Announcements

August 31

- Homeworks 1.1 and 1.2 are due Friday.
- The first quiz is on Friday, during recitation.
  - Quizzes mostly test your understanding of the homework.
  - There will generally be a quiz every Friday when there's no midterm.
  - Check the schedule if you want to know what will be covered.
- My office hours, and those of the teaching assistants, are posted on the website.
  - Many other resources are also contained in the "Help" tab of the website.
  - This includes Math Lab (not to be confused with MyMathLab), a free one-on-many tutoring service, open for many hours most days, provided by the School of Math.

Section 1.3

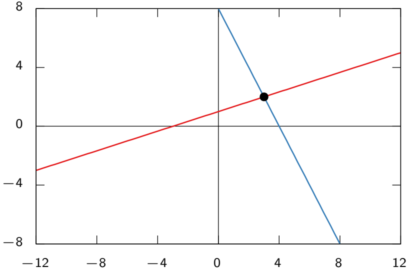
Vector Equations

Motivation

We want to think about the *algebra* in linear algebra (systems of equations and their solution sets) in terms of *geometry* (points, lines, planes, etc).

$$x - 3y = -3$$
$$2x + y = 8$$

$\rightsquigarrow$



This will give us better insight into the properties of systems of equations and their solution sets.

To do this, we need to introduce *n*-dimensional space $\mathbf{R}^n$, and **vectors** inside it.

Line, Plane, Space, ...

Recall that $\mathbf{R}$ denotes the collection of all real numbers, i.e. the number line.

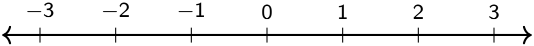
Definition

Let n be a positive whole number. We define

$$\mathbf{R}^n = \text{all ordered } n\text{-tuples of real numbers } (x_1, x_2, x_3, \ldots, x_n).$$

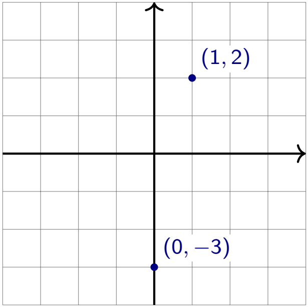
Example

When $n = 1$, we just get $\mathbf{R}$ back: $\mathbf{R}^1 = \mathbf{R}$. Geometrically, this is the *number line*.



Example

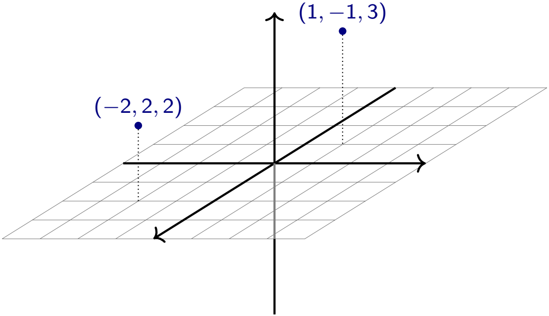
When $n = 2$, we can think of $\mathbf{R}^2$ as the *plane*. This is because every point on the plane can be represented by an ordered pair of real numbers, namely, its x- and y-coordinates.



We can use the elements of $\mathbf{R}^2$ to *label* points on the plane, but $\mathbf{R}^2$ is not defined to be the plane!

Example

When $n = 3$, we can think of $\mathbf{R}^3$ as the *space* we (appear to) live in. This is because every point in space can be represented by an ordered triple of real numbers, namely, its x-, y-, and z-coordinates.



So what is $\mathbf{R}^4$? or $\mathbf{R}^5$? or $\mathbf{R}^n$?
...go back to the *definition*: ordered n-tuples of real numbers

$$(x_1, x_2, x_3, \ldots, x_n).$$

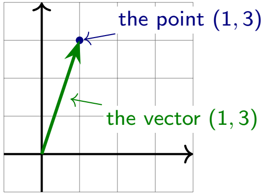
They're still "geometric" spaces, in the sense that our intuition for $\mathbf{R}^2$ and $\mathbf{R}^3$ sometimes extends to $\mathbf{R}^n$, but they're harder to visualize.

We'll make definitions and state theorems that apply to any $\mathbf{R}^n$, but we'll only draw pictures for $\mathbf{R}^2$ and $\mathbf{R}^3$.

Vectors

In the previous slides, we were thinking of elements of $\mathbf{R}^n$ as **points**: in the line, plane, space, etc.

We can also think of them as **vectors**: arrows with a given length and direction.



So the vector points *horizontally* in the amount of its x-coordinate, and *vertically* in the amount of its y-coordinate.

When we think of an element of $\mathbf{R}^n$ as a vector, we write it as a matrix with n rows and one column:

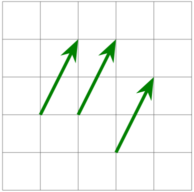
$$v = \begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix}.$$

We'll see why this is useful later.

Points and Vectors

So what is the difference between a point and a vector?

A vector need not start at the origin: *it can be located anywhere*! In other words, an arrow is determined by its length and its direction, not by its location.



These arrows all represent the vector $\begin{pmatrix}1\\2\end{pmatrix}$.

(However, unless otherwise specified, we'll assume a vector starts at the origin.)

This makes sense in the real world: many physical quantities, such as velocity, are represented as vectors. But it makes more sense to think of the velocity of a car as being located at the car.

Another way to think about it: a vector is a *difference* between two points, or the arrow from one point to another.

For instance, $\begin{pmatrix}1\\2\end{pmatrix}$ is the arrow from $(0, 1)$ to $(1, 3)$.

Vector Algebra

Definition

- We can add two vectors together:

$$\begin{pmatrix} a \\ b \\ c \end{pmatrix} + \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} a+x \\ b+y \\ c+z \end{pmatrix}.$$

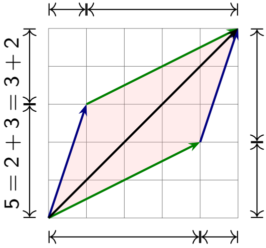
- We can multiply, or **scale**, a vector by a real number c:

$$c\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} c \cdot x \\ c \cdot y \\ c \cdot z \end{pmatrix}.$$

  We call c a **scalar** to distinguish it from a vector. If v is a vector and c is a scalar, cv is called a **scalar multiple** of v.

(And likewise for vectors of length n.) For instance,

$$\begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix} + \begin{pmatrix} 4 \\ 5 \\ 6 \end{pmatrix} = \begin{pmatrix} 5 \\ 7 \\ 9 \end{pmatrix} \quad \text{and} \quad -2\begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix} = \begin{pmatrix} -2 \\ -4 \\ -6 \end{pmatrix}.$$

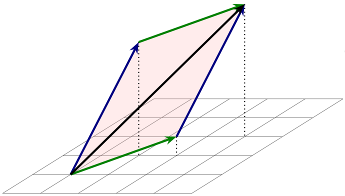


The parallelogram law for vector addition

Geometrically, the sum of two vectors v, w is obtained as follows: place the tail of w at the head of v. Then $v + w$ is the vector whose tail is the tail of v and whose head is the head of w. For example,

$$\begin{pmatrix} 1 \\ 3 \end{pmatrix} + \begin{pmatrix} 4 \\ 2 \end{pmatrix} = \begin{pmatrix} 5 \\ 5 \end{pmatrix}.$$

Why? The width of $v + w$ is the sum of the widths, and likewise with the heights.



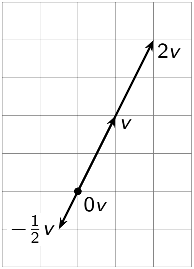
This works in higher dimensions too!

Scalar Multiplication: Geometry

Scalar multiples of a vector

These have the same *direction* but a different *length*.

Some multiples of v.



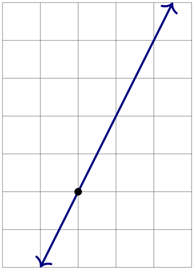
$$v = \begin{pmatrix} 1 \\ 2 \end{pmatrix}$$

$$2v = \begin{pmatrix} 2 \\ 4 \end{pmatrix}$$

$$-\tfrac{1}{2}v = \begin{pmatrix} -\frac{1}{2} \\ -1 \end{pmatrix}$$

$$0v = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

All multiples of v.



So the multiples of v form a *line*.

Linear Combinations

We can add and scalar multiply in the same equation:

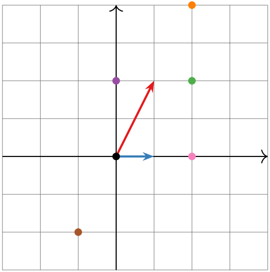
$$w = c_1 v_1 + c_2 v_2 + \cdots + c_p v_p$$

where $c_1, \ldots, c_p$ are scalars, $v_1, \ldots, v_p$ are vectors in $\mathbf{R}^n$, and w is a vector in $\mathbf{R}^n$.

Definition

We call w a **linear combination** of the vectors $v_1, \ldots, v_p$ (with weights $c_1, \ldots, c_p$).

Example



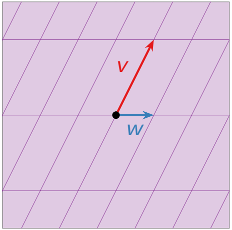
Let $v = \begin{pmatrix} 1 \\ 2 \end{pmatrix}$ and $w = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$. What are some linear combinations of v and w?

- $v + w$
- $v - w$
- $2v + 0w$
- $2w$
- $-v$

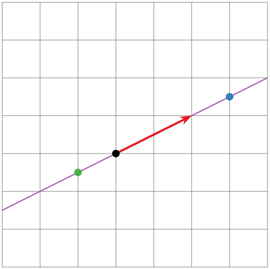
Poll

Is there any vector in $\mathbf{R}^2$ that is *not* a linear combination of v and w?

No: in fact, *every* vector in $\mathbf{R}^2$ is a combination of v and w.



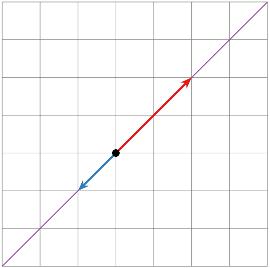
More Examples



What are some linear combinations of $v = \begin{pmatrix} 2 \\ 1 \end{pmatrix}$?

- $\frac{3}{2}v$
- $-\frac{1}{2}v$
- ...

What are *all* linear combinations of v?
All vectors cv for c a real number. I.e., all *scalar multiples* of v. These form a *line*.



Question

What are all linear combinations of $v = \begin{pmatrix} 2 \\ 2 \end{pmatrix}$ and $w = \begin{pmatrix} -1 \\ -1 \end{pmatrix}$?

Answer: The line which contains both vectors.

What's different about this example and the one on the poll?

Systems of Linear Equations

Question

Is $\begin{pmatrix} 8 \\ 16 \\ 3 \end{pmatrix}$ a linear combination of $\begin{pmatrix} 1 \\ 2 \\ 6 \end{pmatrix}$ and $\begin{pmatrix} -1 \\ -2 \\ -1 \end{pmatrix}$?

This means: can we solve the equation

$$x \begin{pmatrix} 1 \\ 2 \\ 6 \end{pmatrix} + y \begin{pmatrix} -1 \\ -2 \\ -1 \end{pmatrix} = \begin{pmatrix} 8 \\ 16 \\ 3 \end{pmatrix}$$

where x and y are the unknowns (the scalars)? Rewrite:

$$\begin{pmatrix} x \\ 2x \\ 6x \end{pmatrix} + \begin{pmatrix} -y \\ -2y \\ -y \end{pmatrix} = \begin{pmatrix} 8 \\ 16 \\ 3 \end{pmatrix} \qquad \text{or} \qquad \begin{pmatrix} x - y \\ 2x - 2y \\ 6x - y \end{pmatrix} = \begin{pmatrix} 8 \\ 16 \\ 3 \end{pmatrix}.$$

This is just a system of linear equations:

$$\begin{aligned} x - y &= 8 \\ 2x - 2y &= 16 \\ 6x - y &= 3 \end{aligned}$$

Systems of Linear Equations

Continued

$$\begin{aligned} x - y &= 8 \\ 2x - 2y &= 16 \\ 6x - y &= 3 \end{aligned}
\quad \xrightarrow{\text{matrix form}} \quad
\left(\begin{array}{cc|c} 1 & -1 & 8 \\ 2 & -2 & 16 \\ 6 & -1 & 3 \end{array}\right)$$

$$\xrightarrow{\text{row reduce}} \quad \left(\begin{array}{cc|c} 1 & 0 & -1 \\ 0 & 1 & -9 \\ 0 & 0 & 0 \end{array}\right)$$

$$\xrightarrow{\text{solution}} \quad \begin{aligned} x &= -1 \\ y &= -9 \end{aligned}$$

Conclusion:

$$-\begin{pmatrix} 1 \\ 2 \\ 6 \end{pmatrix} - 9 \begin{pmatrix} -1 \\ -2 \\ -1 \end{pmatrix} = \begin{pmatrix} 8 \\ 16 \\ 3 \end{pmatrix}$$

What is the relationship between the original vectors and the matrix form of the linear equation? They have the same columns!

Shortcut: You can make the augmented matrix without writing down the system of linear equations first.

Vector Equations and Linear Equations

Summary

The vector equation

$$x_1 v_1 + \cdots + x_p v_p = b,$$

where $v_1, \ldots, v_p, b$ are vectors in $\mathbf{R}^n$ and $x_1, \ldots, x_p$ are scalars, has the same solution set as the linear system with augmented matrix

$$\left(\begin{array}{ccc|c} v_1 & \cdots & v_p & b \end{array} \right),$$

where the v_i's and b are the columns of the matrix.

So we now have (at least) *two* alternative ways of thinking about linear systems of equations:

1. Augmented matrices.
2. Linear combinations of vectors (vector equations).

The last one is more geometric in nature.

Span

It is important to know what are *all* linear combinations of a set of vectors $v_1, \ldots, v_p$ in $\mathbf{R}^n$: it's exactly the collection of all b in $\mathbf{R}^n$ such that the vector equation

$$x_1 v_1 + \cdots + x_p v_p = b$$

has a solution (i.e., is consistent).

"the set of" "such that"

Definition

Let $v_1, \ldots, v_p$ be vectors in $\mathbf{R}^n$. The **span** of $v_1, \ldots, v_p$ is the set of all linear combinations of $v_1, \ldots, v_p$, and is denoted $\text{Span}\{v_1, \ldots, v_p\}$. In symbols:

$$\text{Span}\{v_1, \ldots, v_p\} = \left\{ x_1 v_1 + \cdots + x_p v_p \;\middle|\; x_1, \ldots, x_p \text{ in } \mathbf{R} \right\}.$$

Synonyms: $\text{Span}\{v_1, \ldots, v_p\}$ is the subset **spanned by** or **generated by** $v_1, \ldots, v_p$.

This is the first of several definitions in this class that you simply **must learn**. I will give you other ways to think about Span, and ways to draw pictures, but *this is the definition*. Having a vague idea what Span means will not help you solve any exam problems!

Span

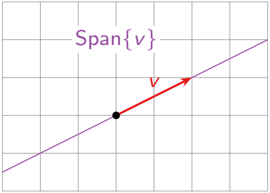
Continued

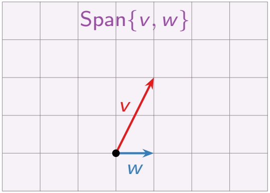
Now we have several equivalent ways of making the same statement:

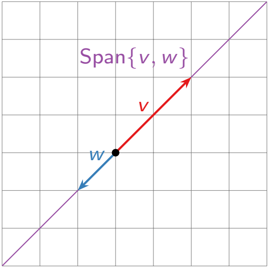
1. A vector b is in the span of $v_1, \ldots, v_p$.
2. The linear system with augmented matrix
$$\left(v_1 \ \cdots \ v_p \ \middle| \ b \right)$$
is consistent.
3. The vector equation
$$x_1 v_1 + \cdots + x_p v_p = b$$
has a solution.

Pictures of Span

Drawing a picture of Span$\{v_1, \ldots, v_p\}$ is the same as drawing a picture of all linear combinations of $v_1, \ldots, v_p$.

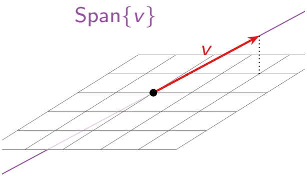


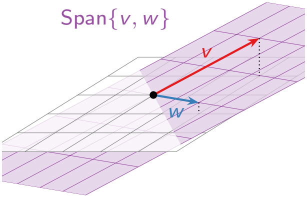


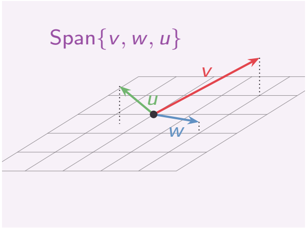


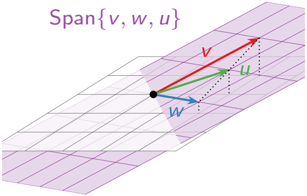
Pictures of Span

In $\mathbf{R}^3$









Poll

How many vectors are in $\text{Span}\{0\}$? Here 0 denotes the zero vector $\begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$.

A. Zero

B. One

C. Infinity

In general, it appears that $\text{Span}\{v_1, \ldots, v_p\}$ is the smallest "linear space" (line, plane, etc.) containing the origin and all of the vectors $v_1, \ldots, v_p$.

We will make this precise later.