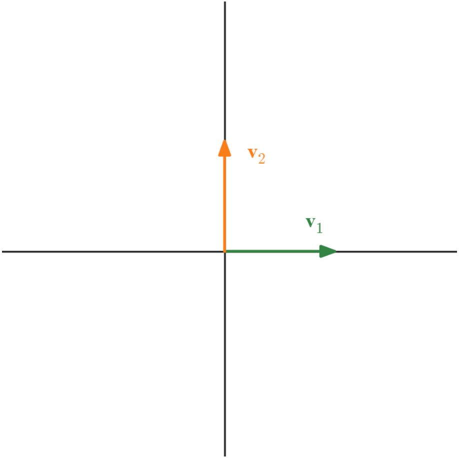
Basis, Eigenvalues and Eigenvectors

Hayk Aprikyan, Hayk Tarkhanyan

Motivation

When talking about vectors/matrices, why do we focus on these vectors?



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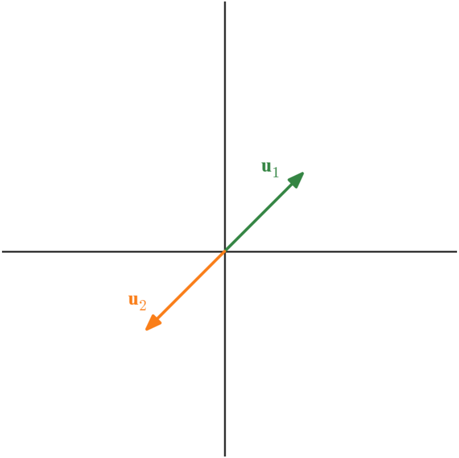
And not on these:



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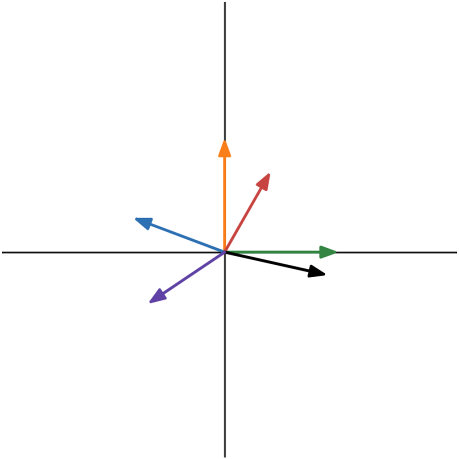

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We call expressions like these:

$$\text{something} \cdot \mathbf{v}_1 + \text{something} \cdot \mathbf{v}_2$$

the **linear combinations** of $\mathbf{v}_1$ and $\mathbf{v}_2$.

In our case, the vector $[4 \;\; 7]$ is a linear combination of $\mathbf{v}_1$ and $\mathbf{v}_2$.

Span

More generally,

Definition

For any vectors $\mathbf{v}_1, \mathbf{v}_2, \ldots, \mathbf{v}_k$ and for any scalars $c_1, c_2, \ldots, c_k$, the expression

$$c_1\mathbf{v}_1 + c_2\mathbf{v}_2 + \ldots + c_k\mathbf{v}_k$$

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So in this sense, all vectors of $\mathbb{R}^2$ can be written as linear combinations of $\mathbf{v}_1$ and $\mathbf{v}_2$! In this case, we say that $\mathbb{R}^2$ is the **span** of $\mathbf{v}_1$ and $\mathbf{v}_2$:

Definition

The set of all possible linear combinations of the vectors $\mathbf{v}_1, \ldots, \mathbf{v}_n$ is called their **span**, i.e.

$$\operatorname{span}\{\mathbf{v}_1, \mathbf{v}_2, \ldots, \mathbf{v}_n\} = \{c_1\mathbf{v}_1 + c_2\mathbf{v}_2 + \ldots + c_n\mathbf{v}_n \mid c_1, c_2, \ldots, c_n \in \mathbb{R}\}.$$

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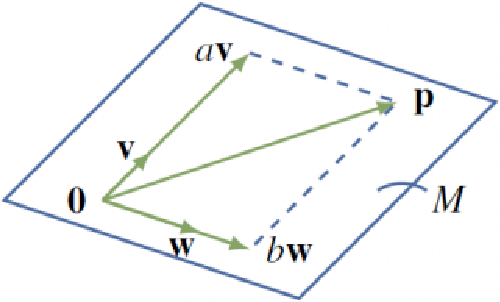

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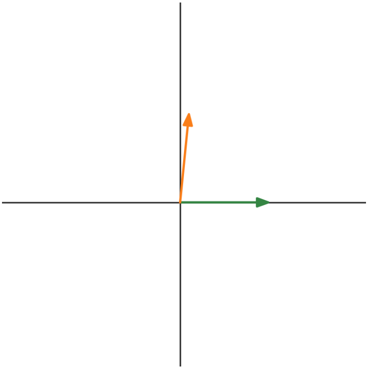
What is the span of vectors $[1 \quad 0]$ and $[0.1 \quad 1]$?



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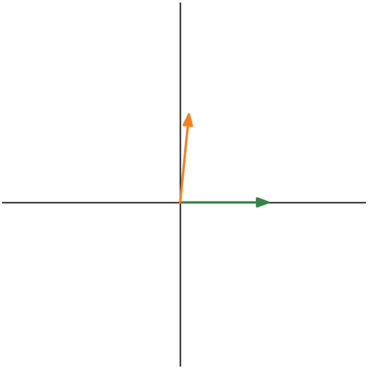

Again, it is the whole $\mathbb{R}^2$: We can express any vector using these two.

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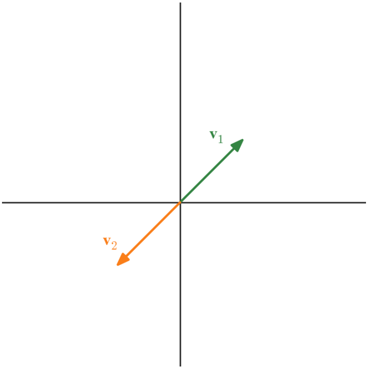

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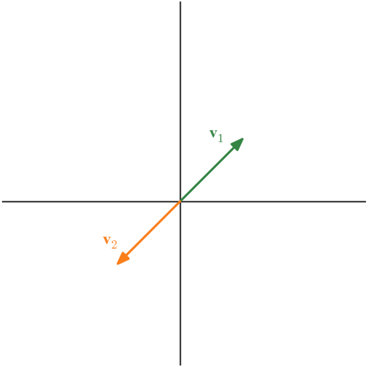

Since they both lie on the line $y = x$, their span is the line $y = x$ itself.

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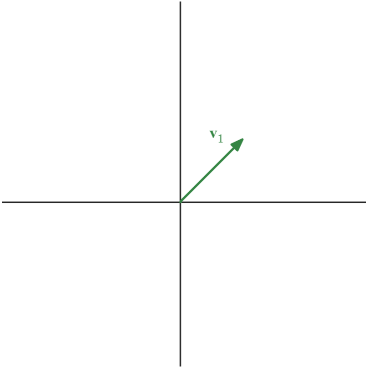
What about the span of the single vector $[1 \quad 1]$?



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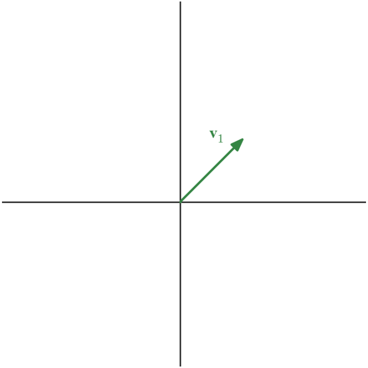

Again, the span of $[1 \quad 1]$ is the line $y = x$.

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But what is the reason that

- in one case (e.g. $\mathbf{v}_1 = [1 \ \ 0]$ and $\mathbf{v}_2 = [0 \ \ 1]$) the span is the whole $\mathbb{R}^2$,
- but in another case (e.g. $\mathbf{u}_1 = [1 \ \ 1]$ and $\mathbf{u}_2 = [-1 \ \ -1]$) the span is only a line?

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Because in the second case, one of the vectors can be expressed by another!

Linear Independence

Indeed, you can express $\mathbf{u}_2$ with $\mathbf{u}_1$:

$$\mathbf{u}_2 = \begin{bmatrix} -1 \\ -1 \end{bmatrix} = -1 \cdot \begin{bmatrix} 1 \\ 1 \end{bmatrix} = (-1) \cdot \mathbf{u}_1,$$

but you **cannot express** $\mathbf{v}_2$ with $\mathbf{v}_1$ (or vice versa).

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In this case, we say that

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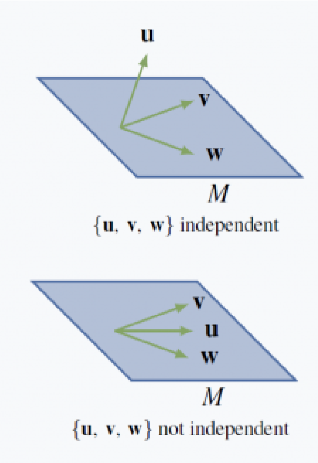
And we say that they are linearly dependent if one of them, say $\mathbf{v}_n$, can be written as

$$\mathbf{v}_n = c_1\mathbf{v}_1 + c_2\mathbf{v}_2 + \cdots + c_{n-1}\mathbf{v}_{n-1}$$

Linear Independence



Check these animations:

- www.desmos.com/calculator/9rnbn0ycdd
- www.desmos.com/calculator/aje8cboe0j

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Geometrically,

- Two vectors are linearly dependent if they lie on the same line,
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There is also another characterization of linear independence (try to prove it by yourself):

Theorem

Vectors $\mathbf{v}_1, \ldots, \mathbf{v}_n$ are linearly independent if and only if the equation

$$c_1\mathbf{v}_1 + c_2\mathbf{v}_2 + \ldots + c_n\mathbf{v}_n = \mathbf{0}$$

is *only* true if $c_1 = c_2 = \ldots = c_n = 0$.

(i.e. if you plug in any numbers other than 0, the sum will not be $\mathbf{0}$).

Basis

So now we can say that the vectors

$$\mathbf{v}_1 = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \qquad \text{and} \qquad \mathbf{v}_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

are linearly independent and their span is $\mathbb{R}^2$.

We call the pairs of vectors like $\mathbf{v}_1$ and $\mathbf{v}_2$ the **basis** of the space $\mathbb{R}^2$.

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The vectors $\mathbf{v}_1, \mathbf{v}_2, \ldots, \mathbf{v}_n$ are called a **basis** of the vector space V if:

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In other words, there are no "irrelevant", "redundant" vectors, and any vector of V can be expressed with $\mathbf{v}_1, \ldots, \mathbf{v}_n$.
(In fact, such representation is always unique, i.e. there is only one way to express $[3 \;\; 4]$ with $\mathbf{v}_1 = [1 \;\; 0]$ and $\mathbf{v}_2 = [0 \;\; 1]$: $\quad 3 \cdot \mathbf{v}_1 + 4 \cdot \mathbf{v}_2$)

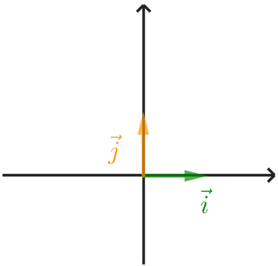
Basis

Example

The vectors

$$\mathbf{e}_1 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad \mathbf{e}_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

form a basis for $\mathbb{R}^2$ and are called the **standard basis**. They are often denoted $\hat{i}, \hat{j}$.



Basis

Example

The linearly independent vectors

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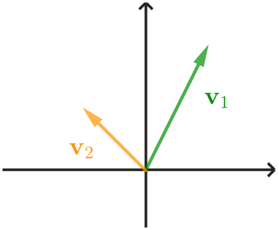
form a basis for $\mathbb{R}^2$ as these vectors are linearly independent and their span is $\mathbb{R}^2$.



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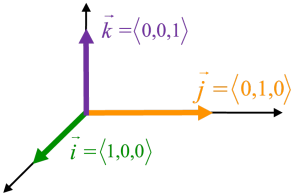
The vectors

$$\mathbf{e}_1 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \quad \mathbf{e}_2 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \quad \mathbf{e}_3 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

form a basis for $\mathbb{R}^3$ and are called the **standard basis**. They are often denoted $\hat{i}, \hat{j}, \hat{k}$.



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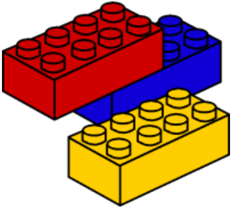
The basis is our Lego set of "building blocks" out of which we build our castle (i.e. the vector space). Since they all have the same number of vectors, we call that number the **dimension** of the space.



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- etc.

The dimension describes how **big** our vector space is. It shows how many linearly independent vectors are there in that vector space at most.

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Getting back to our matrices, our main question remains:

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How can we tell which transformation a matrix represents by just looking at it?

Turns out, the answer is hidden in the concept of basis.

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Where do you think it takes the basis vectors $\mathbf{e}_1 = [1 \quad 0]$ and $\mathbf{e}_2 = [0 \quad 1]$?

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Where do you think it takes the basis vectors $\mathbf{e}_1 = [1 \quad 0]$ and $\mathbf{e}_2 = [0 \quad 1]$?

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Geometric Interpretation of Matrices (last time)

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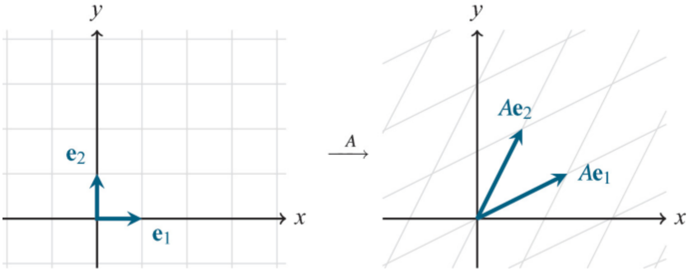

As we see, applying a matrix **transforms the basis vectors $\mathbf{e}_1$ and $\mathbf{e}_2$** into the **columns of the matrix**:

$$\begin{bmatrix} 1 \\ 0 \end{bmatrix} \mapsto \text{1st column of } A$$

$$\begin{bmatrix} 0 \\ 1 \end{bmatrix} \mapsto \text{2nd column of } A$$

Geometric Interpretation of Matrices (last time)

Therefore any vector with coordinates $\begin{bmatrix} a \\ b \end{bmatrix}$ is transformed into

$$a \begin{bmatrix} 2 \\ 1 \end{bmatrix} + b \begin{bmatrix} 1 \\ 2 \end{bmatrix},$$

i.e. the linear transformation sends our basis vectors to its columns, which become a new basis for our space.

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More precisely, if the columns of A are linearly independent, then they form a basis.

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The number of linearly independent columns of the matrix A is called the **rank** of A.

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Finally, peace.

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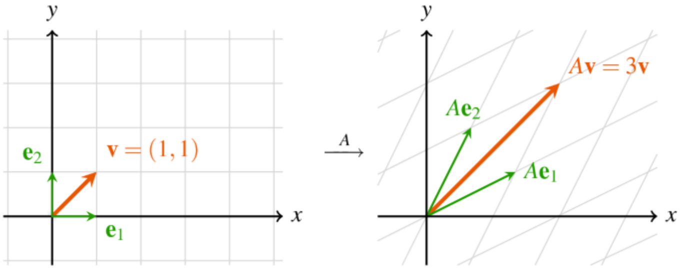
Sometimes the matrix also has some vectors which **do not change their direction** when being multiplied (transformed) by that matrix, rather they get scaled by some number:



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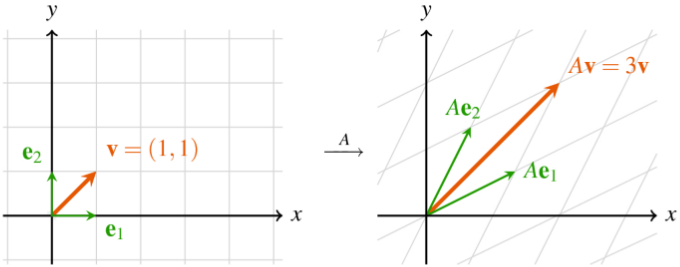

Vectors like these are of special interest to us, and we call them *eigenvectors*.

Eigenvalues and Eigenvectors

Definition

If for some number λ and some non-zero vector $\mathbf{v}$

$$A\mathbf{v} = \lambda\mathbf{v}$$

then we say

- λ is an **eigenvalue** of A,
- $\mathbf{v}$ is an **eigenvector** of A corresponding to the eigenvalue λ.

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Example

For the matrix $A = \begin{bmatrix} 3 & 5 \\ 1 & -1 \end{bmatrix}$ and vector $\mathbf{v} = \begin{bmatrix} 5 \\ 1 \end{bmatrix}$,

$$A\mathbf{v} = \begin{bmatrix} 3 & 5 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} 5 \\ 1 \end{bmatrix} = \begin{bmatrix} 20 \\ 4 \end{bmatrix} = 4\mathbf{v}$$

so $\lambda = 4$ is an eigenvalue of A with eigenvector $\mathbf{v}$.

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so $\lambda = 4$ is an eigenvalue of A with eigenvector $\mathbf{v}$. What about $-3\mathbf{v}$?

Eigenvalues and Eigenvectors

Remark

If $\mathbf{v}$ is an eigenvector of A, then for any scalar $c \neq 0$, $c\mathbf{v}$ is also an eigenvector for A.

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For $A \in \mathbb{R}^{n \times n}$, the set of all eigenvectors of A associated with an eigenvalue λ, together with the zero vector, is called the **eigenspace** of A with respect to λ and is denoted by E_λ.

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Definition

The set of all eigenvalues of A is called the **spectrum** of A.

How can we find the eigenvalues and eigenvectors of a given matrix?

Eigenvalues and Eigenvectors

Suppose $A \in \mathbb{R}^{n \times n}$ is a matrix, and we want to find $x \in \mathbb{R}$ and $\mathbf{v} \in \mathbb{R}^n$ such that:

$$
\begin{aligned}
A\mathbf{v} = x\mathbf{v} = I(x\mathbf{v}) &= xI\mathbf{v} \\
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The polynomial above is called the **characteristic polynomial** of A. Its roots are the eigenvalues of A.

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$$p_A(x) = \det(A - xI) = (3-x)(-1-x) - 5 = x^2 - 2x - 8$$

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Hence, the roots of $p_A(x)$ are $\lambda = 4$ and $\lambda = -2$, so these are the eigenvalues of A. The spectrum of A is $\{4, -2\}$.

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Setting $v_2 = a$ and $v_1 = 5a$ for any scalar $a \in \mathbb{R}$, we will get the solution. There are infinite solutions which are all multiplies of each other:

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Similarly we get $E_{-2} = \{a \cdot [-1 \quad 1]^T \mid \text{for any } a \in \mathbb{R}\}$.

Eigenvalues and Eigenvectors

Again, what we are concerned with, is the *concept* and not the computation.

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As a bonus, we have a surprising theorem:

Theorem

The determinant of a matrix is equal to the product of its eigenvalues:

$$\det(A) = \lambda_1 \cdot \lambda_2 \cdot \ldots \cdot \lambda_n$$

and the trace of a matrix is equal to the sum of its eigenvalues:

$$\mathrm{tr}(A) = \lambda_1 + \lambda_2 + \ldots + \lambda_n$$

Systems of Linear Equations

Let us consider one last application of the matrices.

Question

Imagine scrolling Facebook, when you suddenly see the following problem:
You have 2 types of fruits, apples and oranges. You buy 2 apples and 3 oranges for a total cost of 11 dollars. Additionally, you buy 1 apple and 4 oranges for a total cost of 7 dollars.
Only people with 140 IQ can find the prices of apples and oranges.

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Let x be the cost of one apple and y be the cost of one orange. The problem can be represented as a 2×2 system of linear equations:

$$\begin{cases} 2x + 3y & = 11 \\ x + 4y & = 7 \end{cases}$$

Solving this system will give us the prices of apples (x) and oranges (y).

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A system of m linear equations with n variables can be written as:

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a_{21}x_1 & + & a_{22}x_2 & + & \dots & + & a_{2n}x_n & = & b_2 \\
\vdots & & \vdots & & \dots & & \vdots & & \vdots \\
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Definition

A **particular solution** to the system is a set of values for the variables $(x_1, x_2, \dots, x_n)$ that satisfies all equations simultaneously. The collection of all particular solutions is called the **general solution**.

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So Facebook is just asking: On which vector should you apply this matrix to get $[11 \quad 7]$?

Systems of Linear Equations

Let's consider three systems of linear equations:

a)

$$\begin{cases} 2x + 3y & = 7 \\ 4x - y & = 5 \end{cases}$$

b)

$$\begin{cases} 2x + 3y & = 7 \\ 4x + 6y & = 14 \end{cases}$$

c)

$$\begin{cases} 2x + 3y & = 7 \\ 4x + 6y & = 15 \end{cases}$$

Systems of Linear Equations

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$$\begin{cases} 2x + 3y & = 7 \\ 4x - y & = 5 \end{cases}$$

$$2x + 3y = 7 \Rightarrow 2x = 7 - 3y \Rightarrow x = \frac{7 - 3y}{2}$$

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Solution: $x = 2, \quad y = \frac{1}{2}$

b)

$$\begin{cases} 2x + 3y &= 7 \\ 4x + 6y &= 14 \end{cases}$$

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Systems of Linear Equations

b)

$$\begin{cases} 2x + 3y & = 7 \\ 4x + 6y & = 14 \end{cases}$$

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Infinite solutions: $x = \frac{7-3y}{2}, \quad$ for any $y \in \mathbb{R}$

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$$\begin{cases} 2x + 3y & = 7 \\ 4x + 6y & = 15 \end{cases}$$

Multiplying the first equation by 2 gives:

$$4x + 6y = 14$$

which contradicts the second equation.

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Multiplying the first equation by 2 gives:

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which contradicts the second equation.
No solution.

So as we saw, in general a system of linear equations can have a *unique solution*, *no solution*, or *infinitely many solutions*.

Definition

A system of linear equations is **consistent** if it has at least one solution. A system is *inconsistent* if it has no solutions.

Systems of Linear Equations

Consider the system of three linear equations:

$$\begin{cases} 2x + y - z & = 5 \\ -3x - 2y + 2z & = -8 \\ x + 4y - 3z & = 1 \end{cases}$$

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where

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Theorem (very fundamental)

The system $A\mathbf{x} = \mathbf{b}$ has a unique solution for any vector $\mathbf{b} \in \mathbb{R}^n$, if and only if $\det A \neq 0$ (i.e. A is invertible).