



# Lecture 1 Vectors, Dot Products

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Based on Dr. Ralph Chikhany's Slide

# Logistics

- Course Website: <https://2prime.github.io/teaching/2024-linear-algebra>
- (anonymous) form: <https://forms.gle/Dtw6PRFdnbk8NQWRA>
- **Textbook:** Introduction to Linear Algebra - Fifth Edition, Gilbert Strang
- **Reference:** <http://web.mit.edu/18.06/www/>
- **Grading:**
  - Attendance & Participation 5%
  - Quizzes 15%
  - Problem Sets 10%
  - Exams 70%

# Homework

- **6 Problem Sets**
  - Latex and overleaf (not required)
- Late work policy:
  - For your first late assignment within 12 hours after the deadline (as indicated on Gradescope), no point deductions.
  - All subsequent assignments submitted within 12 hours after the deadline will convert to a zero at the end of semester.
  - In all cases, work submitted 12 hours or more after the deadline will not be accepted.

# Overview of the Course

Brightspace  
Gradescope  
Campuswire

# What is due next week (and every week)

Problem Set 1 – Friday 2/9 11.59 pm  
*(Late work policy applies)*

Recap Quiz 1 – Sunday 2/4 11.59 am  
*(No late work accepted)*

Note: Recap Quiz 1 is timed for 60 minutes to help you get used to the format.  
Future quizzes will be timed for 30-45 minutes

# Intro to the Course

## What is Linear Algebra?

### Linear

- ▶ having to do with lines/planes/etc.
- ▶ For example,  $x + y + 3z = 7$ , not  $\sin, \log, x^2$ , etc.

### Algebra

- ▶ solving equations involving numbers and symbols
- ▶ from al-jebr (Arabic), meaning reunion of broken parts
- ▶ 9<sup>th</sup> century Abu Ja'far Muhammad ibn Muso al-Khwarizmi

study of variables and the rules for manipulating these variables in formulas, rule of calculation

$$\begin{aligned} 2x + y &= 1 \\ x + y &= 1 \end{aligned} \quad \rightarrow \quad A \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}, A = \begin{bmatrix} 2, 1 \\ 1, 1 \end{bmatrix}$$

# Some Applications

Large classes of engineering problems, no matter how huge, can be reduced to linear algebra:

$$Ax = b \quad \text{or}$$

$$Ax = \lambda x$$

“... and now it’s just linear algebra”

Civil Engineering: How much traffic flows through the four labeled segments?

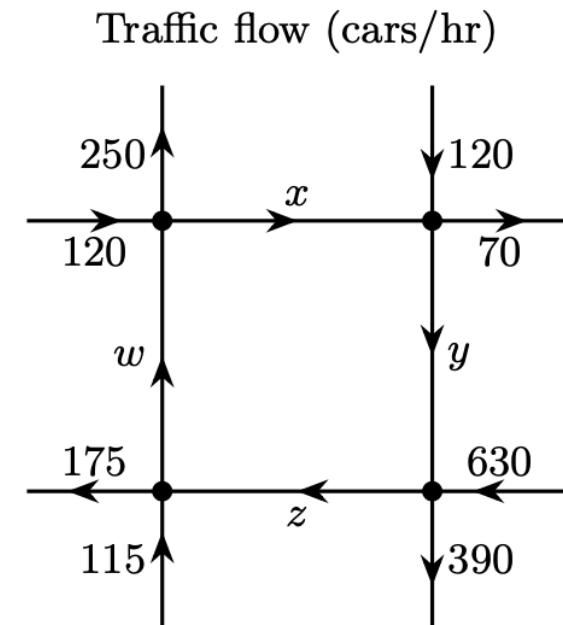
~~~~~ system of linear equations:

$$w + 120 = x + 250$$

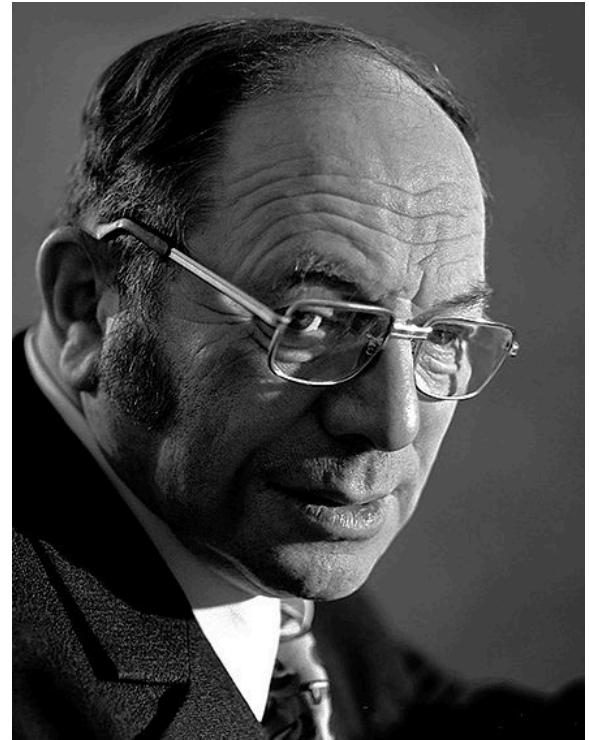
$$x + 120 = y + 70$$

$$y + 630 = z + 390$$

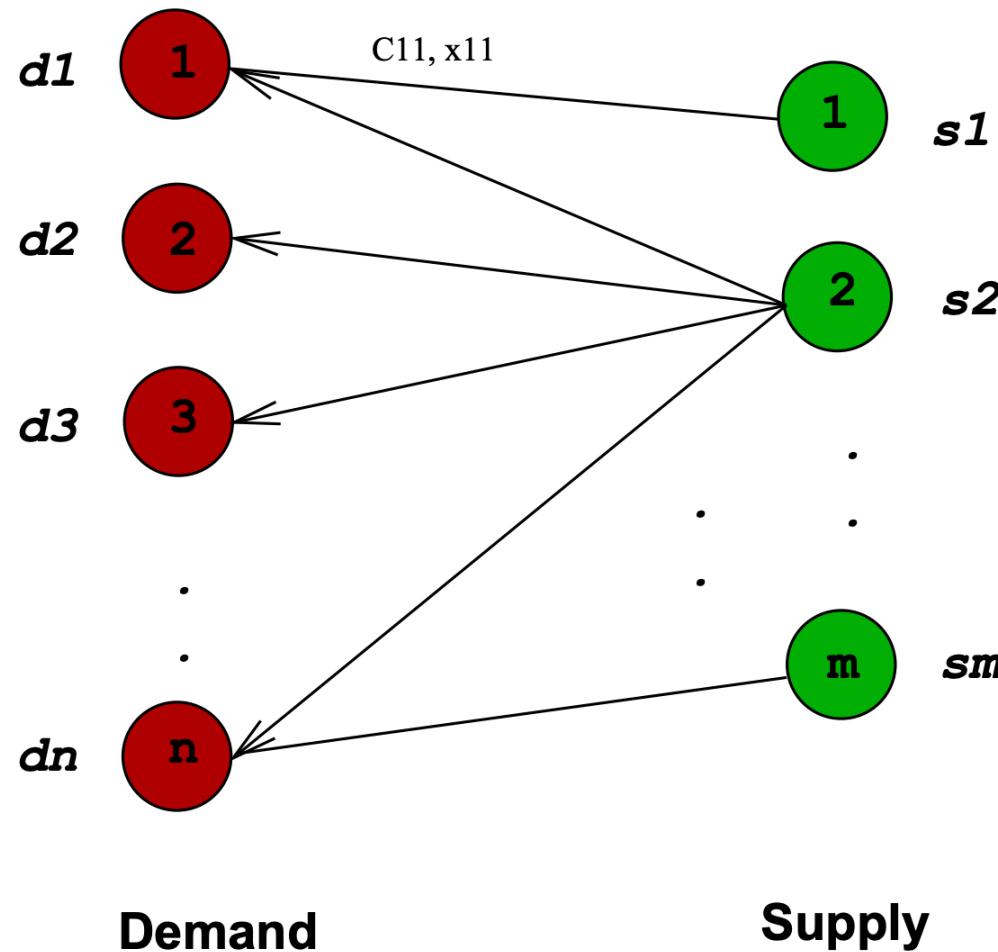
$$z + 115 = w + 175$$



# Linear Programming

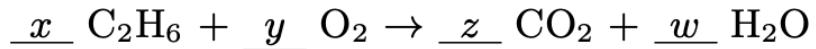


Lenoid Kantorovich  
Nobel Prize in Econ (1975)



# Some Applications

Chemistry: Balancing reaction equations



~~~~~ system of linear equations, one equation for each element.

$$2x = z$$

$$6x = 2w$$

$$2y = 2z$$

Geometry and Astronomy: Find the equation of a circle passing through 3 given points, say  $(1, 0)$ ,  $(0, 1)$ , and  $(1, 1)$ . The general form of a circle is  $a(x^2 + y^2) + bx + cy + d = 0$ .

~~~~~ system of linear equations:

$$a + b + d = 0$$

$$a + c + d = 0$$

$$2a + b + c + d = 0$$

Very similar to: compute the orbit of a planet:

$$ax^2 + by^2 + cxy + dx + ey + f = 0$$

# Some Applications

Biology: In a population of rabbits...

- ▶ half of the new born rabbits survive their first year
- ▶ of those, half survive their second year
- ▶ the maximum life span is three years
- ▶ rabbits produce 0, 6, 8 rabbits in their first, second, and third years

If I know the population in 2016 (in terms of the number of first, second, and third year rabbits), then what is the population in 2017?

~~~~~> system of linear equations:

$$\begin{array}{rcl} 6y_{2016} + 8z_{2016} & = & x_{2017} \\ \frac{1}{2}x_{2016} & = & y_{2017} \\ \frac{1}{2}y_{2016} & = & z_{2017} \end{array}$$

## Question

Does the rabbit population have an asymptotic behavior? Is this even a linear algebra question? Yes, it is!

# Some Applications

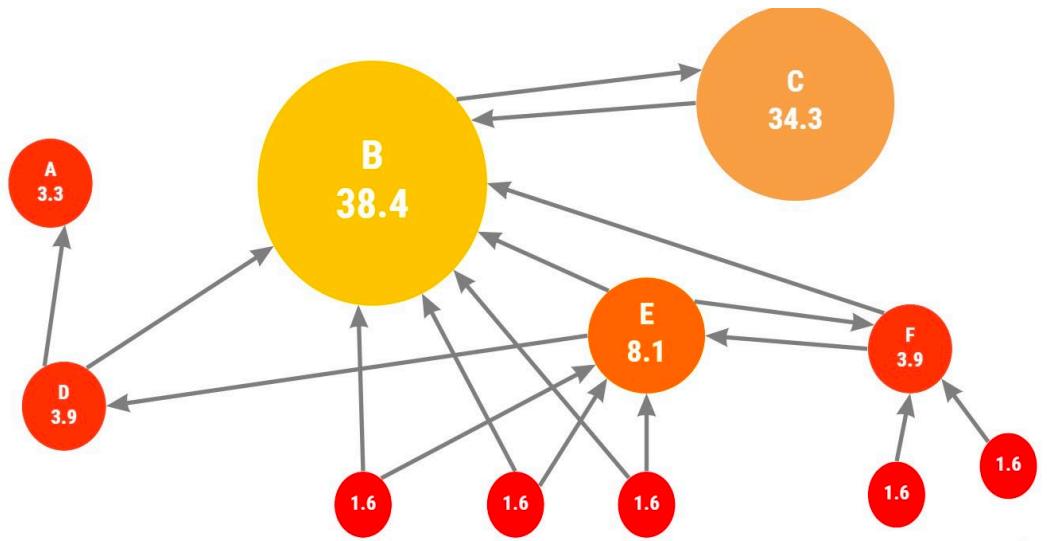
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~~~~~ system of linear equations:

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“Pagerank” Algorithm

## Question

Does the rabbit population have an asymptotic behavior? Is this even a linear algebra question? Yes, it is!

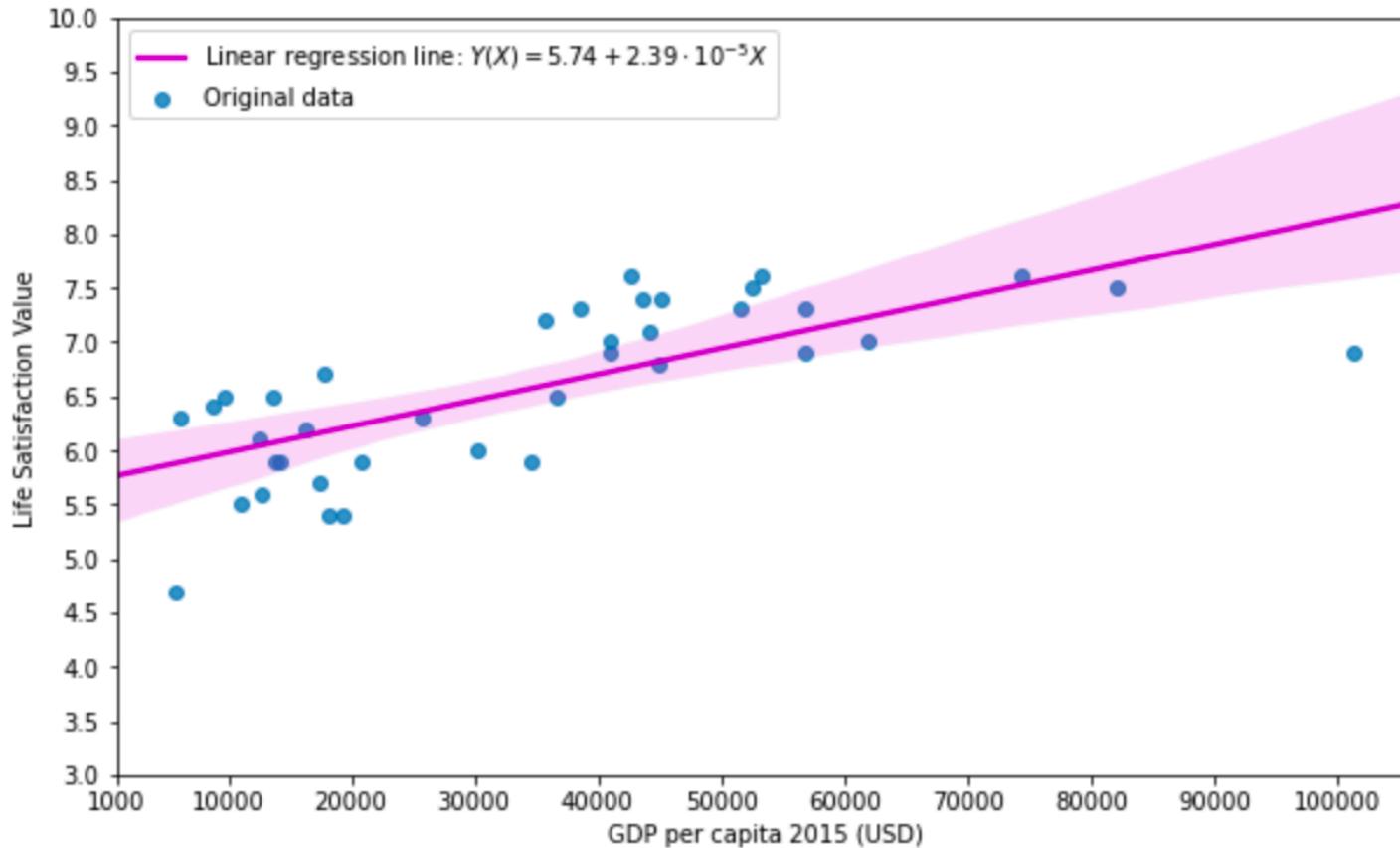
Google: “The 25 billion dollar eigenvector.” Each web page has some importance, which it shares via outgoing links to other pages  
~~~~~ system of linear equations (in gazillions of variables).

Larry Page flies around in a private 747 because he paid attention in his linear algebra class!

# Some Application

- Learning from data: <https://math.mit.edu/classes/18.065/2019SP/>

- 



find the best linear fit!

# Overview of the Course

- ▶ Solve the matrix equation  $Ax = b$ 
  - ▶ Solve systems of linear equations using matrices, row reduction, and inverses.
  - ▶ Solve systems of linear equations with varying parameters using parametric forms for solutions, the geometry of linear transformations, the characterizations of invertible matrices, and determinants.
- ▶ Solve the matrix equation  $Ax = \lambda x$ 
  - ▶ Solve eigenvalue problems through the use of the characteristic polynomial.
  - ▶ Understand the dynamics of a linear transformation via the computation of eigenvalues, eigenvectors, and diagonalization.
- ▶ Almost solve the equation  $Ax = b$ 
  - ▶ Find best-fit solutions to systems of linear equations that have no actual solution using least squares approximations.

# Overview of the Course

Your previous math courses probably focused on how to do (sometimes rather involved) computations.

- ▶ Compute the derivative of  $\sin(\log x) \cos(e^x)$ .
- ▶ Compute  $\int_0^1 (1 - \cos(x)) dx$ .

This is important, **but** Wolfram Alpha can do all these problems better than any of us can. Nobody is going to hire you to do something a computer can do better.

If a computer can do the problem better than you can, then it's just an algorithm: this is not real problem solving.

So what are we going to do?

- ▶ About half the material focuses on how to do linear algebra computations—that is still important.
- ▶ The other half is on *conceptual* understanding of linear algebra. This is much more subtle: it's about figuring out *what question* to ask the computer, or whether you actually need to do any computations at all.



**NYU**

**Let's get this show started!**



NYU

## Strang Sections 1.1 and 1.2

Course notes adapted from *Introduction to Linear Algebra* by Strang (5<sup>th</sup> ed), and *Interactive Linear Algebra* by Margalit and Rabinoff.



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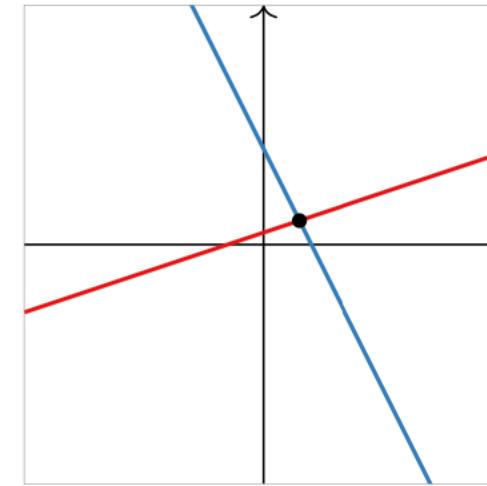
## 1.1 - Vectors

Course notes adapted from *Introduction to Linear Algebra* by Strang (5<sup>th</sup> ed), and *Interactive Linear Algebra* by Margalit and Rabinoff.

# 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).

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



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.

# Motivation

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

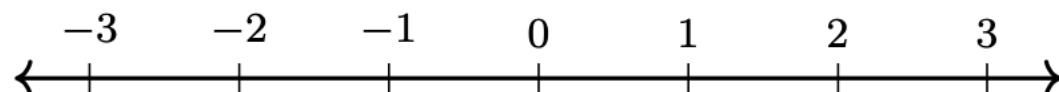
## Definition

Let  $n$  be a positive whole number. We define

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

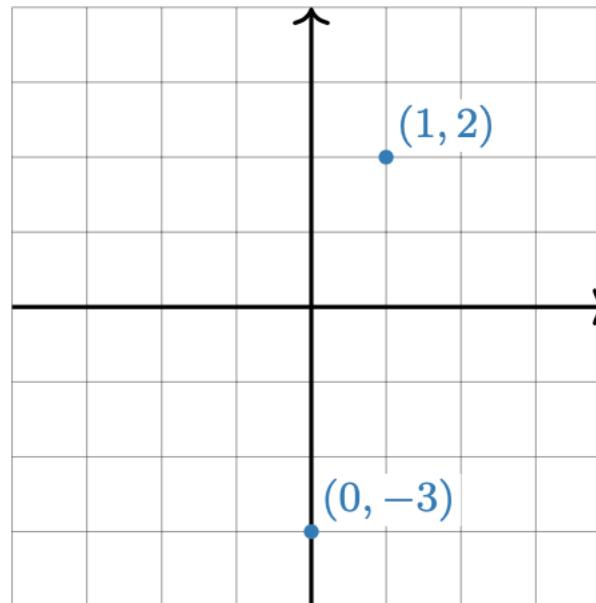
## Example

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



# Motivation

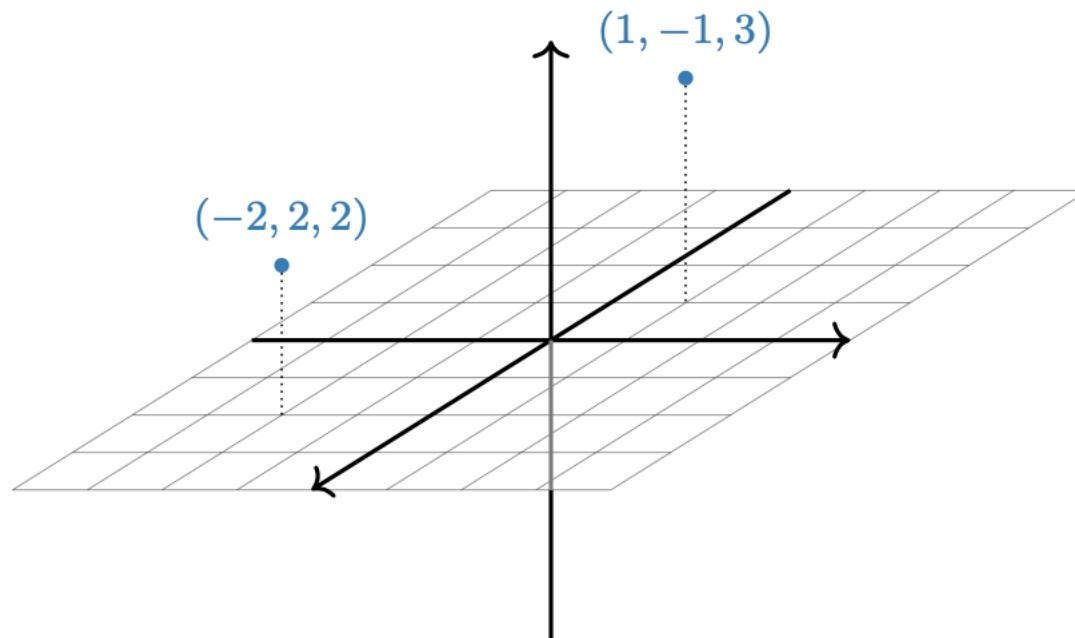
When  $n = 2$ , we can think of  $\mathbf{R}^2$  as the *plane*. This is because every point on the plane can be represented by an ordered pair of real numbers, namely, its  $x$ - and  $y$ -coordinates.



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!

# Motivation

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.



Again, we can use the elements of  $\mathbf{R}^3$  to *label* points in space, but  $\mathbf{R}^3$  is not defined to be space!

# Motivation

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

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

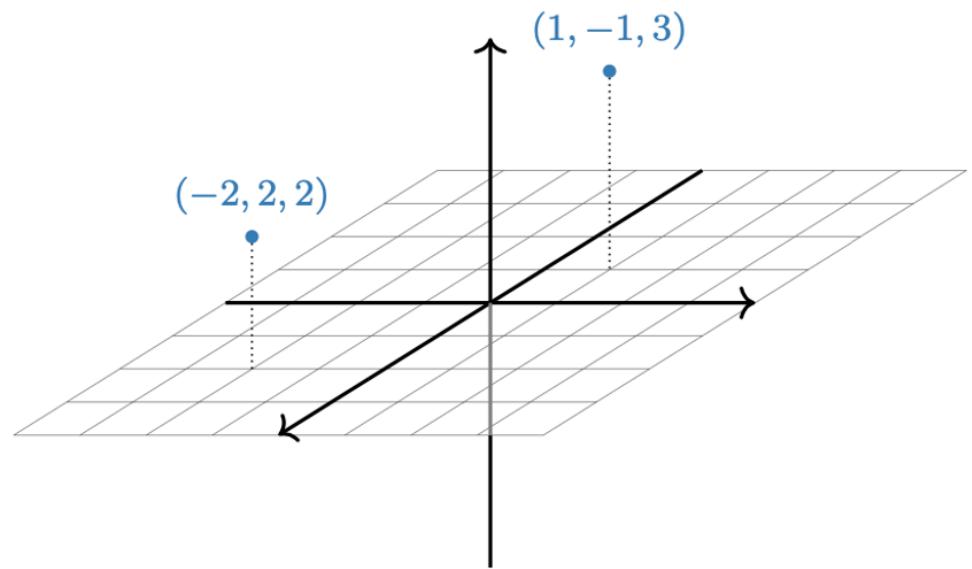
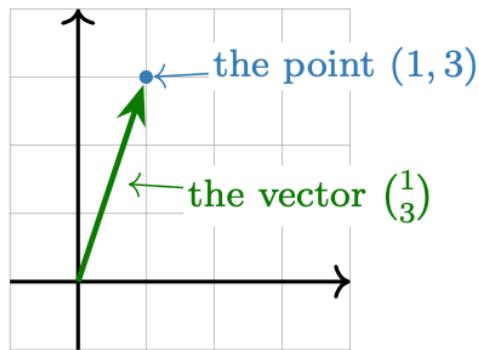
They're still "geometric" spaces, in the sense that our intuition for  $\mathbf{R}^2$  and  $\mathbf{R}^3$  sometimes extends to  $\mathbf{R}^n$ , but they're harder to visualize.

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 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.

# Imagine Manhattan



# Vector Algebra

- 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  $c$ :

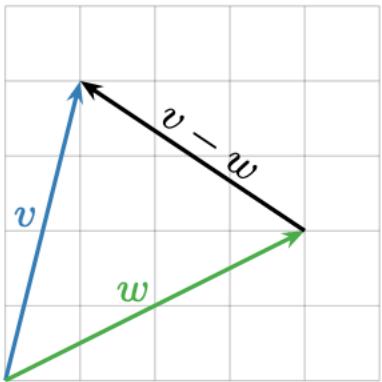
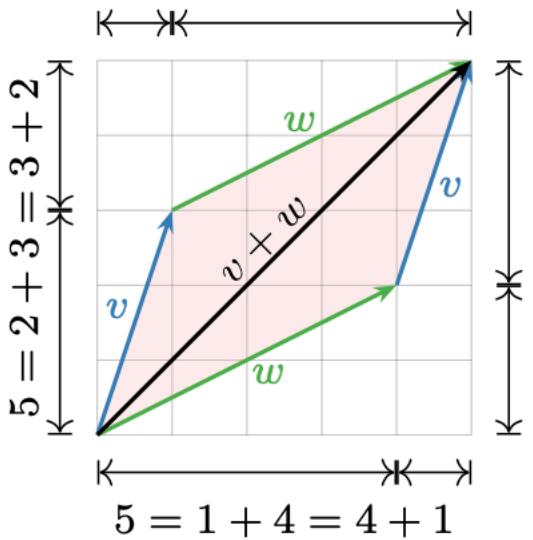
$$c \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \textcolor{red}{c} \cdot x \\ \textcolor{red}{c} \cdot y \\ \textcolor{red}{c} \cdot z \end{pmatrix}.$$

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,

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

# Vector Addition and Subtraction



This works in higher dimensions too!

## 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  $w$ . Doing this both ways creates a **parallelogram**. For example,

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

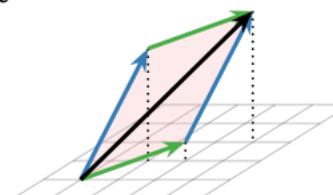
Why? The width of  $v + w$  is the sum of the widths, and likewise with the heights.

## Vector subtraction

Geometrically, the difference of two vectors  $v, w$  is obtained as follows: place the tail of  $v$  and  $w$  at the same point. Then  $v - w$  is the vector from the head of  $v$  to the head of  $w$ . For example,

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

Why? If you add  $v - w$  to  $w$ , you get  $v$ .

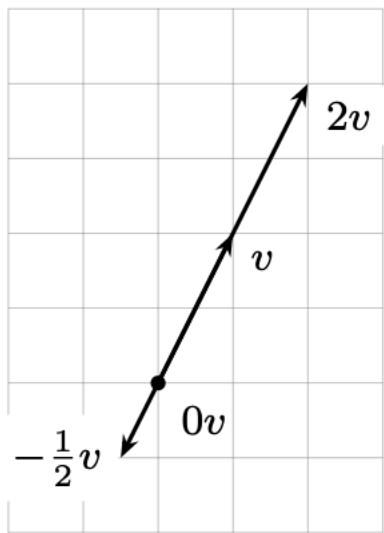


# Scalar Multiplication - Geometry

## Scalar multiples of a vector

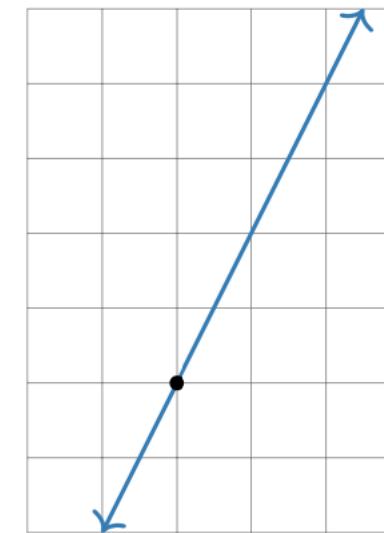
These have the same *direction* but a different *length*.

Some multiples of  $v$ .



All multiples of  $v$ .

$$\begin{aligned}v &= \begin{pmatrix} 1 \\ 2 \end{pmatrix} \\2v &= \begin{pmatrix} 2 \\ 4 \end{pmatrix} \\-\frac{1}{2}v &= \begin{pmatrix} -\frac{1}{2} \\ -1 \end{pmatrix} \\0v &= \begin{pmatrix} 0 \\ 0 \end{pmatrix}\end{aligned}$$



So the scalar multiples of  $v$  form a *line*.

# Linear Combinations

We can add and scalar multiply in the same equation:

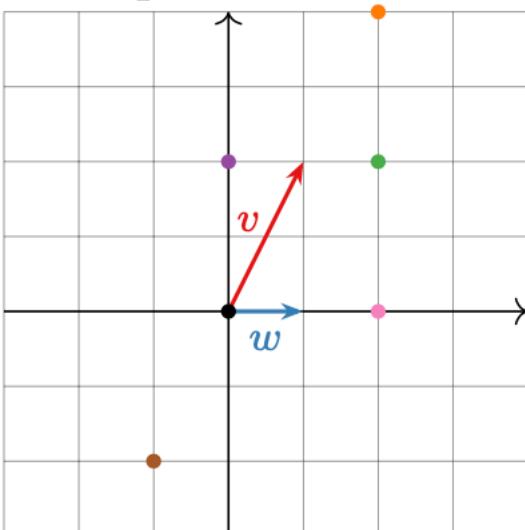
$$w = c_1v_1 + c_2v_2 + \cdots + c_pv_p$$

where  $c_1, c_2, \dots, c_p$  are scalars,  $v_1, v_2, \dots, v_p$  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  $v_1, v_2, \dots, v_p$ . The scalars  $c_1, c_2, \dots, c_p$  are called the **weights** or **coefficients**.

## Example



Let  $v = \begin{pmatrix} 1 \\ 2 \end{pmatrix}$  and  $w = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ .

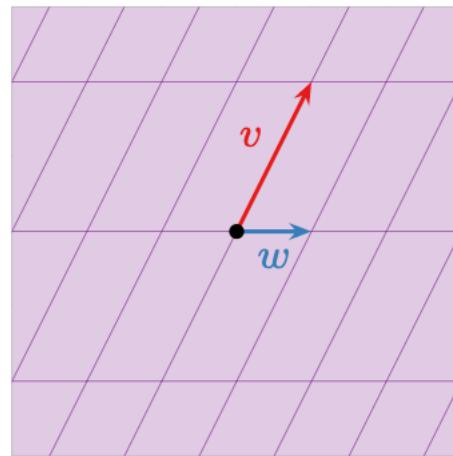
What are some linear combinations of  $v$  and  $w$ ?

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

# Poll

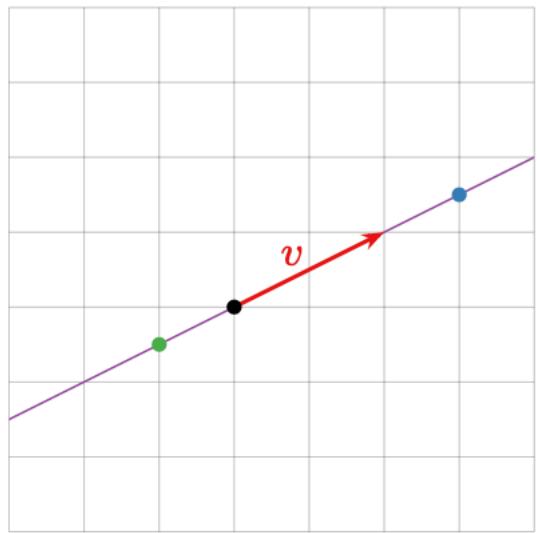
Poll

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



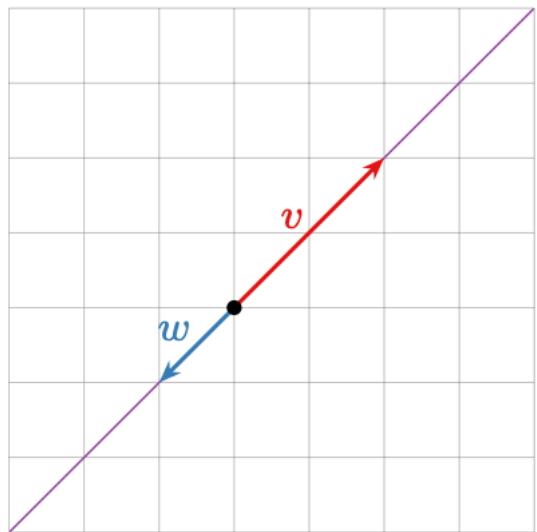
# Examples

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

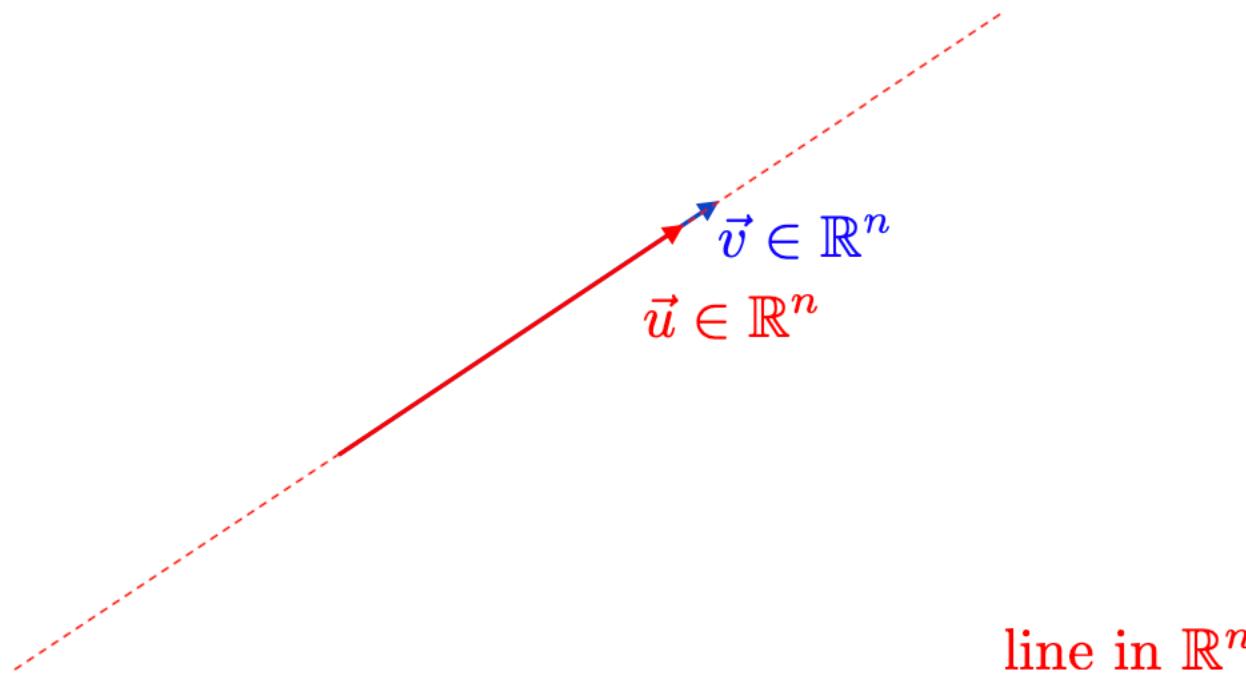


What are all linear combinations of

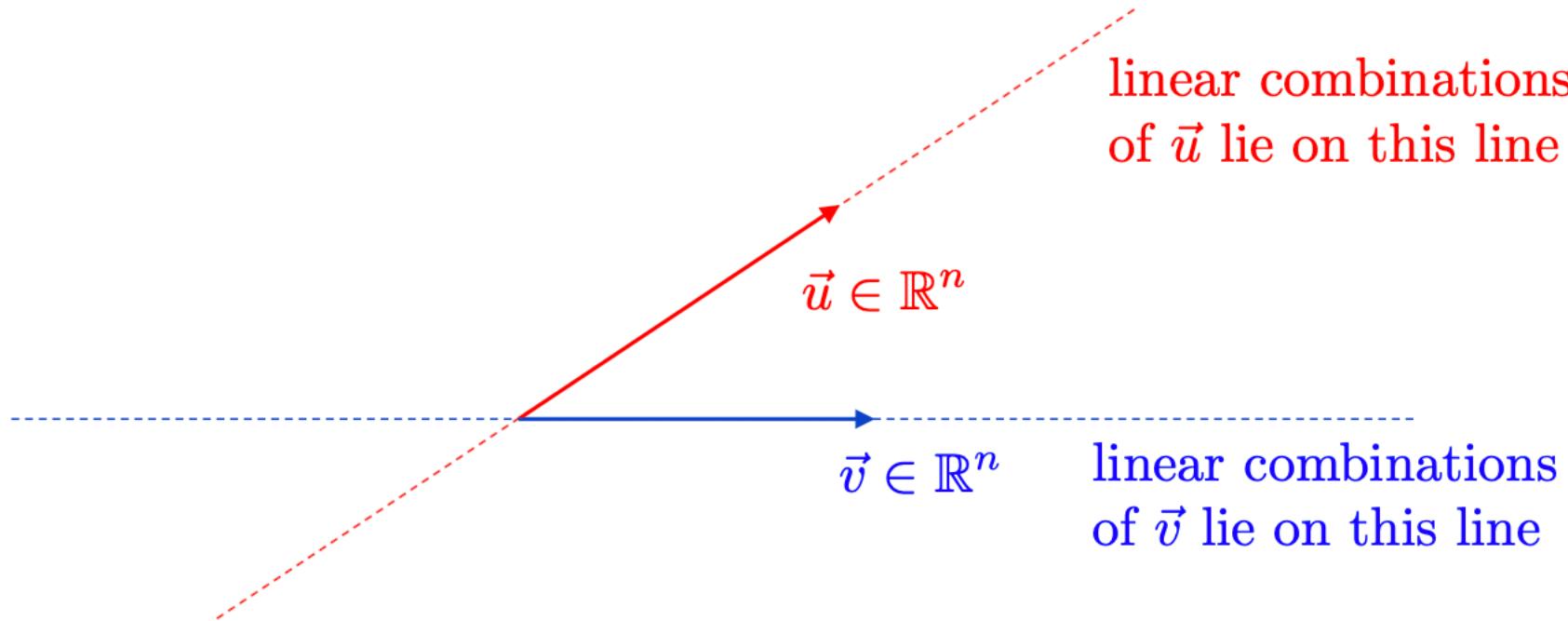
$$v = \begin{pmatrix} 2 \\ 2 \end{pmatrix} \quad \text{and} \quad w = \begin{pmatrix} -1 \\ -1 \end{pmatrix}?$$



# Geometric Interpretation of Linear Combinations



# Geometric Interpretation of Linear Combinations



linear combinations of  $\vec{u}$  and  $\vec{v}$  lie on a plane in  $\mathbb{R}^n$

# Vector Equations

## Question

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



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## 1.2 – Lengths and Dot Products

Course notes adapted from *Introduction to Linear Algebra* by Strang (5<sup>th</sup> ed), and *Interactive Linear Algebra* by Margalit and Rabinoff.

# Dot Product

We need a notion of *angle* between two vectors, and in particular, a notion of *orthogonality* (i.e. when two vectors are perpendicular). This is the purpose of the dot product.

## Definition

The **dot product** of two vectors  $x, y$  in  $\mathbf{R}^n$  is

$$x \cdot y = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} \cdot \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix} \stackrel{\text{def}}{=} x_1y_1 + x_2y_2 + \cdots + x_ny_n.$$

Thinking of  $x, y$  as column vectors, this is the same as  $x^T y$ .

## Example

$$\begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix} \cdot \begin{pmatrix} 4 \\ 5 \\ 6 \end{pmatrix} = (1 \quad 2 \quad 3) \begin{pmatrix} 4 \\ 5 \\ 6 \end{pmatrix} = 1 \cdot 4 + 2 \cdot 5 + 3 \cdot 6 = 32.$$

# Dot Product

Many usual arithmetic rules hold, as long as you remember you can only dot two vectors together, and that the result is a scalar.

- ▶  $x \cdot y = y \cdot x$
- ▶  $(x + y) \cdot z = x \cdot z + y \cdot z$
- ▶  $(cx) \cdot y = c(x \cdot y)$

Dotting a vector with itself is special:

$$\begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} \cdot \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} = x_1^2 + x_2^2 + \cdots + x_n^2.$$

Hence:

- ▶  $x \cdot x \geq 0$
- ▶  $x \cdot x = 0$  if and only if  $x = 0$ .

**Important:**  $x \cdot y = 0$  does *not* imply  $x = 0$  or  $y = 0$ . For example,  
 $\begin{pmatrix} 1 \\ 0 \end{pmatrix} \cdot \begin{pmatrix} 0 \\ 1 \end{pmatrix} = 0$ .

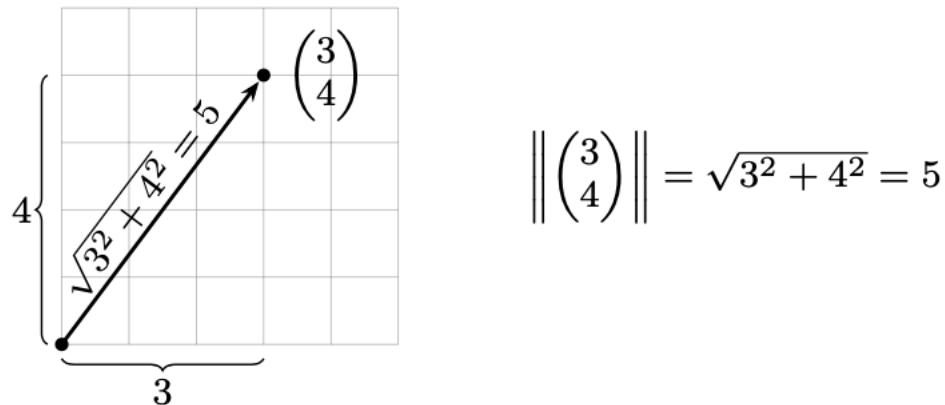
# Dot Product and Length

## Definition

The **length** or **norm** of a vector  $x$  in  $\mathbf{R}^n$  is

$$\|x\| = \sqrt{x \cdot x} = \sqrt{x_1^2 + x_2^2 + \cdots + x_n^2}.$$

Why is this a good definition? The Pythagorean theorem!



## Fact

If  $x$  is a vector and  $c$  is a scalar, then  $\|cx\| = |c| \cdot \|x\|$ .

$$\left\| \begin{pmatrix} 6 \\ 8 \end{pmatrix} \right\| = \left\| 2 \begin{pmatrix} 3 \\ 4 \end{pmatrix} \right\| = 2 \left\| \begin{pmatrix} 3 \\ 4 \end{pmatrix} \right\| = 10$$

# Dot Product and Distance

## Definition

The **distance** between two points  $x, y$  in  $\mathbf{R}^n$  is

$$\text{dist}(x, y) = \|y - x\|.$$

This is just the length of the vector from  $x$  to  $y$ .

## Example

Let  $x = (1, 2)$  and  $y = (4, 4)$ . Then

# Dot Products

## Definition

A **unit vector** is a vector  $v$  with length  $\|v\| = 1$ .

## Example

The unit coordinate vectors are unit vectors:

$$\|e_1\| = \left\| \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \right\| = \sqrt{1^2 + 0^2 + 0^2} = 1$$

## Definition

Let  $x$  be a nonzero vector in  $\mathbf{R}^n$ . The **unit vector in the direction of  $x$**  is the vector  $\frac{x}{\|x\|}$ .

This is in fact a unit vector:

$$\left\| \frac{x}{\|x\|} \right\| = \frac{1}{\|x\|} \|x\| = 1.$$

# Dot Products

## Example

What is the unit vector in the direction of  $x = \begin{pmatrix} 3 \\ 4 \end{pmatrix}$ ?

# Orthogonality

## Definition

Two vectors  $x, y$  are **orthogonal** or **perpendicular** if  $x \cdot y = 0$ .

*Notation:*  $x \perp y$  means  $x \cdot y = 0$ .

# Some Formulas

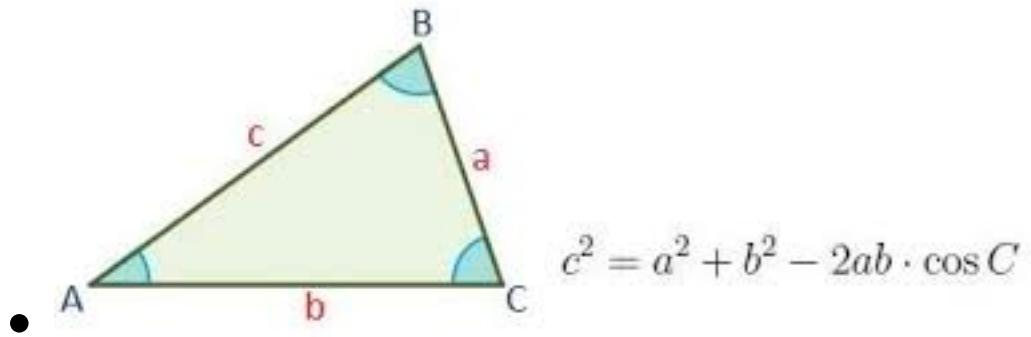
Cosine Formula/Alternate Dot Product Definition:

If  $u$  and  $v$  are nonzero vectors then

$$\frac{u \cdot v}{\|u\|\|v\|} = \cos \theta$$

The sign of the dot product tells us whether  $\theta < \frac{\pi}{2}$  or  $\theta > \frac{\pi}{2}$ . Alternatively, this can be written as  $u \cdot v = \|u\|\|v\| \cos \theta$  for a more general definition of the dot product.

# Generalized Pythagorean theorem



$$c^2 = a^2 + b^2 - 2ab \cdot \cos C$$

# Some Formulas

Cosine Formula/Alternate Dot Product Definition:

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Schwarz Inequality

A consequence of the previous formula is that

$$|u \cdot v| \leq \|u\| \|v\|$$

Triangle Inequality

$$\|u + v\| \leq \|u\| + \|v\|$$