is generally easy to compute.
 24. Answers will vary. Often the closed curve C is composed of several smooth curves. To measure the total circulation, one may have to evaluate line integrals along each curve. Each line integral requires the parameterization of its curve. It may be less work to evaluate one single double (i.e., surface) integral.