
Multivariable Calculus

August 6, 2018

Contents

Part I

Week 0: Review

Vectors

In this section, we review some basics about vectors. This includes the definition of a vector, basic vector operations, standard basis vectors, and notation.

Vectors

In linear algebra, we often worked with vectors. We begin by recalling the (algebraic) definition of a vector in \mathbb{R}^n .

Definition 1. A vector in \mathbb{R}^n is an ordered n -tuple of real numbers. That is, a vector \vec{v} may be written as

$$\vec{v} = (a_1, a_2, \dots, a_n)$$

where a_1, a_2, \dots, a_n are real numbers.

We call the numbers a_i the components or entries of the vector. We call n the dimension of the vector \vec{v} , and say that \vec{v} is n -dimensional.

We write the vector with an arrow above it, as \vec{v} , in order to make the distinction between vectors and *scalars*, which are just real numbers. Some other common notations for vectors are \mathbf{v} and \hat{v} . It's important to make this distinction between vectors and scalars, so you should make use of one of these notations for vectors.

Example 1. $\vec{v} = (1, 3)$ is a vector in \mathbb{R}^2 .

$\vec{w} = (-1, 5, 0)$ is a vector in \mathbb{R}^3 .

$\vec{x} = (1, -2, 3)$ is a vector in \mathbb{R}^3 .

$\vec{y} = (-6, \pi, 1/24, -0.5, 3)$ is a vector in \mathbb{R}^5 .

It's sometimes convenient to write a vector as a column vector instead (particularly when working with linear transformations, which we'll review in a later

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section). We could write

$$\vec{v} = (a_1, a_2, \dots, a_n) = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix}$$

or

$$\vec{v} = (a_1, a_2, \dots, a_n) = \begin{pmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{pmatrix}.$$

The choice between square brackets and parentheses is just a difference in notation, they mean the same thing, and you should feel free to use either.

Example 2. We write the following vectors as column vectors.

$$\vec{v} = (1, 3) = \begin{bmatrix} 1 \\ 3 \end{bmatrix}.$$

$$\vec{w} = (-1, 5, 0) = \begin{bmatrix} -1 \\ 5 \\ 0 \end{bmatrix}.$$

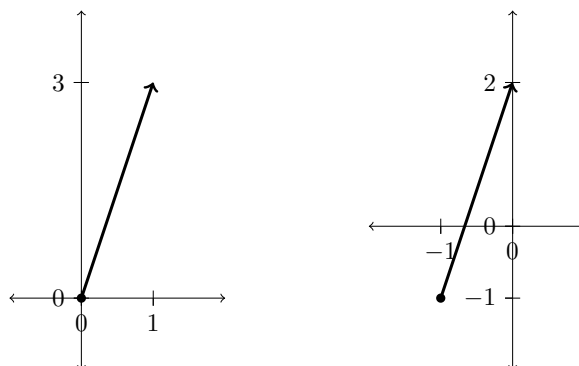
$$\vec{x} = (1, -2, 3) = \begin{bmatrix} 1 \\ -2 \\ 3 \end{bmatrix}.$$

$$\vec{y} = (-6, \pi, 1/24, -0.5, 3) = \begin{bmatrix} -6 \\ \pi \\ 1/24 \\ -0.5 \\ 3 \end{bmatrix}.$$

The Geometric Perspective

We also can think of a vector geometrically, as giving a direction and magnitude, but without a fixed position.

In two or three dimensions, it is useful to visualize a vector as an arrow in \mathbb{R}^n . We might visualize a vector $\vec{v} = (1, 3)$ in \mathbb{R}^2 as the arrow starting at the origin and ending at the point $(1, 3)$, thus giving a direction and a magnitude. However, we typically don't think of a vector as having a set location. We could also visualize the vector \vec{v} as starting at the point $(-1, -1)$ and ending at the point $(0, 2)$. Note that this arrow would have the same direction and magnitude as the one starting at the origin, thus they represent the same vector.



In four or higher dimensions, visualizing anything becomes very difficult. It can still be useful to think of a vector $(1, 2, 3, 4, 5)$ in \mathbb{R}^5 as starting at the origin and ending at the point $(1, 2, 3, 4, 5)$, but you probably won't be able to have a very clear picture of this in your head.

This concept will probably seem more useful once you think about a displacement vector.

Definition 2. Given points $P_1 = (x_1, \dots, x_n)$ and $P_2 = (y_1, \dots, y_n)$ in \mathbb{R}^n , the displacement vector from P_1 to P_2 is

$$\vec{P_1P_2} = (y_1 - x_1, \dots, y_n - x_n).$$

This is the vector that starts at P_1 and ends at P_2 .

Notice that the notation (a_1, \dots, a_n) that we use for a vector in \mathbb{R}^n is identical to the notation that we'd use for a point in \mathbb{R}^n . Since both vectors and points in \mathbb{R}^n are defined as n -tuples of points, they are, in some sense, the same thing. The difference between the two comes when we consider the context and geometric significance of the vector or point that we're working with. As we move into multivariable calculus, we'll often blur the distinction between a vector and a point, and sometimes think of a vector as a point and vice versa. This will be greatly simplify notation, and we promise that it won't be as confusing as it sounds!

Vector Operations

Before defining some basic vector operations, we define what it means for two vectors to be equal. This is done by comparing the components of the vectors.

Definition 3. Two vectors (a_1, a_2, \dots, a_n) and (b_1, b_2, \dots, b_n) in \mathbb{R}^n are equal if their corresponding components are equal, so $a_1 = b_1, a_2 = b_2, \dots, a_n = b_n$.

Notice that, in order to be equal, two vectors must have the same dimension and the same entries in the same order. Thus, the vectors $(1, 3)$ and $(1, 3, 0)$ are not equal.

We now define addition of two vectors of the same dimension, which is done componentwise.

Definition 4. Let $\vec{a} = (a_1, a_2, \dots, a_n)$ and $\vec{b} = (b_1, b_2, \dots, b_n)$ be vectors in \mathbb{R}^n . We define $\vec{a} + \vec{b}$ to be the vector in \mathbb{R}^n given by

$$\vec{a} + \vec{b} = (a_1 + b_1, a_2 + b_2, \dots, a_n + b_n).$$

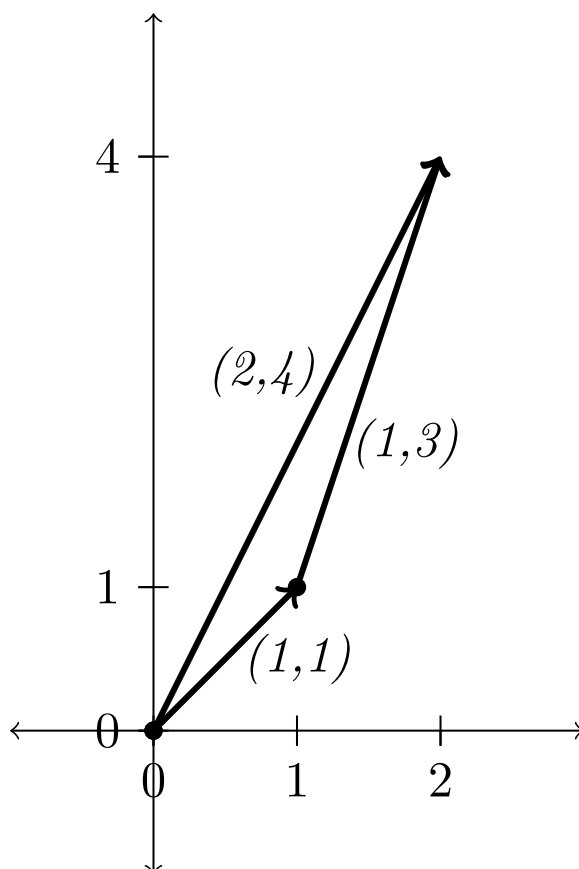
Note that we can only add two vectors if they have the same dimension.

Example 3. Adding the vectors $\vec{a} = (1, -8, 2)$ and $\vec{b} = (3, -1, -2)$, we obtain

$$\begin{aligned}\vec{a} + \vec{b} &= (1, -8, 2) + (3, -1, -2) \\ &= (1 + 3, -8 - 1, 2 - 2) \\ &= (4, -9, 0).\end{aligned}$$

Geometrically, we can add vectors by placing the start point of the second vector at the end point of the first vector, and drawing an arrow from the start point of the first vector to the end point of the second vector.

Example 4. In this example, we add the vectors $(1, 1)$ and $(1, 3)$. Adding these vectors algebraically, we obtain $(2, 4)$. We can also see this geometrically by placing the start point of the vector $(1, 3)$ at the end of the vector $(1, 1)$ (so at the point $(1, 1)$), and drawing the vector from the origin to the end point of the vector $(1, 3)$, which is now at $(2, 4)$.



Another vector operation is scalar multiplication. Here, we multiply a vector by a real number, possibly changing the length of the vector.

Definition 5. Let $\vec{a} = (a_1, \dots, a_n)$ be a vector in \mathbb{R}^n , and let r be a real number (also called a scalar). We define the scalar product $r\vec{a}$ to be

$$r\vec{a} = (ra_1, \dots, ra_n).$$

Thus, we see that scalar multiplication is defined by multiplying each component of the vector by the scalar r .

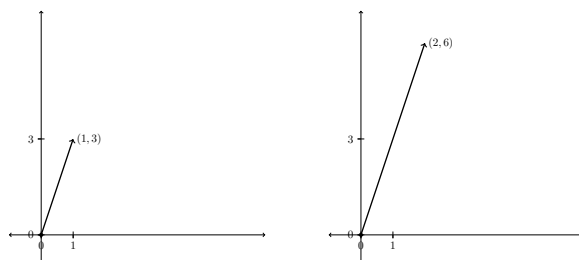
Example 5. $3(1, 5, -2) = (3, 15, -6)$

$$-1(1, 1, 1) = (-1, -1, -1)$$

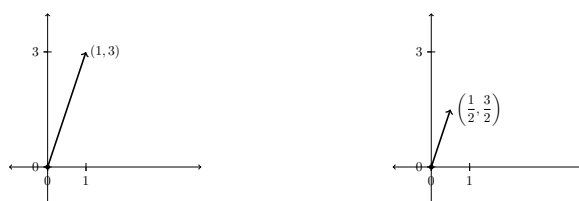
$$0(6, 2, 4) = (0, 0, 0)$$

Now, let's look at what scalar multiplication does geometrically. Consider the vector $(1, 3)$.

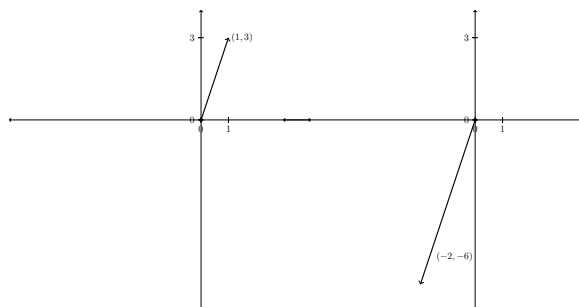
When we multiply $(1, 3)$ by 2, we obtain $(2, 6)$, which is twice as long as $(1, 3)$ and goes in the same direction.



When we multiply $(1, 3)$ by $\frac{1}{2}$, we obtain $(\frac{1}{2}, \frac{3}{2})$, which is half as long as $(1, 3)$ and goes in the same direction.



If we multiply $(1, 3)$ by -2 , we obtain $(-2, -6)$, which is twice as long as $(1, 3)$ and goes in the exact opposite direction.



Thus, we have seen that multiplying a vector by a scalar changes the length of a vector, but not the direction (except for reversing it, if the scalar is negative).

Properties

Now, let's recall some useful properties of vector addition and scalar multiplication.

Proposition 1. Suppose $\vec{a}, \vec{b}, \vec{c}$ are vectors in \mathbb{R}^n and k, l are real numbers. Then

- (a) $\vec{a} + \vec{b} = \vec{b} + \vec{a}$ (vector addition is commutative);
- (b) $\vec{a} + (\vec{b} + \vec{c}) = (\vec{a} + \vec{b}) + \vec{c}$ (vector addition is associative);
- (c) $\vec{a} + \vec{0} = \vec{0} + \vec{a} = \vec{a}$, where $\vec{0} = (0, \dots, 0)$ is the zero vector in \mathbb{R}^n ;
- (d) $(k + l)\vec{a} = k\vec{a} + l\vec{a}$;
- (e) $k(\vec{a} + \vec{b}) = k\vec{a} + k\vec{b}$ (with the previous property, scalar multiplication is distributive);
- (f) $k(l\vec{a}) = (kl)\vec{a} = l(k\vec{a})$;
- (g) $1\vec{a} = \vec{a}$.

These properties tell us different kinds of algebraic manipulations that we can do with vectors.

Standard Basis Vectors

It's often useful to write things in terms of the standard basis vectors for \mathbb{R}^n .

Definition 6. The vectors $\vec{e}_1 = (1, 0, \dots, 0)$, $\vec{e}_2 = (0, 1, 0, \dots, 0)$, ..., $\vec{e}_n = (0, \dots, 0, 1)$ in \mathbb{R}^n are called the standard basis vectors for \mathbb{R}^n .

Note that any vector in \mathbb{R}^n can be written uniquely as a linear combination of the standard unit vectors. For example, in \mathbb{R}^4 ,

$$\begin{aligned}(1, 5, -3, 6) &= 1(1, 0, 0, 0) + 5(0, 1, 0, 0) - 3(0, 0, 1, 0) + 6(0, 0, 0, 1) \\ &= 1\vec{e}_1 + 5\vec{e}_2 - 3\vec{e}_3 + 6\vec{e}_4.\end{aligned}$$

In \mathbb{R}^2 , we sometimes write the standard basis vectors as $\mathbf{i} = (1, 0)$ and $\mathbf{j} = (0, 1)$. This gives us a new notation for vectors, for example we could write

$$(3, 4) = 3\mathbf{i} + 4\mathbf{j}.$$

Similarly, in \mathbb{R}^3 , we sometimes write the standard basis vectors as $\mathbf{i} = (1, 0, 0)$, $\mathbf{j} = (0, 1, 0)$, and $\mathbf{k} = (0, 0, 1)$. We can then write

$$(2, 3, 4) = 2\mathbf{i} + 3\mathbf{j} + 4\mathbf{k}.$$

Summary

In this section, we reviewed some basics about vectors, including the definition of a vector, basic vector operations, standard basis vectors, notation, and the geometric perspective.

The Dot Product

In this section we review the dot product on vectors. This also includes the angle between vectors and the projection of one vector onto another.

The Dot Product

We begin with the definition of the dot product.

Definition 7. The dot product of two vectors $\vec{v} = (v_1, v_2, \dots, v_n)$ and $\vec{w} = (w_1, w_2, \dots, w_n)$ in \mathbb{R}^n is

$$\vec{v} \cdot \vec{w} = v_1 w_1 + v_2 w_2 + \dots + v_n w_n.$$

Notice that the dot product takes two vectors and outputs a scalar.

Example 6. $(1, 6) \cdot (-3, -6) = -3 - 36 = -39$

$$(1, 2, 3) \cdot (7, -2, 4) = 7 - 4 + 12 = 15$$

$$(1, 7, -3) \cdot (3, 0, 1) = 3 + 0 - 3 = 0$$

We can also compute the dot product using the magnitude (or length) of the vectors and the angle in between them.

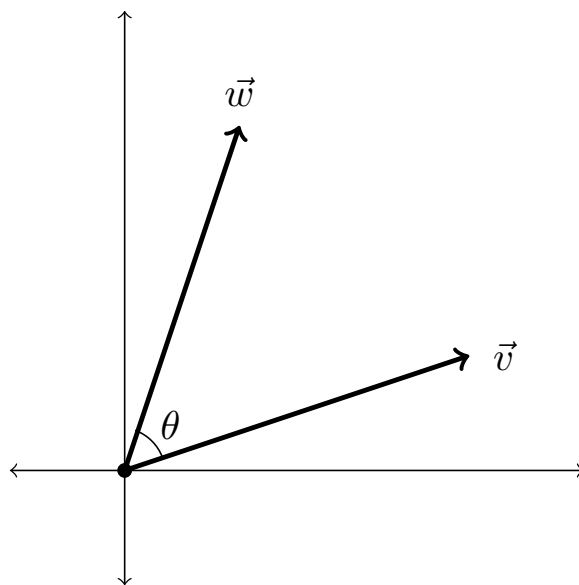
Proposition 2. If \vec{v} and \vec{w} are vectors in \mathbb{R}^n , then

$$\vec{v} \cdot \vec{w} = \|\vec{v}\| \|\vec{w}\| \cos \theta,$$

where $\|\vec{v}\|$ and $\|\vec{w}\|$ are the lengths of the vectors \vec{v} and \vec{w} , respectively, and θ is the angle between \vec{v} and \vec{w} .

This is illustrated in the picture below.

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This provides us with a geometric interpretation of the dot product: it gives us a measure of “how much” in the same direction two vectors are (taking their lengths into account). This also gives us a useful way to compute the angle between two vectors.

Example 7. Consider the vectors $(1, 4)$ and $(-2, 2)$. We have

$$(1, 4) \cdot (-2, 2) = -2 + 8 = 6,$$

$$\|(1, 4)\| = \sqrt{1^2 + 4^2} = \sqrt{17},$$

$$\|(-2, 2)\| = \sqrt{(-2)^2 + 2^2} = \sqrt{8}.$$

From $\vec{v} \cdot \vec{w} = \|\vec{v}\| \|\vec{w}\| \cos \theta$, we then have

$$6 = \sqrt{17}\sqrt{8} \cos \theta.$$

Solving for θ , we obtain the angle between the vectors as

$$\theta = \arccos\left(\frac{6}{\sqrt{17}\sqrt{8}}\right) \approx 59.04^\circ$$

Furthermore, note that for nonzero vectors \vec{v} and \vec{w} in \mathbb{R}^n , their dot product is 0 if and only if $\cos(\theta) = 0$. This means that θ would have to be 90° or 270° , meaning that \vec{v} and \vec{w} are perpendicular.

Proposition 3. Two nonzero vectors \vec{v} and \vec{w} in \mathbb{R}^n are perpendicular if and only if $\vec{v} \cdot \vec{w} = 0$.

This provides us with a very useful algebraic method for determining if two vectors are perpendicular.

Example 8. The vectors $(1, 7, -3)$ and $(3, 0, 1)$ in \mathbb{R}^3 are perpendicular, since

$$(1, 7, -3) \cdot (3, 0, 1) = 3 + 0 - 3 = 0.$$

Projection of one vector onto another

We can also use the dot product to define the projection of one vector onto another.

Definition 8. For vectors \vec{a} and \vec{b} in \mathbb{R}^n , we define the vector projection of \vec{a} onto \vec{b} as

$$\text{proj}_{\vec{b}}(\vec{a}) = \frac{\vec{a} \cdot \vec{b}}{\|\vec{b}\|^2} \vec{b} = \frac{\vec{a} \cdot \vec{b}}{\vec{b} \cdot \vec{b}} \vec{b}.$$

Example 9. We can use this to find the projection of $(2, 4, 3)$ onto $(1, -1, 1)$.

$$\begin{aligned} \text{proj}_{(1, -1, 1)}(2, 4, 3) &= \frac{(2, 4, 3) \cdot (1, -1, 1)}{(1, -1, 1) \cdot (1, -1, 1)} (1, -1, 1) \\ &= \frac{2 - 4 + 3}{1 + 1 + 1} (1, -1, 1) \\ &= \frac{1}{3} (1, -1, 1) \\ &= \left(\frac{1}{3}, -\frac{1}{3}, \frac{1}{3} \right) \end{aligned}$$

Summary

In this section we reviewed the dot product on vectors, the angle between vectors, and the projection of one vector onto another.

The Cross Product

In this section, we review the vector cross product, including the geometric perspective of the cross product, the area of a parallelogram, and the volume of parallelepiped.

The Cross Product

The cross product is fundamentally different from the dot product in a couple of ways. The cross product is defined only on vectors in \mathbb{R}^3 , while the dot product is defined in \mathbb{R}^n for any positive integer n . Furthermore, the cross product takes two vectors and produces another vector, while the dot product takes two vectors and produces a scalar.

We now give the algebraic definition of the cross product.

Definition 9. Let $\vec{a} = (a_1, a_2, a_3)$ and $\vec{b} = (b_1, b_2, b_3)$ be vectors in \mathbb{R}^3 . The cross product of \vec{a} and \vec{b} , denoted $\vec{a} \times \vec{b}$, is defined to be

$$\vec{a} \times \vec{b} = \begin{pmatrix} a_2b_3 - a_3b_2 \\ a_3b_1 - a_1b_3 \\ a_1b_2 - a_2b_1 \end{pmatrix}.$$

Equivalently, we can compute the cross product as

$$\vec{a} \times \vec{b} = \det \begin{pmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \end{pmatrix},$$

where

$$\mathbf{i} = (1, 0, 0),$$

$$\mathbf{j} = (0, 1, 0),$$

$$\mathbf{k} = (0, 0, 1).$$

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Example 10.

$$\begin{aligned}
 (3, 2, -1) \times (9, 0, 2) &= \det \begin{pmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 3 & 2 & -1 \\ 9 & 0 & 2 \end{pmatrix} \\
 &= (2 \cdot 2)\mathbf{i} - (0 \cdot -1)\mathbf{i} + (-1 \cdot 9)\mathbf{j} - (2 \cdot 3)\mathbf{j} + (3 \cdot 0)\mathbf{k} - (9 \cdot -1)\mathbf{k} \\
 &= 4\mathbf{i} - 15\mathbf{j} + 9\mathbf{k} \\
 &= (4, -15, 9)
 \end{aligned}$$

The cross product has some nice algebraic properties, which can be very useful.

Proposition 4. *Let \vec{a} , \vec{b} , and \vec{c} be vectors in \mathbb{R}^3 , and let $k \in \mathbb{R}$ be a scalar. The cross product has the following properties:*

- (a) $\vec{a} \times \vec{b} = -\vec{b} \times \vec{a}$ (the cross product is anticommutative);
- (b) $\vec{a} \times (\vec{b} + \vec{c}) = \vec{a} \times \vec{b} + \vec{a} \times \vec{c}$;
- (c) $(\vec{a} + \vec{b}) \times \vec{c} = \vec{a} \times \vec{c} + \vec{b} \times \vec{c}$ (with the previous property, the cross product is distributive over vector addition);
- (d) $k(\vec{a} \times \vec{b}) = (k\vec{a}) \times \vec{b} = \vec{a} \times (k\vec{b})$.

In particular, it's important to remember that the cross product is *not* commutative, so the order of the vectors matters!

Geometry of the Cross Product

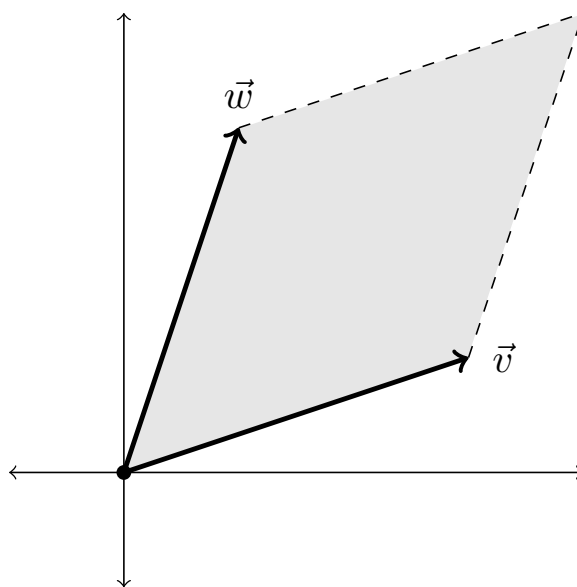
It's often easiest to compute cross products algebraically, but it's easier to understand their significance from a geometric perspective. We now discuss some of the geometric properties of the cross product.

Proposition 5. *Let \vec{a} and \vec{b} be vectors in \mathbb{R}^3 , and consider their cross product $\vec{a} \times \vec{b}$.*

- *The magnitude of the vector $\vec{a} \times \vec{b}$ can be computed as*

$$\|\vec{a} \times \vec{b}\| = \|\vec{a}\| \|\vec{b}\| \sin(\theta),$$

where θ is the angle between the vectors \vec{a} and \vec{b} . Furthermore, this magnitude is equal to the area of the parallelogram determined by \vec{a} and \vec{b} .



- The vector $\vec{a} \times \vec{b}$ is always perpendicular to both \vec{a} and \vec{b} , and follows the right-hand rule. That is, if you take your right hand and orient it so you can curl your fingers from the vector \vec{a} to the \vec{b} , your thumb will be pointing in the same direction as the cross product $\vec{a} \times \vec{b}$.

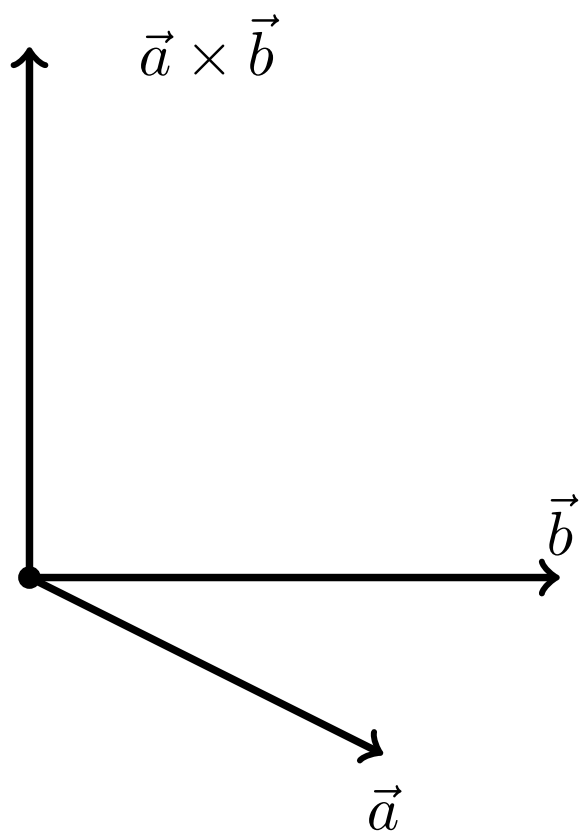
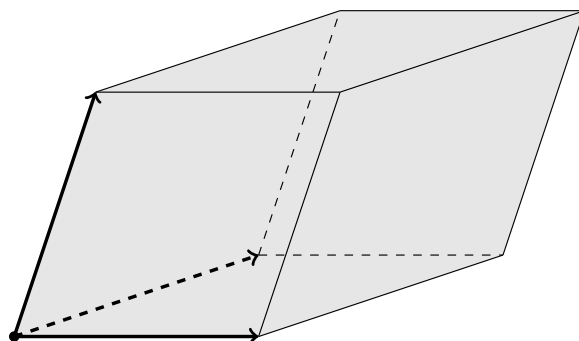


Image this image in \mathbb{R}^3 , so that $\vec{a} \times \vec{b}$ is perpendicular to both \vec{a} and \vec{b} .

Volume of a Parallelepiped

We can use the cross product and dot product together to compute the volume of a parallelepiped.



The volume of the parallelepiped can be computed as the area of the base times the height. We've seen that the area of the base can be computed as the magnitude of a cross product, $\|\vec{a} \times \vec{b}\|$. The height of the parallelepiped can be computed as $\|\vec{c}\| |\cos(\theta)|$, where θ is the angle between the vector \vec{c} and a line perpendicular to the base. We then have that the volume is $\|\vec{a} \times \vec{b}\| \|\vec{c}\| |\cos(\theta)|$, which we can recognize as the absolute value of the dot product of the vectors $\vec{a} \times \vec{b}$ and \vec{c} . Thus we have the following proposition.

Proposition 6. *The volume of the parallelepiped determined by the vectors \vec{a} , \vec{b} , and \vec{c} can be computed as $|(\vec{a} \times \vec{b}) \cdot \vec{c}|$.*

Summary

We've reviewed the cross product, including its properties and geometric perspective, including its use in finding the area of parallelograms and volume of parallelepipeds.

Matrices

In this section, we review matrices, including the determinant and the linear transformation represented by a matrix.

Matrices

We begin with the definition of a matrix.

Definition 10. An $m \times n$ matrix A is a rectangular array of numbers a_{ij} , with m rows and n columns:

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{pmatrix},$$

where the a_{ij} are real numbers for i and j integers with $1 \leq i \leq m$ and $1 \leq j \leq n$.

The numbers a_{ij} are called the entries of the matrix A .

Note that for an entry a_{ij} , the subscript ij describes the location of a_{ij} in the matrix A : i gives the row, and j gives the column.

We can also think of a matrix as a “vector of vectors” in two different ways. If we imagine that the columns of A are vectors in \mathbb{R}^n , then the matrix of A can be viewed as a vector of column vectors. If we imagine that the rows of A are vectors in \mathbb{R}^n , then the matrix A can be viewed as a vector of row vectors.

Matrix Operations

Here, we’ll define matrix addition and matrix multiplication.

In order to be able to add two matrices, they need to have the exact same dimensions. That is, they both need to be $m \times n$ matrices for some fixed values of m and n . When we have two matrices with the same dimensions, we define their sum component-wise or entry-wise.

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Definition 11. Let A and B be two $m \times n$ matrices, with

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{pmatrix},$$

$$B = \begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & & \vdots \\ b_{m1} & b_{m2} & \cdots & b_{mn} \end{pmatrix}.$$

Then we define the matrix sum $A + B$ to be

$$A + B = \begin{pmatrix} a_{11} + b_{11} & a_{12} + b_{12} & \cdots & a_{1n} + b_{1n} \\ a_{21} + b_{21} & a_{22} + b_{22} & \cdots & a_{2n} + b_{2n} \\ \vdots & \vdots & & \vdots \\ a_{m1} + b_{m1} & a_{m2} + b_{m2} & \cdots & a_{mn} + b_{mn} \end{pmatrix},$$

That is, $A + B$ is the $m \times n$ matrix obtained by adding the corresponding entries of A and B .

Example 11. We can add the matrices $A = \begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix}$ and $B = \begin{pmatrix} 7 & 8 & 9 \\ 10 & 11 & 12 \end{pmatrix}$ as follows:

$$\begin{aligned} A + B &= \begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix} + \begin{pmatrix} 7 & 8 & 9 \\ 10 & 11 & 12 \end{pmatrix} \\ &= \begin{pmatrix} 1+7 & 2+8 & 3+9 \\ 4+10 & 5+11 & 6+12 \end{pmatrix} \\ &= \begin{pmatrix} 8 & 10 & 12 \\ 14 & 16 & 18 \end{pmatrix} \end{aligned}$$

Example 12. We cannot add the matrices $A = \begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix}$ and $B = \begin{pmatrix} 7 & 8 \\ 10 & 11 \end{pmatrix}$, because their dimensions don't match.

As you might expect, matrix addition has some nice properties which are inherited from addition of real numbers. We list some of them here.

Proposition 7. Let A , B , and C be $m \times n$ matrices. Then we have

- (a) $A + B = B + A$ (matrix addition is commutative);
- (b) $A + (B + C) = (A + B) + C$ (matrix addition is associative).

Furthermore, there is an $m \times n$ matrix O , called the zero matrix, such that $A + O = A$ for any $m \times n$ matrix A . All of the entries of the zero matrix are the real number 0.

We've seen that matrix addition works in a very natural way, and multiplying a matrix by a scalar (or real number) is similarly nice. We now define scalar multiplication for matrices.

Definition 12. *Let*

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{pmatrix}$$

be an $m \times n$ matrix, and let $k \in \mathbb{R}$ be a scalar. Then the scalar product of k and A , denoted kA , is

$$kA = \begin{pmatrix} ka_{11} & ka_{12} & \cdots & ka_{1n} \\ ka_{21} & ka_{22} & \cdots & ka_{2n} \\ \vdots & \vdots & & \vdots \\ ka_{m1} & ka_{m2} & \cdots & ka_{mn} \end{pmatrix}.$$

That is, we obtain the scalar product by multiplying each entry in A by the scalar k .

Example 13. *We can compute the scalar product of 2 and the matrix $A = \begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix}$ as follows:*

$$\begin{aligned} 2A &= 2 \begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix} \\ &= \begin{pmatrix} 2 \cdot 1 & 2 \cdot 2 & 2 \cdot 3 \\ 2 \cdot 4 & 2 \cdot 5 & 2 \cdot 6 \end{pmatrix} \\ &= \begin{pmatrix} 2 & 4 & 6 \\ 8 & 10 & 12 \end{pmatrix}. \end{aligned}$$

We now list some nice properties of scalar multiplication.

Proposition 8. *Let A and B be $m \times n$ matrices, and let k and l be scalars in \mathbb{R} . Then*

- (a) $(k + l)A = kA + lA$ (*scalar multiplication is distributive over scalar addition*);
- (b) $k(A + B) = kA + kB$ (*scalar multiplication is distributive over matrix addition*);
- (c) $k(lA) = (kl)A = l(kA)$.

We'll now define matrix multiplication, which can be a bit trickier to work with than matrix addition or scalar multiplication. Here are some important things to remember about matrix multiplication:

- Not all matrices can be multiplied. In order to compute the product AB of two matrices A and B , the number of columns in A needs to be the same as the number of rows in B .
- Matrix multiplication is *not* commutative. In fact, its possible that the matrix product AB exists but the product BA does not.

Definition 13. Let A be an $m \times n$ matrix, and let B be an $n \times p$ matrix, with

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{pmatrix},$$

$$B = \begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1p} \\ b_{21} & b_{22} & \cdots & b_{2p} \\ \vdots & \vdots & & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{np} \end{pmatrix}.$$

Note that we are assuming the number of columns in A is the same as the number of rows in B .

We define the matrix product of A and B , denoted AB , to be the $m \times p$ matrix

$$AB = \begin{pmatrix} a_{11}b_{11} + a_{12}b_{21} + \cdots + a_{1n}b_{n1} & a_{11}b_{12} + a_{12}b_{22} + \cdots + a_{1n}b_{n2} & \cdots & a_{11}b_{1p} + a_{12}b_{2p} + \cdots + a_{1n}b_{np} \\ a_{21}b_{11} + a_{22}b_{21} + \cdots + a_{2n}b_{n1} & a_{21}b_{12} + a_{22}b_{22} + \cdots + a_{2n}b_{n2} & \cdots & a_{21}b_{1p} + a_{22}b_{2p} + \cdots + a_{2n}b_{np} \\ \vdots & \vdots & & \vdots \\ a_{m1}b_{11} + a_{m2}b_{21} + \cdots + a_{mn}b_{n1} & a_{m1}b_{12} + a_{m2}b_{22} + \cdots + a_{mn}b_{n2} & \cdots & a_{m1}b_{1p} + a_{m2}b_{2p} + \cdots + a_{mn}b_{np} \end{pmatrix}$$

Equivalently, we could define the ij th entry of AB to be the dot product of the i th row of A with the j th column of B . This makes sense, since the number of columns in A is the same as the number of rows in B (both n), which ensures that the i th row of A and the j th column of B are both vectors in \mathbb{R}^n .

This definition can seem a bit convoluted, and it's easier to understand how matrix multiplication works by going through an example.

Example 14. We can compute the product AB of the matrices $A = \begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix}$

and $B = \begin{pmatrix} 7 & 8 \\ 9 & 10 \\ 11 & 12 \end{pmatrix}$ as follows:

$$\begin{aligned} AB &= \begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix} \begin{pmatrix} 7 & 8 \\ 9 & 10 \\ 11 & 12 \end{pmatrix}, \\ &= \begin{pmatrix} 1 \cdot 7 + 2 \cdot 9 + 3 \cdot 11 & 1 \cdot 8 + 2 \cdot 10 + 3 \cdot 12 \\ 4 \cdot 7 + 5 \cdot 9 + 6 \cdot 11 & 4 \cdot 8 + 5 \cdot 10 + 6 \cdot 12 \end{pmatrix}, \\ &= \begin{pmatrix} 58 & 64 \\ 139 & 154 \end{pmatrix}. \end{aligned}$$

Note that we multiplied a 2×3 matrix by a 3×2 matrix, and we obtained a 2×2 matrix.

We can also compute the product BA for the same matrices as above.

$$\begin{aligned} BA &= \begin{pmatrix} 7 & 8 \\ 9 & 10 \\ 11 & 12 \end{pmatrix} \begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix}, \\ &= \begin{pmatrix} 7 \cdot 1 + 8 \cdot 4 & 7 \cdot 2 + 8 \cdot 5 & 7 \cdot 3 + 8 \cdot 6 \\ 9 \cdot 1 + 10 \cdot 4 & 9 \cdot 2 + 10 \cdot 5 & 9 \cdot 3 + 10 \cdot 6 \\ 11 \cdot 1 + 12 \cdot 4 & 11 \cdot 2 + 12 \cdot 5 & 11 \cdot 3 + 12 \cdot 6 \end{pmatrix}, \\ &= \begin{pmatrix} 39 & 54 & 69 \\ 49 & 68 & 81 \\ 59 & 82 & 105 \end{pmatrix}. \end{aligned}$$

Note that we multiplied a 3×2 matrix by a 2×3 matrix, and we obtained a 3×3 matrix.

Note that in this case $AB \neq BA$; matrix multiplication is not commutative, so the order of the matrices matters!

Although matrix multiplication is not commutative, it still has some nice algebraic properties. We list some of them here.

Proposition 9. Let A , B , and C be matrices of dimensions such that the following operations are defined, and let k be a scalar. Then

- (a) $A(BC) = (AB)C$ (matrix multiplication is associative);
- (b) $k(AB) = (kA)B = A(kB)$;
- (c) $A(B + C) = AB + AC$;
- (d) $(A + B)C = AC + BC$ (with the previous property, matrix multiplication is distributive over matrix addition).

Determinants

When we have a square matrix (meaning an $n \times n$ matrix, where the number of rows and number of columns are the same), we can compute an important number, called the determinant of the matrix. It turns out that this single number can tell us some important things about the matrix!

We begin by defining the determinant of a 2×2 matrix.

Definition 14. Consider the 2×2 matrix $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$. We define the determinant of the matrix A to be

$$\det(A) = ad - bc.$$

We also sometimes use the notation $|A|$ for the determinant of the matrix A .

Note that the determinate of a 2×2 matrix is just a number, not a matrix. We compute the determinant in a couple of examples.

Example 15. We'll compute the determinant of the matrix $A = \begin{pmatrix} 1 & 2 \\ 3 & 4 \end{pmatrix}$.

$$\begin{aligned} \det(A) &= 1 \cdot 4 - 2 \cdot 3 \\ &= -2. \end{aligned}$$

We've defined the determinant of 2×2 matrices, but we haven't defined the determinant of a larger square matrix yet. It turns out that the determinant is defined *inductively*. This means that the determinant of a 3×3 matrix is defined using determinants of 2×2 matrices, the determinant of a 4×4 matrix is defined using determinants of 3×3 matrices, the determinant of a 5×5 matrix is defined using determinants of 4×4 matrices, and so on. This means in order to compute the determinant of a large square matrix, we often need to compute the determinants of many smaller matrices.

We now give the definition of the determinant of an $n \times n$ matrix.

Definition 15. Let A be an $n \times n$ matrix, with entries a_{ij} . We defined the determinant of A to be the number computed by

$$\det(A) = (-1)^{1+1}a_{11}\det(A_{11}) + (-1)^{1+2}a_{12}\det(A_{12}) + \cdots + (-1)^{1+n}a_{1n}\det(A_{1n}),$$

where A_{ij} is the $(n-1) \times (n-1)$ submatrix of A which we obtain by deleting the i th row and j th column from A .

This definition is pretty confusing if you read through it without seeing an example, but this actually follows a nice pattern. This pattern is easier to see with an example.

Example 16. We compute the determinant of the 4×4 matrix,

$$A = \begin{pmatrix} 1 & 4 & 2 & -1 \\ 0 & 0 & -2 & 1 \\ -3 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}.$$

Note that we begin by writing this in terms of determinants of 3×3 matrices. But in order to compute the determinant of each 3×3 matrix, we write it in terms of 2×2 matrices! This winds up being a lot of determinants to compute.

$$\begin{aligned} \det(A) &= (-1)^{1+1} 1 \det \begin{pmatrix} 0 & -2 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + (-1)^{1+2} 4 \det \begin{pmatrix} 0 & -2 & 1 \\ -3 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ &\quad + (-1)^{1+3} 2 \det \begin{pmatrix} 0 & 0 & 1 \\ -3 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} + (-1)^{1+4} (-1) \det \begin{pmatrix} 0 & 0 & -2 \\ -3 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} \end{aligned}$$

We now compute the determinant of each of the 3×3 submatrices, which we

compute using determinants of 2×2 matrices.

$$\begin{aligned}
\det \begin{pmatrix} 0 & -2 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} &= (-1)^{1+1} 0 \det \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + (-1)^{1+2} (-2) \det \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \\
&\quad + (-1)^{1+3} 1 \det \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \\
&= 1 \cdot 0 \cdot (1 \cdot 1 - 0 \cdot 0) + -1 \cdot (-2) \cdot (0 \cdot 1 - 0 \cdot 0) + 1 \cdot 1 \cdot (0 \cdot 0 - 1 \cdot 0) \\
&= 0 \\
\det \begin{pmatrix} 0 & -2 & 1 \\ -3 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} &= (-1)^{1+1} 0 \det \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + (-1)^{1+2} (-2) \det \begin{pmatrix} -3 & 0 \\ 0 & 1 \end{pmatrix} \\
&\quad + (-1)^{1+3} 1 \det \begin{pmatrix} -3 & 1 \\ 0 & 0 \end{pmatrix} \\
&= 1 \cdot 0 \cdot (1 \cdot 1 - 0 \cdot 0) + -1 \cdot (-2) \cdot (-3 \cdot 1 - 0 \cdot 0) + 1 \cdot 1 \cdot (-3 \cdot 0 - 1 \cdot 0) \\
&= 6 \\
\det \begin{pmatrix} 0 & 0 & 1 \\ -3 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} &= (-1)^{1+1} 0 \det \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} + (-1)^{1+2} 0 \det \begin{pmatrix} -3 & 0 \\ 0 & 1 \end{pmatrix} \\
&\quad + (-1)^{1+3} 1 \det \begin{pmatrix} -3 & 0 \\ 0 & 0 \end{pmatrix} \\
&= 1 \cdot 0 \cdot (0 \cdot 1 - 0 \cdot 0) + -1 \cdot 0 \cdot (-3 \cdot 1 - 0 \cdot 0) + 1 \cdot 1 \cdot (-3 \cdot 0 - 0 \cdot 0) \\
&= 0 \\
\det \begin{pmatrix} 0 & 0 & -2 \\ -3 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} &= (-1)^{1+1} 0 \det \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} + (-1)^{1+2} 0 \det \begin{pmatrix} -3 & 1 \\ 0 & 0 \end{pmatrix} \\
&\quad + (-1)^{1+3} (-2) \det \begin{pmatrix} -3 & 0 \\ 0 & 0 \end{pmatrix} \\
&= 1 \cdot 0 \cdot (0 \cdot 0 - 1 \cdot 0) + -1 \cdot 0 \cdot (-3 \cdot 0 - 1 \cdot 0) + 1 \cdot (-2) \cdot (-3 \cdot 0 - 0 \cdot 0) \\
&= 0
\end{aligned}$$

Substituting these in to our computation of the determinant of A , we then obtain

$$\begin{aligned}
\det(A) &= 1 \cdot 1 \cdot 0 + (-1) \cdot 4 \cdot (6) + 1 \cdot 2 \cdot 0 + (-1) \cdot (-1) \cdot 0 \\
&= -24.
\end{aligned}$$

We sometimes call this method of computing a determinant as “expanding along the first row.” This is because we can also compute the determinant of a matrix by similarly expanding along a different row, or even a column.

Proposition 10. *We can similarly compute the determinant of an $n \times n$ matrix*

A by expanding along any row or column. Expanding along the i th row, we have

$$\det(A) = (-1)^{i+1}a_{i1}\det(A_{i1}) + (-1)^{i+2}a_{i2}\det(A_{i2}) + \cdots + (-1)^{i+n}a_{in}\det(A_{in}).$$

Expanding along the j th column, we have

$$\det(A) = (-1)^{1+j}a_{1j}\det(A_{1j}) + (-1)^{2+j}a_{2j}\det(A_{2j}) + \cdots + (-1)^{n+j}a_{nj}\det(A_{nj}).$$

Once again, A_{ij} is the $(n-1) \times (n-1)$ submatrix obtained from A by deleting the i th row and j th column.

It can be useful to think about which row or column will be easiest to expand along. In particular, choosing a row or column with a lot of zeros greatly simplifies computation.

Example 17. We'll once again compute the determinant of the 4×4 matrix

$$A = \begin{pmatrix} 1 & 4 & 2 & -1 \\ 0 & 0 & -2 & 1 \\ -3 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

this time by expanding along the second column. Note that this column is a good choice, since there's only one nonzero element. We have

$$\det(A) = (-1)^{1+2}(4)\det\begin{pmatrix} 0 & -2 & 1 \\ -3 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + (-1)^{2+2}(0)\det\begin{pmatrix} 1 & 2 & -1 \\ -3 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + (-1)^{3+2}(0)\det\begin{pmatrix} 1 & 2 & -1 \\ 0 & -2 & 1 \\ 0 & 0 & 1 \end{pmatrix}$$

We'll only compute the determinant of the submatrix $\begin{pmatrix} 0 & -2 & 1 \\ -3 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$; we

won't bother computing the others since their determinants will be multiplied by 0.

$$\begin{aligned} \det\begin{pmatrix} 0 & -2 & 1 \\ -3 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} &= (-1)^{3+1}(0)\det\begin{pmatrix} -2 & 1 \\ 1 & 0 \end{pmatrix} + (-1)^{3+2}(0)\det\begin{pmatrix} 0 & 1 \\ -3 & 0 \end{pmatrix} + (-1)^{3+3}(1)\det\begin{pmatrix} 0 & -2 \\ -3 & 1 \end{pmatrix} \\ &= 0 + 0 + (1)(1)(0 \cdot 1 - (-2) \cdot (-3)), \\ &= -6. \end{aligned}$$

Once again, we don't bother computing the determinants which will be multiplied by zero. Note that we chose to expand across the last row, since it had two zeroes. Expanding along the first column would also have been a reasonable choice.

Returning to our computation of the determinant of A , we have

$$\begin{aligned} \det(A) &= (-1)^{1+2}(4)\det\begin{pmatrix} 0 & -2 & 1 \\ -3 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + (-1)^{2+2}(0)\det\begin{pmatrix} 1 & 2 & -1 \\ -3 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + (-1)^{3+2}(0)\det\begin{pmatrix} 1 & 2 & -1 \\ 0 & -2 & 1 \\ 0 & 0 & 1 \end{pmatrix} \\ &= (-1)(4)(-6) + 0 + 0 + 0, \\ &= 24. \end{aligned}$$

Notice that this matching our previous computation, expanding along the first row.

One of the most powerful uses of the determinant is to tell us whether or not a matrix is invertible. Recall that an $n \times n$ matrix A is *invertible* if there is a matrix B such that $AB = BA = I_n$, where I_n is the $n \times n$ identity matrix.

Proposition 11. *An $n \times n$ matrix A is invertible if and only if its determinant is nonzero.*

This gives us a convenient way to test if a matrix is invertible, without needing to produce an explicit inverse.

Example 18. *We found that the determinant of the matrix*

$$A = \begin{pmatrix} 1 & 4 & 2 & -1 \\ 0 & 0 & -2 & 1 \\ -3 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

is 24. Since this is nonzero, the matrix A is invertible.

On the other hand, you can verify that the determinant of the matrix

$$B = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 1 & 0 & -1 & -2 \\ -3 & 1 & -1 & 0 \\ -1 & 3 & 1 & 2 \end{pmatrix}$$

is 0. Thus, the matrix B is not invertible.

Linear Transformations

One of the most important uses of matrices is to represent linear transformations. Recall the definition of a linear transformation.

Definition 16. *A function T from \mathbb{R}^n to \mathbb{R}^n is a linear transformation if for all vectors \vec{v} and \vec{w} in \mathbb{R}^n and all scalars $k \in \mathbb{R}$, we have*

$$(a) \quad T(\vec{v} + \vec{w}) = T(\vec{v}) + T(\vec{w});$$

$$(b) \quad T(k\vec{v}) = kT(\vec{v}).$$

We can view an $m \times n$ matrix A as representing a linear transformation from \mathbb{R}^n to \mathbb{R}^m as follows. We write vectors as column vectors, or, equivalently, $n \times 1$ or $m \times 1$ matrices. For an input column vector \vec{v} in \mathbb{R}^n , we multiply \vec{v} by A

on the left, using matrix multiplication. This produces an $m \times 1$ matrix, or, equivalently, a column vector in \mathbb{R}^m . Thus, we can define a function

$$T_A(\vec{v}) = A\vec{v}.$$

Using properties of matrix multiplication, we have that this is a linear transformation. Thus, we have the linear transformation associated to a matrix.

Example 19. Consider the linear transformation T_A from \mathbb{R}^3 to \mathbb{R}^2 corresponding to the 2×3 matrix

$$A = \begin{pmatrix} 1 & -5 & 3 \\ 2 & 0 & -1 \end{pmatrix}.$$

Let investigate the images of several vectors in \mathbb{R}^3 under the linear transformation T_A .

$$\begin{aligned} T_A((1, 2, 3)) &= \begin{pmatrix} 1 & -5 & 3 \\ 2 & 0 & -1 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix} \\ &= \begin{pmatrix} 1 \cdot 1 + -5 \cdot 2 + 3 \cdot 3 \\ 2 \cdot 1 + 0 \cdot 2 + -1 \cdot 3 \end{pmatrix} \\ &= \begin{pmatrix} 0 \\ -1 \end{pmatrix} \end{aligned}$$

$$\begin{aligned} T_A((1, -1, 2)) &= \begin{pmatrix} 1 & -5 & 3 \\ 2 & 0 & -1 \end{pmatrix} \begin{pmatrix} 1 \\ -1 \\ 2 \end{pmatrix} \\ &= \begin{pmatrix} 1 \cdot 1 + -5 \cdot -1 + 3 \cdot 1 \\ 2 \cdot 1 + 0 \cdot -1 + -1 \cdot 1 \end{pmatrix} \\ &= \begin{pmatrix} 9 \\ 1 \end{pmatrix} \end{aligned}$$

$$\begin{aligned} T_A((1, 0, 0)) &= \begin{pmatrix} 1 & -5 & 3 \\ 2 & 0 & -1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \\ &= \begin{pmatrix} 1 \cdot 1 + -5 \cdot 0 + 3 \cdot 0 \\ 2 \cdot 1 + 0 \cdot 0 + -1 \cdot 0 \end{pmatrix} \\ &= \begin{pmatrix} 1 \\ 2 \end{pmatrix} \end{aligned}$$

$$\begin{aligned}
T_A((0, 1, 0)) &= \begin{pmatrix} 1 & -5 & 3 \\ 2 & 0 & -1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \\
&= \begin{pmatrix} 1 \cdot 0 + -5 \cdot 1 + 3 \cdot 0 \\ 2 \cdot 0 + 0 \cdot 1 + -1 \cdot 0 \end{pmatrix} \\
&= \begin{pmatrix} -5 \\ 0 \end{pmatrix}
\end{aligned}$$

$$\begin{aligned}
T_A((0, 0, 1)) &= \begin{pmatrix} 1 & -5 & 3 \\ 2 & 0 & -1 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \\
&= \begin{pmatrix} 1 \cdot 0 + -5 \cdot 0 + 3 \cdot 1 \\ 2 \cdot 0 + 0 \cdot 0 + -1 \cdot 1 \end{pmatrix} \\
&= \begin{pmatrix} 3 \\ -1 \end{pmatrix}
\end{aligned}$$

Notice that when we apply the linear transformation to the standard unit vectors \vec{e}_1 , \vec{e}_2 , and \vec{e}_3 , we obtain the columns of A as the output vector. This observation can be used to reconstruct a matrix from a given linear transformation.

Proposition 12. *Given any linear transformation T from \mathbb{R}^n to \mathbb{R}^m , there is an $m \times n$ matrix such that $T = T_A$.*

Furthermore, the columns of A can be obtained by applying T to the standard unit vectors. More specifically, the j th column of A is given by $T(\vec{e}_j)$.

We can see how this is useful through an example.

Example 20. *Consider the linear transformation T from \mathbb{R}^2 to \mathbb{R}^2 that rotates a vector by 30° counterclockwise. We can see geometrically that, for the standard unit vectors \vec{e}_1 and \vec{e}_2 in \mathbb{R}^2 , we have*

$$\begin{aligned}
T((1, 0)) &= \left(\frac{\sqrt{3}}{2}, \frac{1}{2} \right), \\
T((0, 1)) &= \left(-\frac{1}{2}, \frac{\sqrt{3}}{2} \right).
\end{aligned}$$

These tell us the columns of the matrix corresponding to the linear transformation, so we then know that the rotation can be represented by the matrix

$$A = \begin{pmatrix} \frac{\sqrt{3}}{2} & -\frac{1}{2} \\ \frac{1}{2} & \frac{\sqrt{3}}{2} \end{pmatrix}.$$

Summary

In this section, we reviewed matrix operations and properties, determinants, and linear transformations.

Although we've reviewed some of the most important concepts from linear algebra, there is still a lot of material that we weren't able to include here. Make sure you refer back to your linear algebra textbook if there's anything else you need to review!

Representations of Lines and Planes

In this section, we review the different ways we can represent lines and planes, including parametric representations.

Representations of Lines

When you think of describing a line algebraically, you might think of the standard form

$$y = mx + b,$$

where m is the slope and b is the y -intercept. This is often called *slope-intercept* form.

In addition to slope-intercept form, there are several other ways to represent lines. For example, you may remember using *point-slope* form in single variable calculus. We can describe a line of slope m going through a point (x_0, y_0) with the equation

$$y - y_0 = m(x - x_0).$$

It's important to note that there are many different possible choices for the point (x_0, y_0) . Because of this, unlike slope-intercept form, point-slope form does not give a unique representation of a line.

In linear algebra, we saw that we could parametrize a line using a vector $\vec{v} = (v_1, v_2)$ giving the direction of the line, and a point (x_0, y_0) that the line passes through. We parametrize the line as

$$\begin{aligned}\vec{x}(t) &= (v_1, v_2)t + (x_0, y_0), \\ &= (v_1t + x_0, v_2t + y_0).\end{aligned}$$

Note that this representation works a bit differently from the previous two representations. In slope-intercept form and point-slope form, the line was the set of points (x, y) satisfying the given equation. However, in the parametrization, we plug in values for the parameter t in order to get points on the line.

Unlike slope-intercept form and point-slope form, the parametrization of a line can easily be generalized to three or more dimensions. That is, a line in \mathbb{R}^n through the point \vec{a} and in the direction of the vector \vec{v} can be parametrized as

$$\vec{x}(t) = \vec{v}t + \vec{a},$$

Learning outcomes:
Author(s):

for $t \in \mathbb{R}$.

If we would like to describe a line in higher dimensions using equations (rather than a parametrization), we would need more than one equation. For example, in \mathbb{R}^3 , we would require two equations to determine a line.

Representations of Planes

We also have multiple ways to represent planes. Here, we'll focus on planes in \mathbb{R}^3 .

Recall that a plane can be determined by two vectors (giving the “direction” of the plane) and a point that the plane passes through. We can use this to give a parametrization for the plane through the point \vec{a} and parallel to the vectors \vec{v} and \vec{w} :

$$\vec{x}(s, t) = \vec{v}s + \vec{w}t + \vec{a},$$

for s and t in \mathbb{R} . Note that we require two parameters for the parametrization of the plane.

We can also describe a plane using a single linear equation in x , y , and z . For example,

$$2x + 4y - z = 9$$

defines a plane. A standard way to do this is using a point on the plane and a normal vector to the plane. Recall that a normal vector is perpendicular to every vector in the plane. If $\vec{n} = (n_1, n_2, n_3)$ is a normal vector to a plane passing through the point $\vec{a} = (a_1, a_2, a_3)$, the plane is defined by the equation

$$\vec{n} \cdot (\vec{x} - \vec{a}) = 0.$$

This can be rewritten as

$$n_1(x - a_1) + n_2(y - a_2) + n_3(z - a_3) = 0.$$

Summary

We reviewed various representations of lines and planes, including parametrizations.

Part II

Week 9: Curl

Curl of a Vector Field

Imagine the vector field below represents fluid flow:

Desmos link: <https://www.desmos.com/calculator/vhuoyka1ys>

If we fix the center point of each $+$ above, which way will they rotate? (clockwise/counter-clockwise)

We can describe this concept as microscopic rotation or local rotation, and it turns out that the *curl* of a vector field measures this local rotation.

In this activity, we define curl and focus on computation. In the next activity, we discuss the geometric significance of curl and how it represents local rotation.

Definition of Curl

A curl is an example of an *operator*, which is a mathematical object you've seen before. Roughly speaking, it's a "function" on functions. That is, it takes a function as an input, and produces a function as an output. Here, we're using "function" very broadly - a function could be scalar-valued, a path, or even a vector field!

To prove that you've seen operators before, let's look at a specific example:

Problem 1 What does $\frac{d}{dt}g(t)$ mean?

Multiple Choice:

- (a) Multiply $g(t)$ by the fraction $\frac{d}{dt}$.
- (b) Take the derivative of g with respect to t . ✓

Problem 2 What does $\frac{d}{dt}$ mean?

Multiple Choice:

Learning outcomes:
Author(s):

- (a) The same thing as $\frac{1}{t}$.
- (b) Take the derivative with respect to t . ✓

Problem 3 It turns out that $\frac{d}{dt}$ is an example of an operator.

To introduce the curl, we need to talk about another operator, ∇ which we call the del operator.

What does $\nabla(g(x, y, z))$ mean?

Multiple Choice:

- (a) The change in g .
- (b) $\left(\frac{\partial g}{\partial x}, \frac{\partial g}{\partial y}, \frac{\partial g}{\partial z}\right)$ ✓

Problem 4 From this, we can deduce that ∇ should mean $\left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right)$. Note that this is an operator.

Definition 17. The del operator in \mathbb{R}^n is $\left(\frac{\partial}{\partial x_1}, \frac{\partial}{\partial x_2}, \frac{\partial}{\partial x_3}, \dots, \frac{\partial}{\partial x_n}\right)$.

There's one more ingredient that we need to review in order to define the curl of a vector field, the cross product.

Problem 5 If $\mathbf{v} = (1, 2, 3)$ and $\mathbf{w} = (4, 5, 6)$, what is $\mathbf{v} \times \mathbf{w}$? $(-3, 6, -3)$.

Problem 6 Note that this is computed as the determinant

$$\begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 1 & 2 & 3 \\ 4 & 5 & 6 \end{vmatrix}$$

Problem 7 Given a vector field $\mathbf{F} = (M(x, y, z), N(x, y, z), P(x, y, z))$, how might we interpret $\nabla \times \mathbf{F}$?

$$\begin{aligned}\nabla \times \mathbf{F} &= \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ M & N & P \end{vmatrix} \\ &= \left(\frac{\partial P}{\partial y} - \frac{\partial N}{\partial z}, -\left(\frac{\partial P}{\partial x} - \frac{\partial M}{\partial z} \right), \frac{\partial N}{\partial x} - \frac{\partial M}{\partial y} \right)\end{aligned}$$

Based on this, we give our definition for the curl of a three-dimensional vector field:

Definition 18. The curl of a three-dimensional vector field $\mathbf{F}(x, y, z) = (M(x, y, z), N(x, y, z), P(x, y, z))$ is

$$\begin{aligned}\nabla \times \mathbf{F} &= \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ M & N & P \end{vmatrix} \\ &= \left(\frac{\partial P}{\partial y} - \frac{\partial N}{\partial z}, -\left(\frac{\partial P}{\partial x} - \frac{\partial M}{\partial z} \right), \frac{\partial N}{\partial x} - \frac{\partial M}{\partial y} \right)\end{aligned}$$

Note that this input is a vector field \mathbf{F} in \mathbb{R}^3 , and the output is another vector field in \mathbb{R}^3 .

Problem 8 Let $\mathbf{F} = (e^y, xz, 3z)$. Compute the curl $\nabla \times \mathbf{F}$.

$$\nabla \times \mathbf{F} = (-x, 0, z - e^y)$$

Note that we have only defined the curl for three-dimensional vector fields. However, by being a bit clever, we can extend this definition to two-dimensional vector fields.

Definition 19. If the three-dimensional vector field \mathbf{F} has the form $\mathbf{F}(x, y, z) = (M(x, y), N(x, y), 0)$, then $\nabla \times \mathbf{F}$ is often called the two-dimensional curl of \mathbf{F} . Moreover, if $\mathbf{G}(x, y) = (M(x, y), N(x, y))$ is a vector field in \mathbb{R}^2 , then we define the curl of \mathbf{G} as the curl of the three-dimensional vector field $\tilde{\mathbf{G}}(x, y, z) = (M(x, y), N(x, y), 0)$.

It turns out, the curl of a two-dimensional vector field can be written in a simpler form.

Proposition 13. *The two-dimensional curl of $\mathbf{F}(x, y) = (M(x, y), N(x, y), 0)$ is*

$$\nabla \times \mathbf{F} = \left(0, 0, \frac{\partial N}{\partial x} - \frac{\partial M}{\partial y} \right)$$

Proof From the definition of the curl, we have

$$\nabla \times \mathbf{F} = \left(\frac{\partial P}{\partial y} - \frac{\partial N}{\partial z}, -\left(\frac{\partial P}{\partial x} - \frac{\partial M}{\partial z} \right), \frac{\partial N}{\partial x} - \frac{\partial M}{\partial y} \right).$$

Since the third component, P , of our vector field is identically 0, we have

$$\nabla \times \mathbf{F} = \left(\boxed{0} - \frac{\partial N}{\partial z}, -\left(\boxed{0} - \frac{\partial M}{\partial z} \right), \frac{\partial N}{\partial x} - \frac{\partial M}{\partial y} \right).$$

Both $M(x, y)$ and $N(x, y)$ are constant with respect to z , so we then have

$$\nabla \times \mathbf{F} = \left(\boxed{0}, \boxed{0}, \frac{\partial N}{\partial x} - \frac{\partial M}{\partial y} \right),$$

as desired. ■

Sometimes we refer to $\frac{\partial N}{\partial x} - \frac{\partial M}{\partial y}$ as the curl $\nabla \times \mathbf{F}$ if \mathbf{F} is two-dimensional, instead of writing out the entire vector.

Note that we've only defined the curl of a vector field for two- and three-dimensional vector fields. Why doesn't it make sense to define the curl of a four-dimensional (or higher!) vector field?

Multiple Choice:

- (a) We only exist in three dimensions.
- (b) The cross product is only defined in \mathbf{R}^3 . ✓

Problem 9 Given $\mathbf{F}(x, y) = (y, 0)$, compute the curl $\nabla \times \mathbf{F}$.

$$\nabla \times \mathbf{F} = \boxed{(0, 0, -1)}$$

Problem 10 Given $\mathbf{F}(x, y) = (-y, 0)$, compute the curl $\nabla \times \mathbf{F}$.

$$\nabla \times \mathbf{F} = \boxed{(0, 0, 1)}$$

Let's look at this example, $\mathbf{F}(x, y) = (-y, 0)$. It turns out that this is the vector field from the beginning of this activity:

We imagined that the center of the plus signs were fixed, and determined that the vector field would rotate the plus signs counterclockwise. We claimed that this local rotation had something to do with the curl of the vector field, which we computed to be $\nabla \times \mathbf{F} = (0, 0, 1)$.

In the next activity, we'll study the geometric significance of the curl, and why the curl measures this "microscopic" rotation.

Summary

In this section, we defined the curl of a two- or three-dimensional vector field, which can be computed as follows:

- For a three-dimensional vector field, $\mathbf{F}(x, y, z) = (M(x, y, z), N(x, y, z), P(x, y, z))$, we have $\nabla \times \mathbf{F} = \left(\frac{\partial P}{\partial y} - \frac{\partial N}{\partial z}, -\left(\frac{\partial P}{\partial x} - \frac{\partial M}{\partial z} \right), \frac{\partial N}{\partial x} - \frac{\partial M}{\partial y} \right)$
- The two-dimensional curl of $\mathbf{F}(x, y) = (M(x, y), N(x, y), 0)$ can be computed as

$$\nabla \times \mathbf{F} = \left(0, 0, \frac{\partial N}{\partial x} - \frac{\partial M}{\partial y} \right)$$

In the next activity, we will discuss the geometric significance of the curl, and how it relates to the local rotation of the vector field.

Geometric Significance of Curl

Consider the vector field $\mathbf{F}(x, y) = (-y, 0)$.

We can compute the curl of this vector field,

$$\nabla \times \mathbf{F} = (0, 0, 1)$$

Imagine that we fix a point (representing a particle) in this vector field, but allow it to rotate. If imagine the vector field acting as a force on this particle, which way will it cause the particle to rotate?

(VECTOR FIELD)

Here, we see that the vector field is applying a greater force to the “top” of the particle than to the “bottom.” this will cause the particle to rotate counterclockwise. We describe this type of rotation as *local rotation* or *microscopic rotation*, since it’s the rotation when we “zoom in” on the particle.

It turns out that the curl of a vector field provides a measure of this local rotation - but how are these connected? We will answer this question in this section, discussing the geometric significance of the curl.

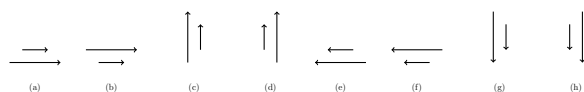
Geometric Significance of Two-dimensional Curl

Recall that, for a two-dimensional vector field $\mathbf{F}(x, y) = (M, N)$, we can compute the curl as

$$\nabla \times \mathbf{F} = (0, 0, N_x - M_y)$$

where N_x is the partial derivative of N with respect to x , and M_y is the partial derivative of M with respect to y . We’ll start by considering how M_y and N_x contribute to local rotation.

First let’s consider the case where $M_y < 0$. In this case, the x -component of the vector field \mathbf{F} is *decreasing* as we move in the positive y direction. Select all pictures which match this situation.



Select All Correct Answers:

Learning outcomes:
Author(s):

Geometric Significance of Curl

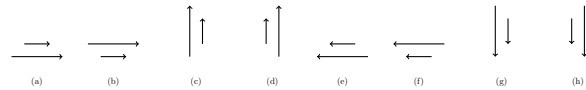
- (a) (a) ✓
- (b) (b)
- (c) (c)
- (d) (d)
- (e) (e)
- (f) (f) ✓
- (g) (g)
- (h) (h)

If $M_y < 0$, which way will this cause a particle in the vector field to rotate?

Multiple Choice:

- (a) Clockwise.
- (b) Counterclockwise. ✓

Now, let's consider the case where $N_x > 0$. This means that the y -component of the vector field \mathbf{F} is increasing as we move in the positive x direction. Select all pictures which match this situation.



Select All Correct Answers:

- (a) (a)
- (b) (b)
- (c) (c)
- (d) (d) ✓
- (e) (e)
- (f) (f)
- (g) (g) ✓
- (h) (h)

If $N_x < 0$, which way will this cause a particle in the vector field to rotate?

Multiple Choice:

- (a) Clockwise.
- (b) Counterclockwise. ✓

We've seen that the signs of N_x and M_y correspond to the direction of local rotation, with $N_x > 0$ and $M_y < 0$ contributing to counterclockwise rotation.

In general, we have that the sign of $N_x - M_y$ corresponds to the direction of local rotation in the plane. In particular, we have the following correspondences:

$$\begin{aligned} N_x - M_y > 0 &\longleftrightarrow \text{counterclockwise local rotation} \\ N_x - M_y < 0 &\longleftrightarrow \text{clockwise local rotation} \\ N_x - M_y = 0 &\longleftrightarrow \text{no local rotation} \end{aligned}$$

Remembering that $N_x - M_y$ is the *curl* of the two-dimensional vector field \mathbf{F} , we now have that the sign of the curl tells us the direction of local rotation for two-dimensional vector fields.

We have a special term for a vector field that never has any local rotation: we call such a vector field *irrotational*.



Furthermore, the length of the curl,

$$\|(0, 0, N_x - M_y)\| = |N_x - M_y|,$$

corresponds to the speed of rotation.

For example, in which case will the particle spin faster?

Multiple Choice:

- (a)  ✓
- (b) 

Note that this corresponds to a larger value of N_x (the change in the y -component of \mathbf{F} as we move in the positive x direction).

We now apply our knowledge of the geometric significance of the curl in a couple of examples.

Example 21. Consider the vector field $\mathbf{F}(x, y) = (-y, x^2)$. Compute the curl of \mathbf{F} , and describe the local rotation of the vector field at the points $(1, 0)$ and $(-4, 1)$.

Explanation. We begin by computing the curl of \mathbf{F} ,

$$\nabla \times \mathbf{F} = (0, 0, \boxed{2x+1}).$$

At the point $(1, 0)$, we have $(\nabla \times \mathbf{F})(1, 0) = (0, 0, \boxed{3})$. Looking at the third component, we see that the sign of $N_x - M_y$ at $(1, 0)$ is (positive/negative/zero). Thus, the local rotation of the vector field at the point $(1, 0)$ is (clockwise/counterclockwise/no rotation).

At the point $(-4, 1)$, we have $(\nabla \times \mathbf{F})(-4, 1) = (0, 0, \boxed{-7})$. Looking at the third component, we see that the sign of $N_x - M_y$ at $(-4, 1)$ is (positive/negative/zero). Thus, the local rotation of the vector field at the point $(-4, 1)$ is (clockwise/counterclockwise/no rotation).

Looking at a graph of the vector field, we can see that this local rotation is reflected in the graph.

(ADD GRAPH, WITH ROTATION?)

Example 22. Let $\mathbf{F}(x, y) = \left(\frac{y}{x^2 + y^2}, \frac{x}{x^2 + y^2} \right)$. Compute the curl $\nabla \times \mathbf{F}$, and interpret it geometrically.

Explanation. Computing our partial derivatives, we have

$$N_x = \frac{\boxed{x^2 + y^2 - 2x^2}}{(x^2 + y^2)^2}$$

and

$$M_y = \frac{\boxed{-x^2 - y^2 + 2x^2}}{(x^2 + y^2)^2}.$$

Then, the curl of \mathbf{F} is

$$\nabla \times \mathbf{F} = (0, 0, \boxed{0}).$$

Thus, we see that there is no local rotation at any point in the vector field. This is particularly interesting once we look at a graph of the vector field.

(GRAPH)

From the graph of the vector field, there certainly seems to be some larger scale, global rotation of the vector field. However, our computation showed that there

is no local rotation. This example illustrates an important distinction: curl measures local rotation of a vector field, which is a different concept from global rotation.

In this section, we saw how the curl of a vector field corresponded to local rotation for a two-dimensional vector field. In the next section, we describe how the curl of a vector field corresponds to local rotation for *three*-dimensional vector fields.

Geometric Significance of Three-dimensional Curl

For a three dimensional vector field $\mathbf{F}(x, y, z) = (M, N, P)$, we can compute the curl of \mathbf{F} as

$$\nabla \times \mathbf{F} = (P_y - N_z, -P_x + M_z, N_x - M_y).$$

Here, the situation is more complicated than in two dimensions. In the plane, there are only two possible ways to rotate: clockwise and counterclockwise. In \mathbb{R}^3 , there are infinitely many different ways to rotate, since we have infinitely many choices of axes. Yikes!

Fortunately, three-dimensional curl still tells about local rotation. In this case, we imagine local rotation as rotation of an infinitesimal (tiny) sphere. This sphere can rotate in infinitely many different ways, depending on which axis we rotate around.

When we look at the components of the curl, this tells us about rotation perpendicular to each of the axes, ignoring rotation in any other direction. Specifically,

$$\begin{aligned} N_x - M_y \text{ (the } z\text{-component of } \mathbf{F}) &\longleftrightarrow \text{rotation perpendicular to the } z\text{-axis} \\ P_y - N_z \text{ (the } x\text{-component of } \mathbf{F}) &\longleftrightarrow \text{rotation perpendicular to the } x\text{-axis} \\ -P_x + M_z \text{ (the } y\text{-component of } \mathbf{F}) &\longleftrightarrow \text{rotation perpendicular to the } y\text{-axis} \end{aligned}$$

Once again, the sign tells us the direction of rotation, with positive sign corresponding to counterclockwise rotation (viewed from the positive axes).

Furthermore, the length of the curl, $\|\nabla \times \mathbf{F}\|$, tells us the speed of rotation, and the direction of $\nabla \times \mathbf{F}$ tells us the axis of rotation.

In \mathbb{R}^3 , we would like to be able to describe the direction of rotation around a given axis. However, this can be tricky, since it's a matter of perspective. Imagine rotation in the xy -plane. If the rotation is clockwise viewed from above, then it will be counterclockwise from below! Fortunately, curl follows the *right hand rule*:

If you point your right thumb in the direct of $\nabla \times \mathbf{F}$, then your fingers will curl in the direction of local rotation.

We now put this to use in an example.

Problem 1 Consider the vector field $\mathbf{F}(x, y, z) = \left(0, \frac{-z}{(y^2 + z^2)^{3/2}}, \frac{y}{(y^2 + z^2)^{3/2}}\right)$. Compute the curl of \mathbf{F} .

$$\nabla \times \mathbf{F} = \left(\frac{-1}{(y^2 + z^2)^{3/2}}, 0, 0 \right)$$

Problem 2 What is the axis of local rotation (at any point)?

Multiple Choice:

- (a) The x -axis. ✓
- (b) The y -axis.
- (c) The z -axis.
- (d) Some other line.

Problem 3 Viewed from the positive x -axis, what is the direction of local rotation (at any point)?

Multiple Choice:

- (a) Clockwise. ✓
- (b) Counterclockwise.

Problem 4 How does the speed of local rotation change as we move closer to the origin?

Multiple Choice:

- (a) Stays the same.
- (b) Gets slower.
- (c) Gets faster. ✓

We've now seen how the curl describes the local rotation of a three-dimensional vector field. In the next section, we'll cover some connections of the curl to previous topics.

Summary

In this section, we studied the geometric significance of the curl. We found that the curl gives a measure of the local rotation of a vector field.

For a two-dimensional vector field, the sign of the curl told us the direction of rotation. Specifically, we have the following correspondence.

$$N_x - M_y > 0 \iff \text{counterclockwise local rotation}$$

$$N_x - M_y < 0 \iff \text{clockwise local rotation}$$

$$N_x - M_y = 0 \iff \text{no local rotation}$$

The magnitude $|N_x - M_y|$ corresponds to speed of rotation.

For a three-dimensional vector field, the components of the curl tell us about local rotation perpendicular to the axes. We also have:

- The length of the curl, $\|\nabla \times \mathbf{F}\|$, corresponds to the speed of rotation.
- The direction of the curl vector $\nabla \times \mathbf{F}$ gives the axis of rotation.
- Curl follows the right hand rule: if you point your thumb in the direction of $\nabla \times \mathbf{F}$, your fingers curl in the direction of local rotation.

In the next section, we'll consider the curl of a conservative vector field, and how the curl connects to Green's Theorem.

Connections of Curl with Older Material

We've defined the curl of a two or three dimensional vector field, and we found that this gives a measure of the local rotation of a vector field.

In this section, we discuss connections of the curl to previous topics from the course. In particular, we find the curl of a conservative vector field, and we restate Green's Theorem in terms of curl.

Curl of a Conservative Vector Field

In this section, we prove that the curl of a conservative vector field will always be zero. Thus, conservative vector fields are irrotational.

Theorem 1. Suppose \mathbf{F} is a C^1 conservative vector field in \mathbb{R}^3 , so there is a function $f : \mathbb{R}^3 \rightarrow \mathbb{R}$ such that $\mathbf{F} = \nabla f$. Then $\nabla \times \mathbf{F} = \mathbf{0}$.

Proof Suppose $\mathbf{F}(x, y, z) = (M, N, P)$ is a C^1 conservative vector field, with $\mathbf{F} = \nabla f$. Then we must have

$$\left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z} \right) = \boxed{(M, N, P)}.$$

Computing the curl of \mathbf{F} , we have

$$\begin{aligned} \nabla \times \mathbf{F} &= \left(\frac{\partial P}{\partial y} - \frac{\partial N}{\partial z}, -\left(\frac{\partial P}{\partial x} - \frac{\partial M}{\partial z} \right), \frac{\partial N}{\partial x} - \frac{\partial M}{\partial y} \right) \\ &= \left(\frac{\partial}{\partial y} \frac{\partial f}{\partial z} - \frac{\partial}{\partial z} \frac{\partial f}{\partial y}, -\left(\frac{\partial}{\partial x} \frac{\partial f}{\partial z} - \frac{\partial}{\partial z} \frac{\partial f}{\partial x} \right), \frac{\partial}{\partial x} \frac{\partial f}{\partial y} - \frac{\partial}{\partial y} \frac{\partial f}{\partial x} \right), \end{aligned}$$

substituting in for the components M , N , and P .

Now, we will use Clairaut's Theorem to simplify this vector. Since $\mathbf{F} = (M, N, P)$ is a C^1 vector field, the partial derivatives of its components ($\frac{\partial M}{\partial y}$, $\frac{\partial M}{\partial z}$, etc.) exist and are continuous. This means that all second-order partial derivatives of f exist and are continuous. Then, by Clairaut's Theorem, the order of differentiation for the second-order mixed partials doesn't matter. In particular, we

Learning outcomes:
Author(s):

have

$$\begin{aligned}\frac{\partial^2 f}{\partial y \partial x} &= \frac{\partial^2 f}{\partial x \partial y} \\ \frac{\partial^2 f}{\partial z \partial x} &= \frac{\partial^2 f}{\partial x \partial z} \\ \frac{\partial^2 f}{\partial z \partial y} &= \frac{\partial^2 f}{\partial y \partial z}.\end{aligned}$$

Using this fact in our computation of the curl, we now have

$$\begin{aligned}\nabla \times \mathbf{F} &= \left(\frac{\partial^2 f}{\partial y \partial z} - \frac{\partial^2 f}{\partial z \partial y}, -\left(\frac{\partial^2 f}{\partial x \partial z} - \frac{\partial^2 f}{\partial z \partial x} \right), \frac{\partial^2 f}{\partial x \partial y} - \frac{\partial^2 f}{\partial y \partial x} \right) \\ &= \boxed{(0, 0, 0)}\end{aligned}$$

Thus, we have shown that the curl of a conservative vector field is zero. ■

So, conservative vector fields are irrotational. A reasonable follow-up question would be: if the curl of a vector field is zero, is the vector field necessarily conservative? We'll leave this as an open question for the reader, with the suggestion that you think about how you can use past results, and what hypotheses are necessary for this converse to be true.

Curl and Green's Theorem

In this section, we see that we've actually already seen the curl of a vector field. It turns out that the curl showed up in Green's Theorem, we just didn't know that it was the curl yet.

Recall the statement of Green's Theorem:

Theorem 2. *Let D be a closed and bounded region in \mathbb{R}^2 , whose boundary ∂D consists of finitely many simple, closed, piecewise C^1 curves. Orient the boundary ∂D so that D is on the left as one travels along ∂D .*

Let $\mathbf{F}(x, y) = (M, N)$ be a C^1 vector field defined on D . Then,

$$\oint_C \mathbf{F} \cdot d\mathbf{s} = \iint_D \left(\frac{\partial N}{\partial x} - \frac{\partial M}{\partial y} \right) dx dy.$$

The integrand of the double integral, $\frac{\partial N}{\partial x} - \frac{\partial M}{\partial y}$, should now look familiar. This mysterious quantity is actually the two-dimensional curl of the vector field \mathbf{F} !

Using this realization, we can now restate Green's Theorem in terms of the curl of \mathbf{F} .

Theorem 3. *Let D be a closed and bounded region in \mathbb{R}^2 , whose boundary ∂D consists of finitely many simple, closed, piecewise C^1 curves. Orient the boundary ∂D so that D is on the left as one travels along ∂D .*

Let $\mathbf{F}(x, y) = (M, N)$ be a C^1 vector field defined on D . Then,

$$\oint_C \mathbf{F} \cdot d\mathbf{s} = \iint_D \nabla \times \mathbf{F} \, dxdy.$$

Now, let's think a bit more about what Green's Theorem is saying here.

The vector line integral, $\oint_C \mathbf{F} \cdot d\mathbf{s}$, computes the global circulation of the vector field around the boundary of the region.

The double integral $\iint_D \nabla \times \mathbf{F} \, dxdy$ is computed by integrating curl over the region D . We can think of this as “adding up” the local rotation of the vector field.

Thus, we can think of Green's Theorem as saying that the global circulation of the vector field around the boundary is equal to the total local rotation across the region. If you think about it, this does make some sense!

Summary

In this activity, we connected the curl of a vector field to concepts we've covered previously. In particular, we showed that the curl of a C^1 conservative vector field is zero, and we restated Green's Theorem in terms of curl.

Online Homework

Online Problems

Problem 1 Compute the curl of the vector field $\mathbf{F}(x, y, z) = (-2y \cos(3x), 3x \sin(-2y), 0)$.

$$\nabla \times \mathbf{F} = \boxed{(0, 0, 2 \cos(3x) - 3 \sin(2y))}$$

Find the curl of \mathbf{F} at the point $(x, y, z) = (\pi, \pi, \pi)$.

$$(\nabla \times \mathbf{F})(\pi, \pi, \pi) = \boxed{(0, 0, -2)}$$

Is \mathbf{F} a conservative vector field?

Multiple Choice:

- (a) Yes.
- (b) No. ✓
- (c) Not enough information.

Justify your answer.

Free Response:

Problem 2 Compute the curl of the vector field $\mathbf{F}(x, y, z) = (yz, 2xz, 3xy)$.

$$\nabla \times \mathbf{F} = \boxed{(x, -2y, z)}$$

Find the curl of \mathbf{F} at the point $(x, y, z) = (0, 0, 0)$.

$$\nabla \times \mathbf{F} = \boxed{(0, 0, 0)}$$

Is \mathbf{F} irrotational?

Multiple Choice:

Learning outcomes:
Author(s):

- (a) Yes.
- (b) No. ✓
- (c) Not enough information.

Problem 3 Compute the curl of the vector field $\mathbf{F}(x, y, z) = (x^2, y^3, z^4)$.

$$\nabla \times \mathbf{F} = \boxed{(0, 0, 0)}.$$

Find the curl of \mathbf{F} at the point $(x, y, z) = (1, 2, 3)$.

$$(\nabla \times \mathbf{F})(1, 2, 3) = \boxed{(0, 0, 0)}.$$

Is \mathbf{F} irrotational?

Multiple Choice:

- (a) Yes. ✓
- (b) No.
- (c) Not enough information.

Problem 4 Compute the two-dimensional curl of the vector field $\mathbf{F}(x, y) = (-xy, xy)$.

$$\nabla \times \mathbf{F} = \left(0, 0, \boxed{x + y}\right)$$

Describe the local rotation of \mathbf{F} at the point $(1, 1)$.

Multiple Choice:

- (a) Counterclockwise. ✓
- (b) Clockwise.
- (c) No rotation.

Describe the local rotation of \mathbf{F} at the point $(-1, 1)$.

Multiple Choice:

- (a) Counterclockwise.

- (b) Clockwise.
- (c) No rotation. ✓

Describe the local rotation of \mathbf{F} at the point $(-1, -1)$.

Multiple Choice:

- (a) Counterclockwise.
- (b) Clockwise. ✓
- (c) No rotation.

Problem 5 Compute the curl of the vector field $\mathbf{F}(x, y) = (2x - y, -x + 4y)$.

$$\nabla \times \mathbf{F} = (0, 0, \boxed{0})$$

Is \mathbf{F} conservative?

Multiple Choice:

- (a) Yes. ✓
- (b) No.

Problem 6 Find a potential function f for \mathbf{F} , so that $\nabla f = \mathbf{F}$.

$$f(x, y) = \boxed{x^2 - xy + 2y^2}$$

Problem 7 Compute the curl of the vector field $\mathbf{F}(x, y) = (2y, 3x)$.

$$\nabla \times \mathbf{F} = (0, 0, \boxed{1})$$

Is \mathbf{F} conservative?

Multiple Choice:

- (a) Yes.
- (b) No. ✓

Problem 8 Compute the curl of the vector field $\mathbf{F}(x, y) = (2x, 3y)$.

$$\nabla \times \mathbf{F} = (0, 0, \boxed{0})$$

Is \mathbf{F} conservative?

Multiple Choice:

- (a) Yes. ✓
- (b) No.

Problem 9 Find a potential function f for \mathbf{F} , so that $\nabla f = \mathbf{F}$.

$$f(x, y) = \boxed{x^2 + \frac{3}{2}y^2}$$

Problem 10 Compute the curl of the vector field $\mathbf{F}(x, y) = (-4x + y \cos(x), \sin(x))$.

$$\nabla \times \mathbf{F} = (0, 0, \boxed{0})$$

Is \mathbf{F} conservative?

Multiple Choice:

- (a) Yes. ✓
- (b) No.

Problem 11 Find a potential function f for \mathbf{F} , so that $\nabla f = \mathbf{F}$.

$$f(x, y) = \boxed{-2x^2 + y \sin(x)}$$

Problem 12 Compute the curl of the vector field $\mathbf{F}(x, y, z) = (\sin(x), y^2, e^z)$.

$$\nabla \times \mathbf{F} = \boxed{(0, 0, 0)}$$

Is \mathbf{F} conservative?

Multiple Choice:

- (a) Yes. ✓
- (b) No.

Problem 13 Find a potential function f for \mathbf{F} , so that $\nabla f = \mathbf{F}$.

$$f(x, y, z) = \boxed{-\cos(x) + \frac{1}{2}y^2 + e^z}$$

Written Homework

Written Problems

Problem 1 Prove that, for C^1 vector fields \mathbf{F} and \mathbf{G} in \mathbb{R}^3 ,

$$\nabla \times (\mathbf{F} + \mathbf{G}) = \nabla \times \mathbf{F} + \nabla \times \mathbf{G}.$$

(This shows that the curl is an additive operator, so the curl of a sum is the sum of the curls.)

Problem 2 (a) Compute the curl of the vector field $\mathbf{F} = (x, y, z)$. Explain why your answer makes sense geometrically.

(b) Suppose we have a C^1 vector field $\mathbf{F}(x, y, z) = (f(x), g(y), h(z))$. Compute the curl of \mathbf{F} , and explain why your answer makes sense geometrically.

Problem 3 (a) Consider the function $f(x, y, z) = e^x \sin(y) + z^2 \cos(y)$. Compute ∇f , and verify that $\nabla \times (\nabla f) = \mathbf{0}$.

(b) Prove that for any C^2 function $f : \mathbb{R}^3 \rightarrow \mathbb{R}$, the curl of the gradient of f is zero. That is, prove that

$$\nabla \times (\nabla f) = \mathbf{0}.$$

Professional Problem

Problem 4 Consider a wheel W centered at a point on the z -axis, rotating about the z -axis. In this problem, we will investigate how the rotation of this wheel relates to the curl of a vector field describing its motion.

Learning outcomes:
Author(s):

Let P be a point on the wheel W , of distance d from the center. The rotation of the wheel can be describe by the vector $\mathbf{w} = \omega \mathbf{k}$, where ω is the angular speed of the wheel W . You may assume that ω is constant. Let $\mathbf{x}(x, y, z)$ give the position of P at time t .

- (a) Carefully explain why $\mathbf{x}'(t)$ is orthogonal to both \mathbf{w} and $\mathbf{x}(t)$. Then use the angle θ in the figure to show that $\mathbf{x}'(t) = \mathbf{w} \times \mathbf{x}(t)$. We can therefore define a “velocity field $\mathbf{F}(x, y, z) = \mathbf{w} \times (x, y, z)$, which describes the motion of the wheel W . In other words, every point on W has velocity given by $\mathbf{F}(x, y, z)$.
- (b) Show that $\mathbf{x}'(t) = (-\omega y, \omega x)$.
- (c) Show that $\nabla \times \mathbf{F} = 2\mathbf{w}$. Hence if the motion of an object is described by the velocity field \mathbf{F} , the curl vector points in the direction of the axis of (positive) rotation, and its length is proportional to the angular speed of the rotation.

ADD IMAGE

Hint: What is the linear speed of P in terms of \mathbf{x} ?

Recall that angular speed equals linear speed divided by radius. How you can write this in terms of ω , d , and \mathbf{x} ?

Be sure your solution addresses why $\mathbf{x}'(t)$ is $\mathbf{w} \times \mathbf{x}(t)$, and not $\mathbf{x}(t) \times \mathbf{w}$.

Extra Problems

Online Problems

Problem 1 Compute the curl of the vector field $\mathbf{F}(x, y, z) = (x, y, z)$.

$$\nabla \times \mathbf{F}(x, y, z) = \boxed{(0, 0, 0)}$$

Problem 2 Compute the 2-dimensional curl of the vector field $\mathbf{F}(x, y) = (xy^2, y \sin(x^2))$. Your answer should be given as a vector.

$$\nabla \times \mathbf{F}(x, y, z) = \boxed{(0, 0, 2xy(\cos(x^2) - 1))}$$

Problem 3 Compute the 2-dimensional curl of the vector field $\mathbf{F}(x, y) = (e^{xy}, \cos(y))$. Your answer should be given as a vector.

$$\nabla \times \mathbf{F}(x, y, z) = \boxed{(0, 0, -xe^{xy})}$$

Problem 4 Compute the curl of the vector field $\mathbf{F}(x, y, z) = (y, z, x)$.

$$\nabla \times \mathbf{F}(x, y, z) = \boxed{(-1, -1, -1)}$$

Problem 5 Compute the curl of the vector field $\mathbf{F}(x, y, z) = (yz, xz, xy)$.

$$\nabla \times \mathbf{F}(x, y, z) = \boxed{(0, 0, 0)}$$

Learning outcomes:
Author(s):

Problem 6 Compute the curl of the vector field $\mathbf{F}(x, y, z) = (\sin(x), \cos(y), xy)$.

$$\nabla \times \mathbf{F}(x, y, z) = \boxed{(x, -y, 0)}$$

Problem 7 Compute the curl of the vector field $\mathbf{F}(x, y, z) = (0, x^3, \sin(x + y))$.

$$\nabla \times \mathbf{F}(x, y, z) = \boxed{(\cos(x + y), -\cos(x + y), 3x^2)}$$

Problem 8 Compute the curl of the vector field $\mathbf{F}(x, y, z) = (e^{xy}, \cos(z), e^y)$.

$$\nabla \times \mathbf{F}(x, y, z) = \boxed{(e^y + \sin(z), 0, -xe^{xy})}$$

Problem 9 Compute the 2-dimensional curl of the vector field $\mathbf{F}(x, y) = (y, x)$. Your answer should be given as a vector.

$$\nabla \times \mathbf{F}(x, y, z) = \boxed{(0, 0, 0)}$$

Problem 10 Compute the 2-dimensional curl of the vector field $\mathbf{F}(x, y) = (y, -x)$. Your answer should be given as a vector.

$$\nabla \times \mathbf{F}(x, y, z) = \boxed{(0, 0, -2)}$$

Problem 11 Compute the 2-dimensional curl of the vector field $\mathbf{F}(x, y) = (x^2y + 3xy, xy^4 - 2x^2y)$. Your answer should be given as a vector.

$$\nabla \times \mathbf{F}(x, y, z) = \boxed{(0, 0, -x^2 - 3x - 4xy + y^4)}$$

Problem 12 Compute the curl of the vector field $\mathbf{F}(x, y, z) = (yz, 2xz, 3xy)$.

$$\nabla \times \mathbf{F} = \boxed{(x, -2y, z)}$$

Find the curl of \mathbf{F} at the point $(x, y, z) = (0, 0, 0)$.

$$\nabla \times \mathbf{F} = \boxed{(0, 0, 0)}$$

Is \mathbf{F} irrotational?

Multiple Choice:

- (a) Yes.
- (b) No. ✓
- (c) Not enough information.

Problem 13 Compute the curl of the vector field $\mathbf{F}(x, y, z) = (x^2, y^3, z^4)$.

$$\nabla \times \mathbf{F} = \boxed{(0, 0, 0)}.$$

Find the curl of \mathbf{F} at the point $(x, y, z) = (1, 2, 3)$.

$$(\nabla \times \mathbf{F})(1, 2, 3) = \boxed{(0, 0, 0)}.$$

Is \mathbf{F} irrotational?

Multiple Choice:

- (a) Yes. ✓
- (b) No.
- (c) Not enough information.

Problem 14 Compute the two-dimensional curl of the vector field $\mathbf{F}(x, y) = (-xy, xy)$.

$$\nabla \times \mathbf{F} = \left(0, 0, \boxed{x + y}\right)$$

Describe the local rotation of \mathbf{F} at the point $(1, 1)$.

Multiple Choice:

- (a) Counterclockwise. ✓
- (b) Clockwise.
- (c) No rotation.

Describe the local rotation of \mathbf{F} at the point $(-1, 1)$.

Multiple Choice:

- (a) Counterclockwise.
- (b) Clockwise.
- (c) No rotation. ✓

Describe the local rotation of \mathbf{F} at the point $(-1, -1)$.

Multiple Choice:

- (a) Counterclockwise.
- (b) Clockwise. ✓
- (c) No rotation.

Problem 15 Find the 2-dimensional curl of the vector field $\mathbf{F}(x, y) = (-y, x)$. Your answer should be given as a vector.

$$\nabla \times \mathbf{F} = \boxed{(0, 0, 2)}$$

Is this vector field irrotational?

Multiple Choice:

- (a) Yes
- (b) No ✓

Describe the direction of the local rotation of this vector field.

Multiple Choice:

- (a) Clockwise
- (b) Counterclockwise ✓
- (c) No rotation

Plot this vector field. *INCLUDE GRAPHING STUFF*

Find the 2-dimensional curl of the vector field $\mathbf{G}(x, y) = \left(\frac{-y}{x^2 + y^2}, \frac{-y}{x^2 + y^2} \right)$.

Your answer should be given as a vector.

$$\nabla \times \mathbf{G} = \boxed{(0, 0, 0)}$$

Is this vector field irrotational?

Multiple Choice:

- (a) Yes ✓
- (b) No

Describe the direction of the local rotation of this vector field.

Multiple Choice:

- (a) Clockwise
- (b) Counterclockwise
- (c) No rotation ✓

Plot this vector field. *INCLUDE GRAPHING STUFF*Although the vector field \mathbf{F} and \mathbf{G} have the same flow lines, we see that one is irrotational and the other is not. Why does this happen?**Multiple Choice:**

- (a) Math is broken.
- (b) Curl describes local rotation, not global rotation. ✓

Problem 16 Compute the curl of the vector field $\mathbf{F}(x, y, z) = (-2y \cos(3x), 3x \sin(-2y), 0)$.

$$\nabla \times \mathbf{F} = \boxed{(0, 0, 2 \cos(3x) - 3 \sin(2y))}$$

Find the curl of \mathbf{F} at the point $(x, y, z) = (\pi, \pi, \pi)$.

$$(\nabla \times \mathbf{F})(\pi, \pi, \pi) = \boxed{(0, 0, -2)}$$

Is \mathbf{F} a conservative vector field?**Multiple Choice:**

- (a) Yes.
- (b) No. ✓
- (c) Not enough information.

Justify your answer.

Free Response:

Problem 17 Compute the curl of the vector field $\mathbf{F}(x, y, z) = (ze^{xz} + z \sin(x), xe^{xy}, -\cos(x))$.

$$\nabla \times \mathbf{F}(x, y, z) = \boxed{(0, x^2 e^{xz}, xy e^{xy} + e^{xy})}$$

Is this vector field conservative?

Multiple Choice:

- (a) Yes
- (b) No ✓

Problem 18 Compute the curl of the vector field $\mathbf{F}(x, y) = (2x - y, -x + 4y)$.

$$\nabla \times \mathbf{F} = (0, 0, \boxed{0})$$

Is \mathbf{F} conservative?

Multiple Choice:

- (a) Yes. ✓
- (b) No.

Problem 19 Find a potential function f for \mathbf{F} , so that $\nabla f = \mathbf{F}$.

$$f(x, y) = \boxed{x^2 - xy + 2y^2}$$

Problem 20 Compute the curl of the vector field $\mathbf{F}(x, y) = (2y, 3x)$.

$$\nabla \times \mathbf{F} = (0, 0, \boxed{1})$$

Is \mathbf{F} conservative?

Multiple Choice:

- (a) Yes.
 (b) No. ✓
-

Problem 21 Compute the curl of the vector field $\mathbf{F}(x, y) = (2x, 3y)$.

$$\nabla \times \mathbf{F} = (0, 0, \boxed{0})$$

Is \mathbf{F} conservative?

Multiple Choice:

- (a) Yes. ✓
 (b) No.

Problem 22 Find a potential function f for \mathbf{F} , so that $\nabla f = \mathbf{F}$.

$$f(x, y) = \boxed{x^2 + \frac{3}{2}y^2}$$

Problem 23 Compute the curl of the vector field $\mathbf{F}(x, y) = (-4x + y \cos(x), \sin(x))$.

$$\nabla \times \mathbf{F} = (0, 0, \boxed{0})$$

Is \mathbf{F} conservative?

Multiple Choice:

- (a) Yes. ✓
 (b) No.

Problem 24 Find a potential function f for \mathbf{F} , so that $\nabla f = \mathbf{F}$.

$$f(x, y) = \boxed{-2x^2 + y \sin(x)}$$

Problem 25 Compute the curl of the vector field $\mathbf{F}(x, y, z) = (\sin(x), y^2, e^z)$.

$$\nabla \times \mathbf{F} = \boxed{(0, 0, 0)}$$

Is \mathbf{F} conservative?

Multiple Choice:

- (a) Yes. ✓
- (b) No.

Problem 26 Find a potential function f for \mathbf{F} , so that $\nabla f = \mathbf{F}$.

$$f(x, y, z) = \boxed{-\cos(x) + \frac{1}{2}y^2 + e^z}$$

Problem 27 Compute the curl of the vector field $\mathbf{F}(x, y, z) = (x, y, z)$.

$$\nabla \times \mathbf{F}(x, y, z) = \boxed{(0, 0, 0)}$$

Is this vector field conservative?

Multiple Choice:

- (a) Yes ✓
- (b) No

Problem 28 Find a potential function f for \mathbf{F} , so that $\nabla f = \mathbf{F}$.

$$f(x, y, z) = \boxed{\frac{1}{2}x^2 + \frac{1}{2}y^2 + \frac{1}{2}z^2}$$

Problem 29 Compute the curl of the vector field $\mathbf{F}(x, y, z) = (z, 4yz, x^2 + 3y)$.

$$\nabla \times \mathbf{F}(x, y, z) = \boxed{(3 - 4y, 1 - 2x, 0)}$$

Is this vector field conservative?

Multiple Choice:

- (a) Yes
 (b) No ✓

Problem 30 Compute the curl of the vector field $\mathbf{F}(x, y, z) = (ye^{xy} + z \cos(x), xe^{xy}, \sin(x))$.

$$\nabla \times \mathbf{F}(x, y, z) = \boxed{(0, 0, 0)}$$

Is this vector field conservative?

Multiple Choice:

- (a) Yes ✓
 (b) No

Problem 31 Find a potential function f for \mathbf{F} , so that $\nabla f = \mathbf{F}$.

$$f(x, y, z) = \boxed{e^{xy} + \sin(x)z}$$

Written Problems

Problem 32 Prove that, for C^1 vector fields \mathbf{F} and \mathbf{G} in \mathbb{R}^3 ,

$$\nabla \times (\mathbf{F} + \mathbf{G}) = \nabla \times \mathbf{F} + \nabla \times \mathbf{G}.$$

(This shows that the curl is an additive operator, so the curl of a sum is the sum of the curls.)

Problem 33 Let \mathbf{F} and \mathbf{G} be vector fields in \mathbb{R}^3 , and let a and b be real numbers. Prove that

$$\nabla \times (a\mathbf{F} + b\mathbf{G}) = a(\nabla \times \mathbf{F}) + b(\nabla \times \mathbf{G}).$$

Problem 34 Let \mathbf{F} be a vector field in \mathbb{R}^3 , and let $f : \mathbb{R}^3 \rightarrow \mathbb{R}$ be a scalar valued function. Prove that

$$\nabla \times (f\mathbf{F}) = f(\nabla \times \mathbf{F}) + (\nabla f) \times \mathbf{F}.$$

Problem 35 Let $\mathbf{F}(x, y, z) = \frac{c\mathbf{r}}{\|\mathbf{r}\|^3}$, where c is constant and $\mathbf{r} = (x, y, z)$. Prove that the curl of \mathbf{F} , $\nabla \times \mathbf{F}$, is zero.

Problem 36 Let $\mathbf{F}(x, y, z) = (x, y, z)$, and let $\mathbf{a} \in \mathbb{R}^3$ be a vector with constant entries. Prove that

$$\nabla \times (\mathbf{a} \times \mathbf{F}) = 2\mathbf{a}.$$

Problem 37 (a) Compute the curl of the vector field $\mathbf{F} = (x, y, z)$. Explain why your answer makes sense geometrically.

(b) Suppose we have a C^1 vector field $\mathbf{F}(x, y, z) = (f(x), g(y), h(z))$. Compute the curl of \mathbf{F} , and explain why your answer makes sense geometrically.

Problem 38 (a) Consider the function $f(x, y, z) = e^x \sin(y) + z^2 \cos(y)$. Compute ∇f , and verify that $\nabla \times (\nabla f) = \mathbf{0}$.

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$$\nabla \times (\nabla f) = \mathbf{0}.$$