DeepLearning.AI

Math for Machine Learning

Linear algebra - Week 1

Systems of linear equations
Singular and non-singular matrices
Determinants
Rank of a matrix
Row reduction
Null space

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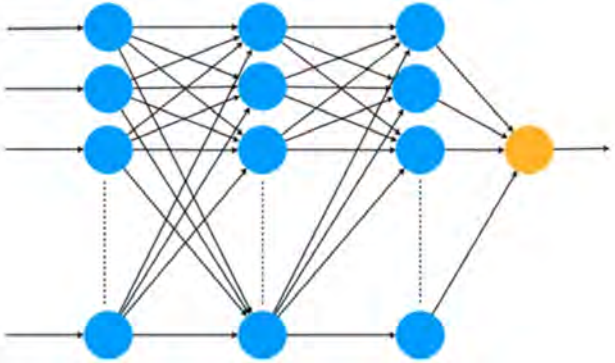
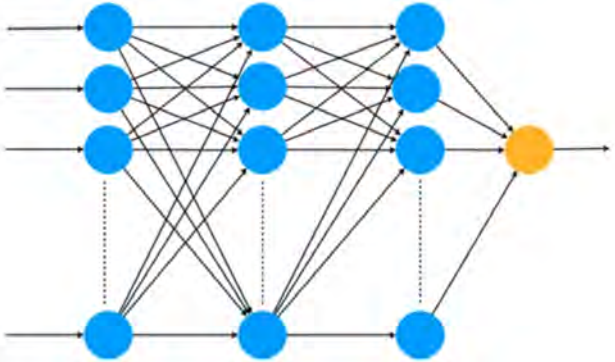
System of Linear Equations

Machine learning motivation

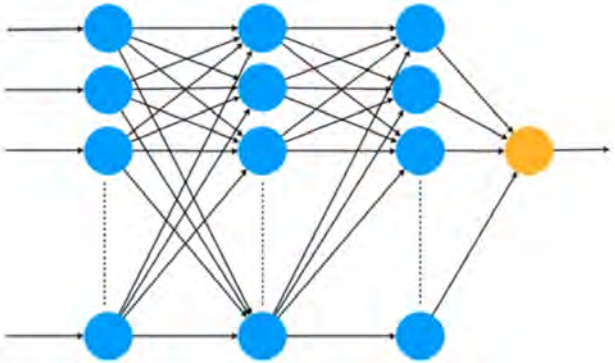
Neural networks - Matrix operations



Neural networks - Matrix operations

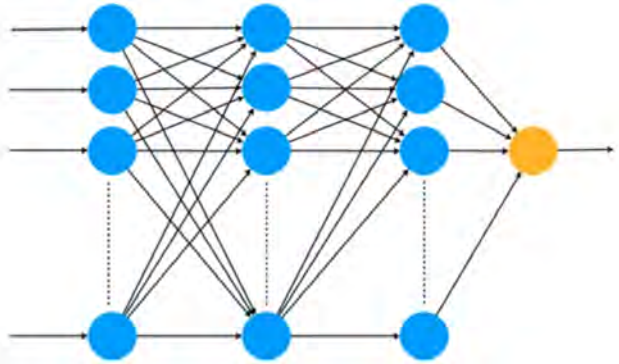


Neural networks - Matrix operations



Yes, it’s a face

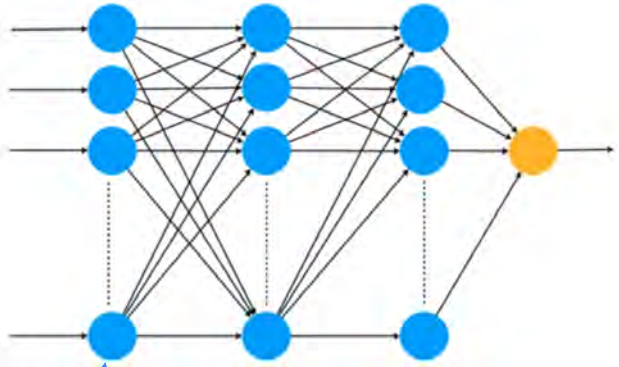
Neural networks - Matrix operations



Yes, it's a face

Matrix

Neural networks - Matrix operations

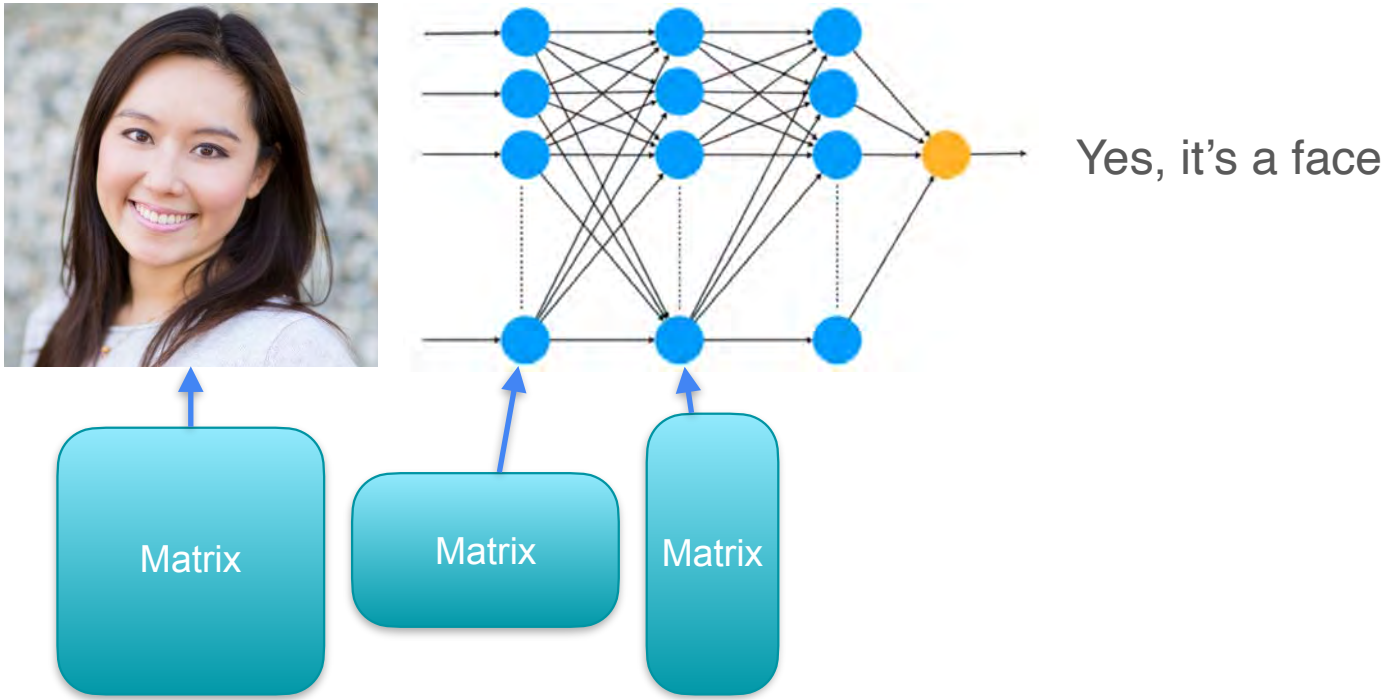


Yes, it's a face

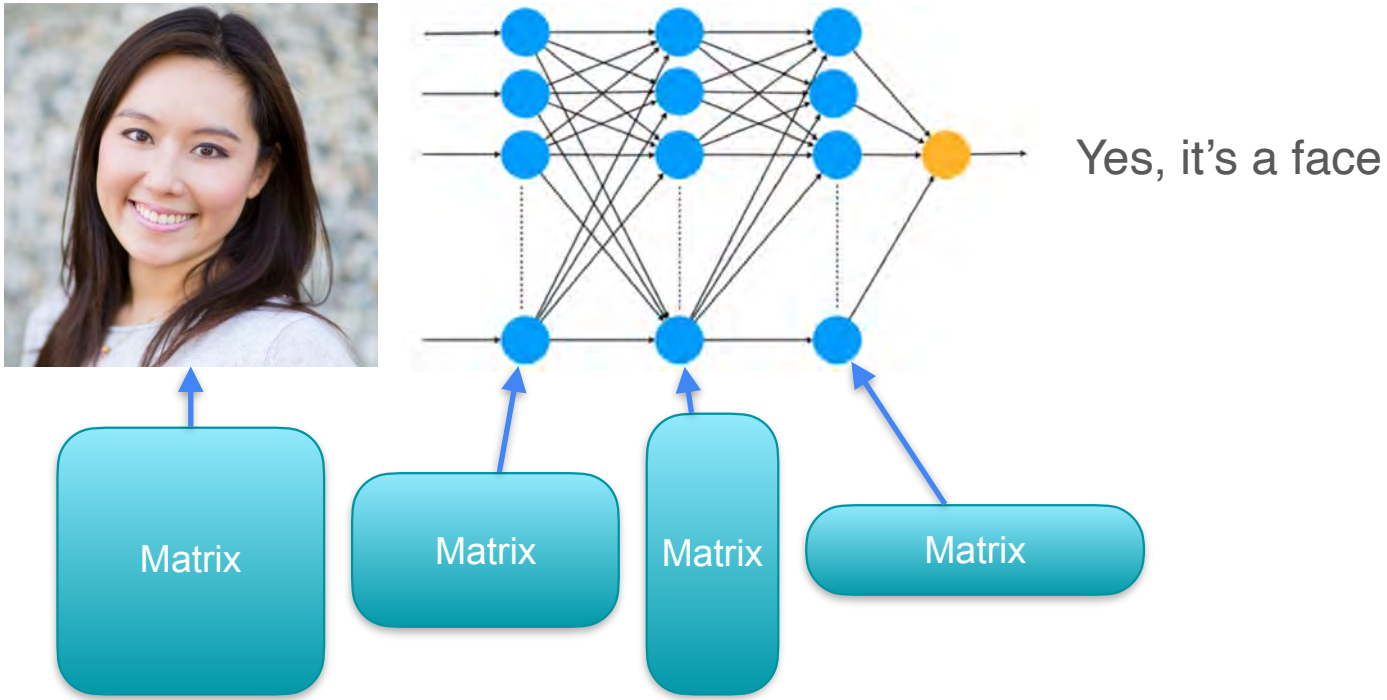
Matrix

Matrix

Neural networks - Matrix operations



Neural networks - Matrix operations



Neural networks - image recognition

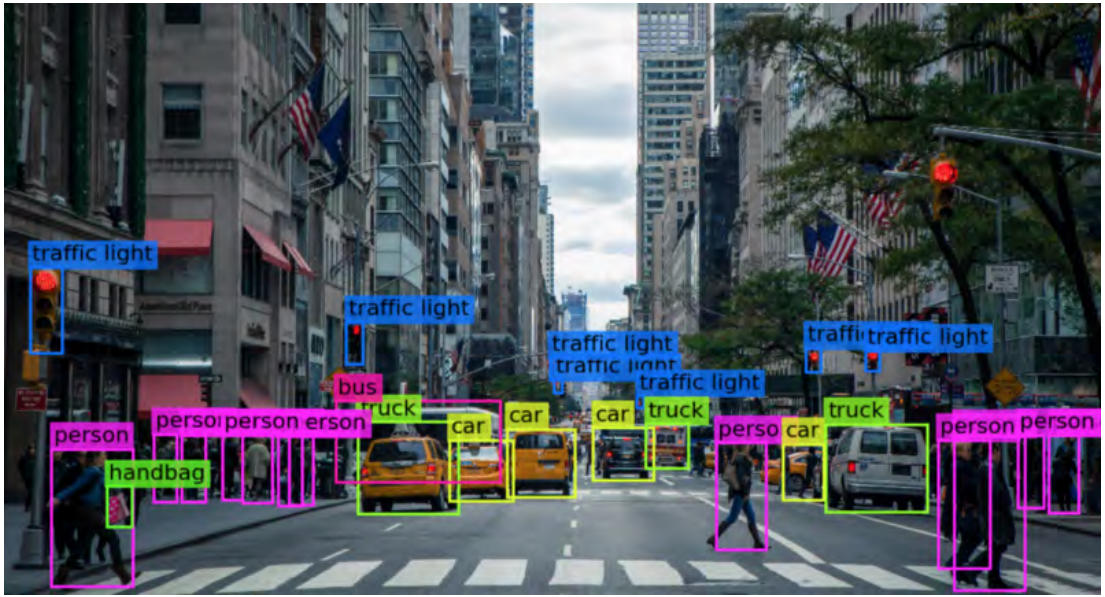


Image recognition in a busy street in New York.

- Image recognition: Getting the computer to see images and recognize what is on them.

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System of Linear Equations

System of sentences

Systems of sentences

Systems of sentences

System 1

The dog is **black**
The cat is **orange**

Systems of sentences

System 1

The dog is **black**

The cat is **orange**

System 2

The dog is **black**

The dog is **black**

Systems of sentences

System 1

The dog is **black**
The cat is **orange**

System 2

The dog is **black**
The dog is **black**

System 3

The dog is **black**
The dog is **white**

Systems of sentences

System 1

The dog is **black**
The cat is **orange**

Complete

System 2

The dog is **black**
The dog is **black**

System 3

The dog is **black**
The dog is **white**

Systems of sentences

System 1

The dog is **black**
The cat is **orange**

Complete

System 2

The dog is **black**
The dog is **black**

Redundant

System 3

The dog is **black**
The dog is **white**

Systems of sentences

System 1

The dog is **black**
The cat is **orange**

Complete

System 2

The dog is **black**
The dog is **black**

Redundant

System 3

The dog is **black**
The dog is **white**

Contradictory

Systems of sentences

System 1

The dog is **black**
The cat is **orange**

Complete

System 2

The dog is **black**
The dog is **black**

Redundant

Singular

System 3

The dog is **black**
The dog is **white**

Contradictory

Singular

Systems of sentences

System 1

The dog is **black**
The cat is **orange**

Complete

Non-singular

System 2

The dog is **black**
The dog is **black**

Redundant

Singular

System 3

The dog is **black**
The dog is **white**

Contradictory

Singular

Systems of sentences

System 1

The dog is **black**
The cat is **orange**
The bird is **red**

System 2

The dog is **black**
The dog is **black**
The bird is **red**

System 3

The dog is **black**
The dog is **black**
The dog is **black**

System 4

The dog is **black**
The dog is white
The bird is **red**

Systems of sentences

System 1

The dog is **black**
The cat is **orange**
The bird is **red**

Complete

Non-singular

System 2

The dog is **black**
The dog is **black**
The bird is **red**

System 3

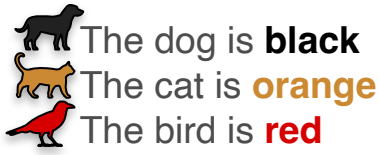
The dog is **black**
The dog is **black**
The dog is **black**

System 4

The dog is **black**
The dog is white
The bird is **red**

Systems of sentences

System 1

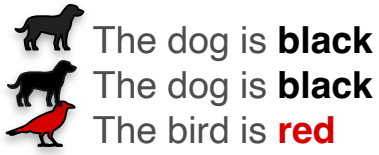


The dog is **black**
The cat is **orange**
The bird is **red**

Complete

Non-singular

System 2

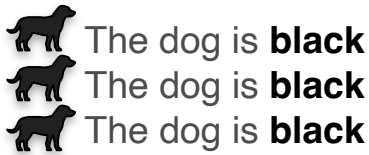


The dog is **black**
The dog is **black**
The bird is **red**

Redundant

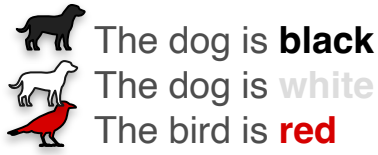
Singular

System 3



The dog is **black**
The dog is **black**
The dog is **black**

System 4



The dog is **black**
The dog is white
The bird is **red**

Systems of sentences

System 1

The dog is **black**
The cat is **orange**
The bird is **red**

Complete

Non-singular

System 2

The dog is **black**
The dog is **black**
The bird is **red**

Redundant

Singular

System 3

The dog is **black**
The dog is **black**
The dog is **black**

Redundant

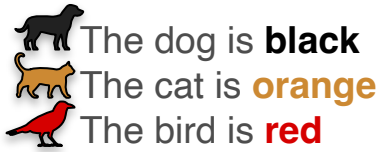
Singular

System 4

The dog is **black**
The dog is white
The bird is **red**

Systems of sentences

System 1

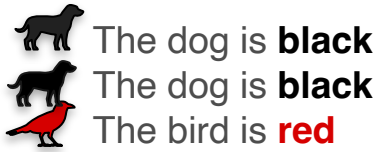


The dog is **black**
The cat is **orange**
The bird is **red**

Complete

Non-singular

System 2

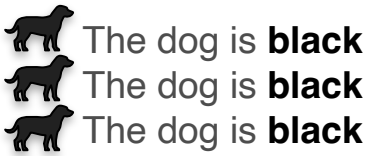


The dog is **black**
The dog is **black**
The bird is **red**

Redundant

Singular

System 3

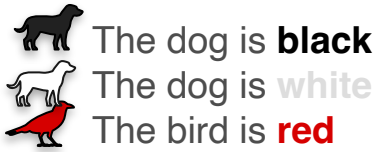


The dog is **black**
The dog is **black**
The dog is **black**

Redundant

Singular

System 4



The dog is **black**
The dog is white
The bird is **red**

Contradictory

Singular

Quiz: Systems of sentences

Given this system:

- Between the dog, the cat, and the bird, one is red.
- Between the dog and the cat, one is orange.
- The dog is black.

Problem 1:

What color is the bird?

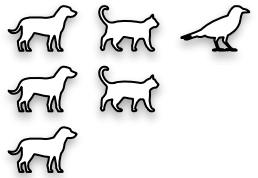
Problem 2:

Is this system singular or non-singular?

Solution: Systems of information

Given this system:

- Between the dog, the cat, and the bird, one is red.
- Between the dog and the cat, one is orange.
- The dog is black.



Solution: Systems of information

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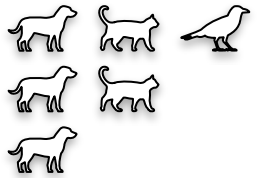

Solution 1:

Solution: Systems of information

Given this system:

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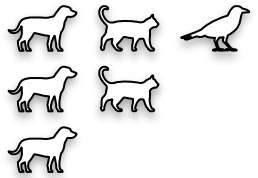

Solution 1:

The bird is red.

Solution: Systems of information

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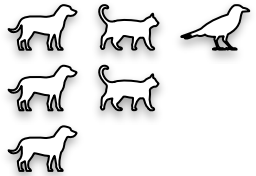

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The bird is red.

Solution: Systems of information

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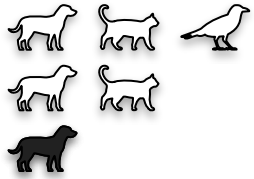

Solution 1:

The bird is red.

Solution: Systems of information

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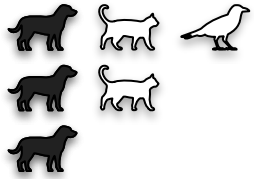
- The dog is black.



Solution 1:

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Solution: Systems of information

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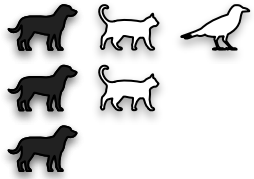

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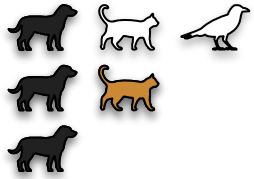

Solution 1:

The bird is red.

Solution: Systems of information

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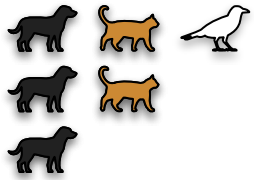

Solution 1:

The bird is red.

Solution: Systems of information

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- Between the dog, the cat, and the bird, one is red.
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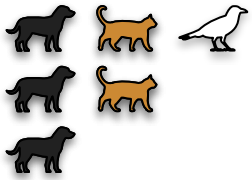
- The dog is black.



Solution 1:

The bird is red.

Solution: Systems of information

Given this system:

- Between the dog, the cat, and the bird, one is red.
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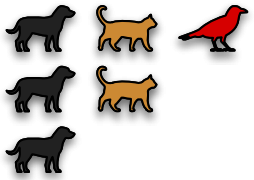


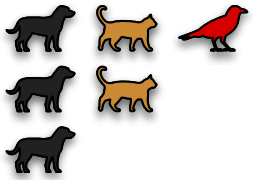
Solution 1:

The bird is red.

Solution: Systems of information

Given this system:

- Between the dog, the cat, and the bird, one is red.
- Between the dog and the cat, one is orange.
- The dog is black.



Solution 1:

The bird is red.

Solution 2:

It is non-singular.

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System of Linear Equations

System of equations

Sentences → Equations

Sentences

Between the dog and the cat, one is black.

Sentences → Equations

Sentences

Between the dog and the cat, one is black.

Sentences with numbers

The price of an apple and a banana is $10.

Sentences → Equations

Sentences

Between the dog and the cat, one is black.

Sentences with numbers

The price of an apple and a banana is $10.

Equations

a + b = 10

Quiz: Systems of equations 1

You go two days in a row and collect this information:

- **Day 1:** You bought an apple and a banana and they cost $10.
- **Day 2:** You bought an apple and two bananas and they cost $12.

Question: How much does each fruit cost?

Solution: Systems of equations 1

- **Day 1:** You bought an apple and a banana and they cost $10.
- **Day 2:** You bought an apple and two bananas and they cost $12.
- **Solution:** An apple costs $8, a banana costs $2.

Solution: Systems of equations 1

- **Day 1:** You bought an apple and a banana and they cost $10.

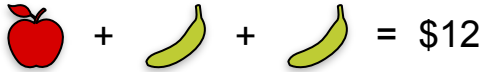
- **Day 2:** You bought an apple and two bananas and they cost $12.

- **Solution:** An apple costs $8, a banana costs $2.

Solution: Systems of equations 1

- **Day 1:** You bought an apple and a banana and they cost $10.

- **Day 2:** You bought an apple and two bananas and they cost $12.



- **Solution:** An apple costs $8, a banana costs $2.

Solution: Systems of equations 1

- **Day 1:** You bought an apple and a banana and they cost $10.

- **Day 2:** You bought an apple and two bananas and they cost $12.

- **Solution:** An apple costs $8, a banana costs $2.

Solution: Systems of equations 1

- **Day 1:** You bought an apple and a banana and they cost $10.

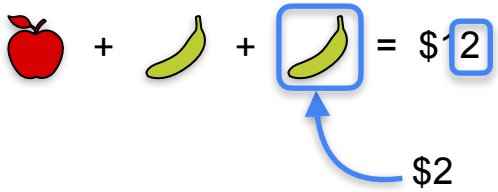
- **Day 2:** You bought an apple and two bananas and they cost $12.

- **Solution:** An apple costs $8, a banana costs $2.

Solution: Systems of equations 1

- **Day 1:** You bought an apple and a banana and they cost $10.

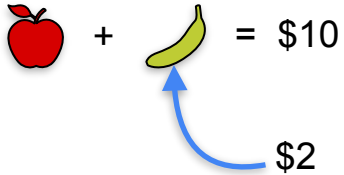
- **Day 2:** You bought an apple and two bananas and they cost $12.



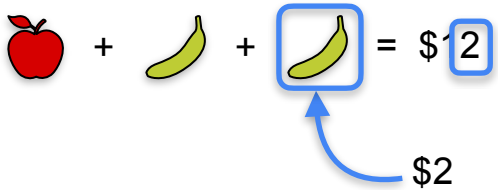
- **Solution:** An apple costs $8, a banana costs $2.

Solution: Systems of equations 1

- **Day 1:** You bought an apple and a banana and they cost $10.



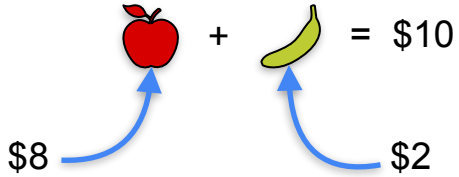
- **Day 2:** You bought an apple and two bananas and they cost $12.



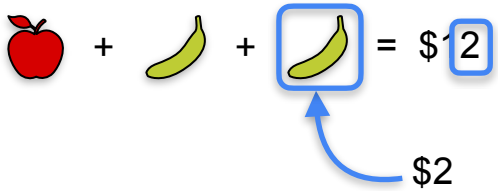
- **Solution:** An apple costs $8, a banana costs $2.

Solution: Systems of equations 1

- **Day 1:** You bought an apple and a banana and they cost $10.



- **Day 2:** You bought an apple and two bananas and they cost $12.



- **Solution:** An apple costs $8, a banana costs $2.

Quiz: Systems of equations 2

You go two days in a row and collect this information:

- **Day 1:** You bought an apple and a banana and they cost $10.
- **Day 2:** You bought two apples and two bananas and they cost $20.

Question: How much does each fruit cost?

Solution: Systems of equations 2

- **Day 1:** You bought an apple and a banana and they cost $10.

- **Day 2:** You bought two apples and two bananas and they cost $20.

Solution: Systems of equations 2

- **Day 1:** You bought an apple and a banana and they cost $10.

- **Day 2:** You bought two apples and two bananas and they cost $20.

Solution: Systems of equations 2

- **Day 1:** You bought an apple and a banana and they cost $10.

- **Day 2:** You bought two apples and two bananas and they cost $20.

Solution: Systems of equations 2

- **Day 1:** You bought an apple and a banana and they cost $10.

- **Day 2:** You bought two apples and two bananas and they cost $20.

Same thing!!!

Solution: Systems of equations 2

- **Day 1:** You bought an apple and a banana and they cost $10.

- **Day 2:** You bought two apples and two bananas and they cost $20.

Same thing!!!

8 2

Solution: Systems of equations 2

- **Day 1:** You bought an apple and a banana and they cost $10.

- **Day 2:** You bought two apples and two bananas and they cost $20.

Same thing!!!

8 2

5 5

Solution: Systems of equations 2

- **Day 1:** You bought an apple and a banana and they cost $10.

- **Day 2:** You bought two apples and two bananas and they cost $20.

Same thing!!!

8	2
5	5
8.3	1.7

Solution: Systems of equations 2

- **Day 1:** You bought an apple and a banana and they cost $10.

- **Day 2:** You bought two apples and two bananas and they cost $20.

Same thing!!!

8	2
5	5
8.3	1.7
0	10

Solution: Systems of equations 2

- **Day 1:** You bought an apple and a banana and they cost $10.

- **Day 2:** You bought two apples and two bananas and they cost $20.

Same thing!!!

8	2
5	5
8.3	1.7
0	10

Infinitely many solutions!

Quiz: Systems of equations 3

You go two days in a row and collect this information:

- **Day 1:** You bought an apple and a banana and they cost $10.
- **Day 2:** You bought two apples and two bananas and they cost $24.

Question: How much does each fruit cost?

Solution: Systems of equations 3

- **Day 1:** You bought an apple and a banana and they cost $10.

- **Day 2:** You bought two apples and two bananas and they cost $24.

Solution: Systems of equations 3

- **Day 1:** You bought an apple and a banana and they cost $10.

- **Day 2:** You bought two apples and two bananas and they cost $24.

Solution: Systems of equations 3

- **Day 1:** You bought an apple and a banana and they cost $10.

- **Day 2:** You bought two apples and two bananas and they cost $24.

Solution: Systems of equations 3

- **Day 1:** You bought an apple and a banana and they cost $10.

- **Day 2:** You bought two apples and two bananas and they cost $24.

Solution: Systems of equations 3

- **Day 1:** You bought an apple and a banana and they cost $10.

- **Day 2:** You bought two apples and two bananas and they cost $24.

Contradiction!

Solution: Systems of equations 3

- **Day 1:** You bought an apple and a banana and they cost $10.

- **Day 2:** You bought two apples and two bananas and they cost $24.

Contradiction!

No solutions!

Systems of equations

Systems of equations

System 1

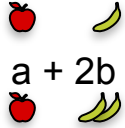
- a + b = 10

- a + 2b = 12

Systems of equations

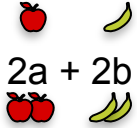
System 1

- a + b = 10
- a + 2b = 12



System 2

- a + b = 10
- 2a + 2b = 20



Systems of equations

System 1

- a + b = 10
- a + 2b = 12

System 2

- a + b = 10
- 2a + 2b = 20

System 3

- a + b = 10
- 2a + 2b = 24

Systems of equations

System 1

- a + b = 10
- a + 2b = 12

Unique solution:

System 2

- a + b = 10
- 2a + 2b = 20

System 3

- a + b = 10
- 2a + 2b = 24

Systems of equations

System 1

- a + b = 10
- a + 2b = 12

System 2

- a + b = 10
- 2a + 2b = 20

System 3

- a + b = 10
- 2a + 2b = 24

Unique solution:

a = 8

b = 2

Systems of equations

System 1

- a + b = 10
- a + 2b = 12

System 2

- a + b = 10
- 2a + 2b = 20

System 3

- a + b = 10
- 2a + 2b = 24

Unique solution:

a = 8

b = 2

Complete

Systems of equations

System 1

- a + b = 10
- a + 2b = 12

System 2

- a + b = 10
- 2a + 2b = 20

System 3

- a + b = 10
- 2a + 2b = 24

Unique solution:

a = 8

b = 2

Complete

Non-singular

Systems of equations

System 1

- a + b = 10
- a + 2b = 12

Unique solution:

a = 8

b = 2

Complete

Non-singular

System 2

- a + b = 10
- 2a + 2b = 20

Infinite solutions

System 3

- a + b = 10
- 2a + 2b = 24

Systems of equations

System 1

- a + b = 10
- a + 2b = 12

Unique solution:

a = 8

b = 2

Complete

Non-singular

System 2

- a + b = 10
- 2a + 2b = 20

Infinite solutions

a = 8

b = 2

System 3

- a + b = 10
- 2a + 2b = 24

Systems of equations

System 1

- a + b = 10
- a + 2b = 12

Unique solution:

a = 8

b = 2

Complete

Non-singular

System 2

- a + b = 10
- 2a + 2b = 20

Infinite solutions

a = 8, 7

b = 2, 3

System 3

- a + b = 10
- 2a + 2b = 24

Systems of equations

System 1

- a + b = 10
- a + 2b = 12

Unique solution:

a = 8

b = 2

System 2

- a + b = 10
- 2a + 2b = 20

Infinite solutions

a = 8 , 7 , 6

b = 2 3 4

System 3

- a + b = 10
- 2a + 2b = 24

Complete

Non-singular

Systems of equations

System 1

- a + b = 10
- a + 2b = 12

System 2

- a + b = 10
- 2a + 2b = 20

System 3

- a + b = 10
- 2a + 2b = 24

Unique solution:

a = 8
b = 2

Infinite solutions

a = 8 , 7 , 6 …
b = 2 3 4

Complete

Non-singular

Systems of equations

System 1

- a + b = 10
- a + 2b = 12

Unique solution:

a = 8

b = 2

Complete

Non-singular

System 2

- a + b = 10
- 2a + 2b = 20

Infinite solutions

a = 8 , 7 , 6 …

b = 2 3 4

Redundant

System 3

- a + b = 10
- 2a + 2b = 24

Systems of equations

System 1

- a + b = 10
- a + 2b = 12

Unique solution:

a = 8

b = 2

Complete

Non-singular

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- 2a + 2b = 20

Infinite solutions

a = 8 , 7 , 6 …

b = 2 3 4

Redundant

Singular

System 3

- a + b = 10
- 2a + 2b = 24

Systems of equations

System 1

- a + b = 10
- a + 2b = 12

Unique solution:

a = 8

b = 2

Complete

Non-singular

System 2

- a + b = 10
- 2a + 2b = 20

Infinite solutions

a = 8, 7, 6, …

b = 2, 3, 4

Redundant

Singular

System 3

- a + b = 10
- 2a + 2b = 24

No solution

Systems of equations

System 1

- a + b = 10
- a + 2b = 12

Unique solution:

a = 8

b = 2

Complete

Non-singular

System 2

- a + b = 10
- 2a + 2b = 20

Infinite solutions

a = 8, 7, 6, …

b = 2, 3, 4

Redundant

Singular

System 3

- a + b = 10
- 2a + 2b = 24

No solution

Contradictory

Systems of equations

System 1

- a + b = 10
- a + 2b = 12

Unique solution:

a = 8

b = 2

Complete

Non-singular

System 2

- a + b = 10
- 2a + 2b = 20

Infinite solutions

a = 8 , 7 , 6 …

b = 2 3 4

Redundant

Singular

System 3

- a + b = 10
- 2a + 2b = 24

No solution

Contradictory

Singular

What is a linear equation?

Linear

Non-linear

What is a linear equation?

Linear

$a + b = 10$

Non-linear

What is a linear equation?

Linear

$a + b = 10$

$2a + 3b = 15$

Non-linear

What is a linear equation?

Linear

$a + b = 10$

$2a + 3b = 15$

$3.4a - 48.99b + 2c = 122.5$

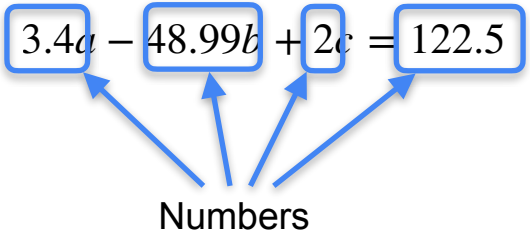
Non-linear

What is a linear equation?

Linear

$a + b = 10$

$2a + 3b = 15$



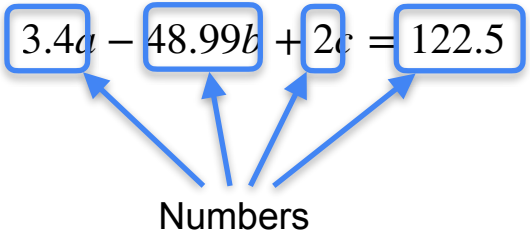
Non-linear

What is a linear equation?

Linear

$a + b = 10$

$2a + 3b = 15$



Non-linear

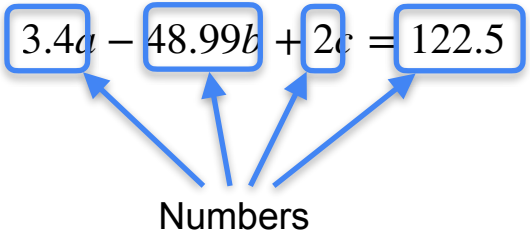
$a^2 + b^2 = 10$

What is a linear equation?

Linear

$a + b = 10$

$2a + 3b = 15$



Non-linear

$a^2 + b^2 = 10$

$\sin(a) + b^5 = 15$

What is a linear equation?

Linear

$a + b = 10$

$2a + 3b = 15$

$3.4a - 48.99b + 2c = 122.5$

Numbers

Non-linear

$a^2 + b^2 = 10$

$\sin(a) + b^5 = 15$

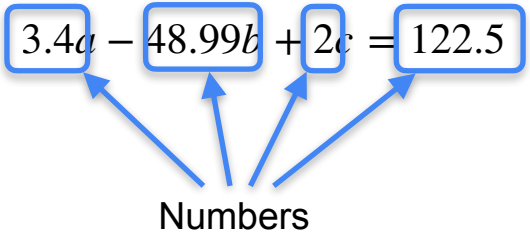
$2^a - 3^b = 0$

What is a linear equation?

Linear

$a + b = 10$

$2a + 3b = 15$



Non-linear

$a^2 + b^2 = 10$

$\sin(a) + b^5 = 15$

$2^a - 3^b = 0$

$ab^2 + \frac{b}{a} - \frac{3}{b} - \log(c) = 4^a$

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System of Linear Equations

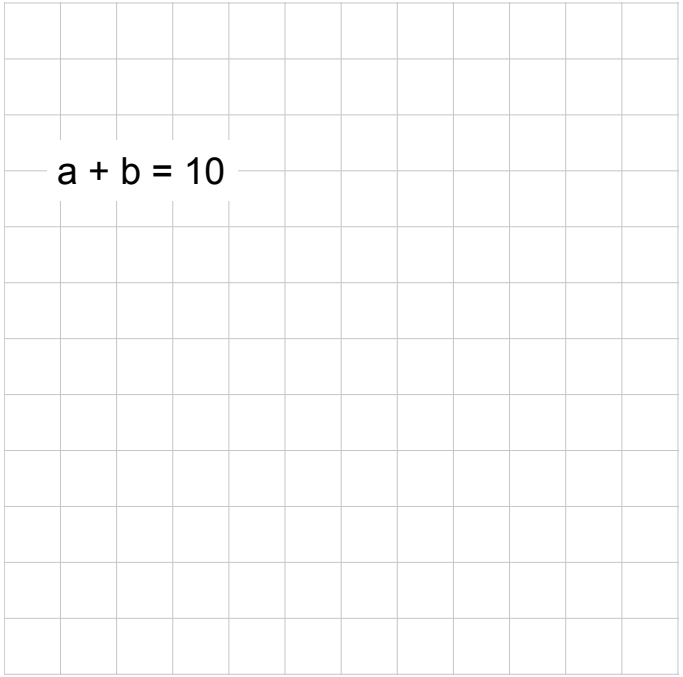
System of equations as lines

Linear equation → line

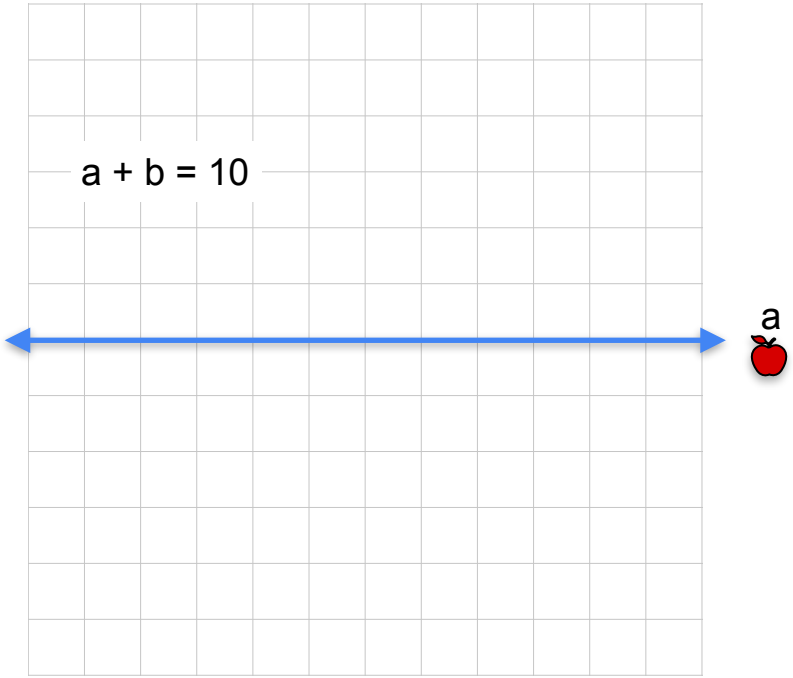
Linear equation → line

$a + b = 10$

Linear equation → line



Linear equation → line



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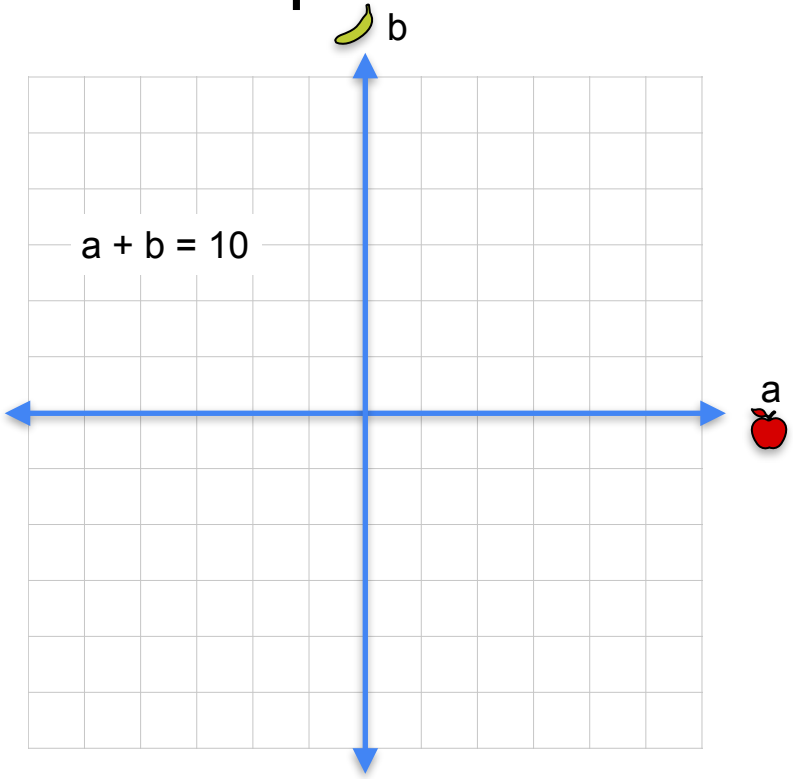

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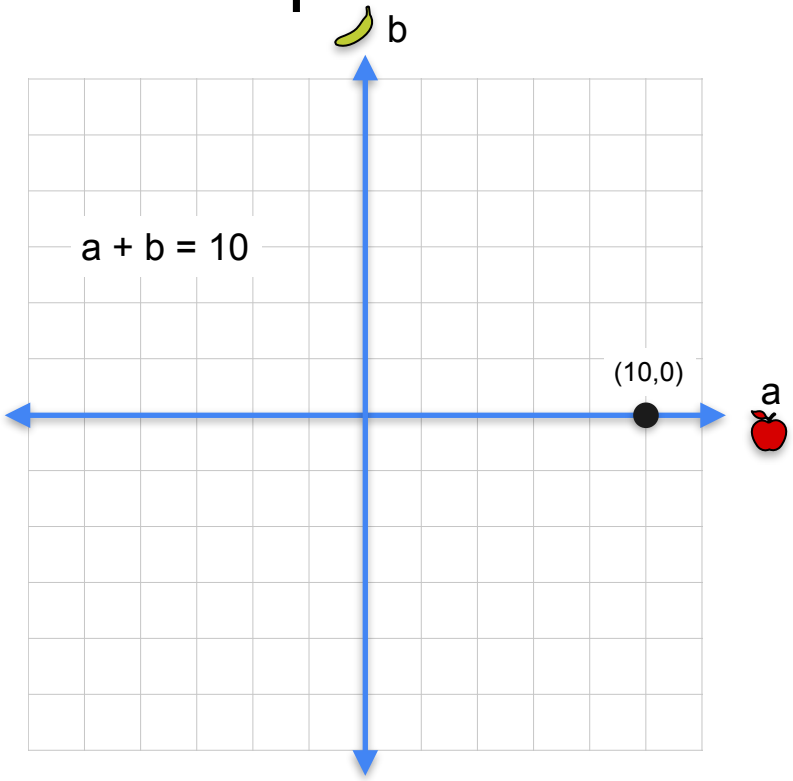

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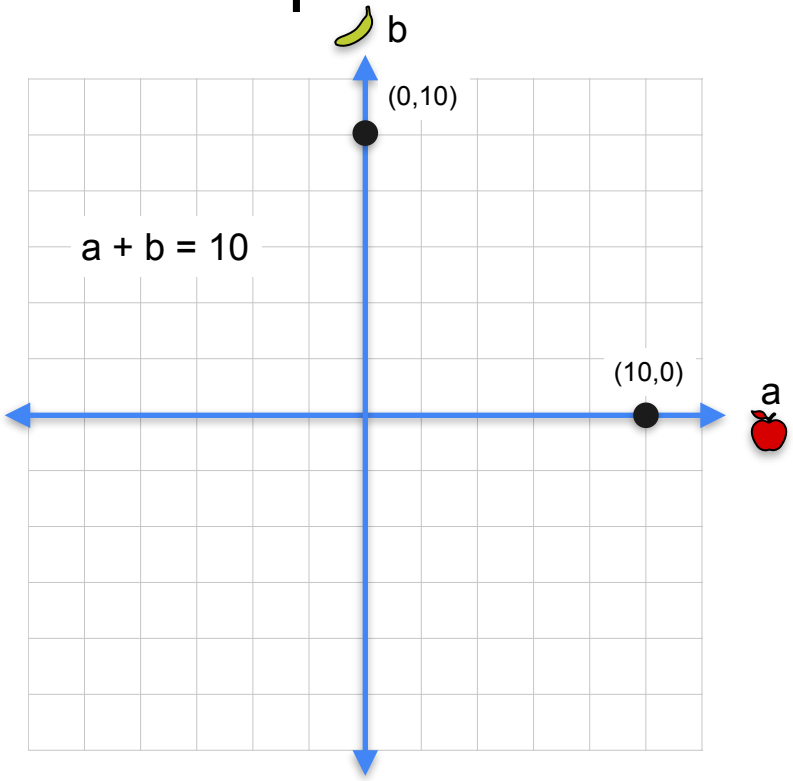

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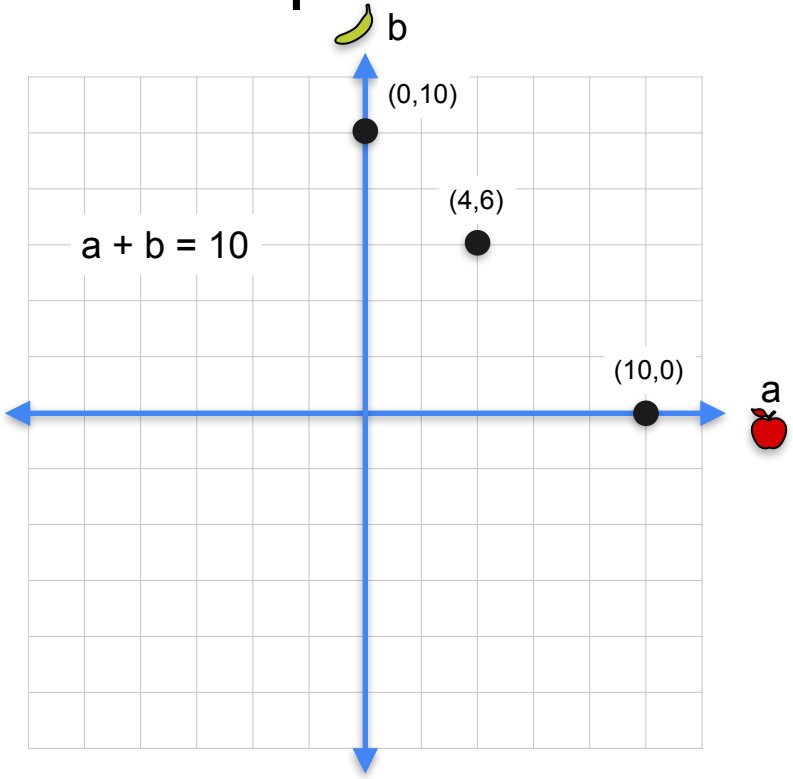

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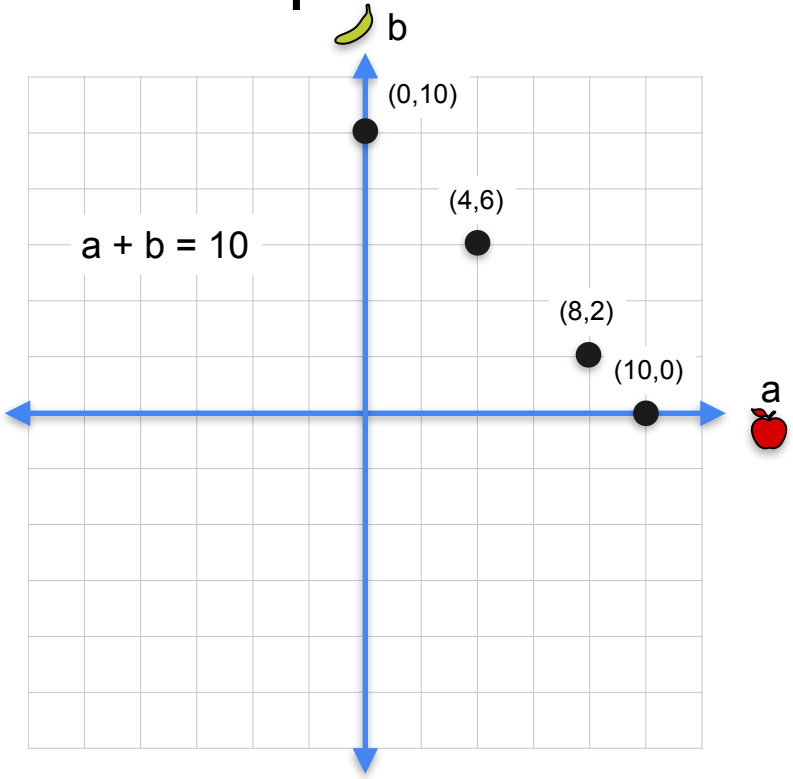
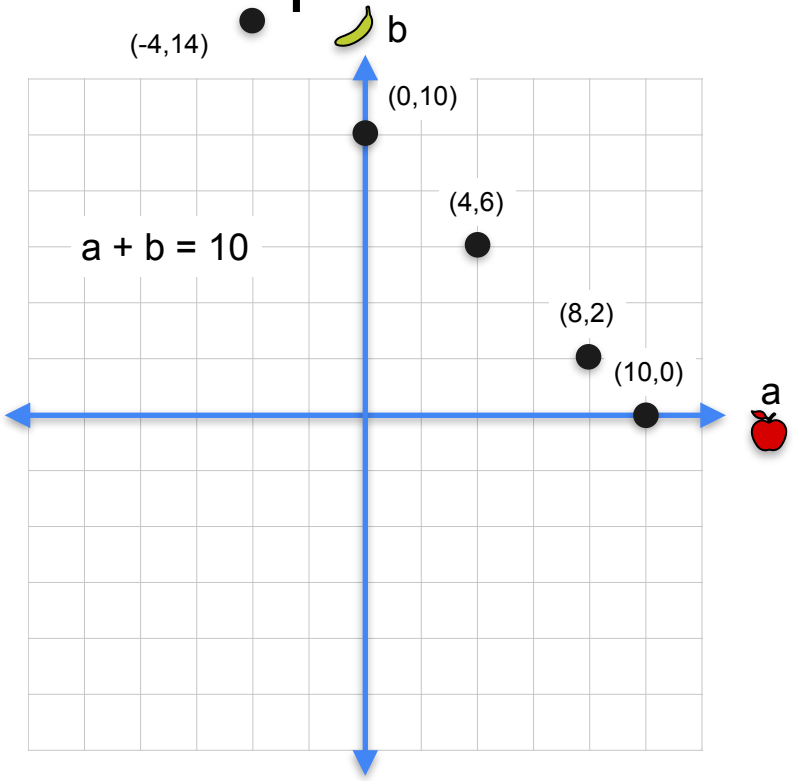
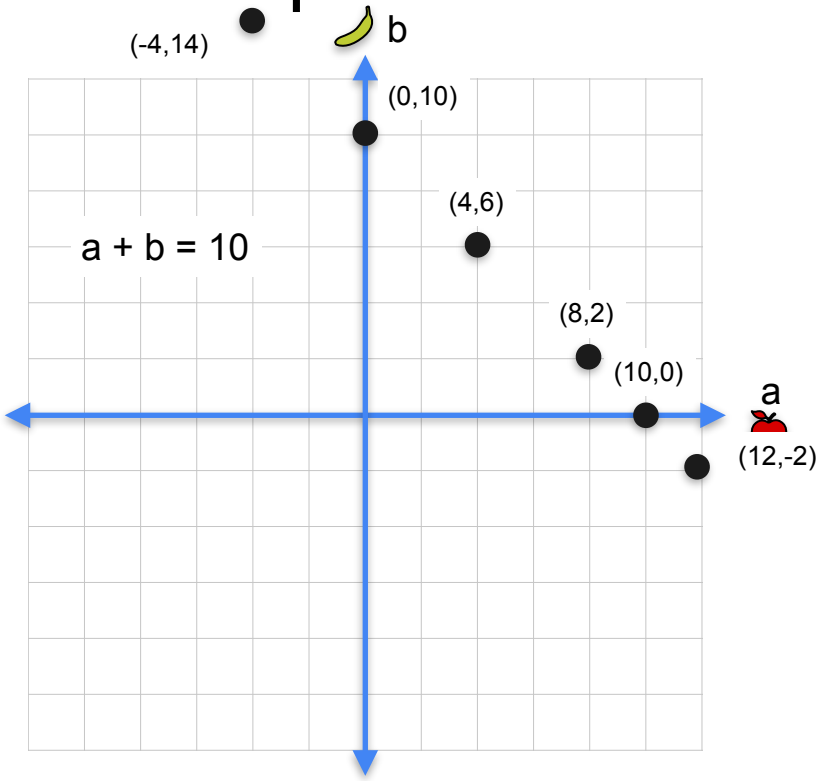


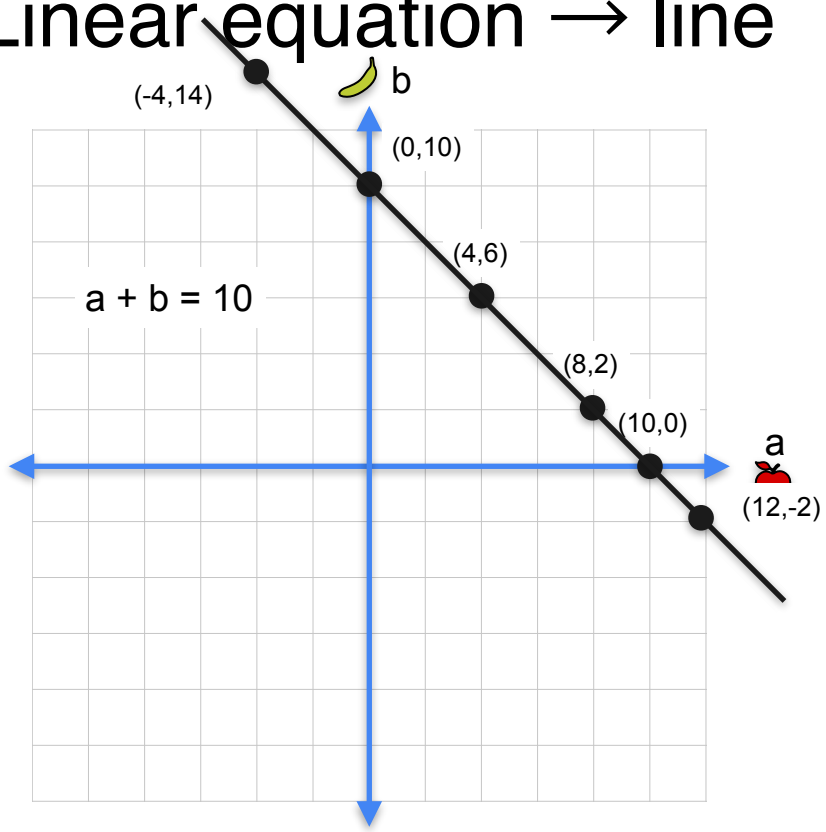
Linear equation → line



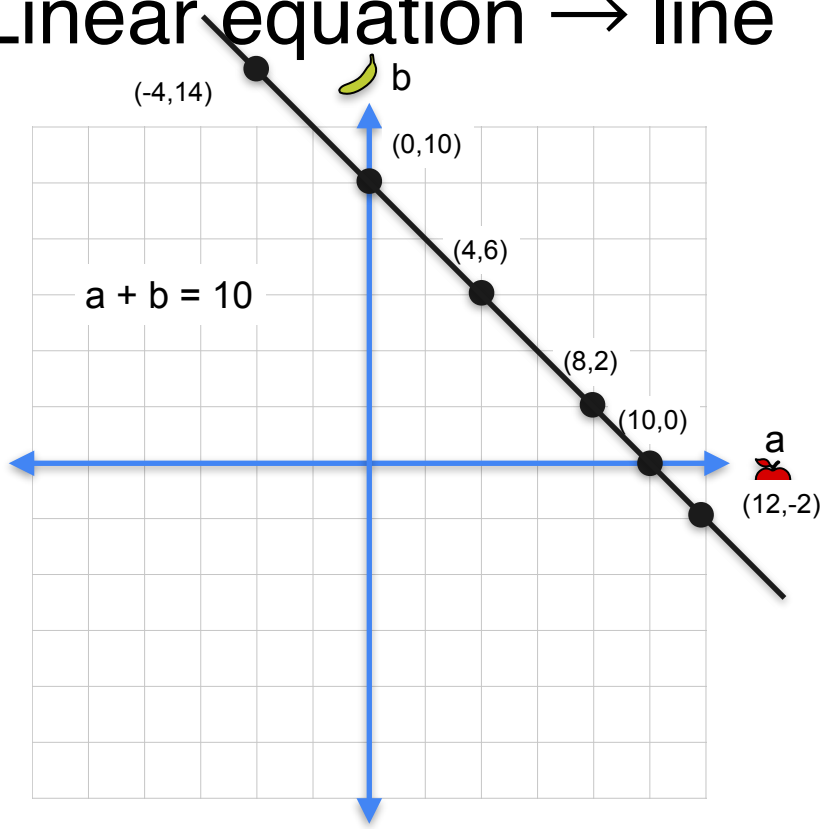
Linear equation → line

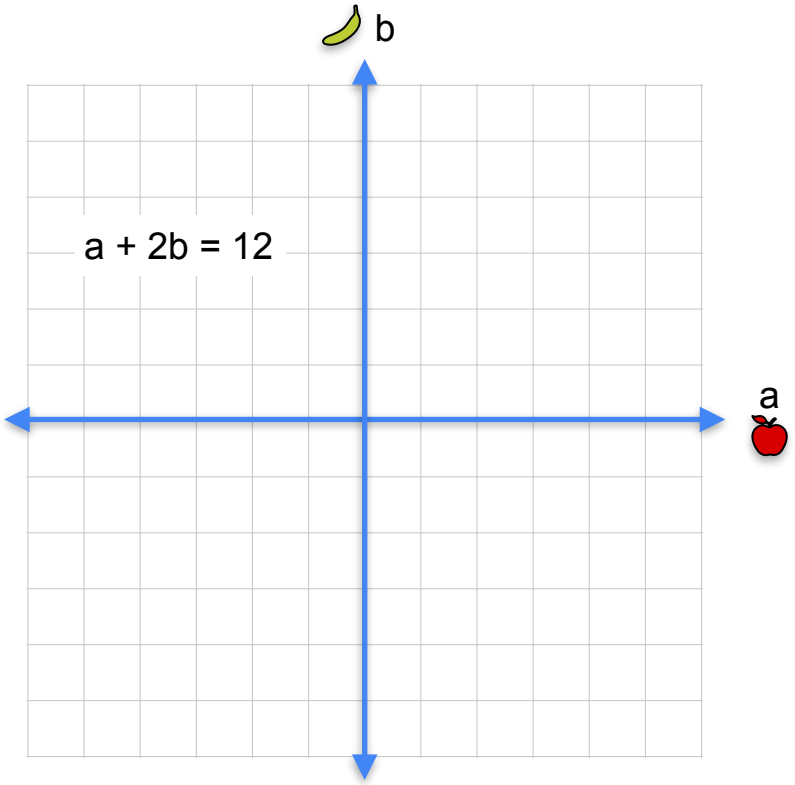


Linear equation → line

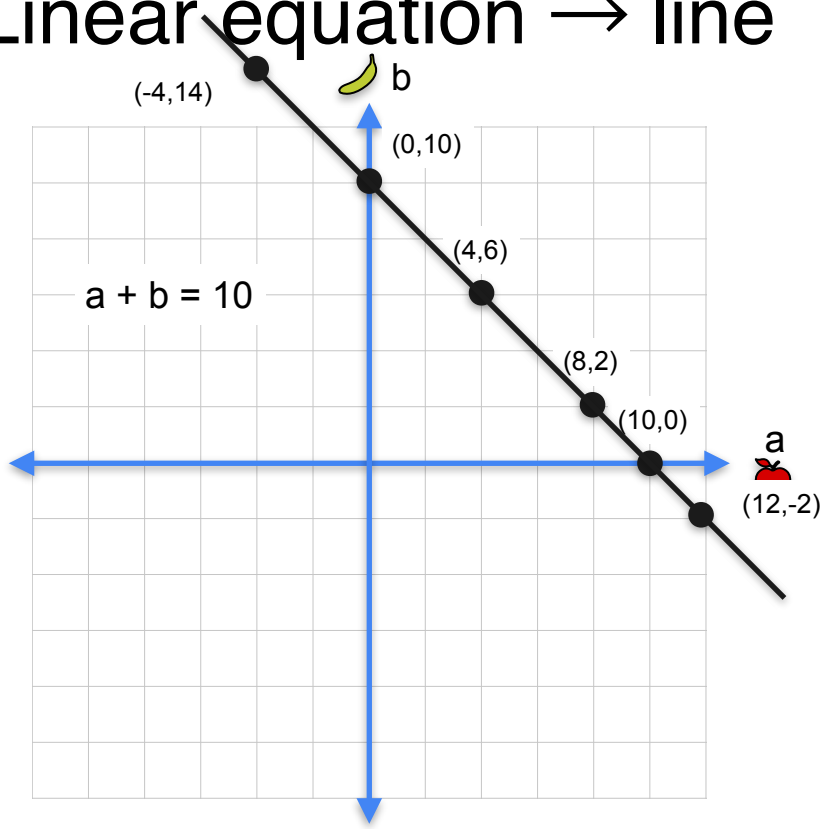


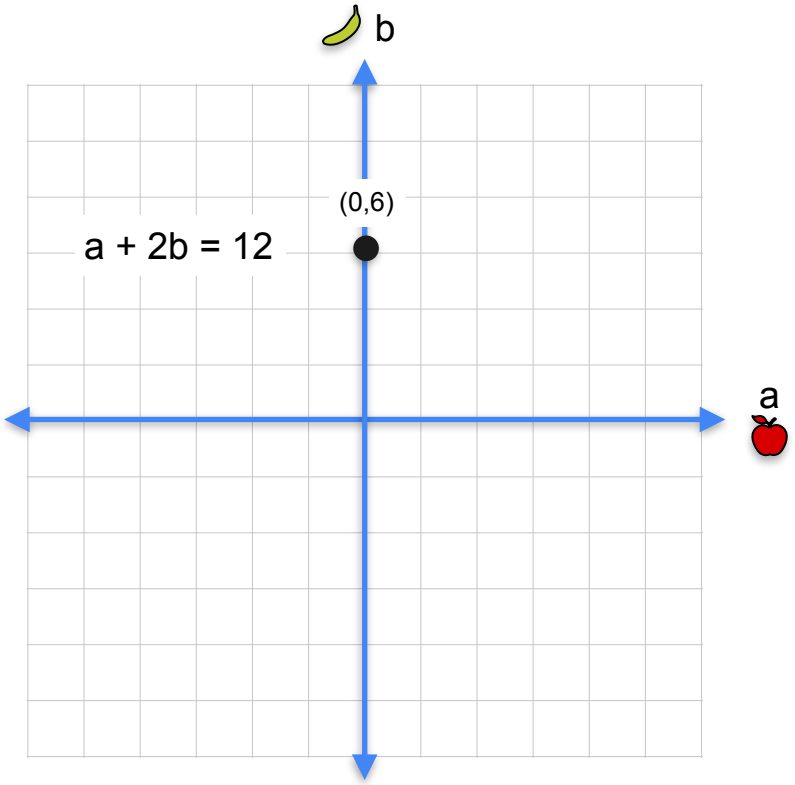
Linear equation → line



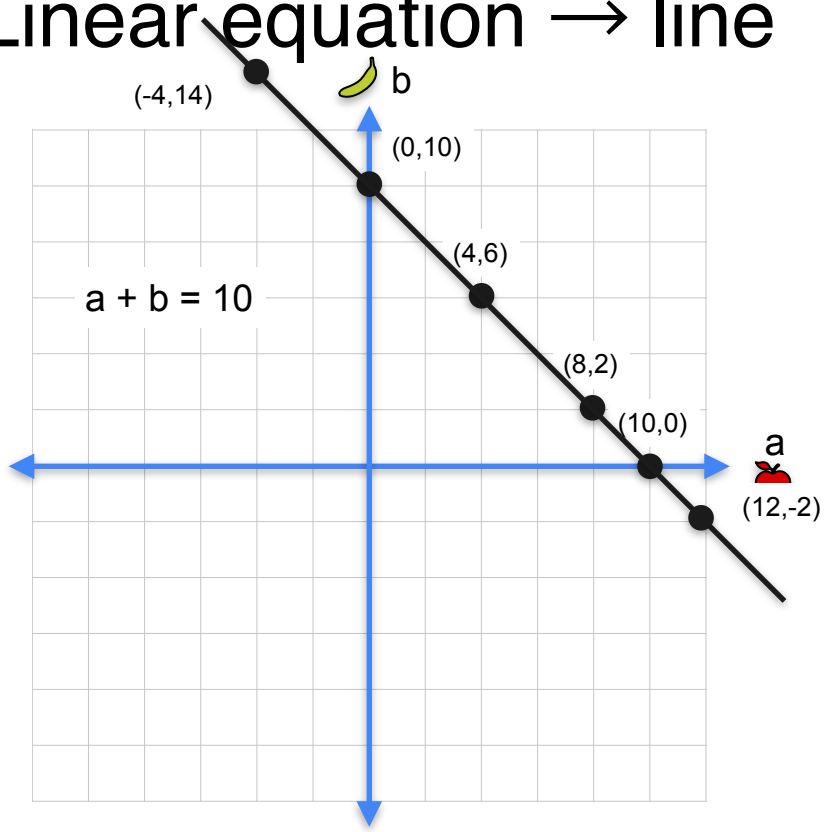


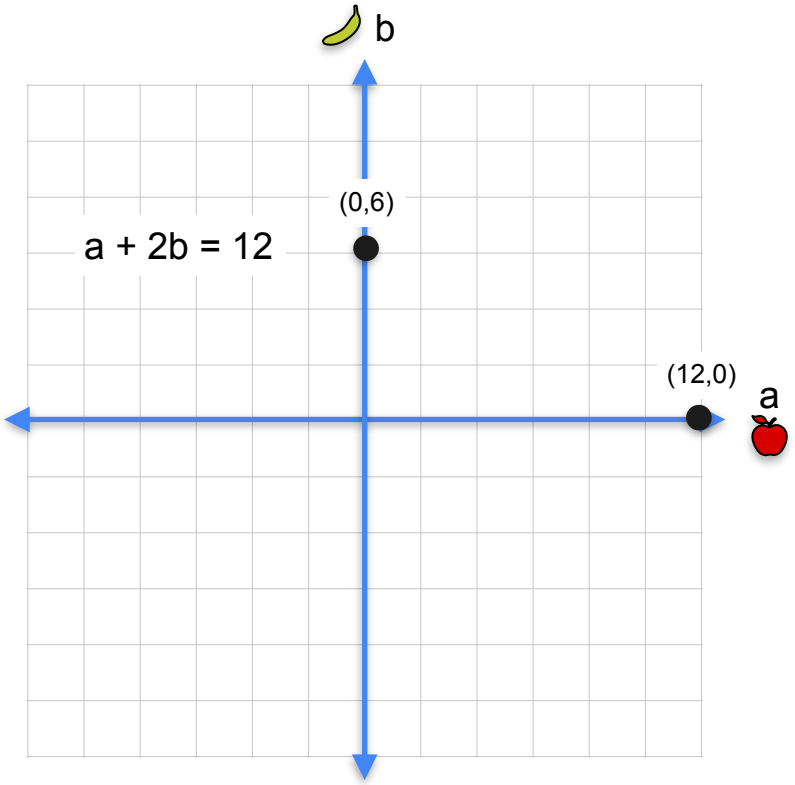
Linear equation → line



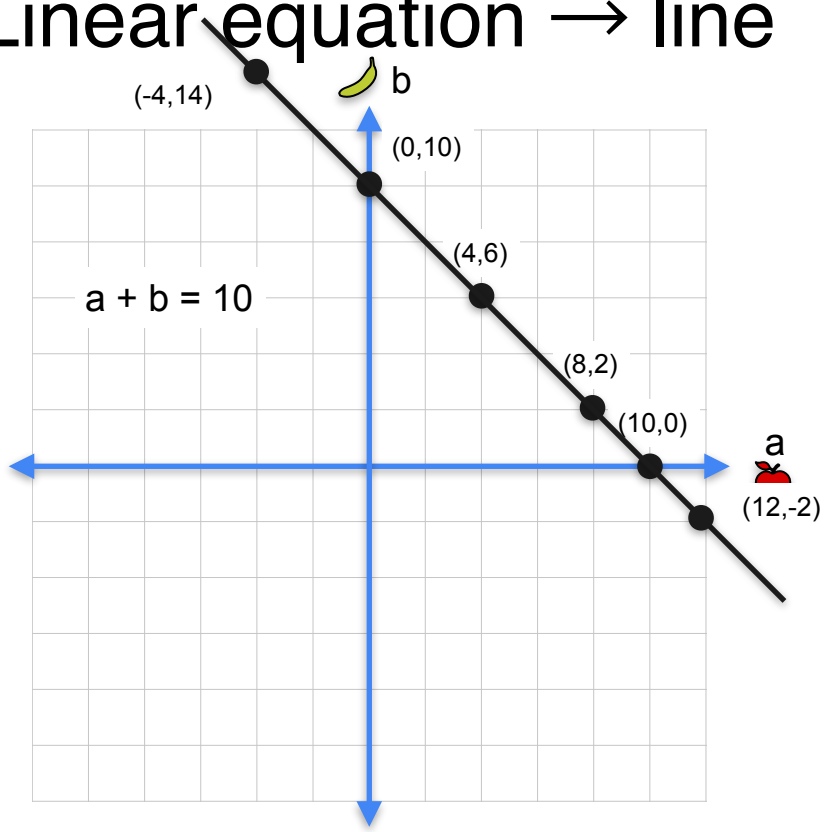


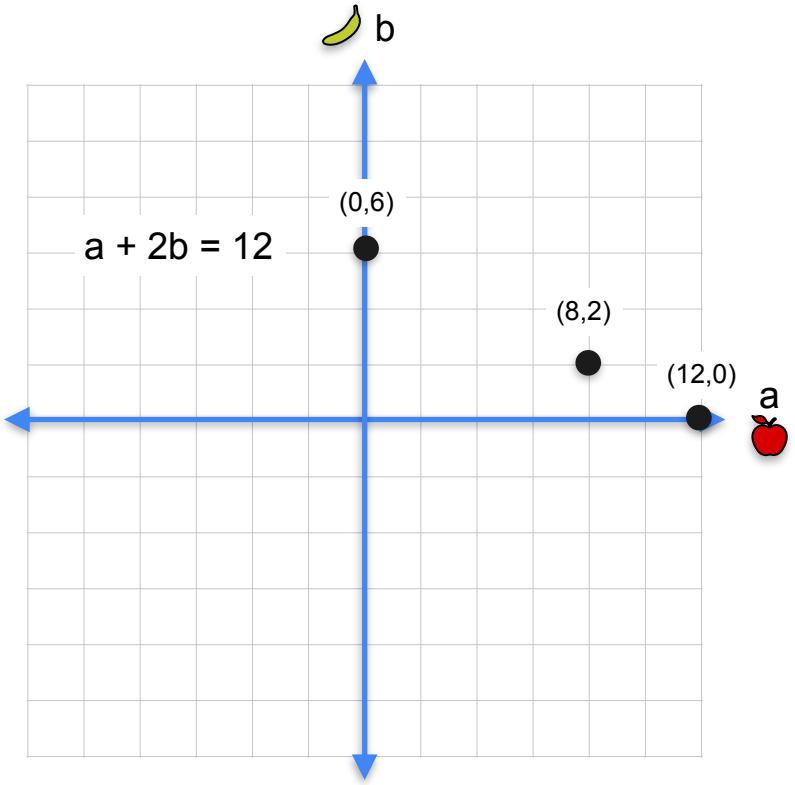
Linear equation → line



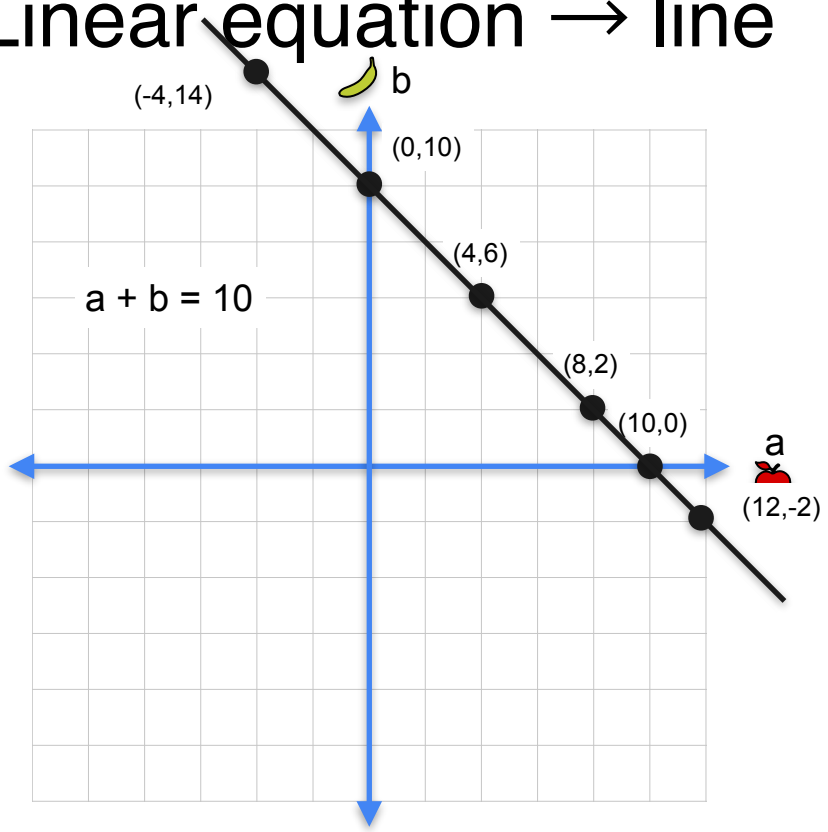


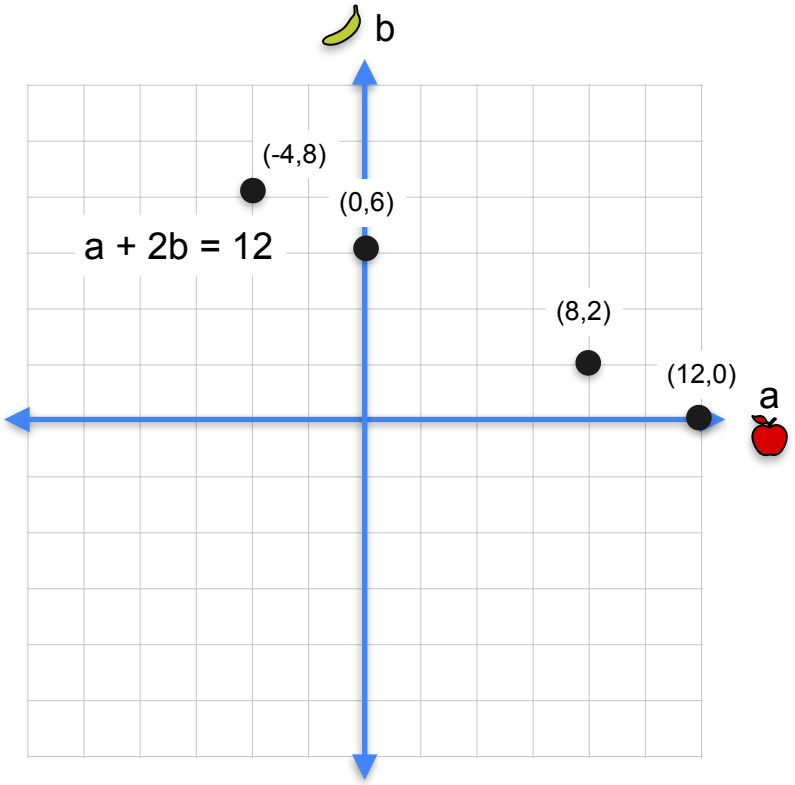
Linear equation → line



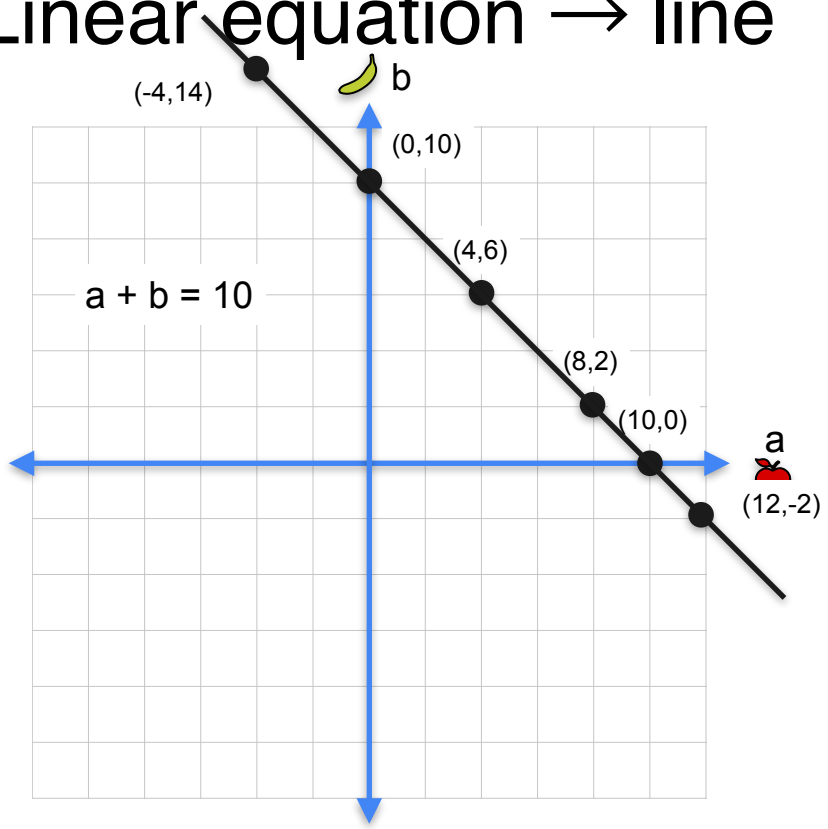


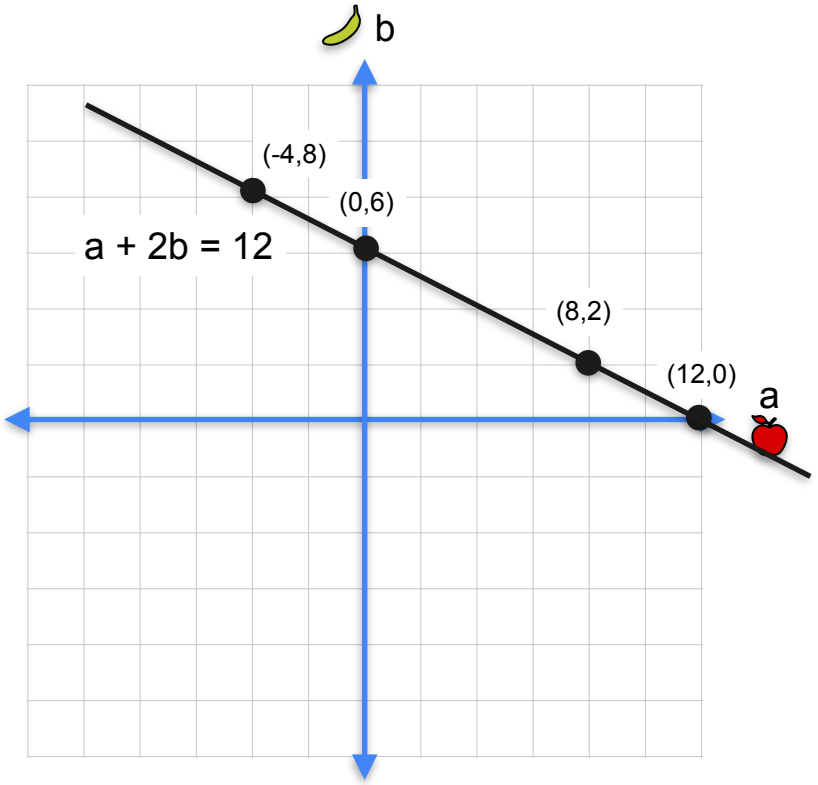
Linear equation → line





Linear equation → line





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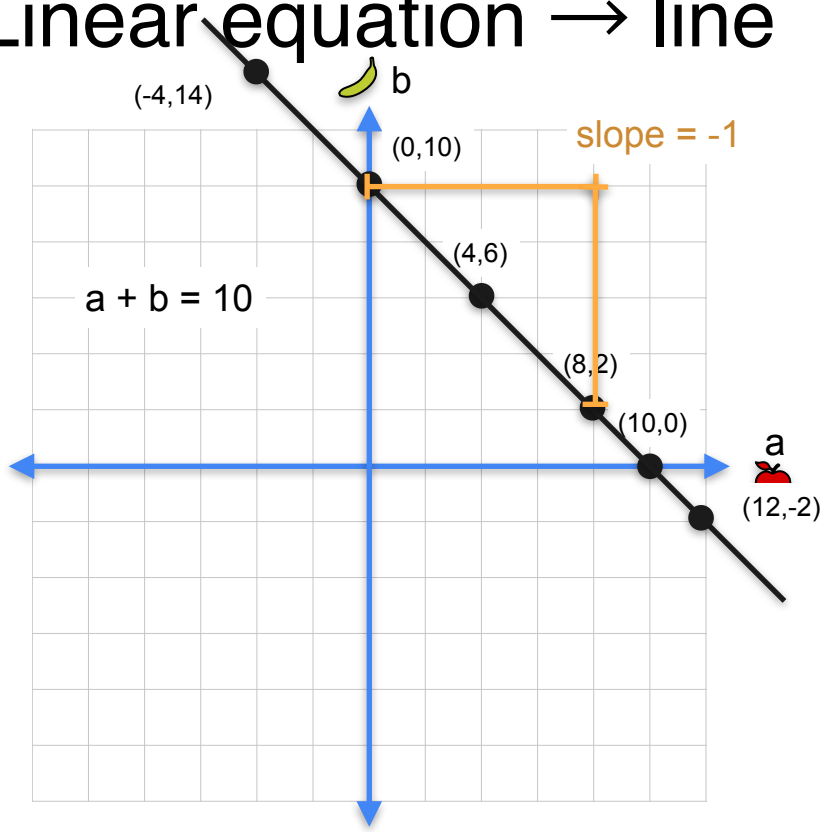

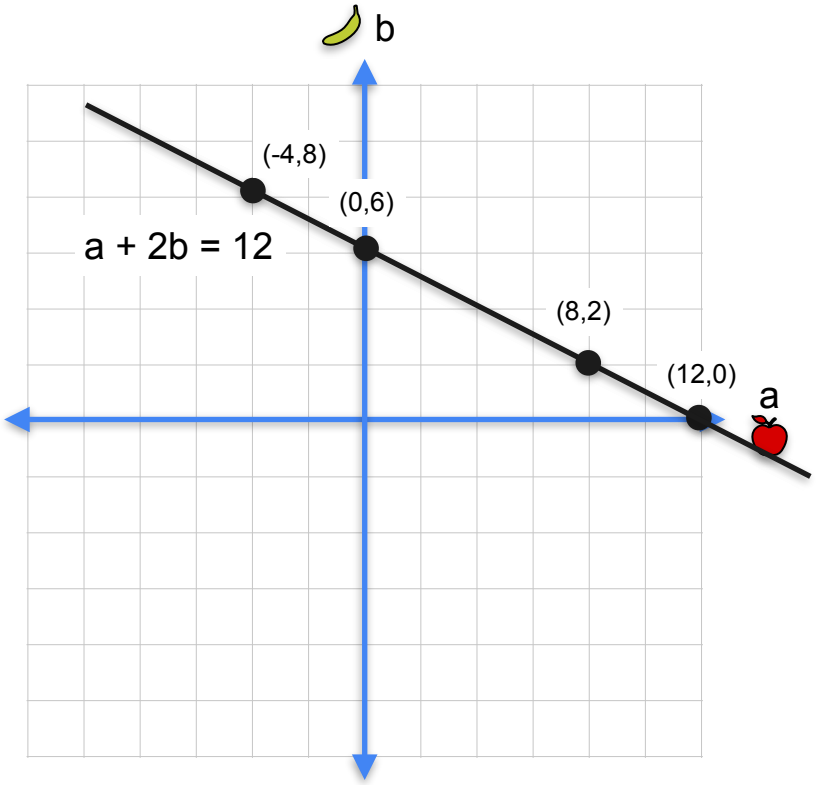

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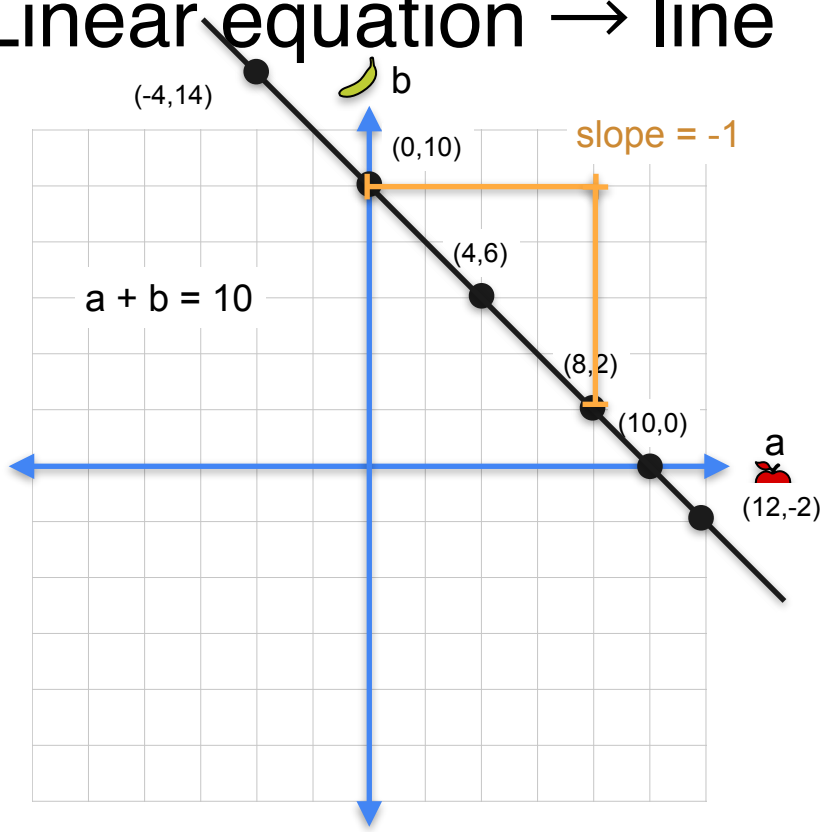
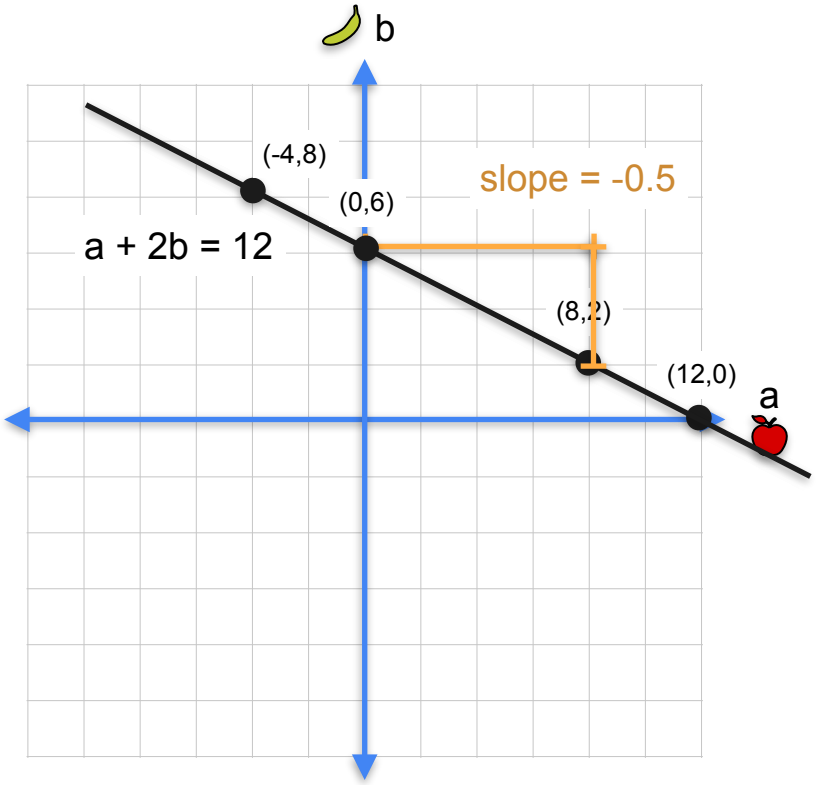
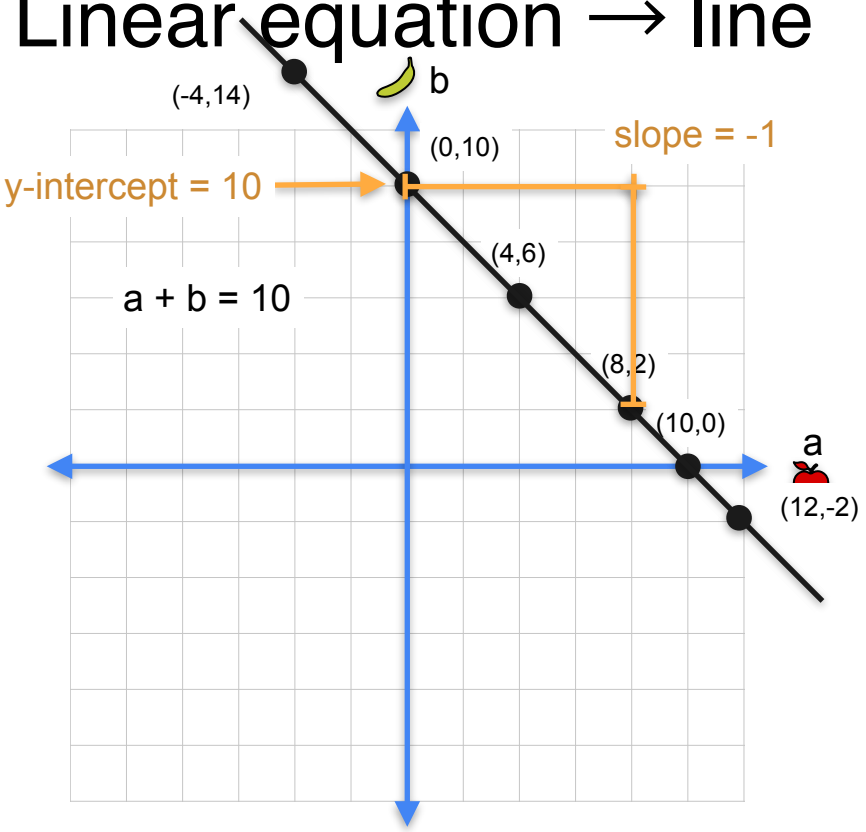
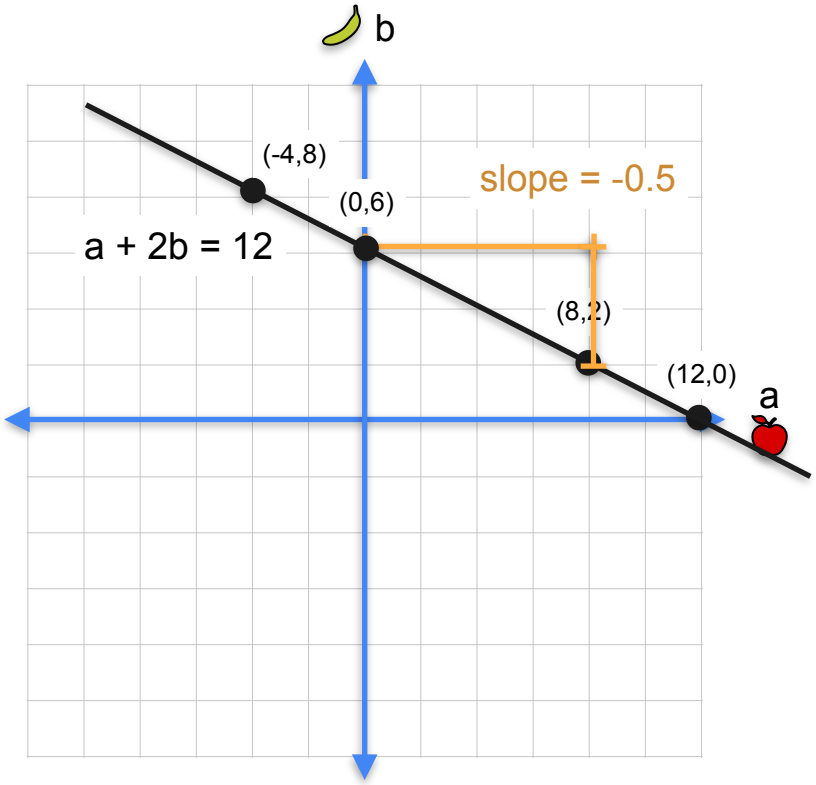


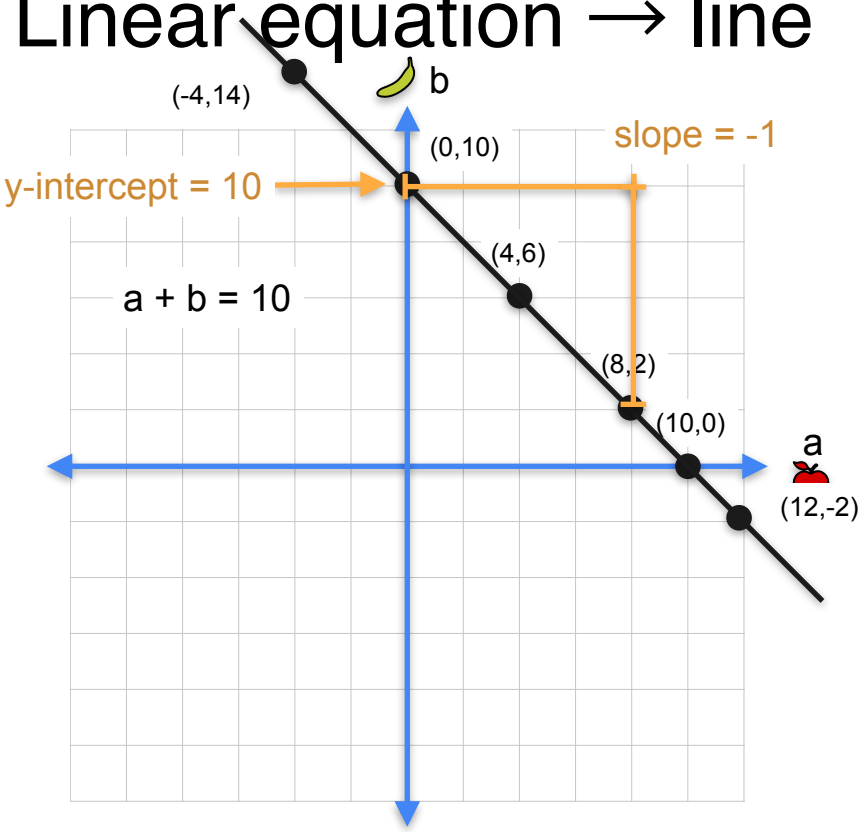


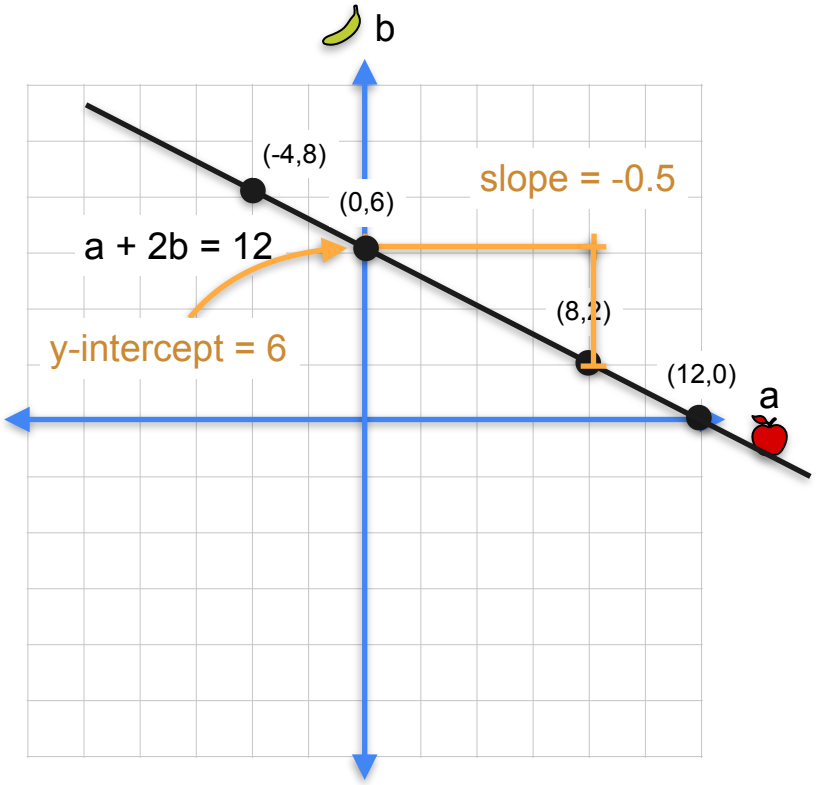
Linear equation → line



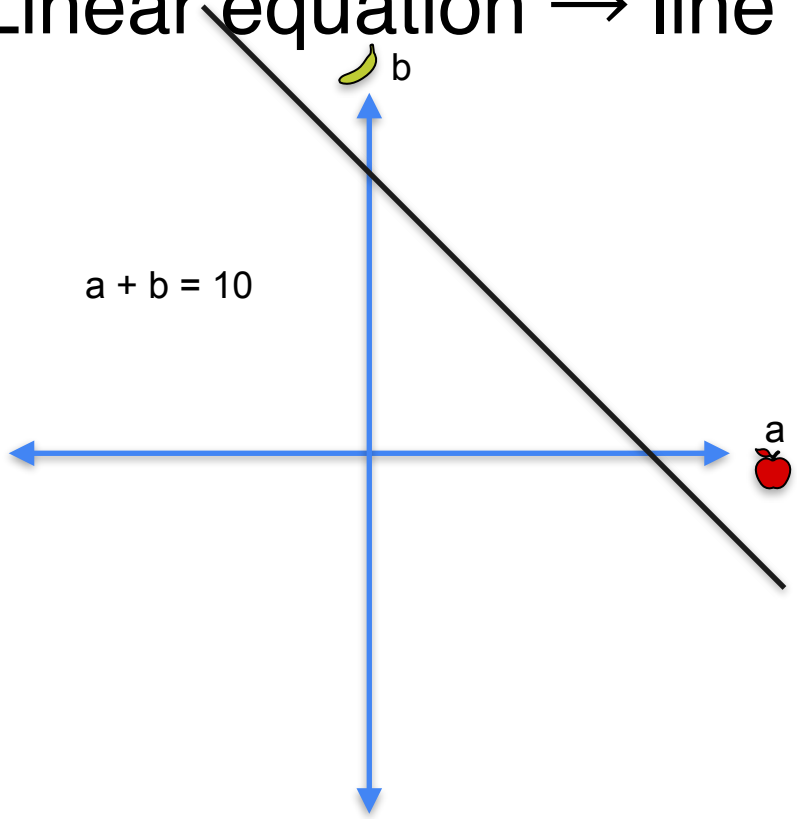


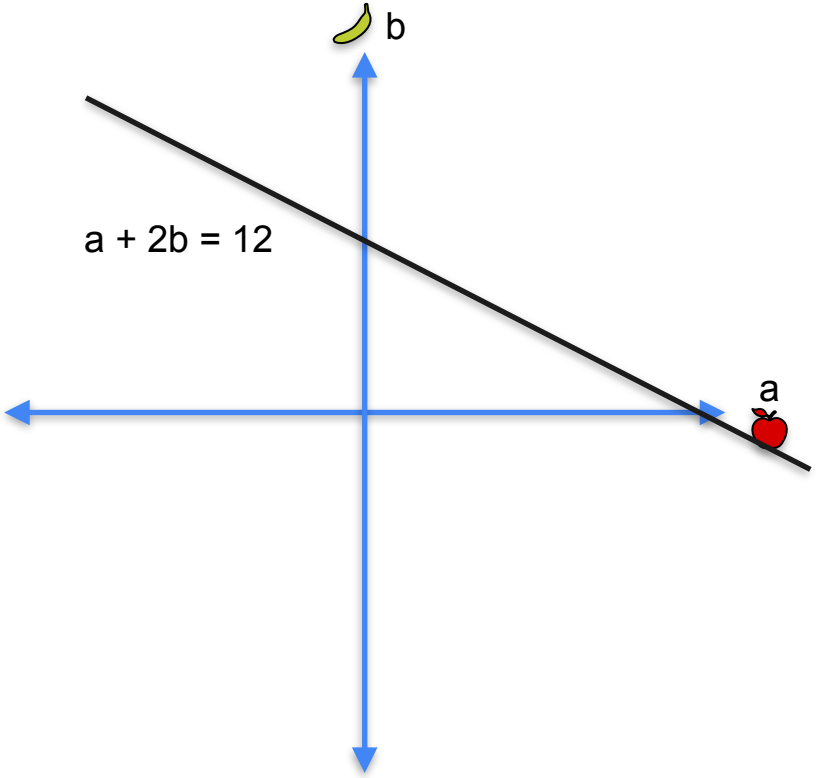
Linear equation → line



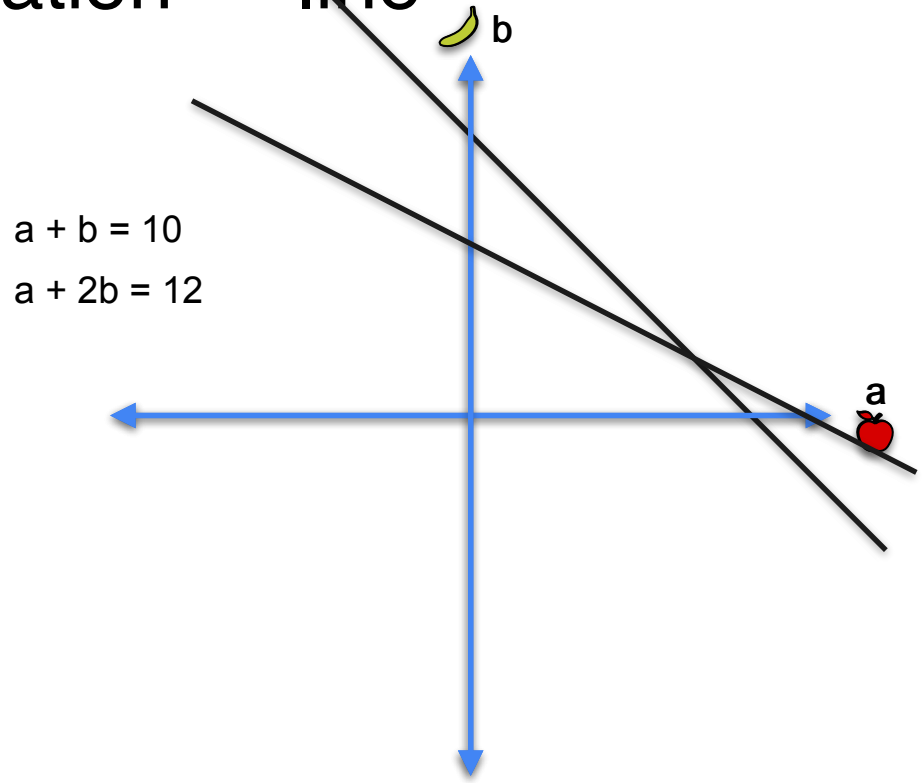


Linear equation → line

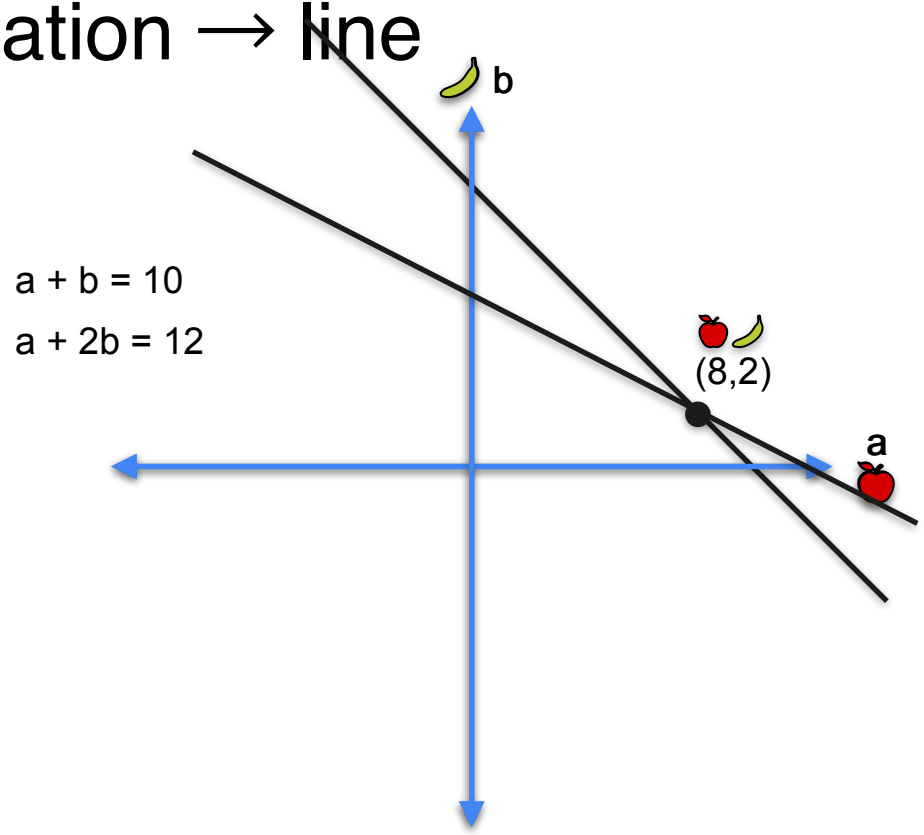




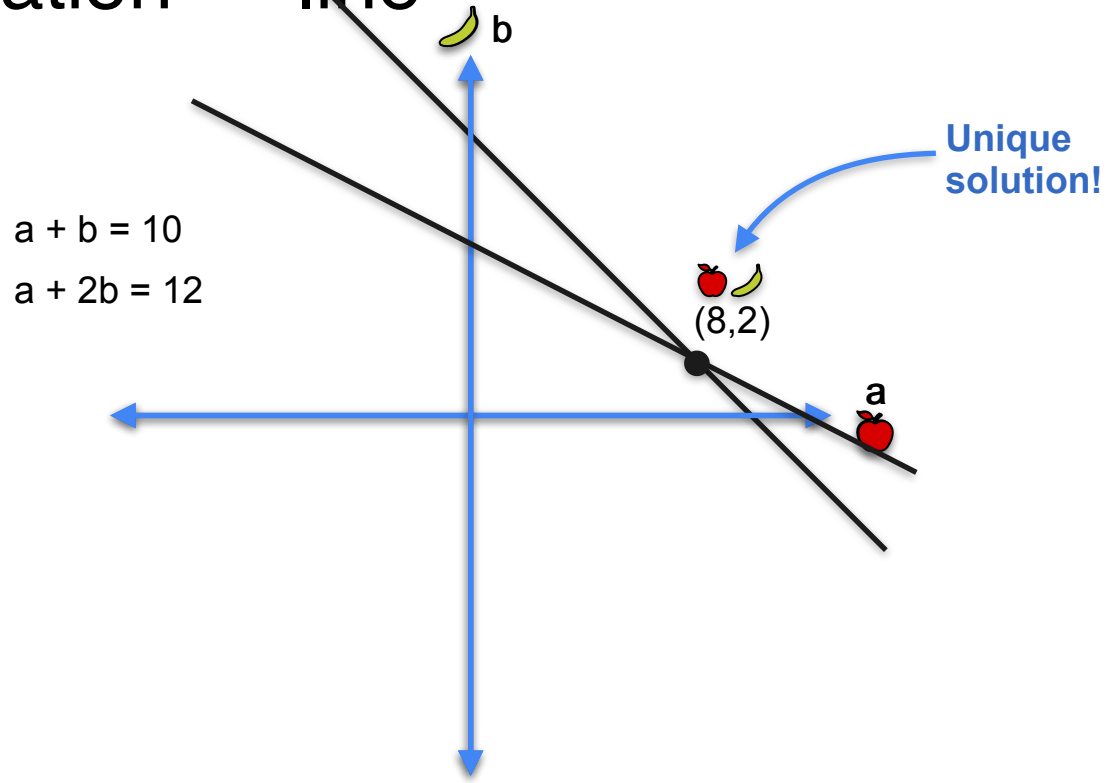
Linear equation → line



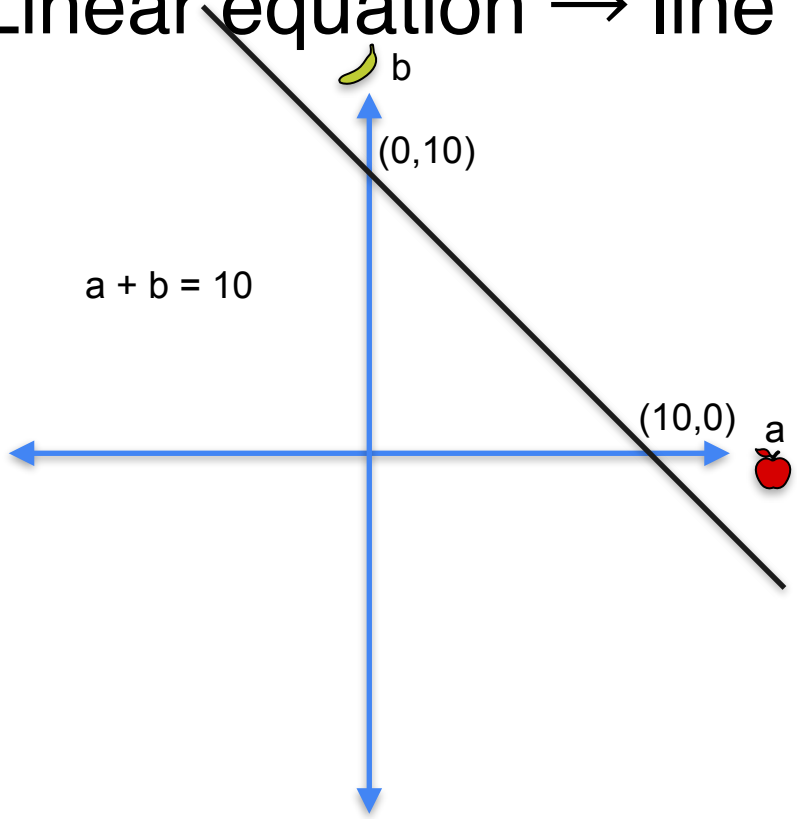
Linear equation → line

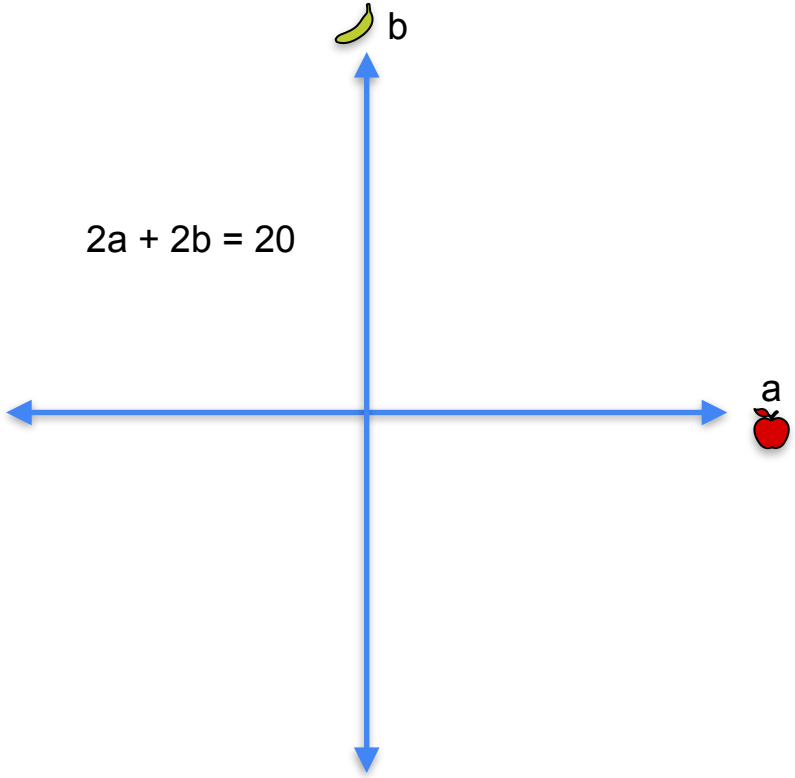


Linear equation → line

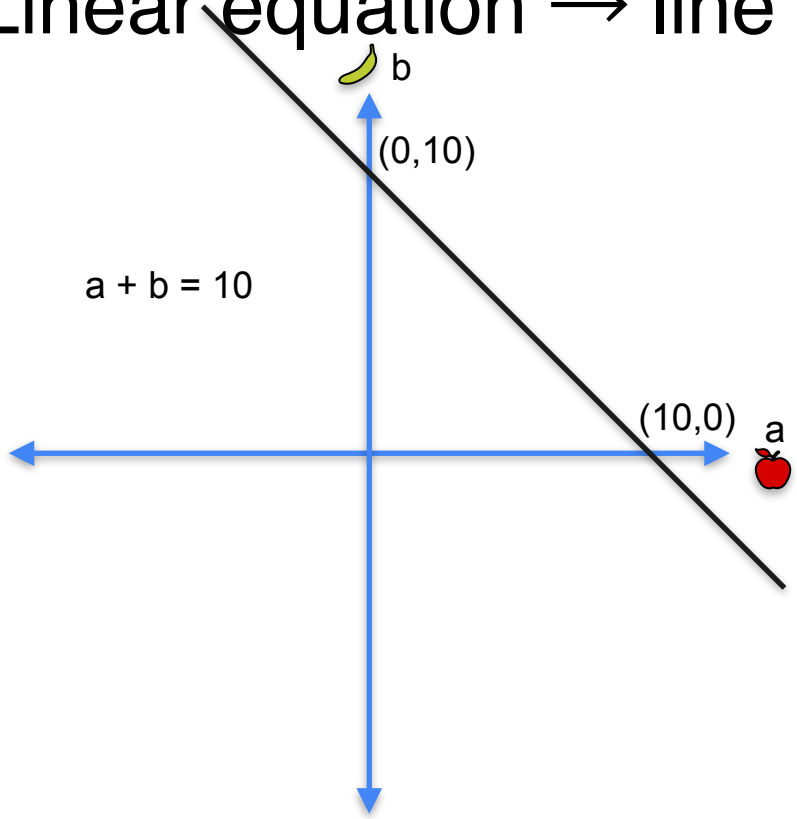


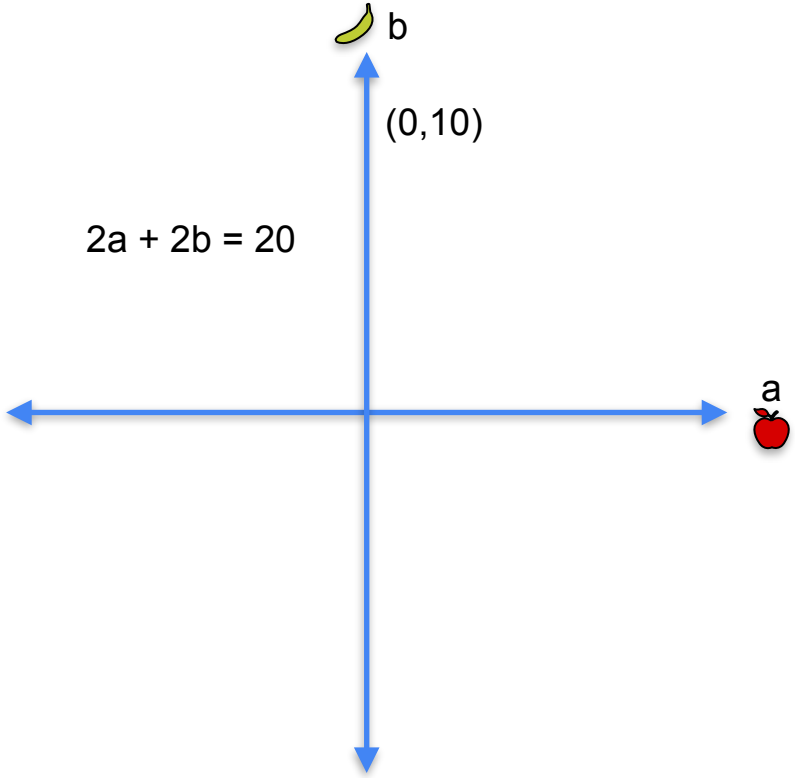
Linear equation → line



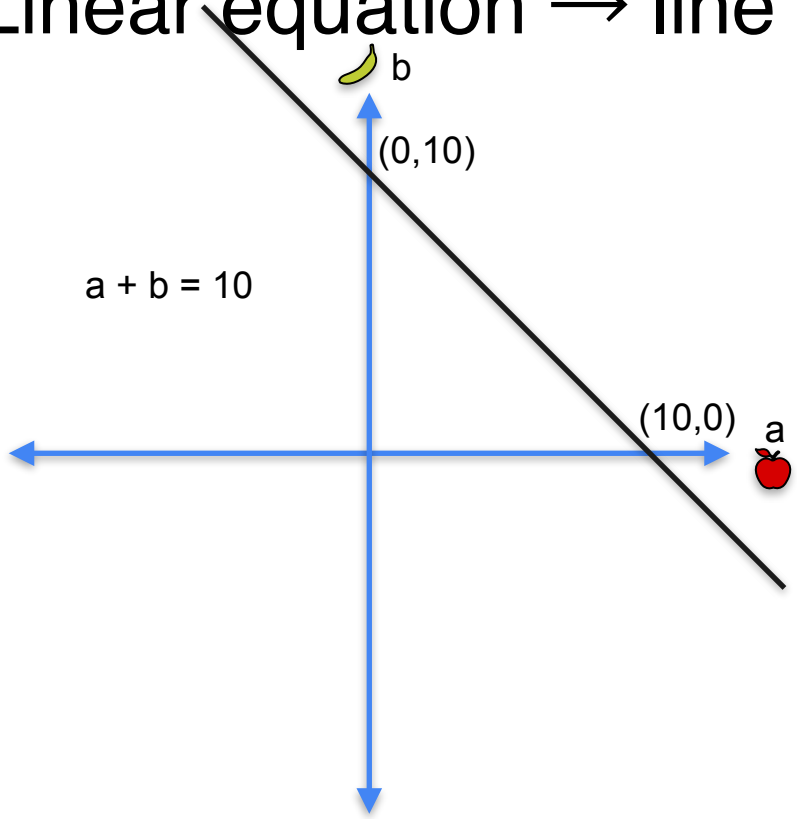


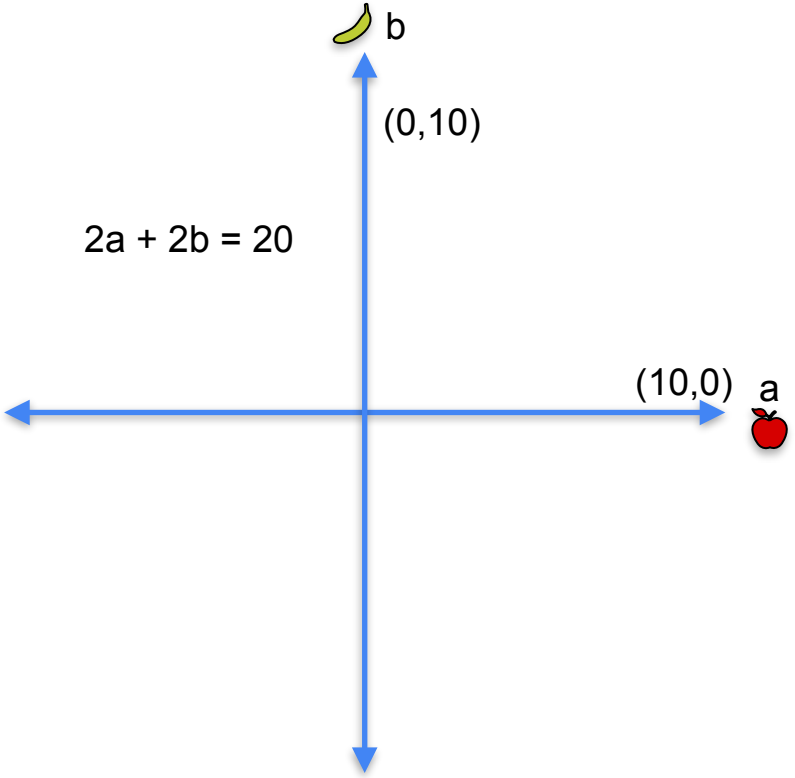
Linear equation → line



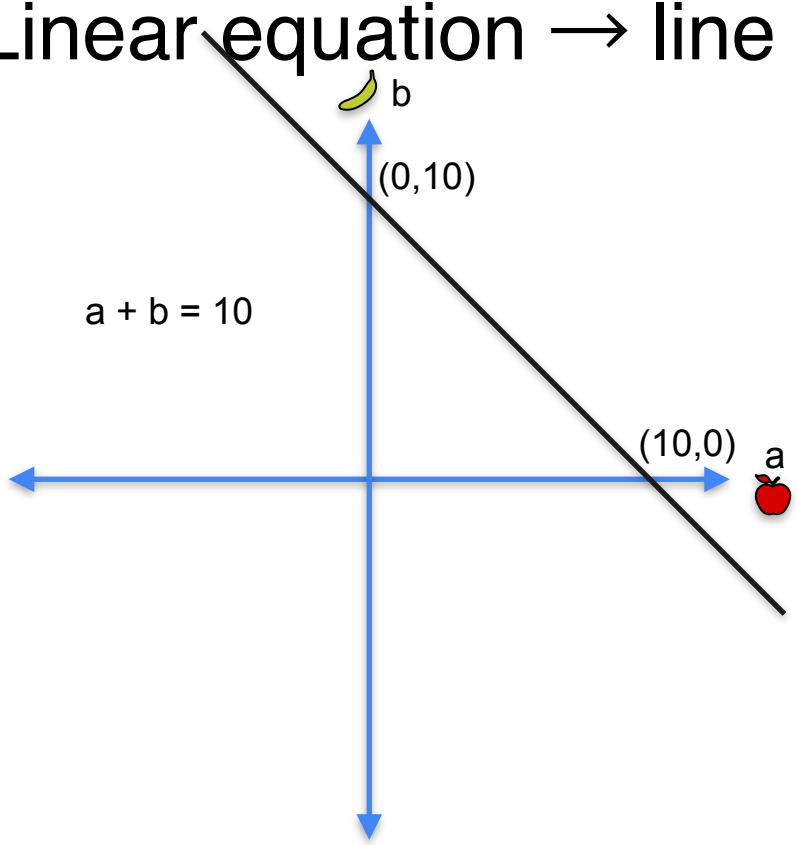


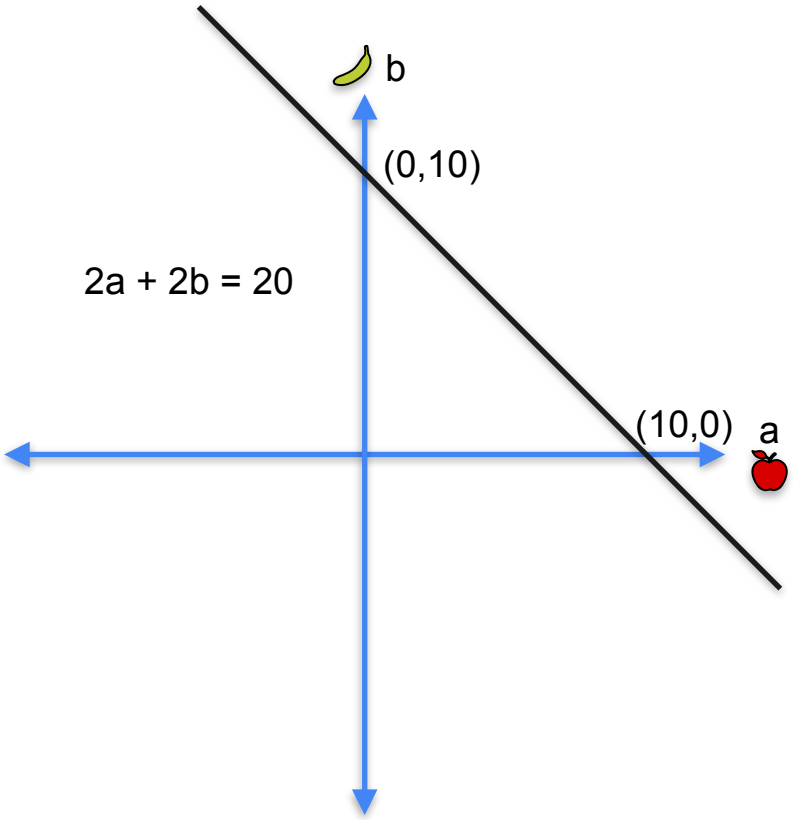
Linear equation → line



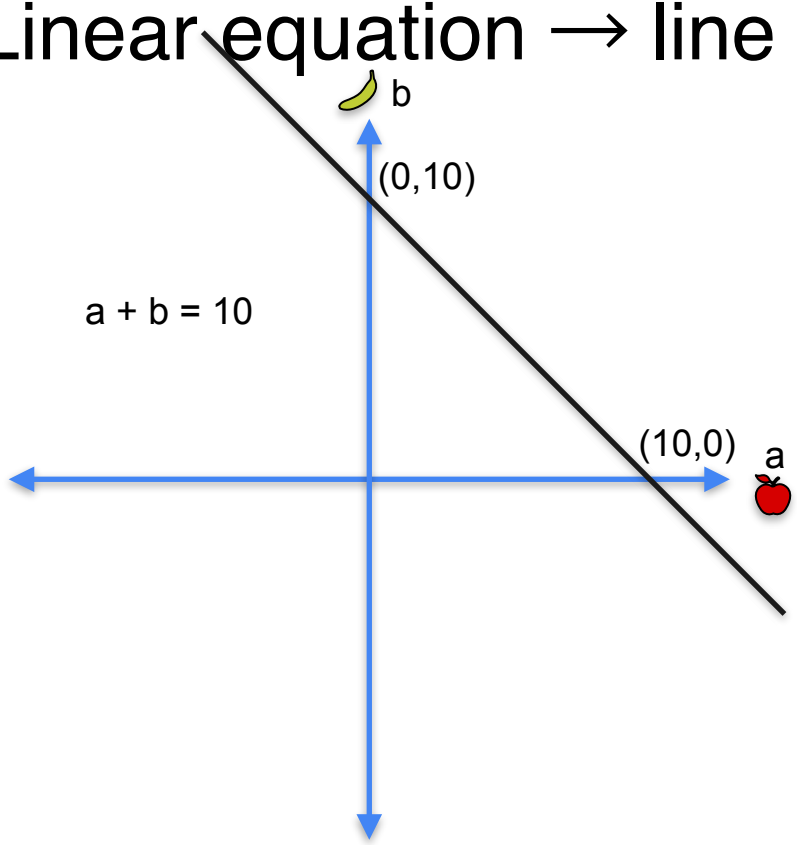


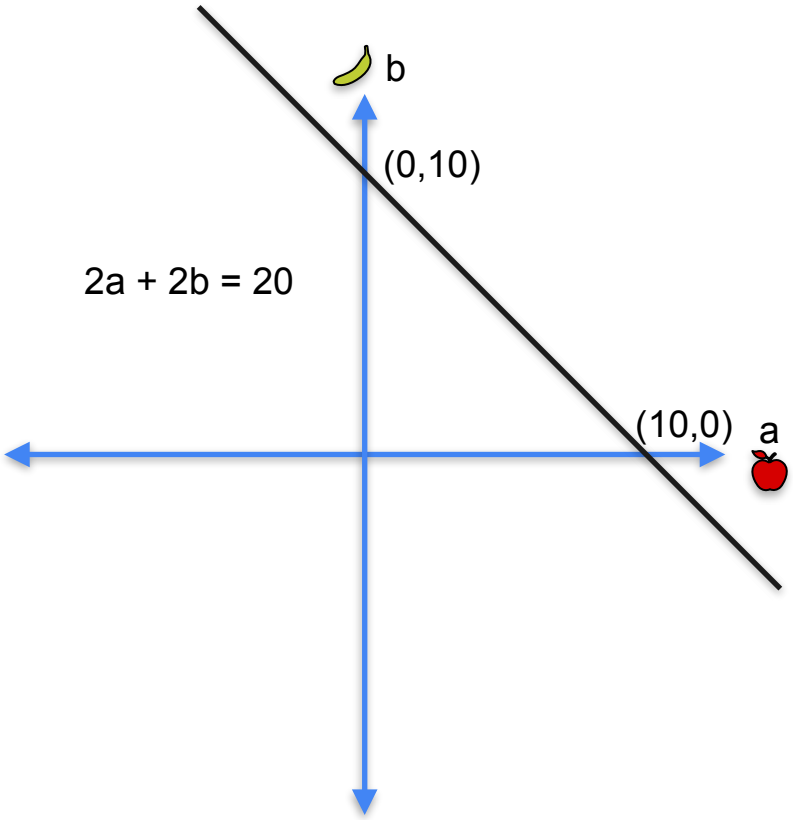
Linear equation → line



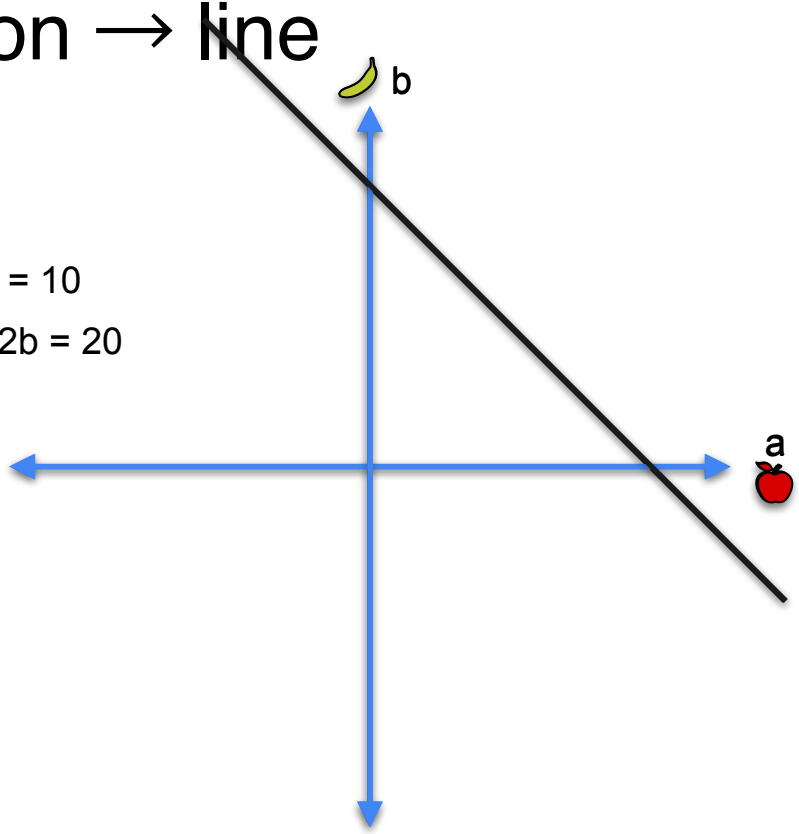


Linear equation → line





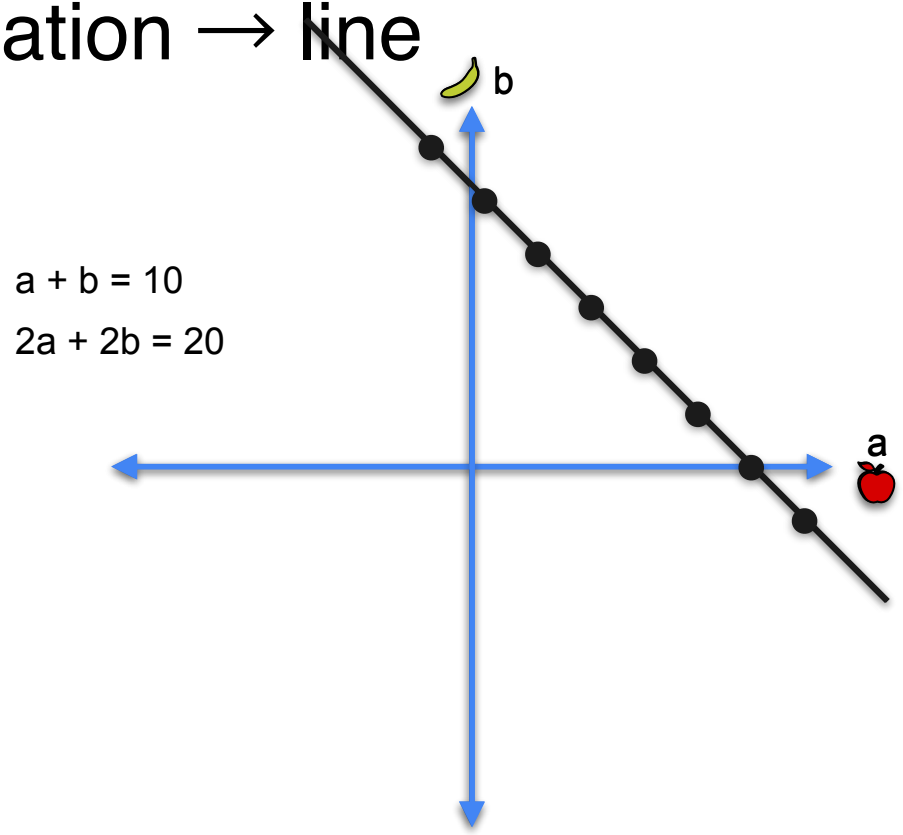
Linear equation → line



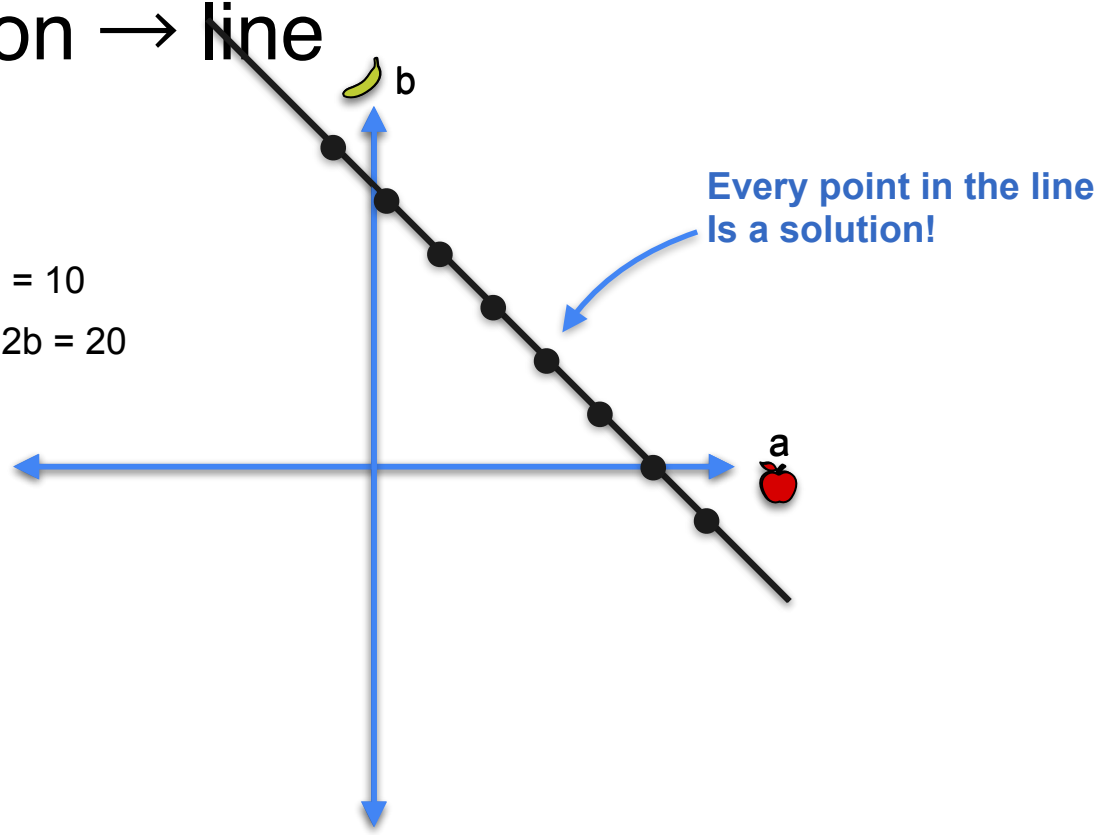
$a + b = 10$

$2a + 2b = 20$

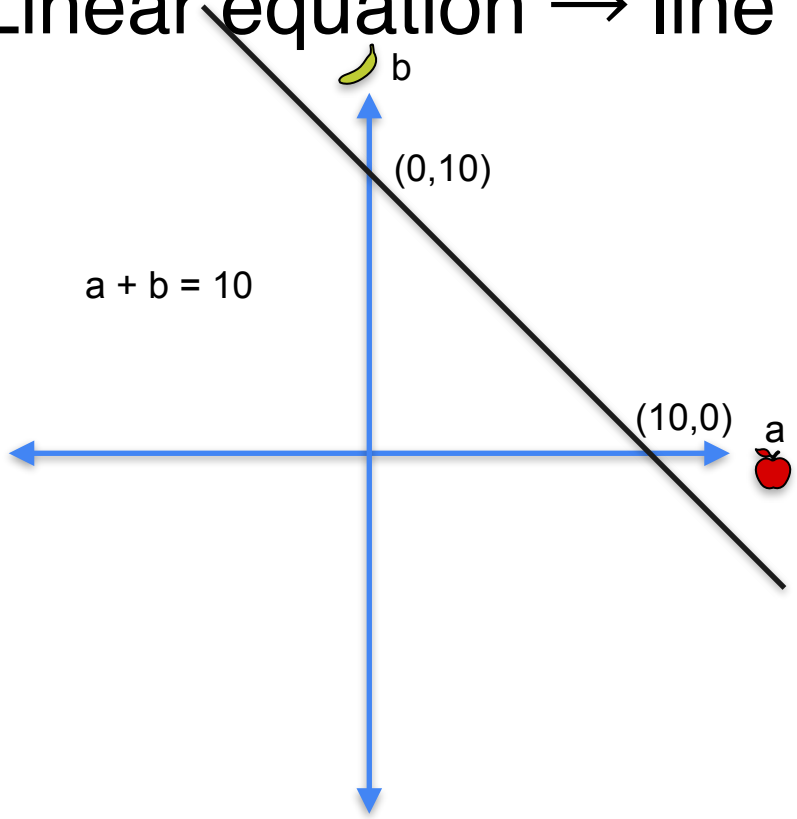
Linear equation → line

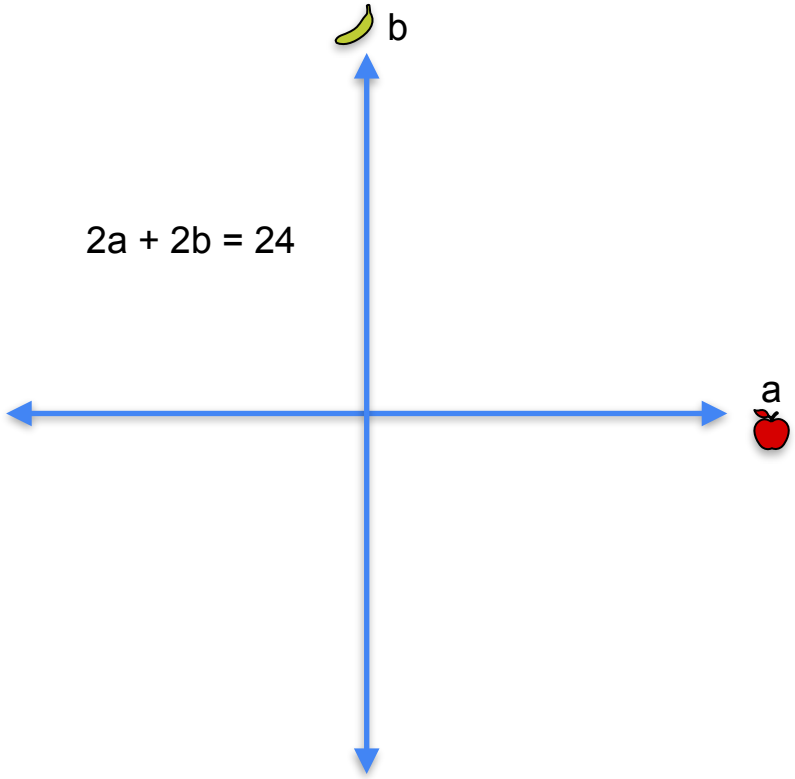


Linear equation → line

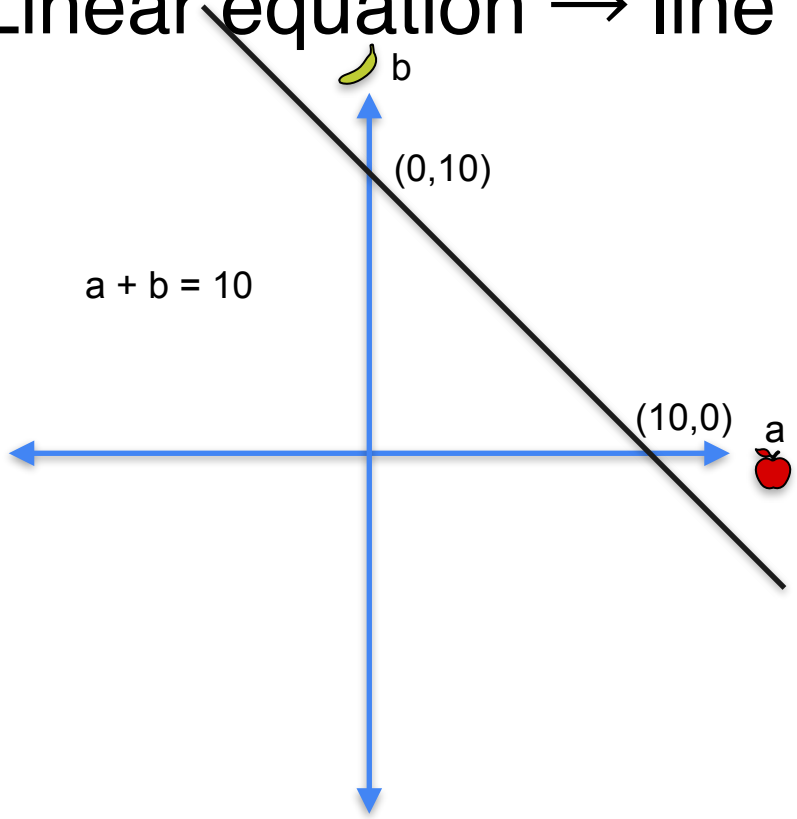


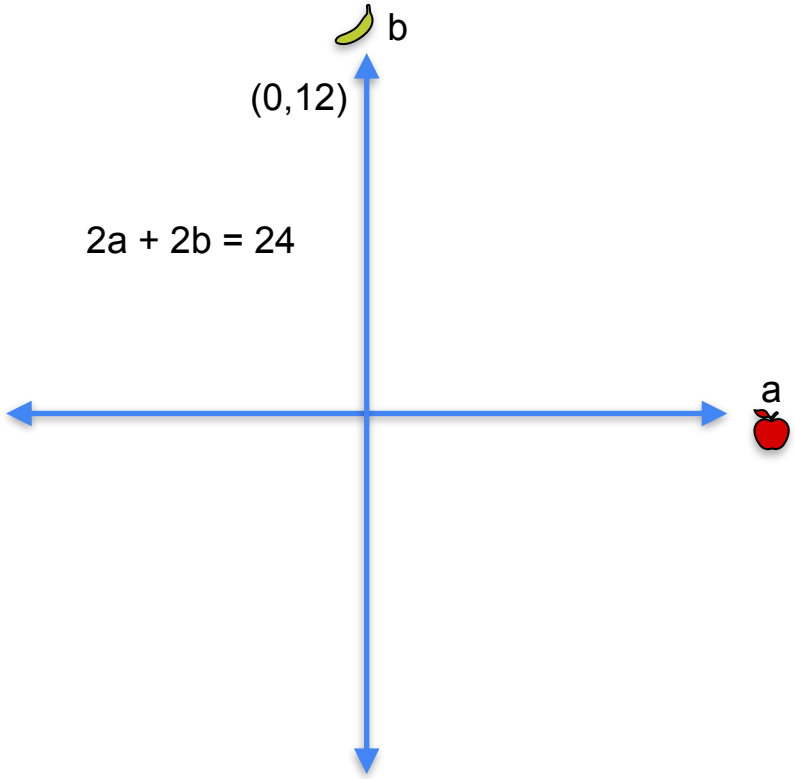
Linear equation → line



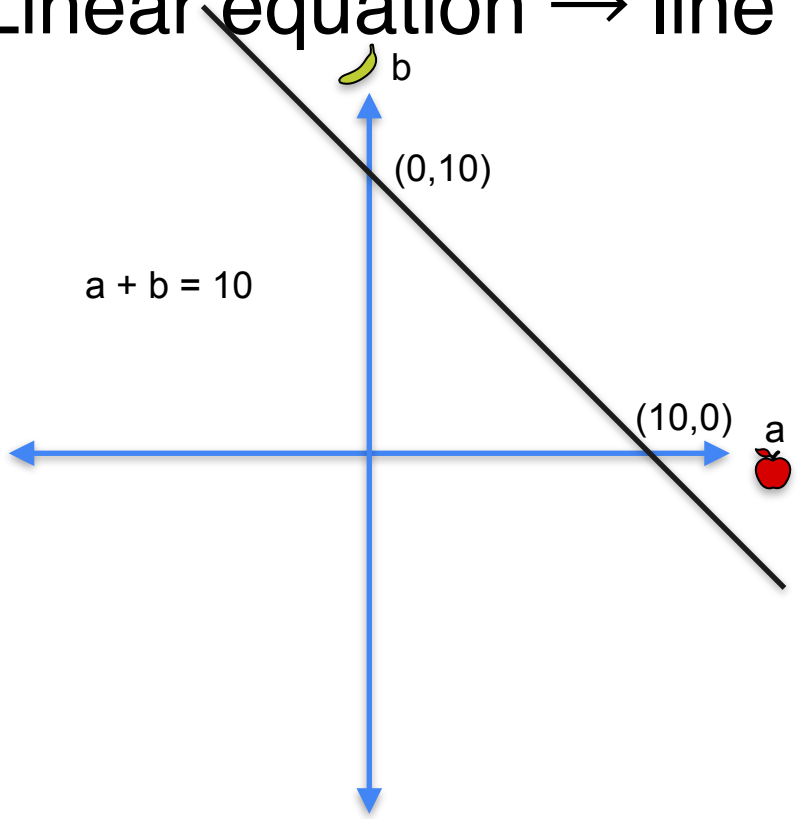


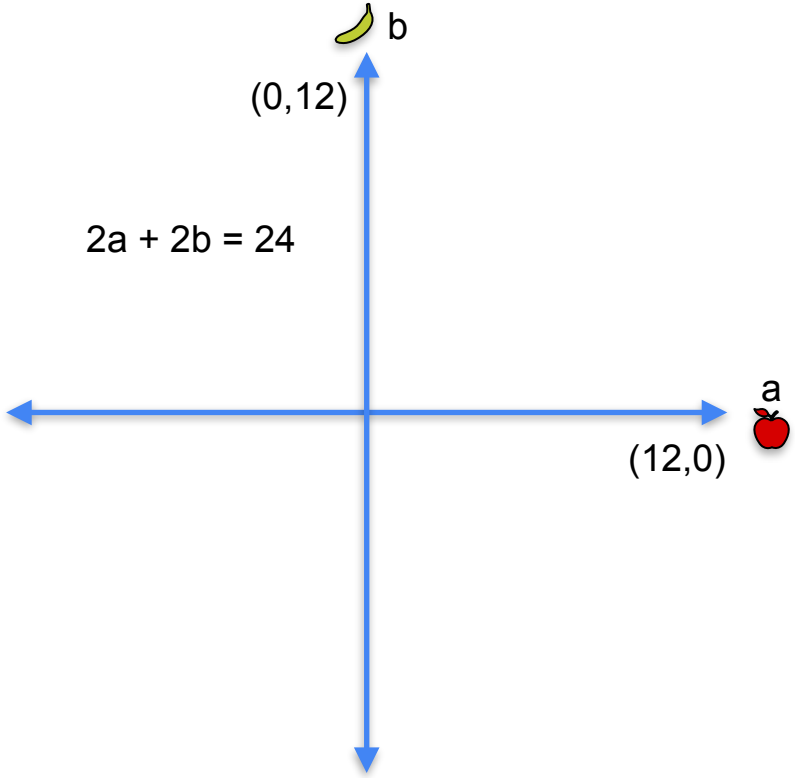
Linear equation → line



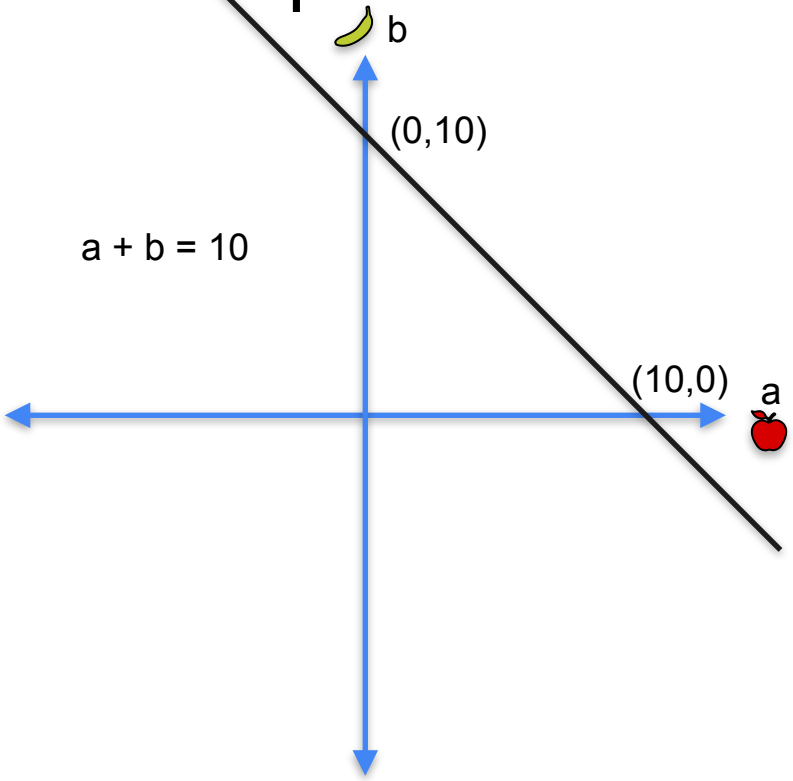


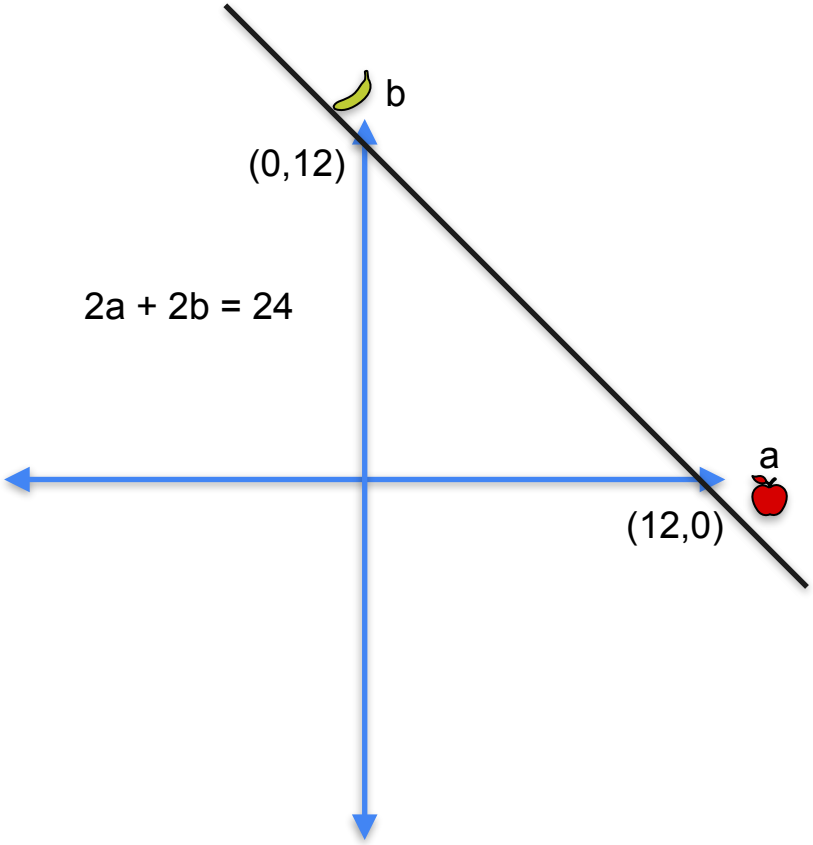
Linear equation → line



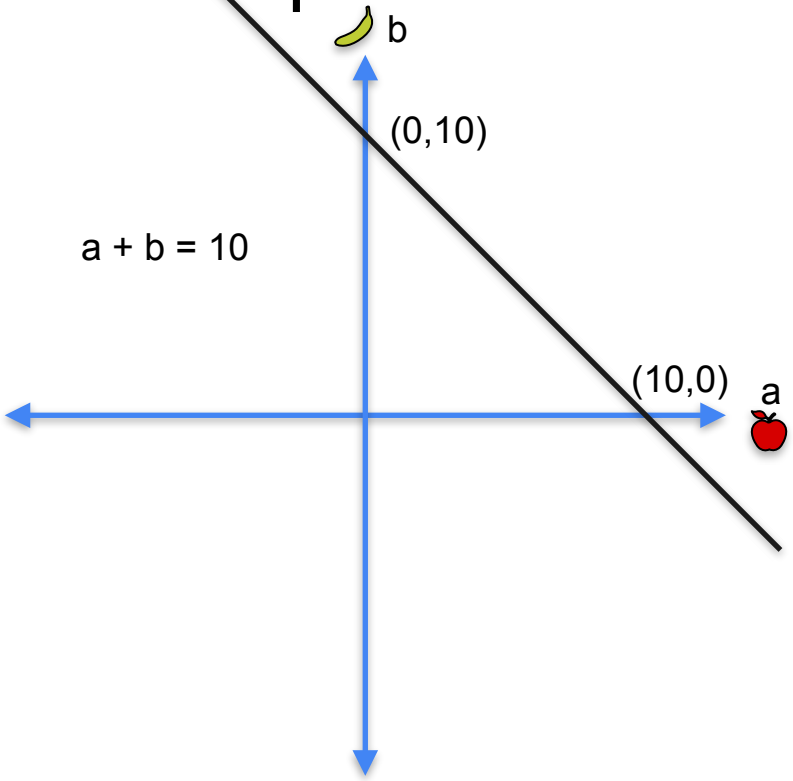


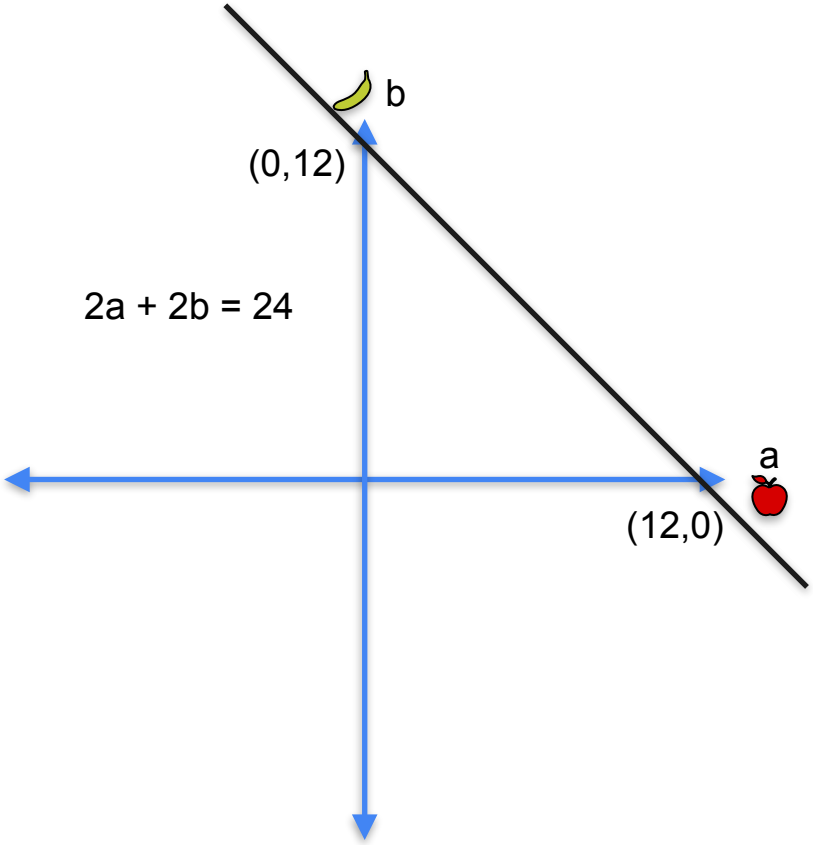
Linear equation → line



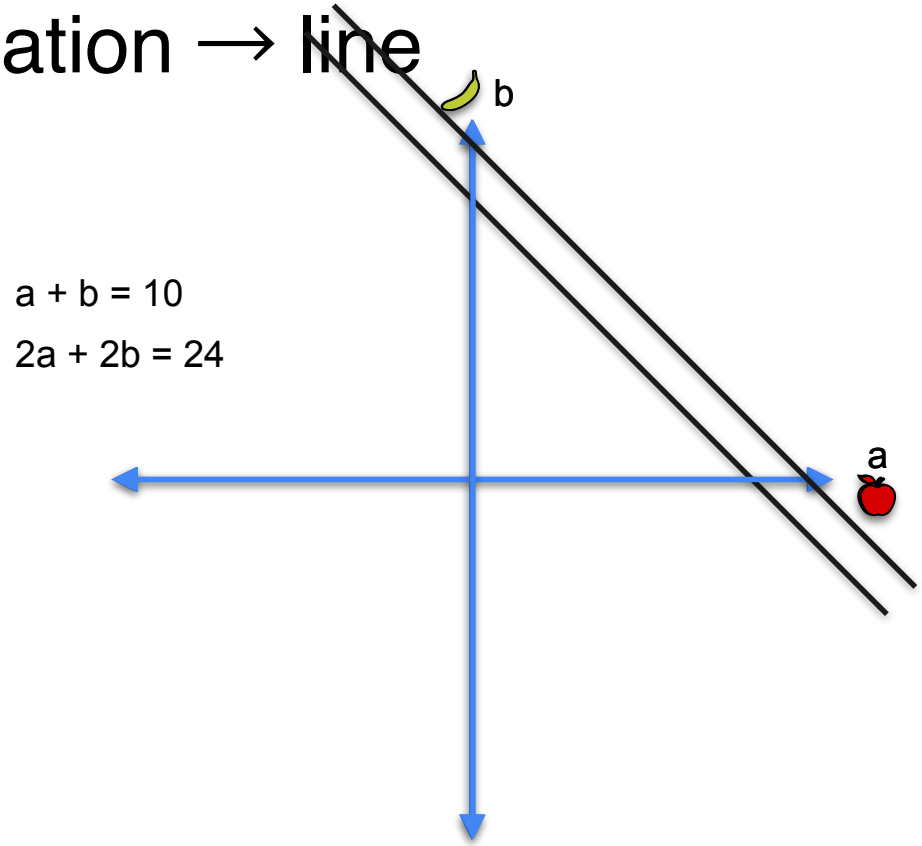


Linear equation → line

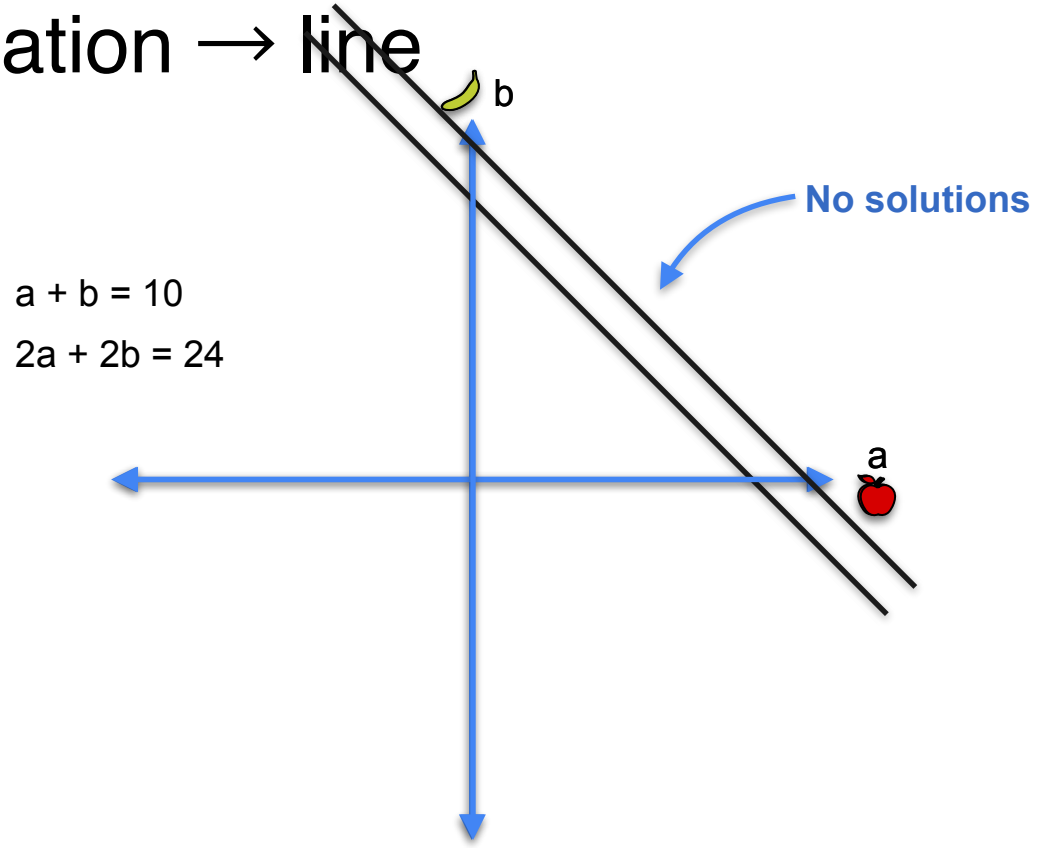




Linear equation → line



Linear equation → line



Systems of equations as lines

Systems of equations as lines

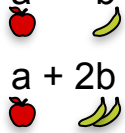
System 1

- a + b = 10
- a + 2b = 12

Systems of equations as lines

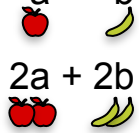
System 1

- a + b = 10
- a + 2b = 12



System 2

- a + b = 10
- 2a + 2b = 20



Systems of equations as lines

System 1

- a + b = 10
- a + 2b = 12

System 2

- a + b = 10
- 2a + 2b = 20

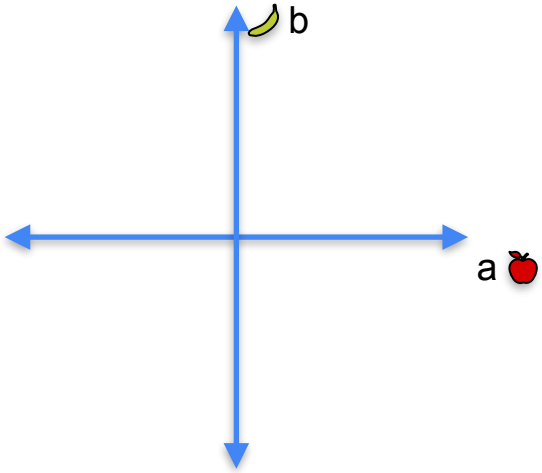
System 3

- a + b = 10
- 2a + 2b = 24

Systems of equations as lines

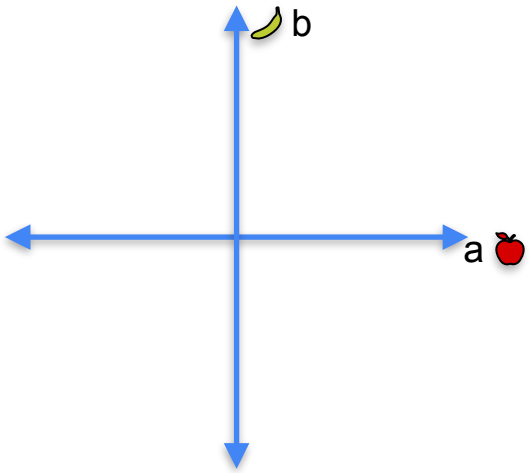
System 1

- a + b = 10
- a + 2b = 12



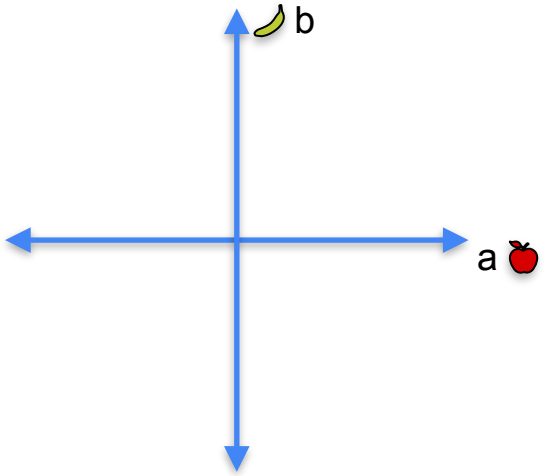
System 2

- a + b = 10
- 2a + 2b = 20



System 3

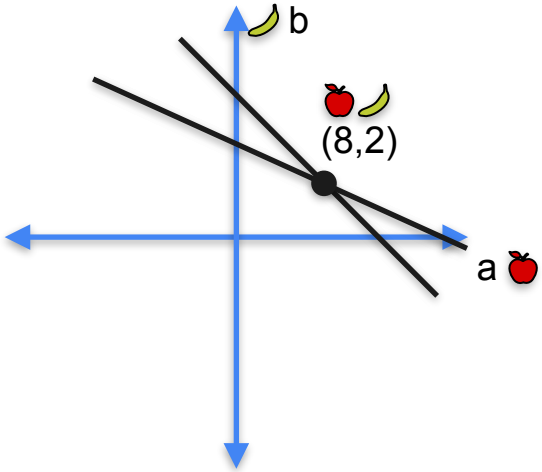
- a + b = 10
- 2a + 2b = 24



Systems of equations as lines

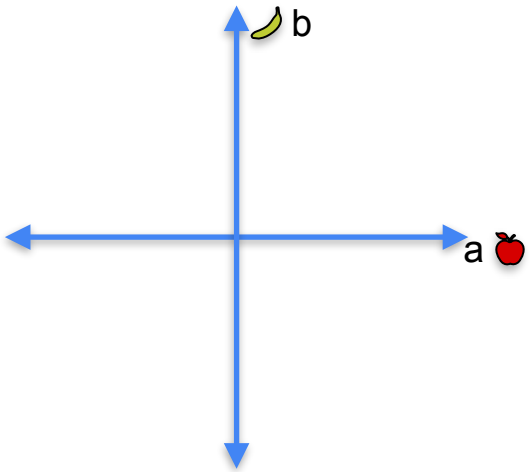
System 1

- a + b = 10
- a + 2b = 12



System 2

- a + b = 10
- 2a + 2b = 20



System 3

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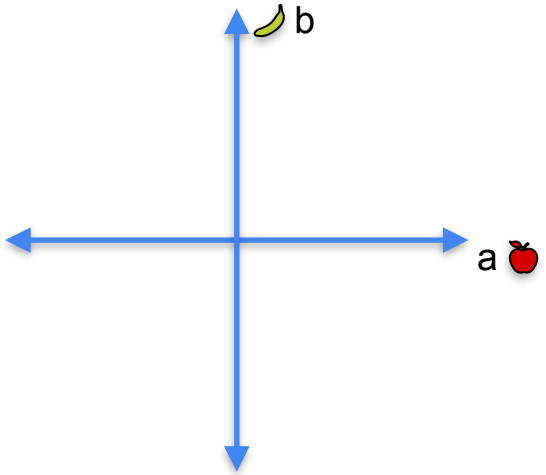

Systems of equations as lines

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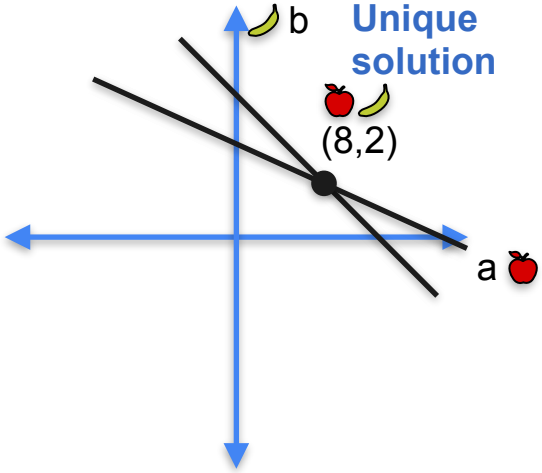

System 2

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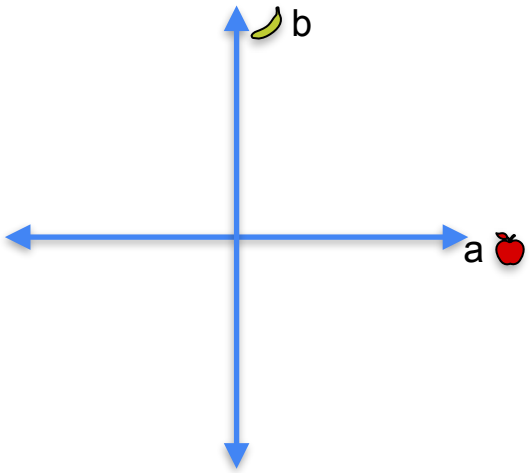

System 3

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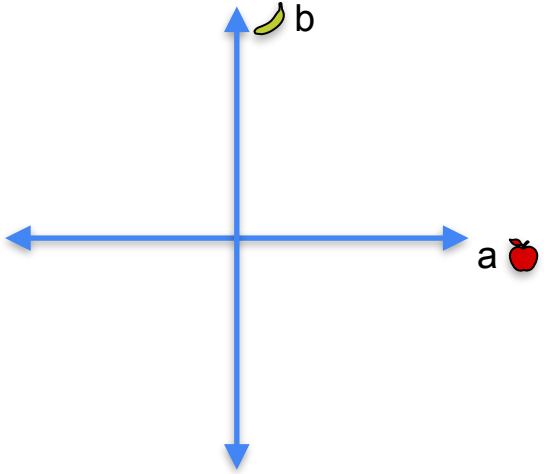

Systems of equations as lines

System 1

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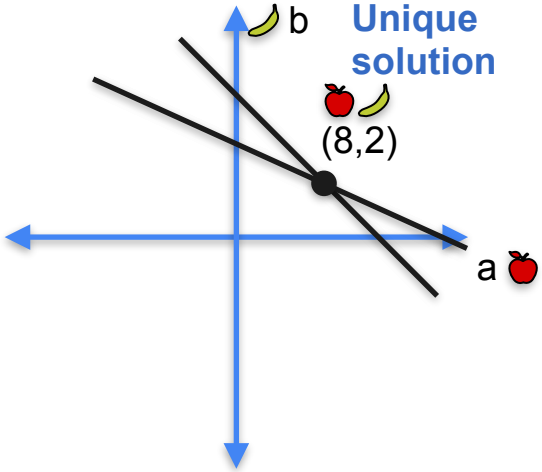

System 2

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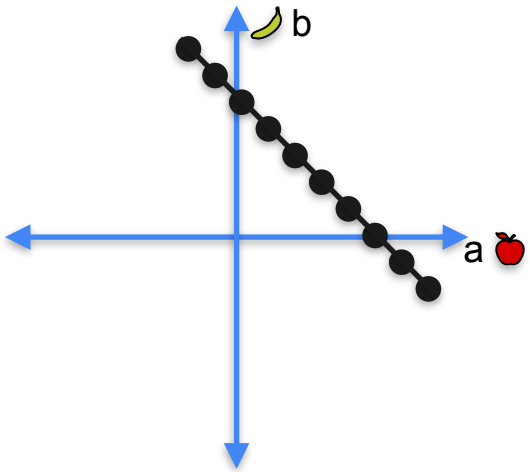

System 3

- a + b = 10
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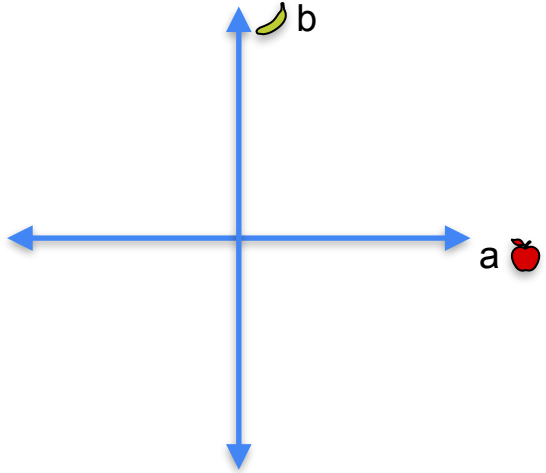

Systems of equations as lines

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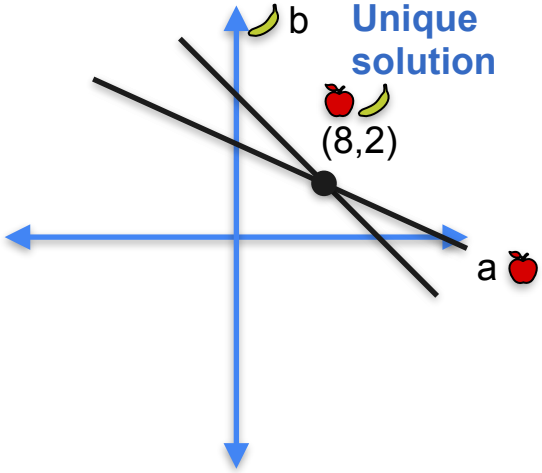

System 2

- a + b = 10
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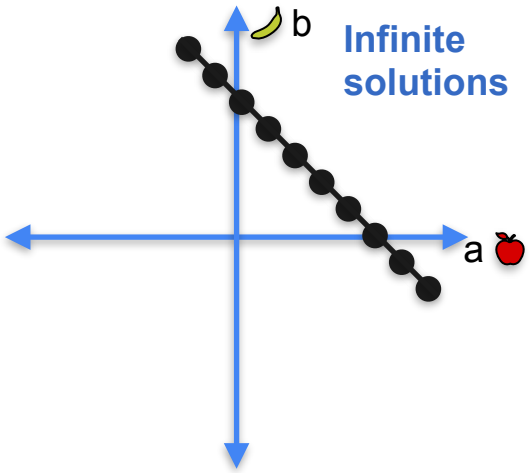

System 3

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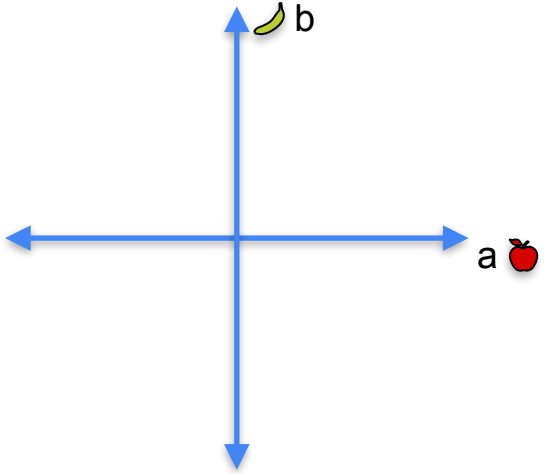

Systems of equations as lines

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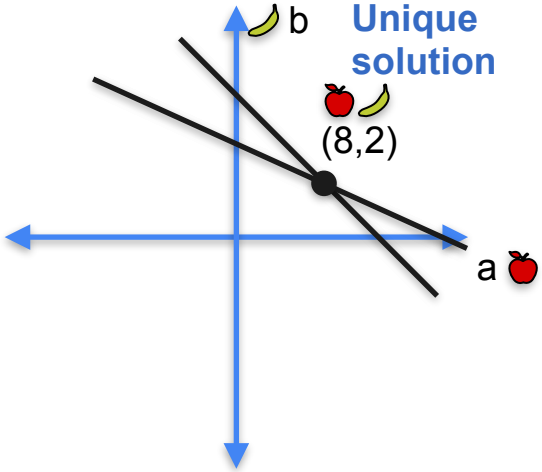

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- a + b = 10
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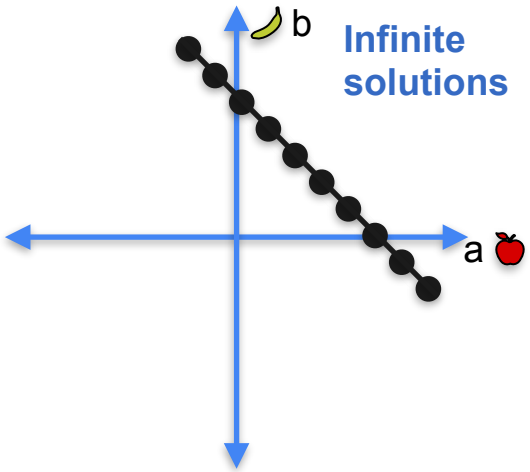

System 3

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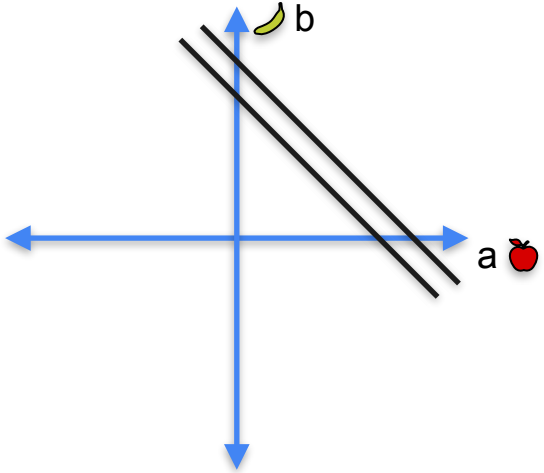

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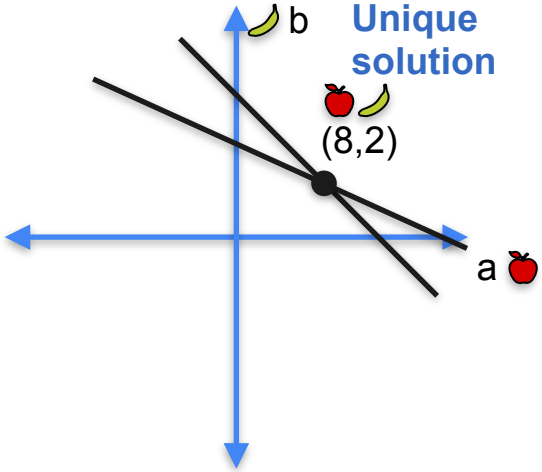

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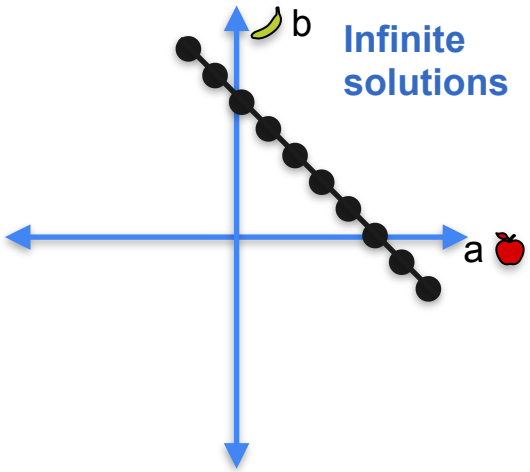
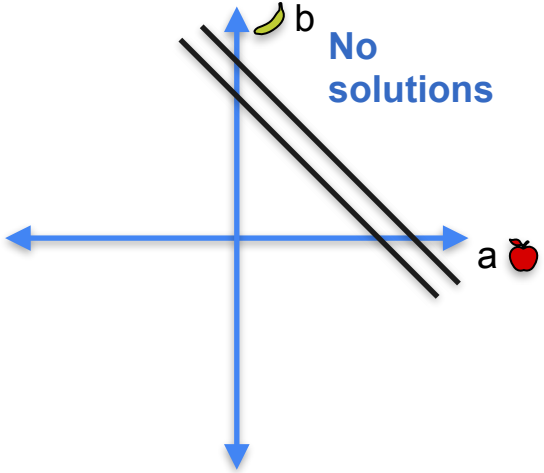
- a + b = 10
- 2a + 2b = 20



System 3

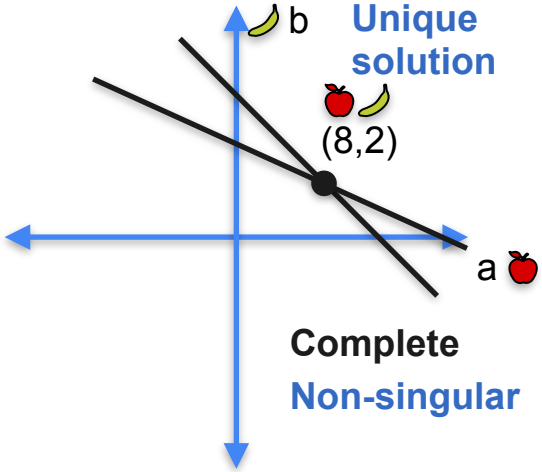
- a + b = 10
- 2a + 2b = 24



Systems of equations as lines

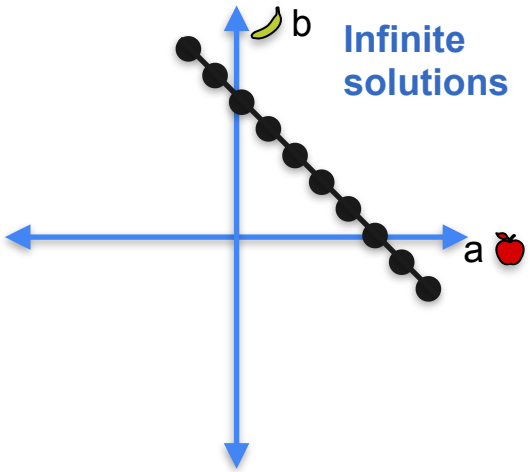
System 1

- a + b = 10
- a + 2b = 12



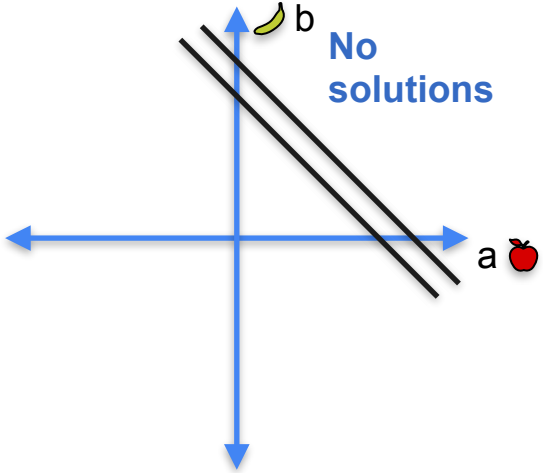
System 2

- a + b = 10
- 2a + 2b = 20



System 3

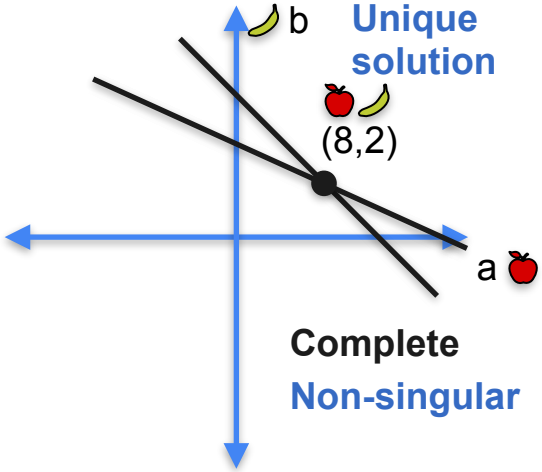
- a + b = 10
- 2a + 2b = 24



Systems of equations as lines

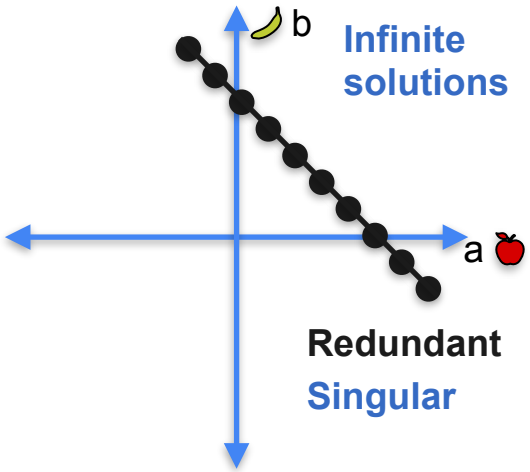
System 1

- a + b = 10
- a + 2b = 12



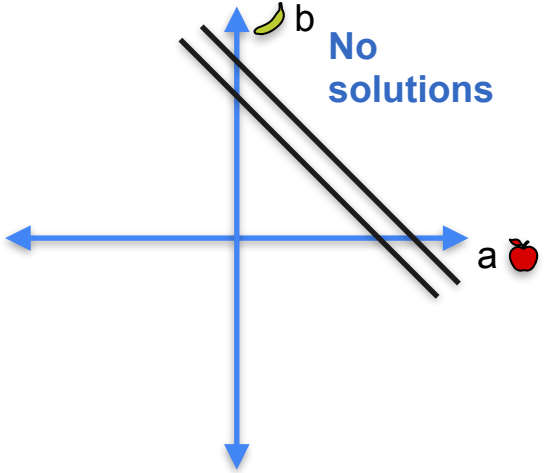
System 2

- a + b = 10
- 2a + 2b = 20



System 3

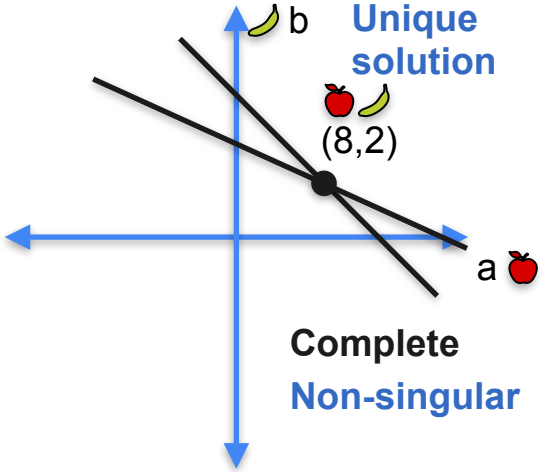
- a + b = 10
- 2a + 2b = 24



Systems of equations as lines

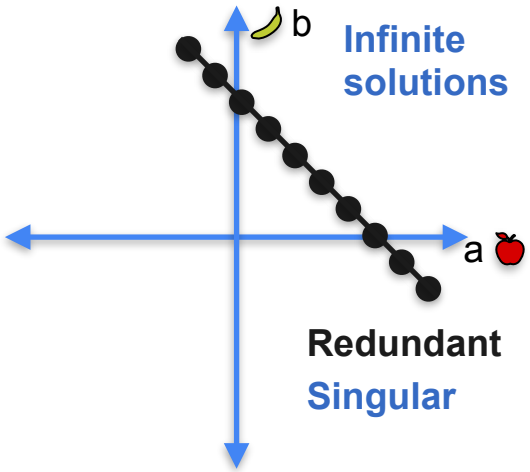
System 1

- a + b = 10
- a + 2b = 12



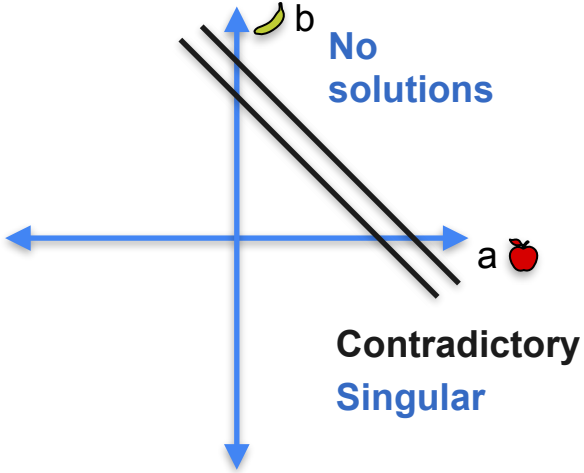
System 2

- a + b = 10
- 2a + 2b = 20



System 3

- a + b = 10
- 2a + 2b = 24



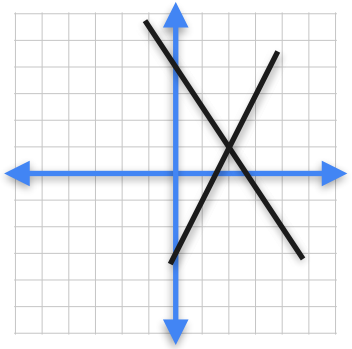
Quiz

Problem 1

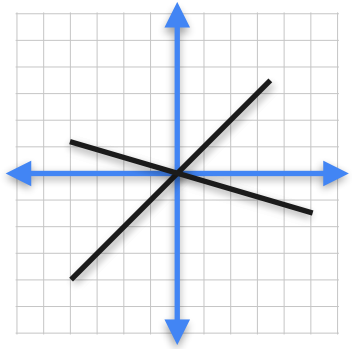
Which of the following plots corresponds to the system of equations:

- $3a + 2b = 8$
- $2a - b = 3$

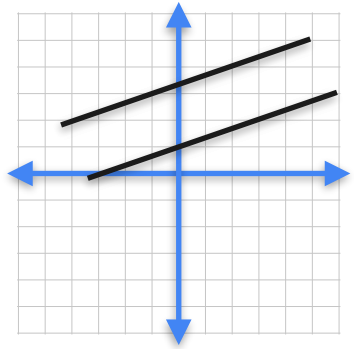
a)



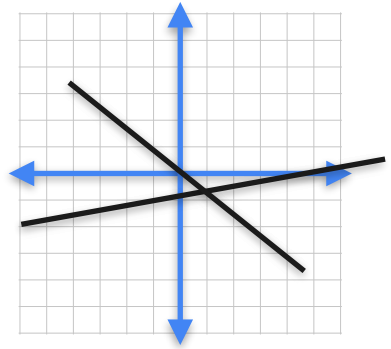
b)



c)



d)



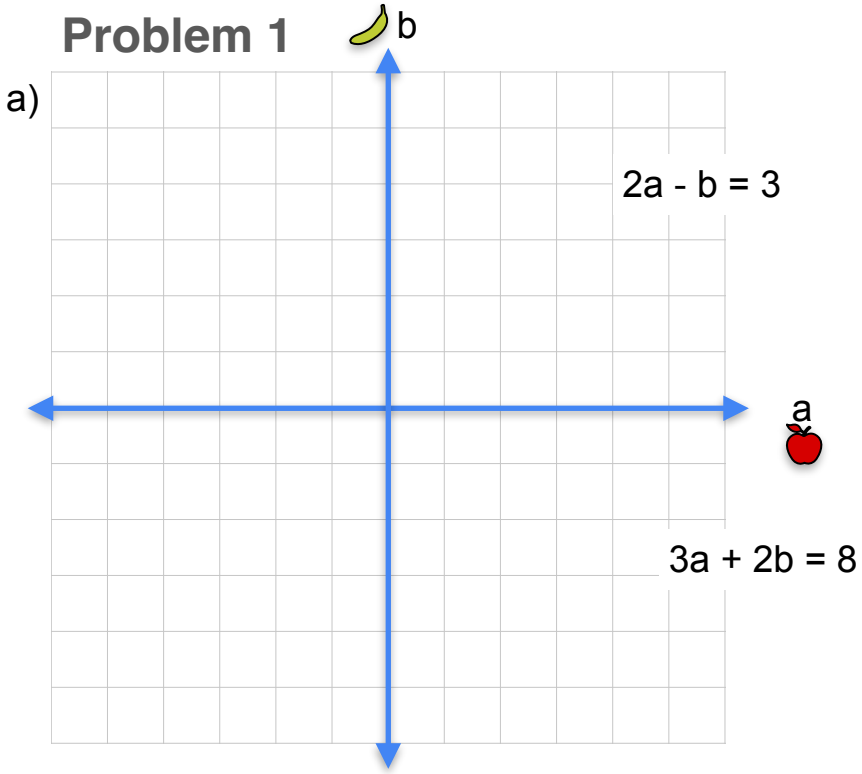
Problem 2

Is this system singular or non-singular?

Solution

Problem 1

a)

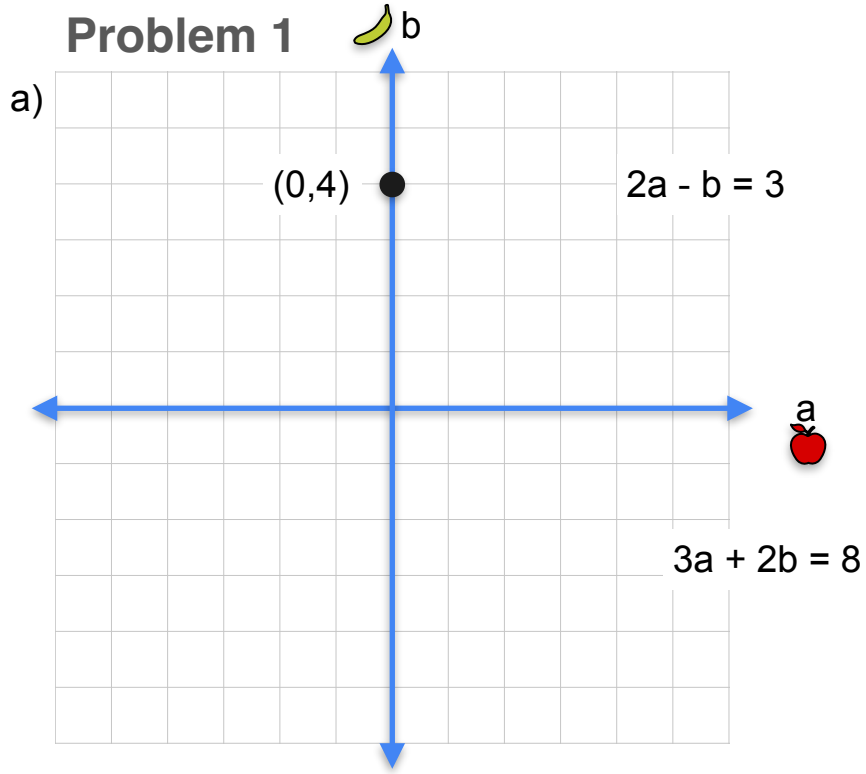


Problem 2

Since the lines cross at a unique point, the system is non-singular.

Solution

Problem 1

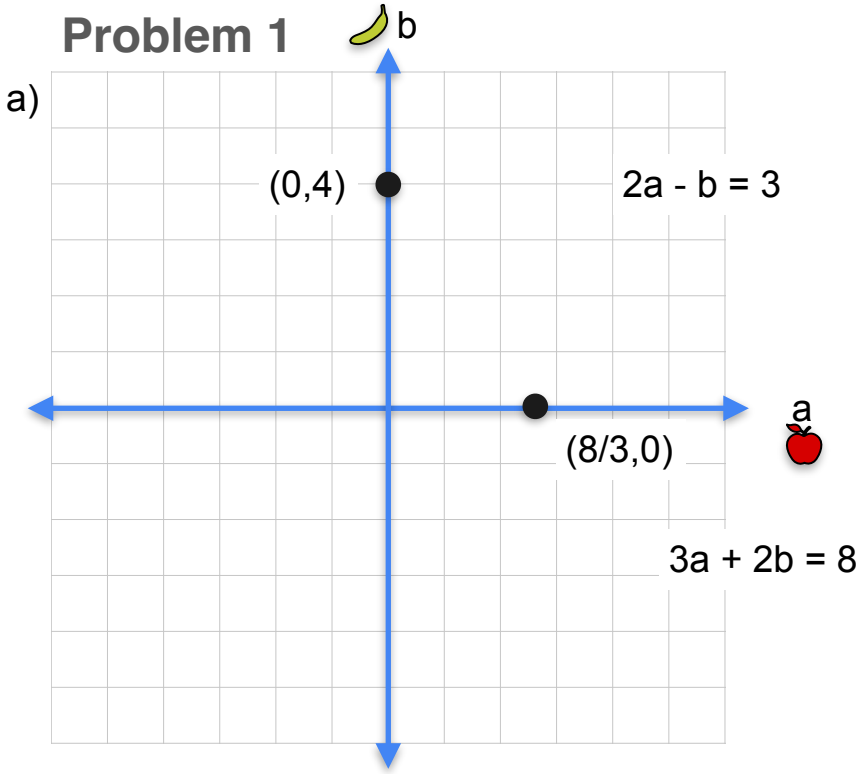


Problem 2

Since the lines cross at a unique point, the system is non-singular.

Solution

Problem 1



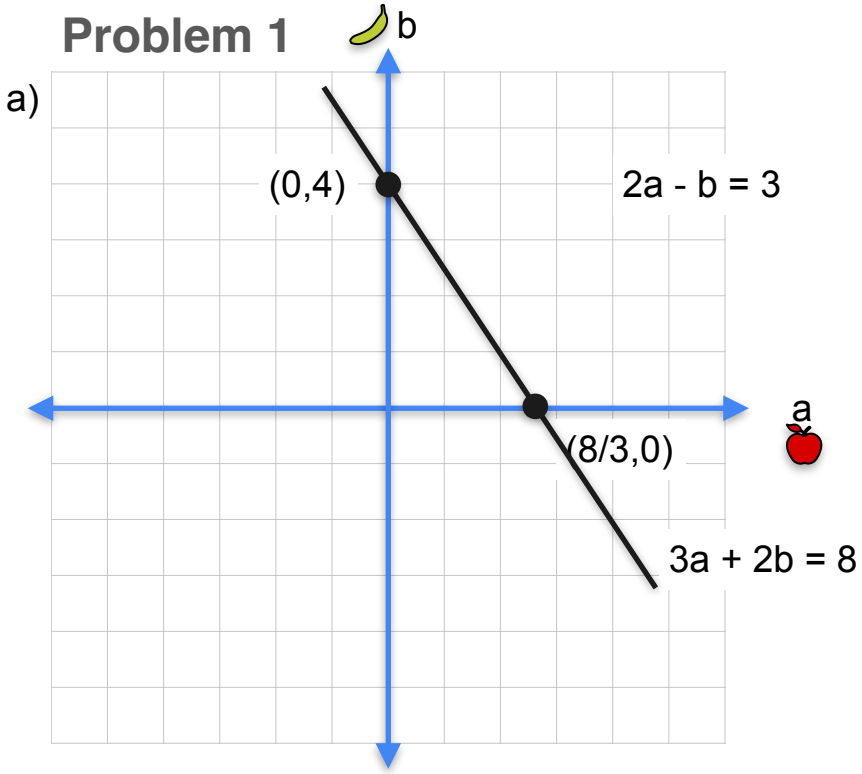
Problem 2

Since the lines cross at a unique point, the system is non-singular.

Solution

Problem 1

a)

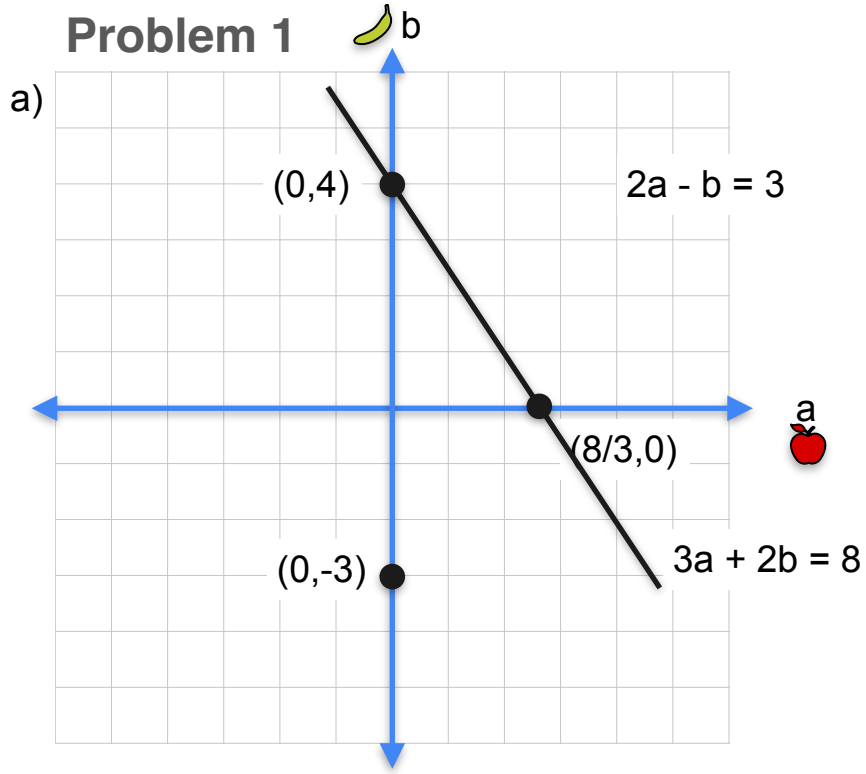


Problem 2

Since the lines cross at a unique point, the system is non-singular.

Solution

Problem 1



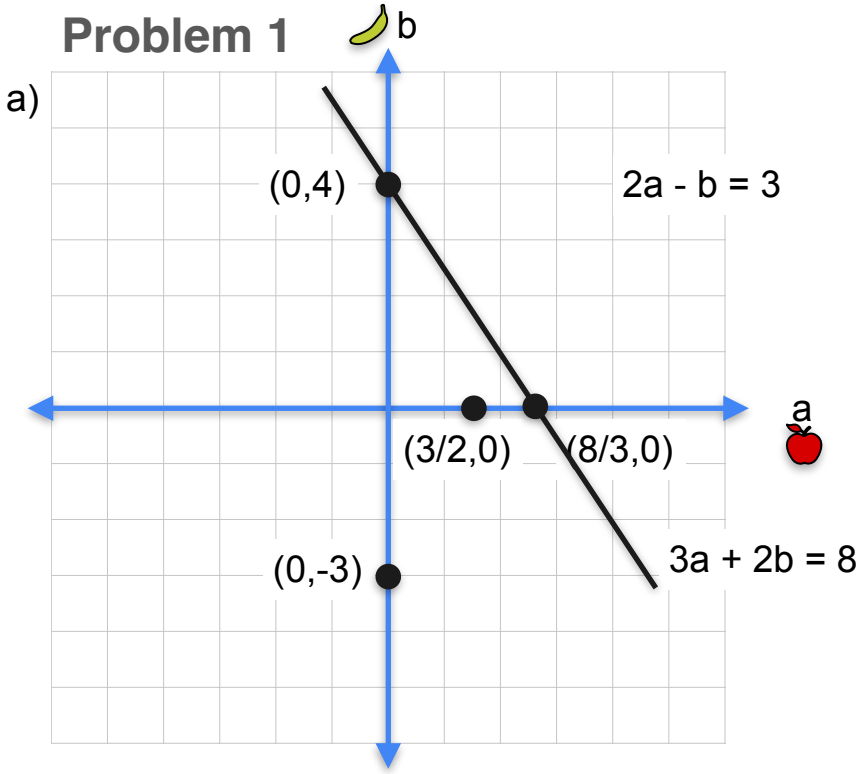
Problem 2

Since the lines cross at a unique point, the system is non-singular.

Solution

Problem 1

a)



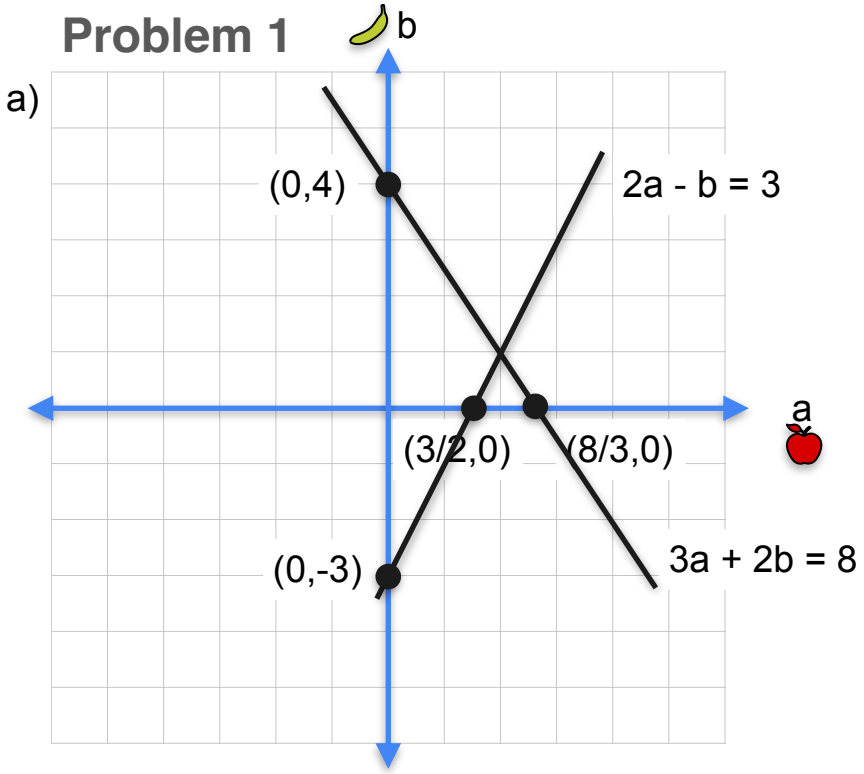
Problem 2

Since the lines cross at a unique point, the system is non-singular.

Solution

Problem 1

a)

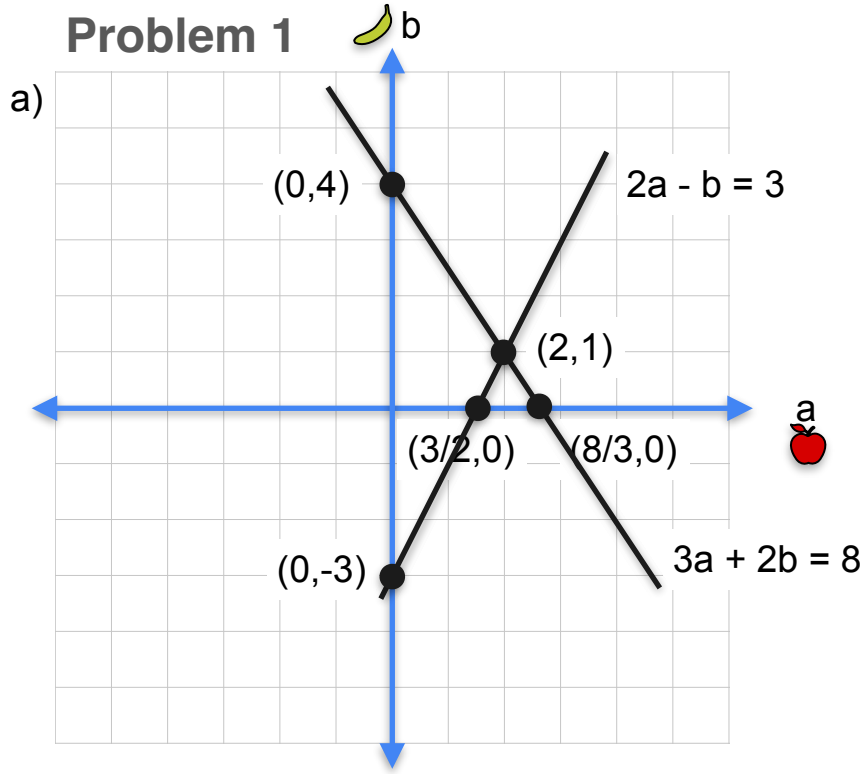


Problem 2

Since the lines cross at a unique point, the system is non-singular.

Solution

Problem 1



Problem 2

Since the lines cross at a unique point, the system is non-singular.

DeepLearning.AI

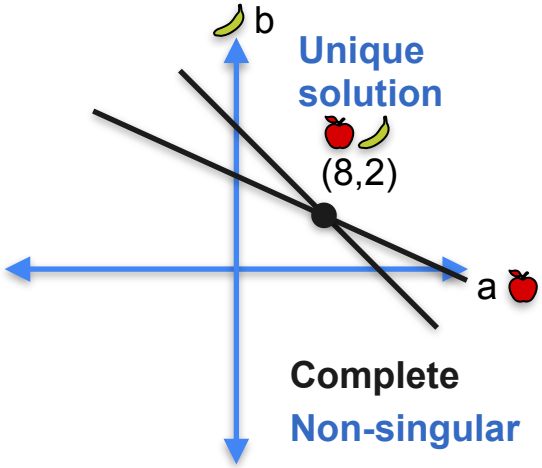
System of Linear Equations

A geometric notion of singularity

Systems of equations as lines

System 1

- a + b = 10
- a + 2b = 12

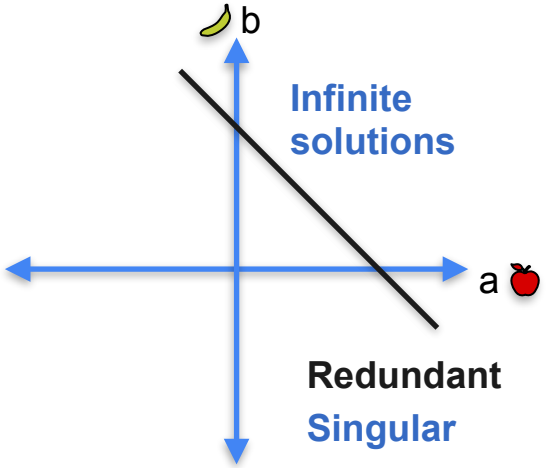


Complete

Non-singular

System 2

- a + b = 10
- 2a + 2b = 20

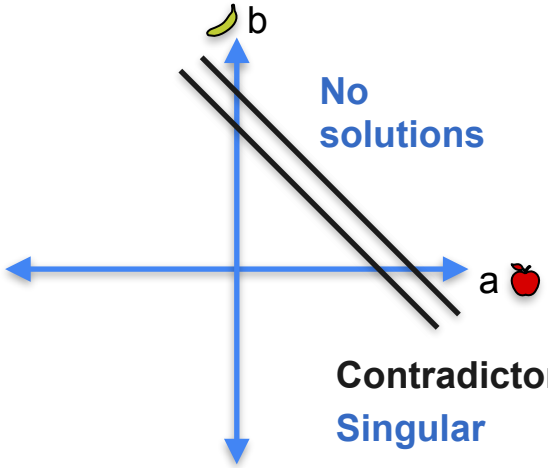


Redundant

Singular

System 3

- a + b = 10
- 2a + 2b = 24



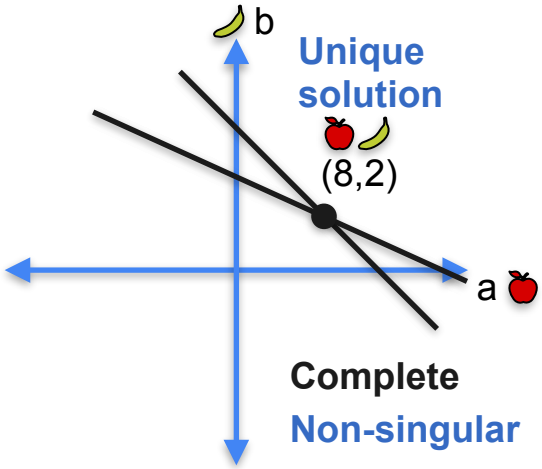
Contradictory

Singular

Systems of equations as lines

System 1

- a + b = 10
- a + 2b = 12

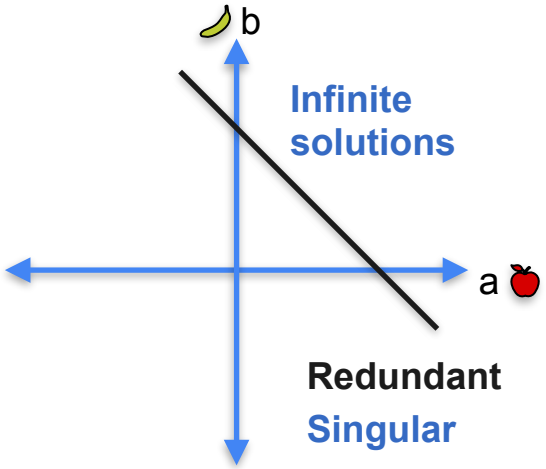


Complete

Non-singular

System 2

- a + b = 10
- 2a + 2b = 20

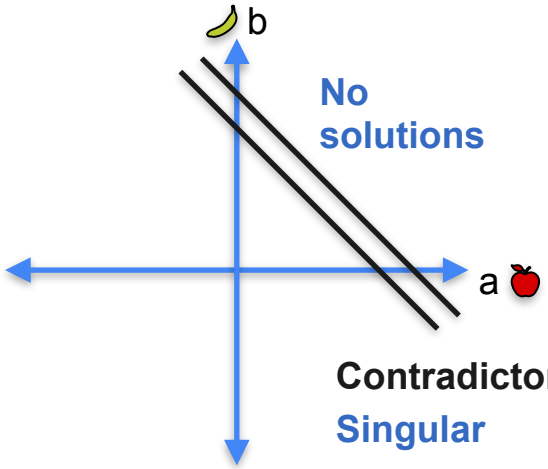


Redundant

Singular

System 3

- a + b = 10
- 2a + 2b = 24



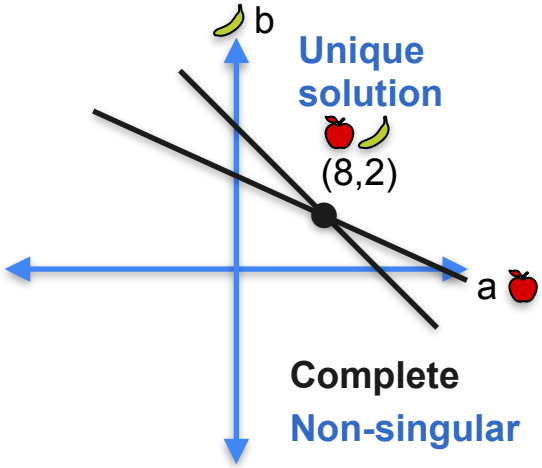
Contradictory

Singular

Systems of equations as lines

System 1

- a + b = 0
- a + 2b = 0

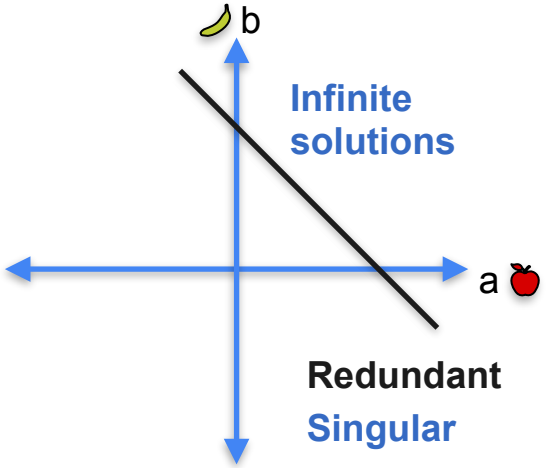


Complete

Non-singular

System 2

- a + b = 10
- 2a + 2b = 20

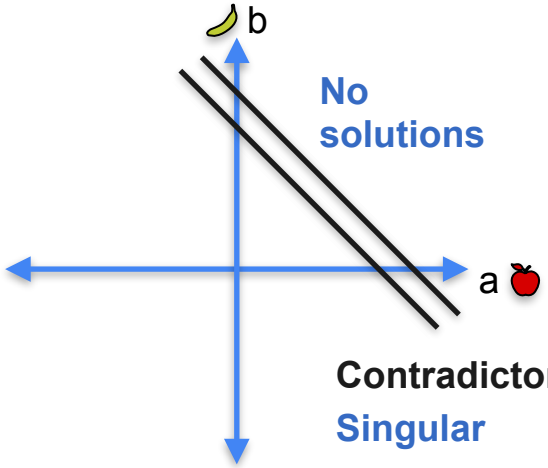


Redundant

Singular

System 3

- a + b = 10
- 2a + 2b = 24



Contradictory

Singular

Systems of equations as lines

System 1

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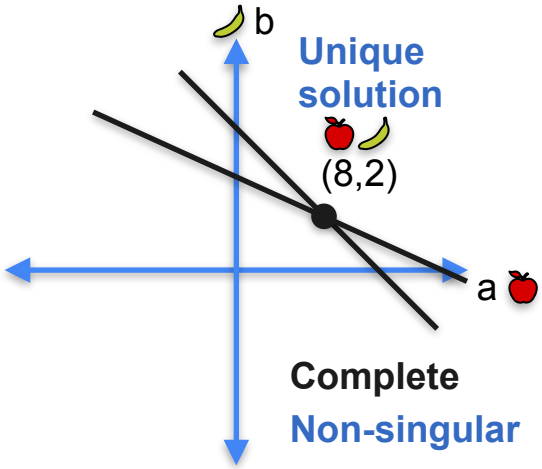
- a + 2b = 0

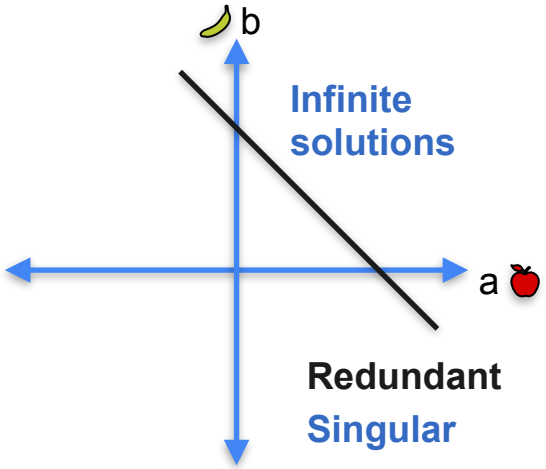


Complete

Non-singular

System 2

- a + b = 0
- 2a + 2b = 0

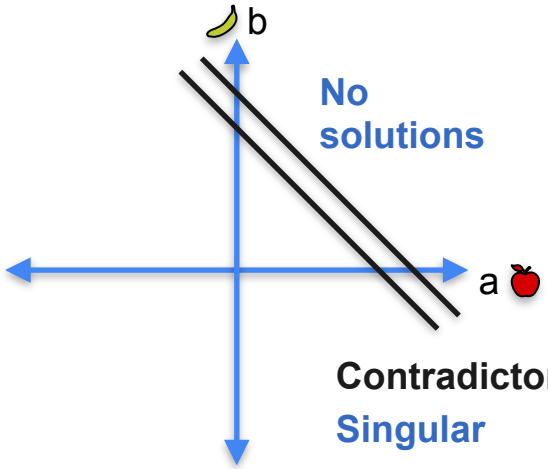


Redundant

Singular

System 3

- a + b = 10
- 2a + 2b = 24



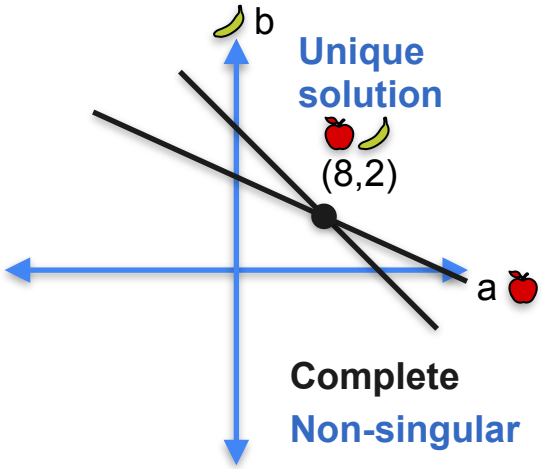
Contradictory

Singular

Systems of equations as lines

System 1

- a + b = 0
- a + 2b = 0

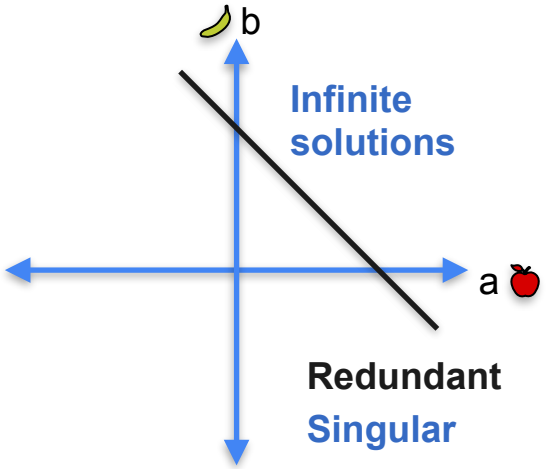


Complete

Non-singular

System 2

- a + b = 0
- 2a + 2b = 0

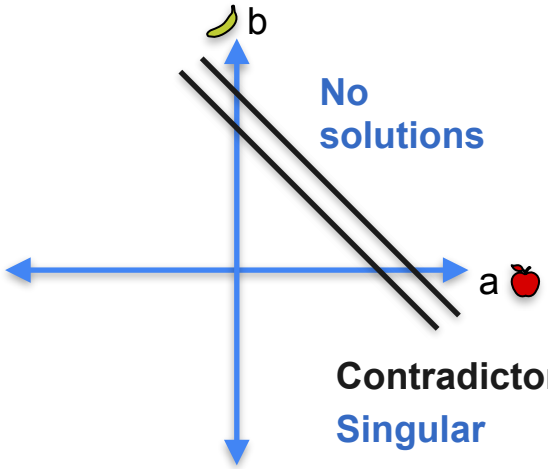


Redundant

Singular

System 3

- a + b = 0
- 2a + 2b = 0



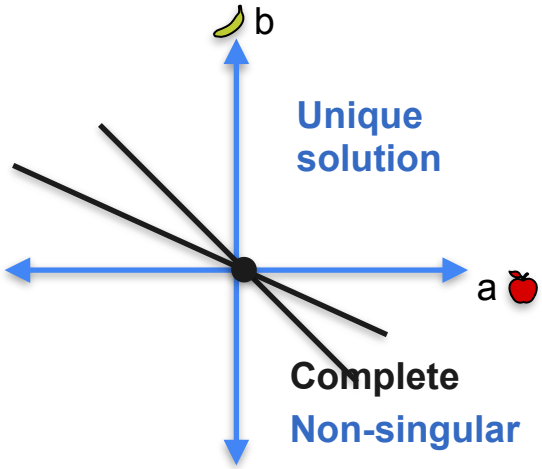
Contradictory

Singular

Systems of equations as lines

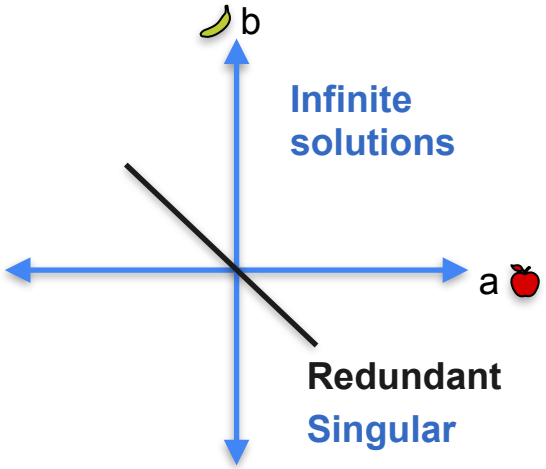
System 1

- a + b = 0
- a + 2b = 0



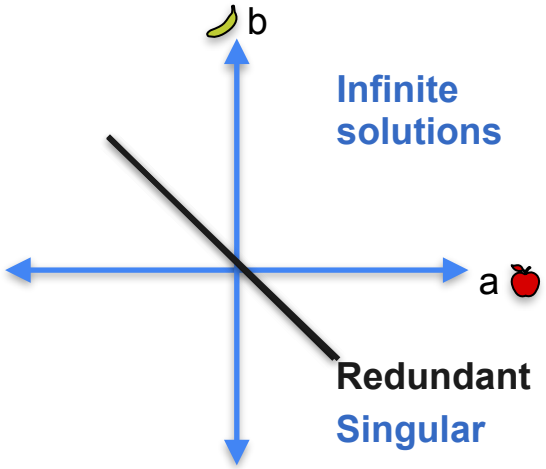
System 2

- a + b = 0
- 2a + 2b = 0



System 3

- a + b = 0
- 2a + 2b = 0



DeepLearning.AI

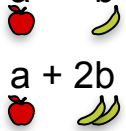
System of Linear Equations

Singular vs nonsingular matrices

Systems of equations as matrices

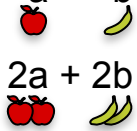
System 1

- a + b = 0
- a + 2b = 0



System 2

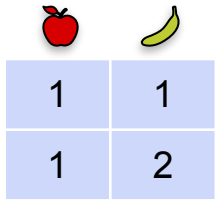
- a + b = 0
- 2a + 2b = 0



Systems of equations as matrices

System 1

- a + b = 0
- a + 2b = 0



1	1
1	2

System 2

- a + b = 0
- 2a + 2b = 0

Systems of equations as matrices

System 1

- a + b = 0
- a + 2b = 0

1	1
1	2

System 2

- a + b = 0
- 2a + 2b = 0

1	1
2	2

Systems of equations as matrices

System 1

- a + b = 0
- a + 2b = 0

1	1
1	2

Non-singular system

(Unique solution)

System 2

- a + b = 0
- 2a + 2b = 0

1	1
2	2

Systems of equations as matrices

System 1

- a + b = 0
- a + 2b = 0

1	1
1	2

Non-singular system

Non-singular matrix

(Unique solution)

System 2

- a + b = 0
- 2a + 2b = 0

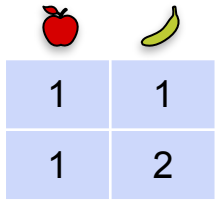
1	1
2	2

Systems of equations as matrices

System 1

- a + b = 0
- a + 2b = 0

Non-singular system



1	1
1	2

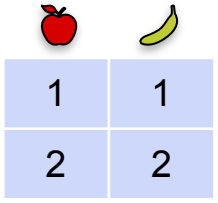
Non-singular matrix

(Unique solution)

System 2

- a + b = 0
- 2a + 2b = 0

Singular system



1	1
2	2

(Infinitely many solutions)

Systems of equations as matrices

System 1

- a + b = 0
- a + 2b = 0

1	1
1	2

Non-singular system

Non-singular matrix

(Unique solution)

System 2

- a + b = 0
- 2a + 2b = 0

1	1
2	2

Singular system

Singular matrix

(Infinitely many solutions)

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System of Linear Equations

Linear dependence and independence

Linear dependence between rows

Non-singular

- a + b = 0
- a + 2b = 0

1	1
1	2

Singular system

- a + b = 0
- 2a + 2b = 0

1	1
2	2

Linear dependence between rows

Non-singular

- a + b = 0
- a + 2b = 0

1	1
1	2

Singular system

- a + b = 0
- 2a + 2b = 0

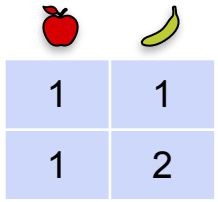
1	1
2	2

Second equation is a multiple of the first one

Linear dependence between rows

Non-singular

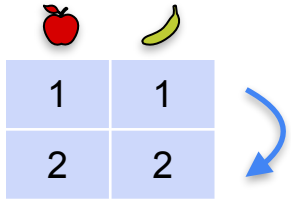
- a + b = 0
- a + 2b = 0



Singular system

- a + b = 0
- 2a + 2b = 0

Second equation is a multiple of the first one



Second row is a multiple of the first row

Linear dependence between rows

Non-singular

- a + b = 0
- a + 2b = 0

1	1
1	2

Singular system

- a + b = 0
- 2a + 2b = 0

1	1
2	2

Second equation is a multiple of the first one

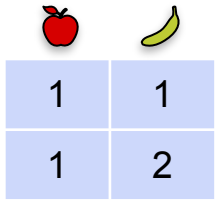
Second row is a multiple of the first row

Rows are *linearly dependent*

Linear dependence between rows

Non-singular

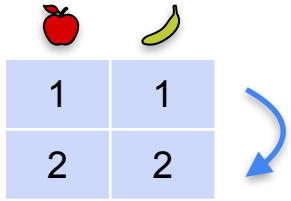
- a + b = 0
- a + 2b = 0



No equation is a multiple of the other one

Singular system

- a + b = 0
- 2a + 2b = 0



Second equation is a multiple of the first one

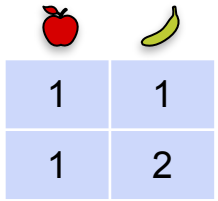
Second row is a multiple of the first row

Rows are *linearly dependent*

Linear dependence between rows

Non-singular

- a + b = 0
- a + 2b = 0

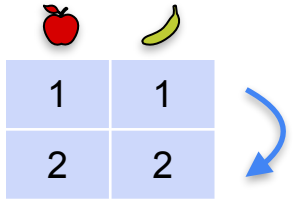


No equation is a multiple of the other one

No row is a multiple of the other one

Singular system

- a + b = 0
- 2a + 2b = 0



Second equation is a multiple of the first one

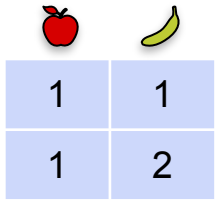
Second row is a multiple of the first row

Rows are *linearly dependent*

Linear dependence between rows

Non-singular

- a + b = 0
- a + 2b = 0



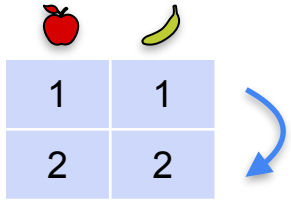
No equation is a multiple of the other one

No row is a multiple of the other one

Rows are *linearly independent*

Singular system

- a + b = 0
- 2a + 2b = 0



Second equation is a multiple of the first one

Second row is a multiple of the first row

Rows are *linearly dependent*

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System of Linear Equations

The determinant

Linear dependence between rows

Non-singular matrix

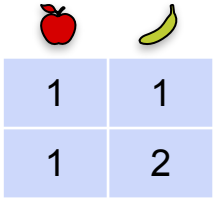
1	1
1	2

Singular matrix

1	1
2	2

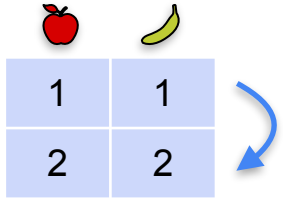
Linear dependence between rows

Non-singular matrix



1	1
1	2

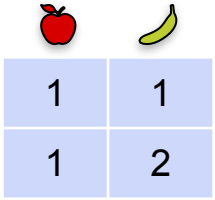
Singular matrix



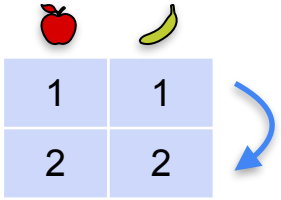
1	1
2	2

Linear dependence between rows

Non-singular matrix



Singular matrix



Linear dependence between rows

Non-singular matrix

1	1
1	2

Singular matrix

1	1
2	2

1	1	x 2	=

Linear dependence between rows

Non-singular matrix

1	1
1	2

Singular matrix

1	1
2	2

1	1	x 2	=	2	2

Linear dependence between rows

Non-singular matrix

1	1
1	2

Singular matrix

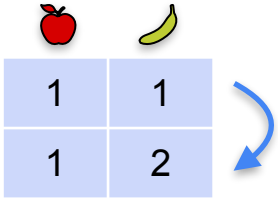
1	1
2	2

1	1	x 2	=	2	2

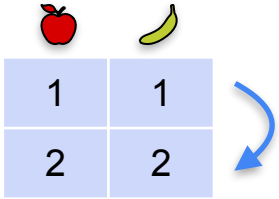
Rows linearly dependent

Linear dependence between rows

Non-singular matrix



Singular matrix

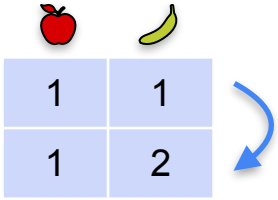


1	1	x 2	=	2	2

Rows linearly dependent

Linear dependence between rows

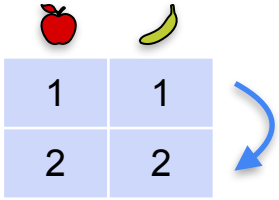
Non-singular matrix



1	1
1	2

1	1

Singular matrix



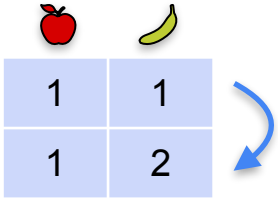
1	1
2	2

1	1	x 2	=	2	2

Rows linearly dependent

Linear dependence between rows

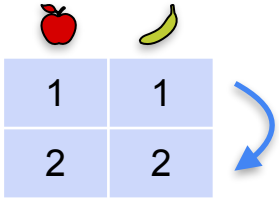
Non-singular matrix



1	1
1	2

1	1	x ?	=	

Singular matrix



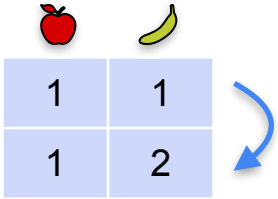
1	1
2	2

1	1	x 2	=	2	2

Rows linearly dependent

Linear dependence between rows

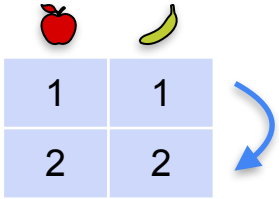
Non-singular matrix



1	1
1	2

1	1	x ?	=	1	2

Singular matrix



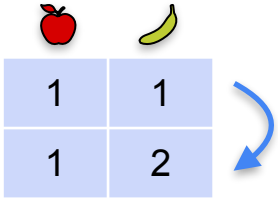
1	1
2	2

1	1	x 2	=	2	2

Rows linearly dependent

Linear dependence between rows

Non-singular matrix

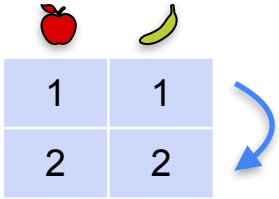


1	1
1	2

1	1	x ?	=	1	2

Rows linearly independent

Singular matrix



1	1
2	2

1	1	x 2	=	2	2

Rows linearly dependent

Determinant

a	b
c	d

Matrix is singular if

a	b	* k =	c	d

Determinant

a	b
c	d

$$ak = c$$

Matrix is singular if

a	b	* k =	c	d

Determinant

a	b
c	d

$$ak = c$$

$$bk = d$$

Matrix is singular if

a	b	* k =	c	d

Determinant

a	b
c	d

$$ak = c$$

$$bk = d$$

$$\frac{c}{a} = \frac{d}{b} = k$$

Matrix is singular if

a	b	* k =	c	d

Determinant

a	b
c	d

$$ak = c$$

$$bk = d$$

$$\frac{c}{a} = \frac{d}{b} = k$$

Matrix is singular if

a	b	* k =	c	d

$$ad = bc$$

Determinant

a	b
c	d

Matrix is singular if

a	b	* k =	c	d

$$ak = c$$

$$bk = d$$

$$\frac{c}{a} = \frac{d}{b} = k$$

$$ad = bc$$

$$ad - bc = 0$$

Determinant

a	b
c	d

$$ak = c$$

$$bk = d$$

$$\frac{c}{a} = \frac{d}{b} = k$$

Matrix is singular if

a	b	* k =	c	d

$$ad = bc$$

Determinant

$$ad - bc = 0$$

Determinant

a	b
c	d

Determinant $= ad - bc$

$$ak = c$$

$$bk = d$$

$$\frac{c}{a} = \frac{d}{b} = k$$

Matrix is singular if

a	b	* k	=	c	d

$$ad = bc$$

Determinant

$$ad - bc = 0$$

Determinant

a	b
c	d

Determinant $= ad - bc$

a

d

$$ak = c$$

$$bk = d$$

$$\frac{c}{a} = \frac{d}{b} = k$$

Matrix is singular if

a	b	* k =	c	d

$$ad = bc$$

Determinant

$$ad - bc = 0$$

Determinant

a	b
c	d

Determinant $= ad - bc$

a

\-

d

$$ak = c$$

$$bk = d$$

$$\frac{c}{a} = \frac{d}{b} = k$$

Matrix is singular if

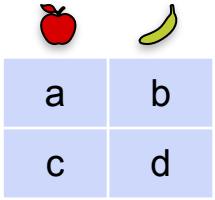
a	b	* k =	c	d

$$ad = bc$$

Determinant

$$ad - bc = 0$$

Determinant



Determinant $= ad - bc$

a d - b c

$$ak = c$$

$$bk = d$$

$$\frac{c}{a} = \frac{d}{b} = k$$

Matrix is singular if

a b * k = c d

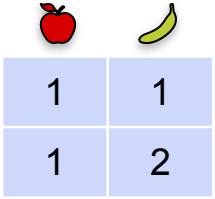
$$ad = bc$$

Determinant

$$ad - bc = 0$$

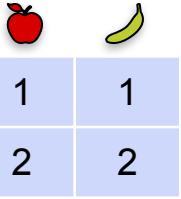
Determinant

Non-singular matrix



1	1
1	2

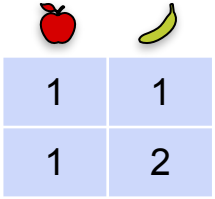
Singular matrix



1	1
2	2

Determinant

Non-singular matrix

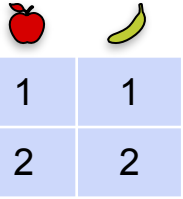


1	1
1	2

Determinant

$$\begin{vmatrix} 1 & 1 \\ 1 & 2 \end{vmatrix} = 1 \cdot 2 - 1 \cdot 1$$

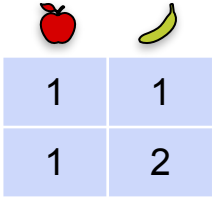
Singular matrix



1	1
2	2

Determinant

Non-singular matrix

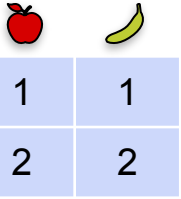


1	1
1	2

Determinant

$$1 \cdot 2 - 1 \cdot 1 = 1$$

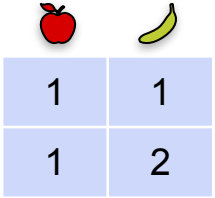
Singular matrix



1	1
2	2

Determinant

Non-singular matrix

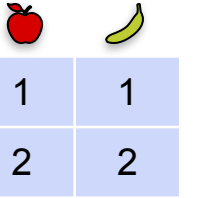


1	1
1	2

Determinant

$$1 \cdot 2 - 1 \cdot 1 = 1$$

Singular matrix

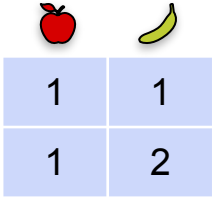


1	1
2	2

Determinant

Determinant

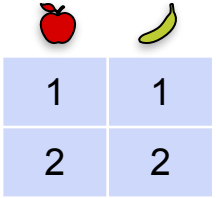
Non-singular matrix



Determinant

$$1 \cdot 2 - 1 \cdot 1 = 1$$

Singular matrix

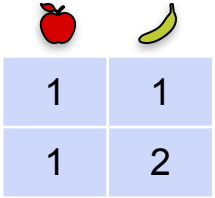


Determinant

$$1 \cdot 2 - 2 \cdot 1 = 0$$

Determinant

Non-singular matrix

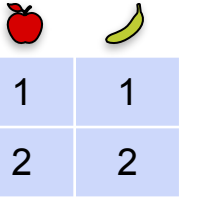


1	1
1	2

Determinant

$$1 \cdot 2 - 1 \cdot 1 = 1$$

Singular matrix



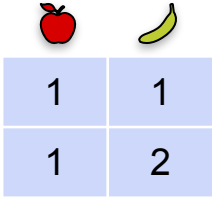
1	1
2	2

Determinant

$$1 \cdot 2 - 2 \cdot 1 = 0$$

Determinant

Non-singular matrix

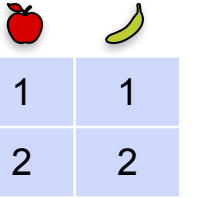


1	1
1	2

Determinant

$$1 \cdot 2 - 1 \cdot 1 = 1$$

Singular matrix

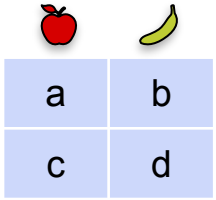


1	1
2	2

Determinant

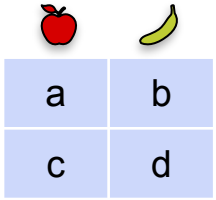
$$1 \cdot 2 - 2 \cdot 1 = 0$$

Determinant and singularity



$$ad - bc$$

Determinant and singularity



$$ad - bc$$

Matrix is singular ⟷ **Determinant is zero**

Quiz: Determinant

Problem 1: Find the determinant of the following matrices

Matrix 1

5	1
-1	3

Matrix 2

2	-1
-6	3

Problem 2: Are these matrices singular or non-singular?

Solutions: Determinant

Matrix 1: det = $5 \cdot 3 - 1 \cdot (-1) = 15 + 1 = 16$

5	1
-1	3

Non-singular

Matrix 2: det = $2 \cdot 3 - (-1) \cdot (-6) = 6 - 6 = 0$

2	-1
-6	3

Singular

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System of Linear Equations

System of equations (3x3)

Quiz: Systems of equations

Problem 1: You're trying to figure out the price of apples, bananas, and cherries at the store. You go three days in a row, and bring this information.

- **Day 1:** You bought an apple, a banana, and a cherry, and paid $10.
- **Day 2:** You bought an apple, two bananas, and a cherry, and paid $15.
- **Day 3:** You bought an apple, a banana, and two cherries, and paid $12.

How much does each fruit cost?

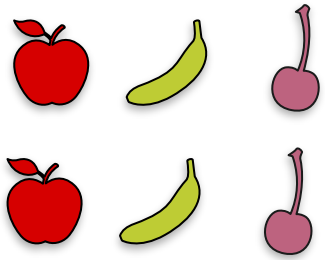
Solution: Systems of equations

Solution: Systems of equations

Solution: Systems of equations

$10

Solution: Systems of equations



$10

Solution: Systems of equations

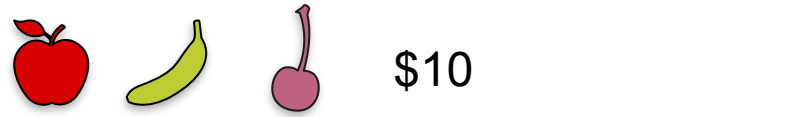
$10

Solution: Systems of equations

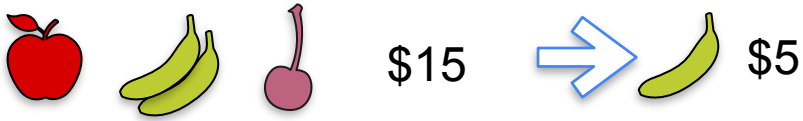
$10

$15

Solution: Systems of equations



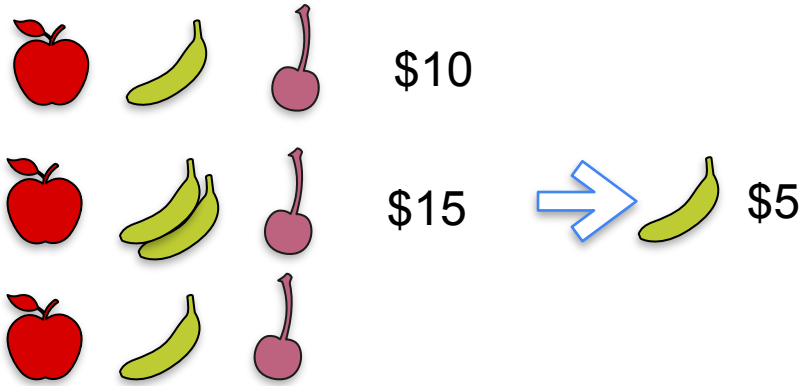
$10



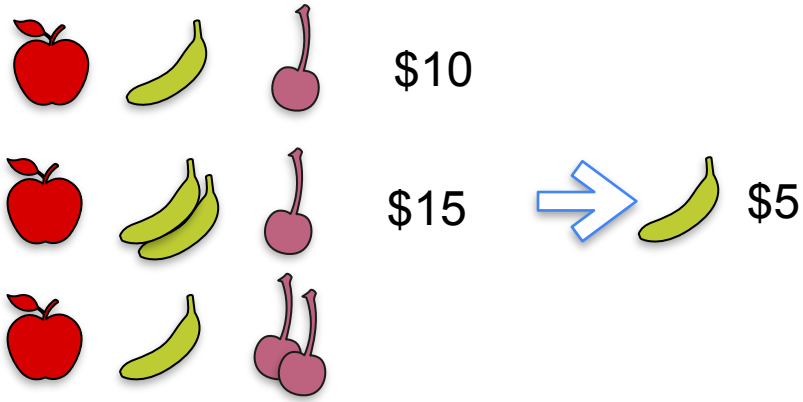
$15

$5

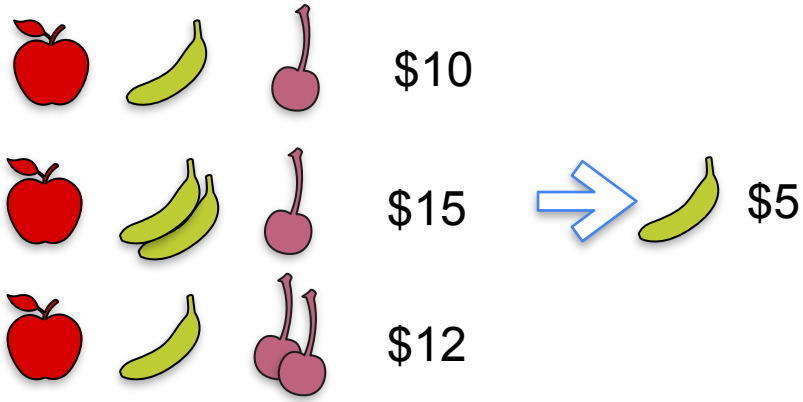
Solution: Systems of equations



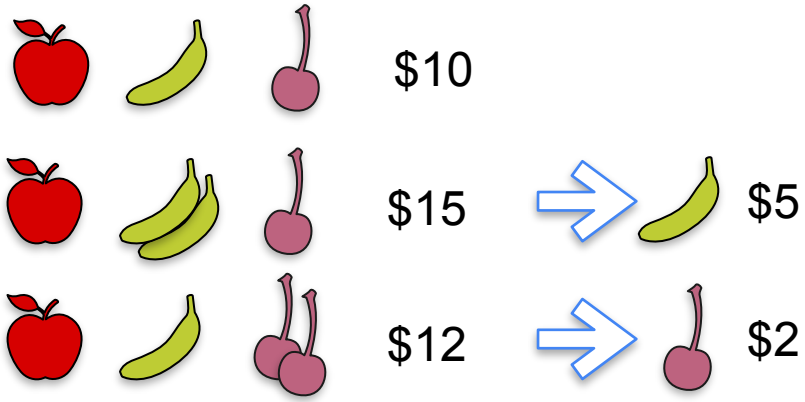
Solution: Systems of equations



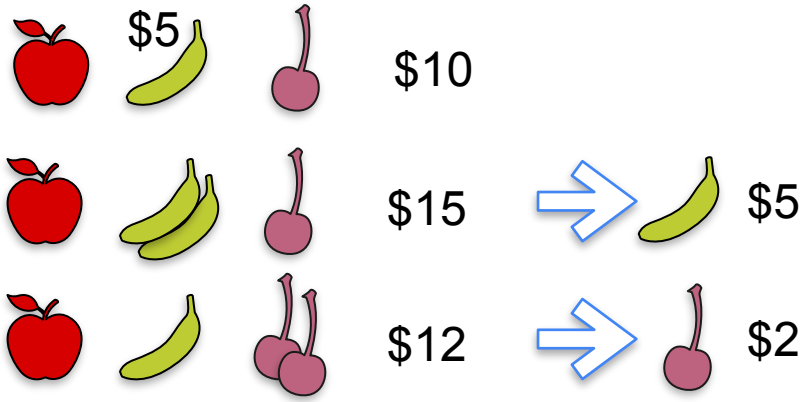
Solution: Systems of equations



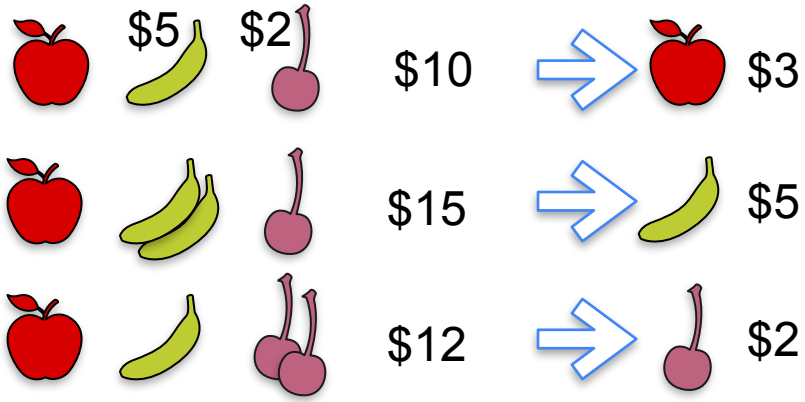
Solution: Systems of equations



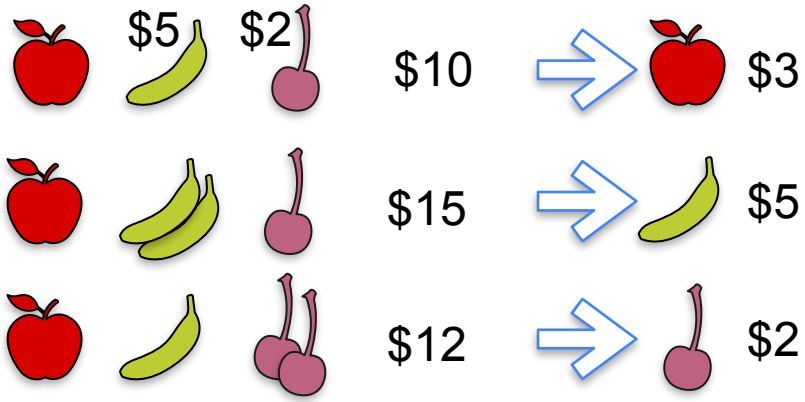
Solution: Systems of equations



Solution: Systems of equations



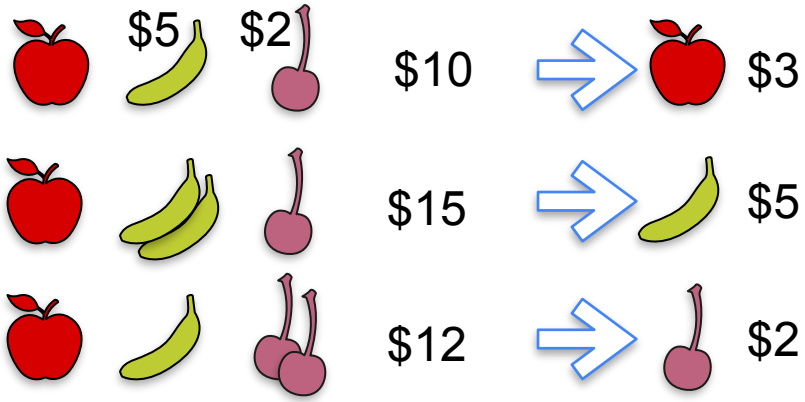
Solution: Systems of equations



System of equations 1

$$a + b + c = 10$$
$$a + 2b + c = 15$$
$$a + b + 2c = 12$$

Solution: Systems of equations



System of equations 1

$$a + b + c = 10$$
$$a + 2b + c = 15$$
$$a + b + 2c = 12$$

Solution

$$a = 3$$
$$b = 5$$
$$c = 2$$

Quiz: More systems of equations

System 2

$$a + b + c = 10$$
$$a + b + 2c = 15$$
$$a + b + 3c = 20$$

System 3

$$a + b + c = 10$$
$$a + b + 2c = 15$$
$$a + b + 3c = 18$$

System 4

$$a + b + c = 10$$
$$2a + 2b + 2c = 20$$
$$3a + 3b + 3c = 30$$

Solutions: More systems of equations

System 2

$$a + b + c = 10$$
$$a + b + 2c = 15$$
$$a + b + 3c = 20$$

System 3

$$a + b + c = 10$$
$$a + b + 2c = 15$$
$$a + b + 3c = 18$$

System 4

$$a + b + c = 10$$
$$2a + 2b + 2c = 20$$
$$3a + 3b + 3c = 30$$

Solutions: More systems of equations

System 2

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 20$

Infinitely many sols.

System 3

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 18$

System 4

$a + b + c = 10$
$2a + 2b + 2c = 20$
$3a + 3b + 3c = 30$

Solutions: More systems of equations

System 2

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 20$

Infinitely many sols.

$c = 5$

System 3

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 18$

System 4

$a + b + c = 10$
$2a + 2b + 2c = 20$
$3a + 3b + 3c = 30$

Solutions: More systems of equations

System 2

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 20$

Infinitely many sols.

$c = 5$

$a + b = 5$

System 3

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 18$

System 4

$a + b + c = 10$
$2a + 2b + 2c = 20$
$3a + 3b + 3c = 30$

Solutions: More systems of equations

System 2

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 20$

Infinitely many sols.

$c = 5$

$a + b = 5$

(0,5,5), (1,4,5), (2,3,5), …

System 3

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 18$

System 4

$a + b + c = 10$
$2a + 2b + 2c = 20$
$3a + 3b + 3c = 30$

Solutions: More systems of equations

System 2

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 20$

Infinitely many sols.

$c = 5$

$a + b = 5$

(0,5,5), (1,4,5), (2,3,5), …

System 3

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 18$

No solutions

System 4

$a + b + c = 10$
$2a + 2b + 2c = 20$
$3a + 3b + 3c = 30$

Solutions: More systems of equations

System 2

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 20$

Infinitely many sols.

$c = 5$

$a + b = 5$

(0,5,5), (1,4,5), (2,3,5), …

System 3

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 18$

No solutions

From 1st and 2nd:

$c = 5$

From 2nd and 3rd:

$c = 3$

System 4

$a + b + c = 10$
$2a + 2b + 2c = 20$
$3a + 3b + 3c = 30$

Solutions: More systems of equations

System 2

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 20$

Infinitely many sols.

$c = 5$

$a + b = 5$

(0,5,5), (1,4,5), (2,3,5), …

System 3

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 18$

No solutions

From 1st and 2nd:
$c = 5$
From 2nd and 3rd:
$c = 3$

System 4

$a + b + c = 10$
$2a + 2b + 2c = 20$
$3a + 3b + 3c = 30$

Infinitely many solutions

Solutions: More systems of equations

System 2

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 20$

Infinitely many sols.

$c = 5$

$a + b = 5$

(0,5,5), (1,4,5), (2,3,5), …

System 3

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 18$

No solutions

From 1st and 2nd:
$c = 5$
From 2nd and 3rd:
$c = 3$

System 4

$a + b + c = 10$
$2a + 2b + 2c = 20$
$3a + 3b + 3c = 30$

Infinitely many solutions

Any 3 numbers that add to 10 work.
(0,0,10), (2,7,1), …

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System of Linear Equations

Singular vs non-singular matrices

Constants don’t matter for singularity

System 1

$a + b + c = 10$
$a + 2b + c = 15$
$a + b + 2c = 12$

System 2

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 20$

System 3

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 18$

System 4

$a + b + c = 10$
$2a + 2b + 2c = 15$
$3a + 3b + 3c = 20$

Constants don’t matter for singularity

System 1

$a + b + c = 10$
$a + 2b + c = 15$
$a + b + 2c = 12$

System 2

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 20$

System 3

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 18$

System 4

$a + b + c = 10$
$2a + 2b + 2c = 15$
$3a + 3b + 3c = 20$

Unique solution

Constants don’t matter for singularity

System 1

$a + b + c = 10$
$a + 2b + c = 15$
$a + b + 2c = 12$

Unique solution

System 2

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 20$

Infinite solutions

System 3

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 18$

System 4

$a + b + c = 10$
$2a + 2b + 2c = 15$
$3a + 3b + 3c = 20$

Constants don’t matter for singularity

System 1

$a + b + c = 10$
$a + 2b + c = 15$
$a + b + 2c = 12$

Unique solution

System 2

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 20$

Infinite solutions

System 3

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 18$

No solutions

System 4

$a + b + c = 10$
$2a + 2b + 2c = 15$
$3a + 3b + 3c = 20$

Constants don’t matter for singularity

System 1

$a + b + c = 10$
$a + 2b + c = 15$
$a + b + 2c = 12$

Unique solution

System 2

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 20$

Infinite solutions

System 3

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 18$

No solutions

System 4

$a + b + c = 10$
$2a + 2b + 2c = 15$
$3a + 3b + 3c = 20$

Infinite solutions

Constants don’t matter for singularity

System 1	System 2	System 3	System 4
$a + b + c = 10$ $a + 2b + c = 15$ $a + b + 2c = 12$	$a + b + c = 10$ $a + b + 2c = 15$ $a + b + 3c = 20$	$a + b + c = 10$ $a + b + 2c = 15$ $a + b + 3c = 18$	$a + b + c = 10$ $2a + 2b + 2c = 15$ $3a + 3b + 3c = 20$
Unique solution	**Infinite solutions**	**No solutions**	**Infinite solutions**
Complete			

Constants don’t matter for singularity

System 1

$a + b + c = 10$
$a + 2b + c = 15$
$a + b + 2c = 12$

Unique solution

Complete

System 2

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 20$

Infinite solutions

Redundant

System 3

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 18$

No solutions

System 4

$a + b + c = 10$
$2a + 2b + 2c = 15$
$3a + 3b + 3c = 20$

Infinite solutions

Constants don’t matter for singularity

System 1

$a + b + c = 10$
$a + 2b + c = 15$
$a + b + 2c = 12$

Unique solution

Complete

System 2

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 20$

Infinite solutions

Redundant

System 3

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 18$

No solutions

Contradictory

System 4

$a + b + c = 10$
$2a + 2b + 2c = 15$
$3a + 3b + 3c = 20$

Infinite solutions

Constants don’t matter for singularity

System 1	System 2	System 3	System 4
$a + b + c = 10$ $a + 2b + c = 15$ $a + b + 2c = 12$	$a + b + c = 10$ $a + b + 2c = 15$ $a + b + 3c = 20$	$a + b + c = 10$ $a + b + 2c = 15$ $a + b + 3c = 18$	$a + b + c = 10$ $2a + 2b + 2c = 15$ $3a + 3b + 3c = 20$
Unique solution	**Infinite solutions**	**No solutions**	**Infinite solutions**
Complete	**Redundant**	**Contradictory**	**Redundant**

Constants don’t matter for singularity

System 1	System 2	System 3	System 4
$a + b + c = 10$ $a + 2b + c = 15$ $a + b + 2c = 12$	$a + b + c = 10$ $a + b + 2c = 15$ $a + b + 3c = 20$	$a + b + c = 10$ $a + b + 2c = 15$ $a + b + 3c = 18$	$a + b + c = 10$ $2a + 2b + 2c = 15$ $3a + 3b + 3c = 20$
Unique solution	**Infinite solutions**	**No solutions**	**Infinite solutions**
Complete	**Redundant**	**Contradictory**	**Redundant**
Non-singular			

Constants don’t matter for singularity

System 1	System 2	System 3	System 4
$a + b + c = 10$ $a + 2b + c = 15$ $a + b + 2c = 12$	$a + b + c = 10$ $a + b + 2c = 15$ $a + b + 3c = 20$	$a + b + c = 10$ $a + b + 2c = 15$ $a + b + 3c = 18$	$a + b + c = 10$ $2a + 2b + 2c = 15$ $3a + 3b + 3c = 20$
Unique solution	**Infinite solutions**	**No solutions**	**Infinite solutions**
Complete	**Redundant**	**Contradictory**	**Redundant**
Non-singular	**Singular**		

Constants don’t matter for singularity

System 1

$a + b + c = 10$
$a + 2b + c = 15$
$a + b + 2c = 12$

Unique solution

Complete

Non-singular

System 2

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 20$

Infinite solutions

Redundant

Singular

System 3

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 18$

No solutions

Contradictory

Singular

System 4

$a + b + c = 10$
$2a + 2b + 2c = 15$
$3a + 3b + 3c = 20$

Infinite solutions

Redundant

Constants don’t matter for singularity

System 1	System 2	System 3	System 4
$a + b + c = 10$ $a + 2b + c = 15$ $a + b + 2c = 12$	$a + b + c = 10$ $a + b + 2c = 15$ $a + b + 3c = 20$	$a + b + c = 10$ $a + b + 2c = 15$ $a + b + 3c = 18$	$a + b + c = 10$ $2a + 2b + 2c = 15$ $3a + 3b + 3c = 20$
Unique solution	**Infinite solutions**	**No solutions**	**Infinite solutions**
Complete	**Redundant**	**Contradictory**	**Redundant**
Non-singular	**Singular**	**Singular**	**Singular**

Constants don’t matter for singularity

System 1

$a + b + c = 10$
$a + 2b + c = 15$
$a + b + 2c = 12$

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

System 2

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 20$

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 3

$a + b + c = 10$
$a + b + 2c = 15$
$a + b + 3c = 18$

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 4

$a + b + c = 10$
$2a + 2b + 2c = 20$
$3a + 3b + 3c = 30$

$a + b + c = 0$
$2a + 2b + 2c = 0$
$3a + 3b + 3c = 0$

Constants don’t matter for singularity

System 1

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

System 2

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 3

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 4

$a + b + c = 0$
$2a + 2b + 2c = 0$
$3a + 3b + 3c = 0$

Constants don’t matter for singularity

System 1

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

Unique solution:
$a = 0$
$b = 0$
$c = 0$

System 2

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 3

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 4

$a + b + c = 0$
$2a + 2b + 2c = 0$
$3a + 3b + 3c = 0$

Constants don’t matter for singularity

System 1

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

Unique solution:
$a = 0$
$b = 0$
$c = 0$

Complete

Non-singular

System 2

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 3

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 4

$a + b + c = 0$
$2a + 2b + 2c = 0$
$3a + 3b + 3c = 0$

Constants don’t matter for singularity

System 1

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

Unique solution:
a = 0
b = 0
c = 0

Complete

Non-singular

System 2

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

Infinite solutions:
c = 0
a + b = 0
(i.e., a = -b)

System 3

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 4

$a + b + c = 0$
$2a + 2b + 2c = 0$
$3a + 3b + 3c = 0$

Constants don’t matter for singularity

System 1

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

Unique solution:
a = 0
b = 0
c = 0

Complete

Non-singular

System 2

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

Infinite solutions:
c = 0
a + b = 0
(i.e., a = -b)

Redundant

Singular

System 3

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 4

$a + b + c = 0$
$2a + 2b + 2c = 0$
$3a + 3b + 3c = 0$

Constants don’t matter for singularity

System 1

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

Unique solution:
a = 0
b = 0
c = 0

Complete

Non-singular

System 2

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

Infinite solutions:
c = 0
a + b = 0
(i.e., a = -b)

Redundant

Singular

System 3

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 4

$a + b + c = 0$
$2a + 2b + 2c = 0$
$3a + 3b + 3c = 0$

Infinite solutions:
a + b +c = 0
(i.e., c = - a - b)

Constants don’t matter for singularity

System 1

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

Unique solution:
$a = 0$
$b = 0$
$c = 0$

Complete

Non-singular

System 2

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

Infinite solutions:
$c = 0$
$a + b = 0$
(i.e., $a = -b$)

Redundant

Singular

System 3

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 4

$a + b + c = 0$
$2a + 2b + 2c = 0$
$3a + 3b + 3c = 0$

Infinite solutions:
$a + b + c = 0$
(i.e., $c = - a - b$)

Redundant

Singular

Constants don’t matter for singularity

System 1

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

System 2

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 3

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 4

$a + b + c = 0$
$2a + 2b + 2c = 0$
$3a + 3b + 3c = 0$

Constants don’t matter for singularity

System 1

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

1	1	1
1	2	1
1	1	2

System 2

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 3

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 4

$a + b + c = 0$
$2a + 2b + 2c = 0$
$3a + 3b + 3c = 0$

Constants don’t matter for singularity

System 1

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

1	1	1
1	2	1
1	1	2

System 2

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

1	1	1
1	1	2
1	1	3

System 3

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 4

$a + b + c = 0$
$2a + 2b + 2c = 0$
$3a + 3b + 3c = 0$

Constants don’t matter for singularity

System 1

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

1	1	1
1	2	1
1	1	2

System 2

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

1	1	1
1	1	2
1	1	3

System 3

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 4

$a + b + c = 0$
$2a + 2b + 2c = 0$
$3a + 3b + 3c = 0$

1	1	1
2	2	2
3	3	3

Constants don’t matter for singularity

System 1

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

1	1	1
1	2	1
1	1	2

Non-singular

System 2

$$a + b + c = 0$$
$$a + b + 2c = 0$$
$$a + b + 3c = 0$$

1	1	1
1	1	2
1	1	3

System 3

$$a + b + c = 0$$
$$a + b + 2c = 0$$
$$a + b + 3c = 0$$

System 4

$$a + b + c = 0$$
$$2a + 2b + 2c = 0$$
$$3a + 3b + 3c = 0$$

1	1	1
2	2	2
3	3	3

Constants don’t matter for singularity

System 1

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

1	1	1
1	2	1
1	1	2

Non-singular

System 2

$$a + b + c = 0$$
$$a + b + 2c = 0$$
$$a + b + 3c = 0$$

1	1	1
1	1	2
1	1	3

Singular

System 3

$$a + b + c = 0$$
$$a + b + 2c = 0$$
$$a + b + 3c = 0$$

System 4

$$a + b + c = 0$$
$$2a + 2b + 2c = 0$$
$$3a + 3b + 3c = 0$$

1	1	1
2	2	2
3	3	3

Constants don’t matter for singularity

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1	1	2

Non-singular

System 2

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

1	1	1
1	1	2
1	1	3

Singular

System 3

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

System 4

$a + b + c = 0$
$2a + 2b + 2c = 0$
$3a + 3b + 3c = 0$

1	1	1
2	2	2
3	3	3

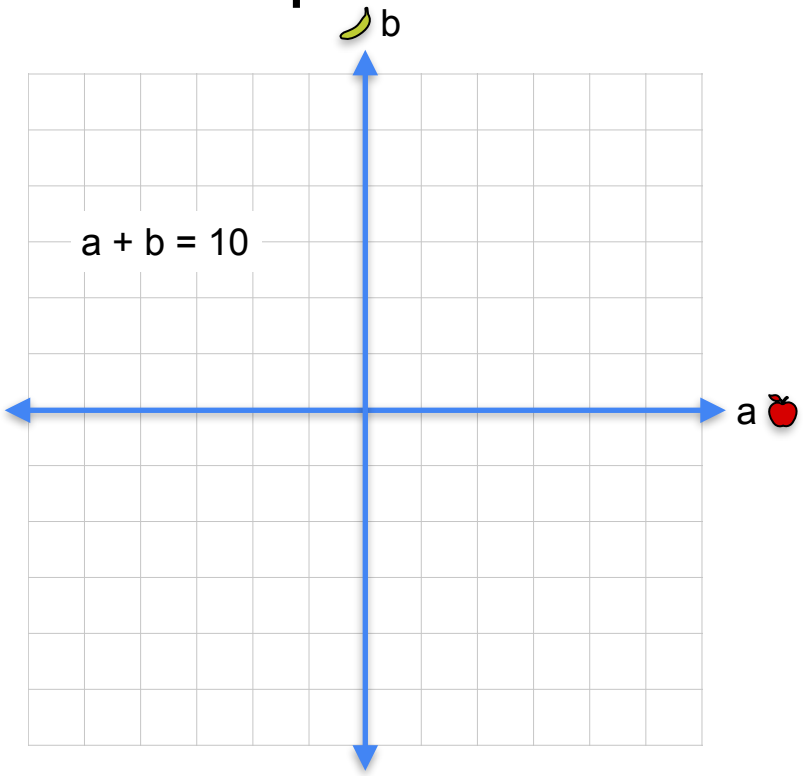
Singular

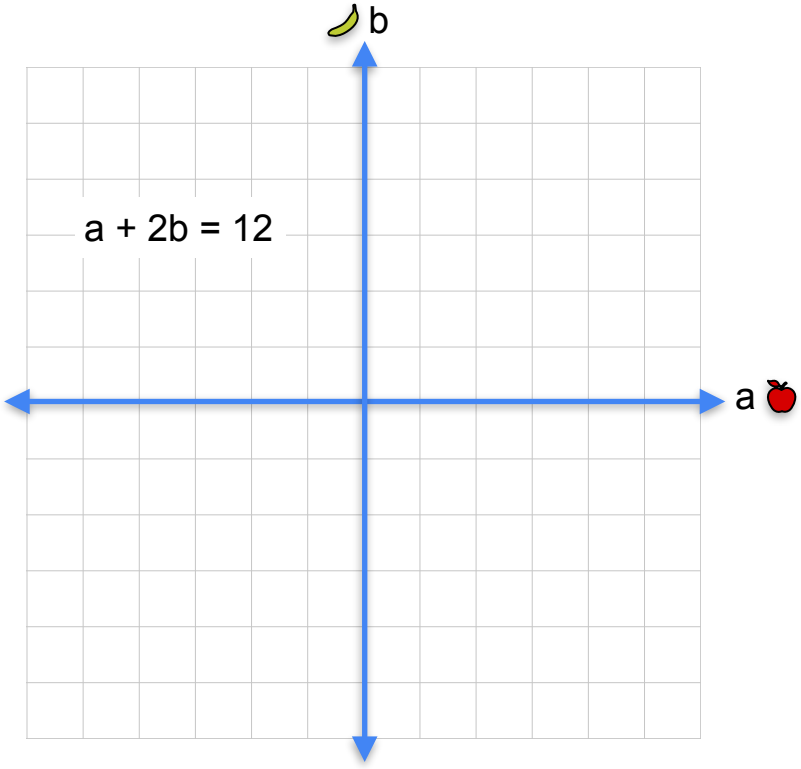
DeepLearning.AI

System of Linear Equations

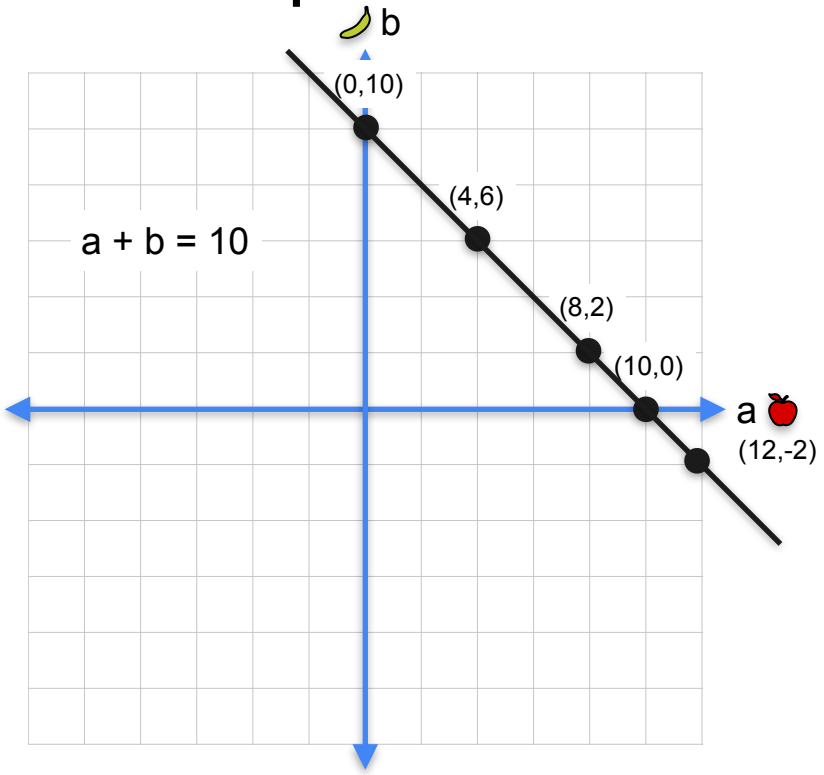
System of equations as planes (3x3)

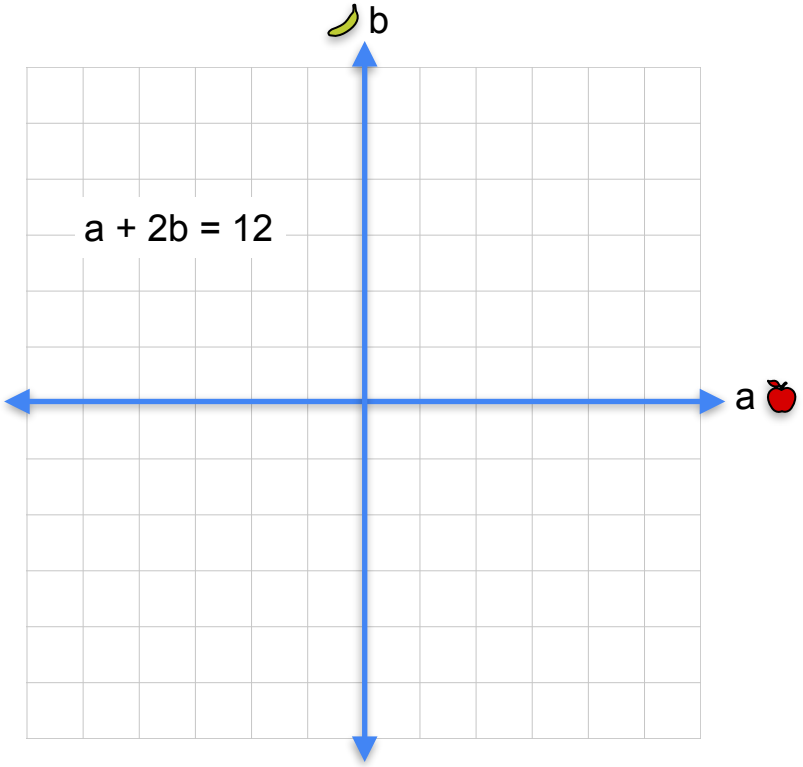
Linear equation in 2 variables -> Line



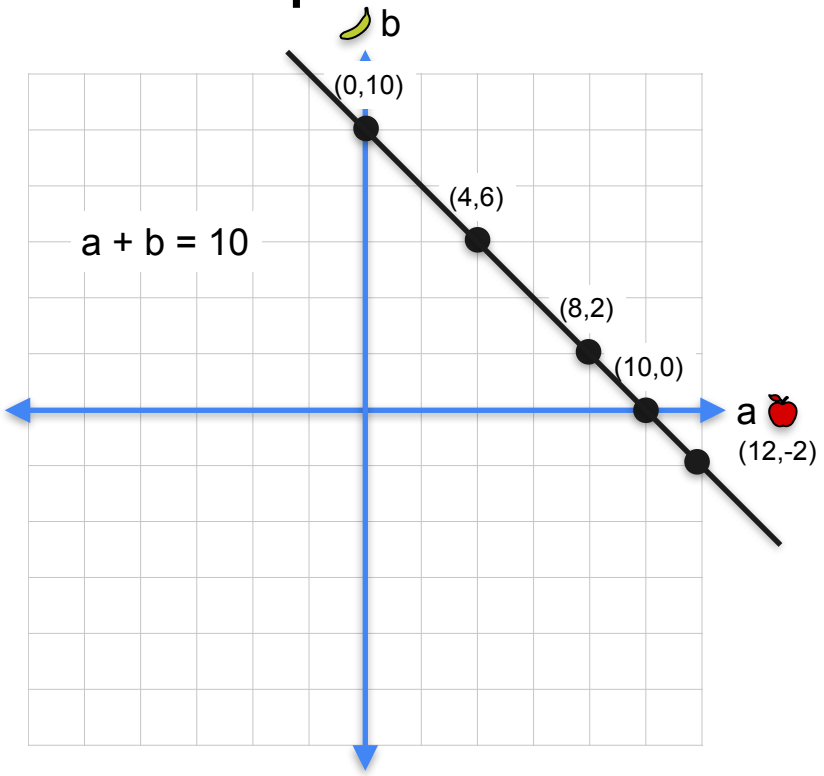


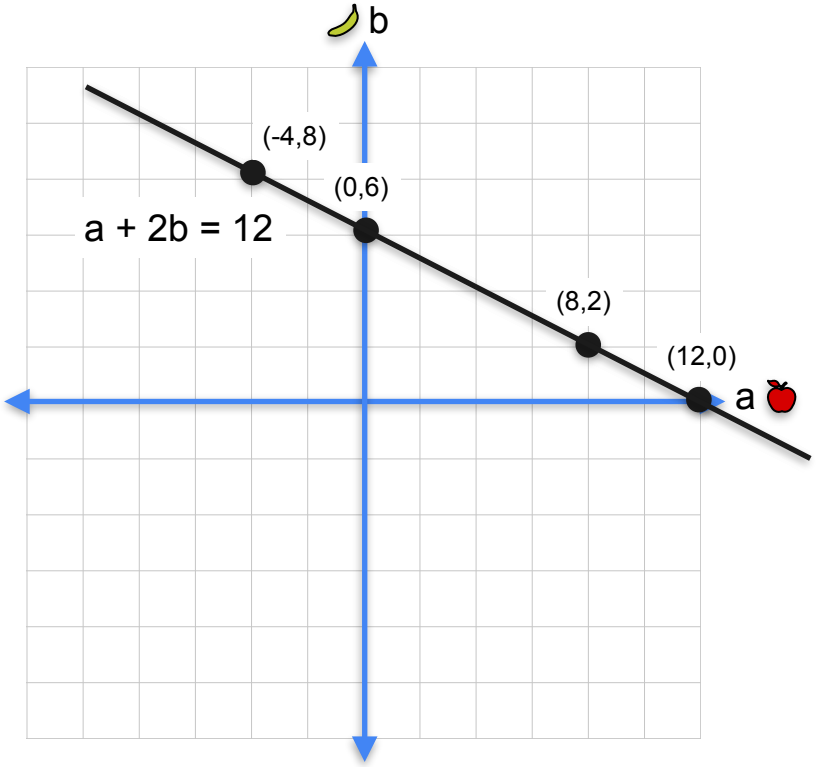
Linear equation in 2 variables -> Line





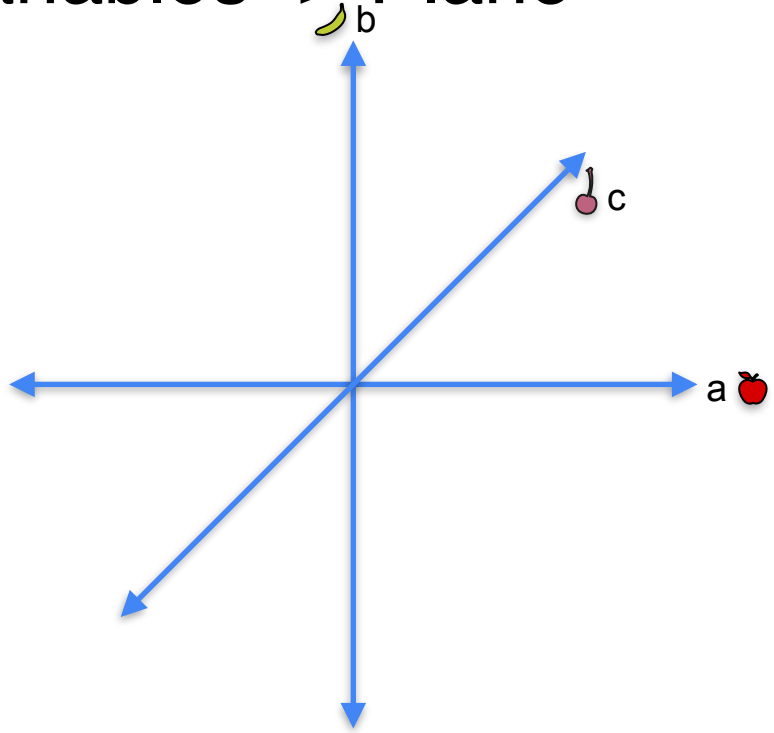
Linear equation in 2 variables -> Line





Linear equation in 3 variables -> Plane

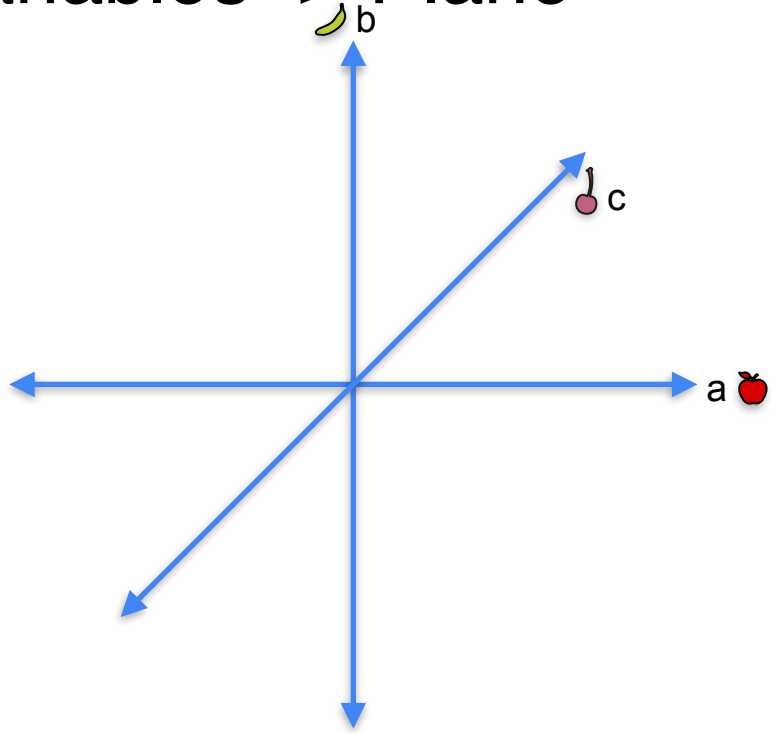
$a + b + c = 1$



Linear equation in 3 variables -> Plane

$a + b + c = 1$

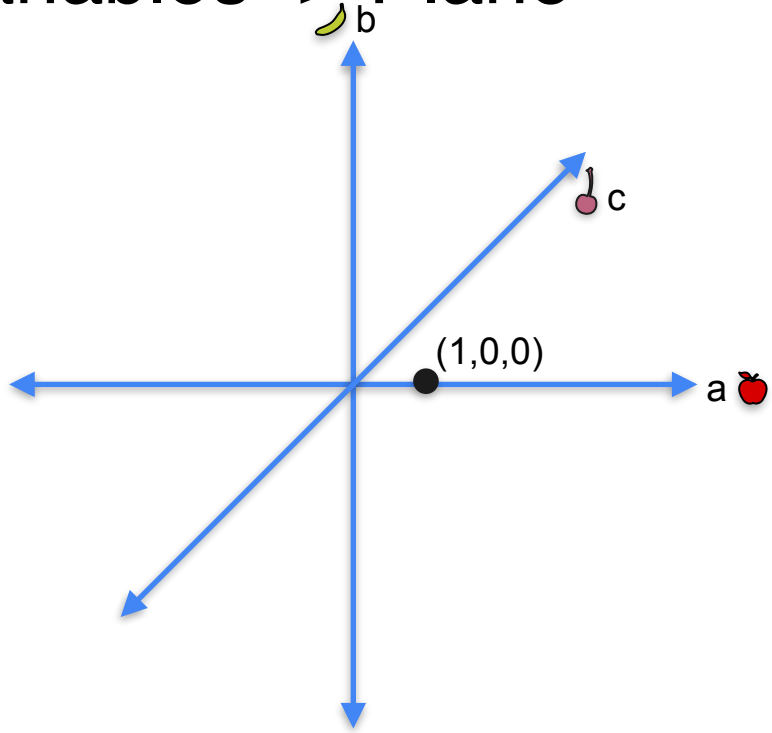
$1 + 0 + 0 = 1$



Linear equation in 3 variables -> Plane

$a + b + c = 1$

$1 + 0 + 0 = 1$

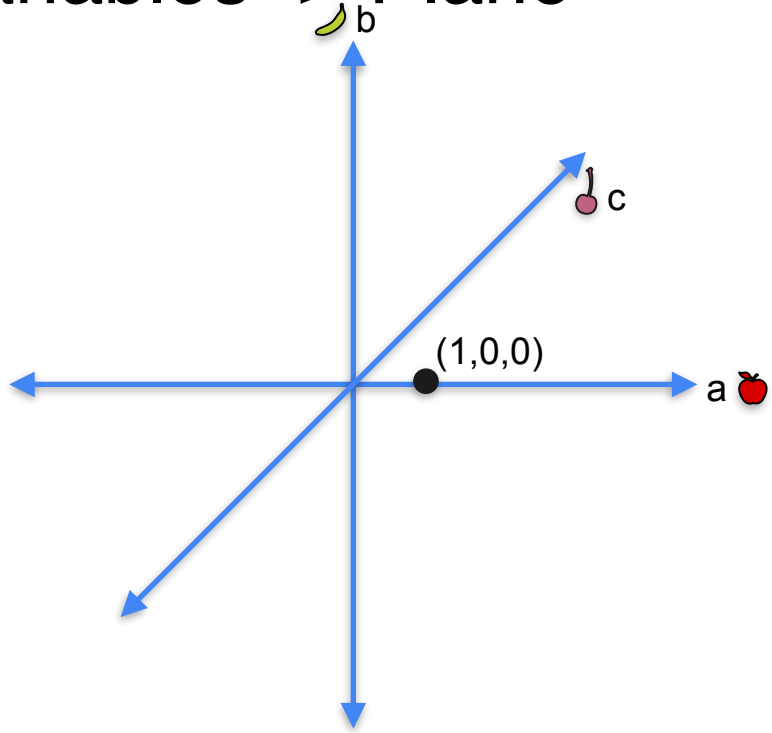


Linear equation in 3 variables -> Plane

$a + b + c = 1$

$1 + 0 + 0 = 1$

$0 + 1 + 0 = 1$

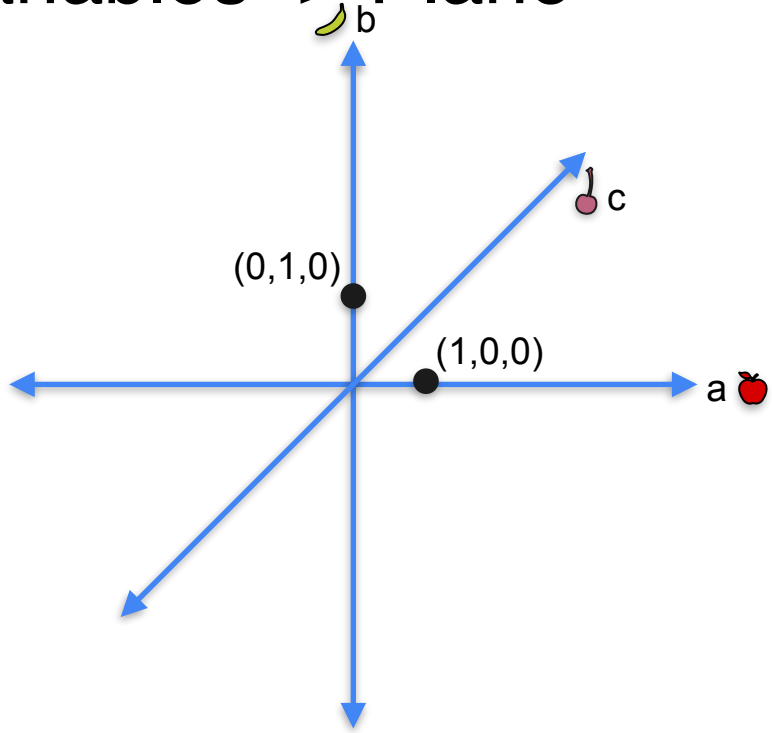


Linear equation in 3 variables -> Plane

$a + b + c = 1$

$1 + 0 + 0 = 1$

$0 + 1 + 0 = 1$



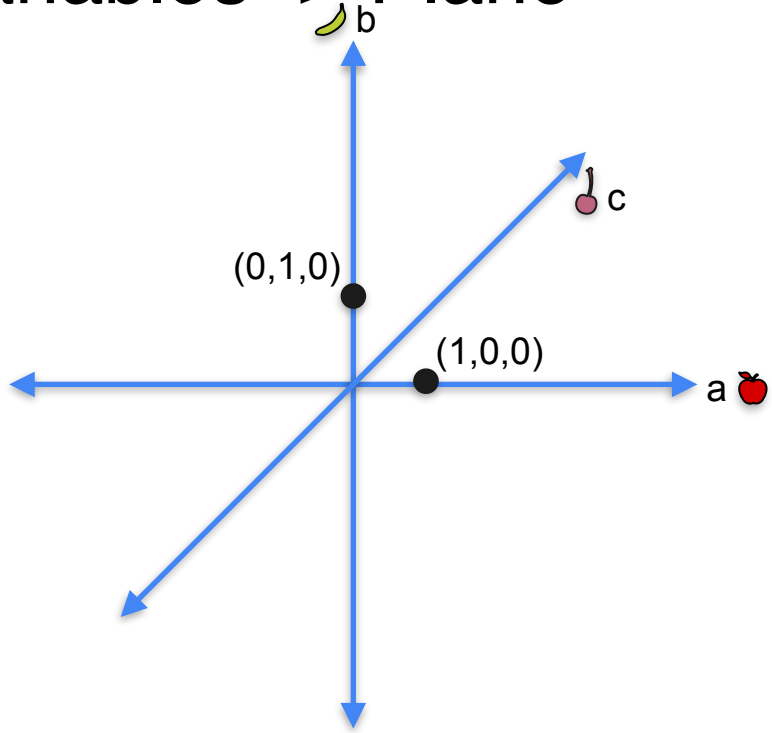
Linear equation in 3 variables -> Plane

$a + b + c = 1$

$1 + 0 + 0 = 1$

$0 + 1 + 0 = 1$

$0 + 0 + 1 = 1$



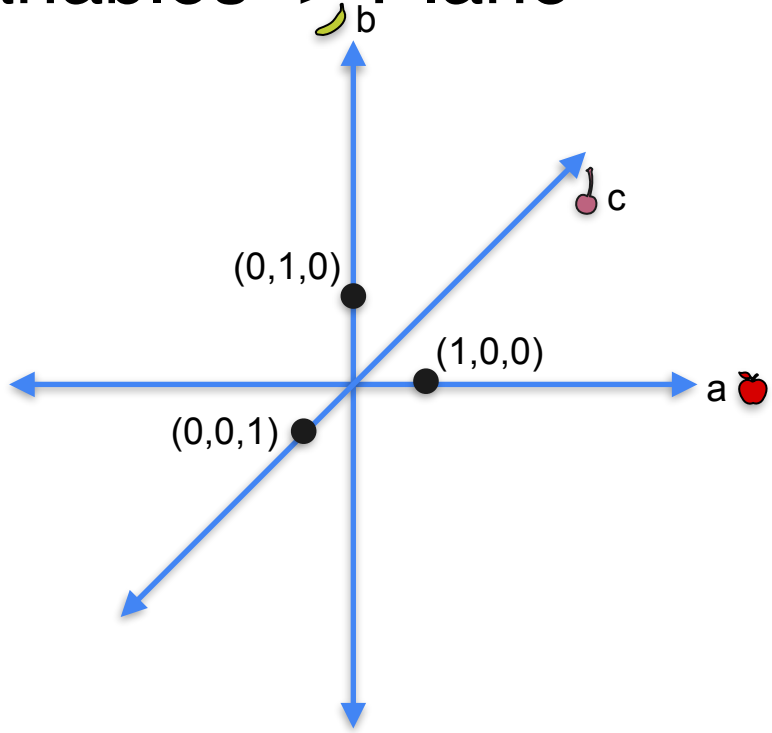
Linear equation in 3 variables -> Plane

$a + b + c = 1$

$1 + 0 + 0 = 1$

$0 + 1 + 0 = 1$

$0 + 0 + 1 = 1$



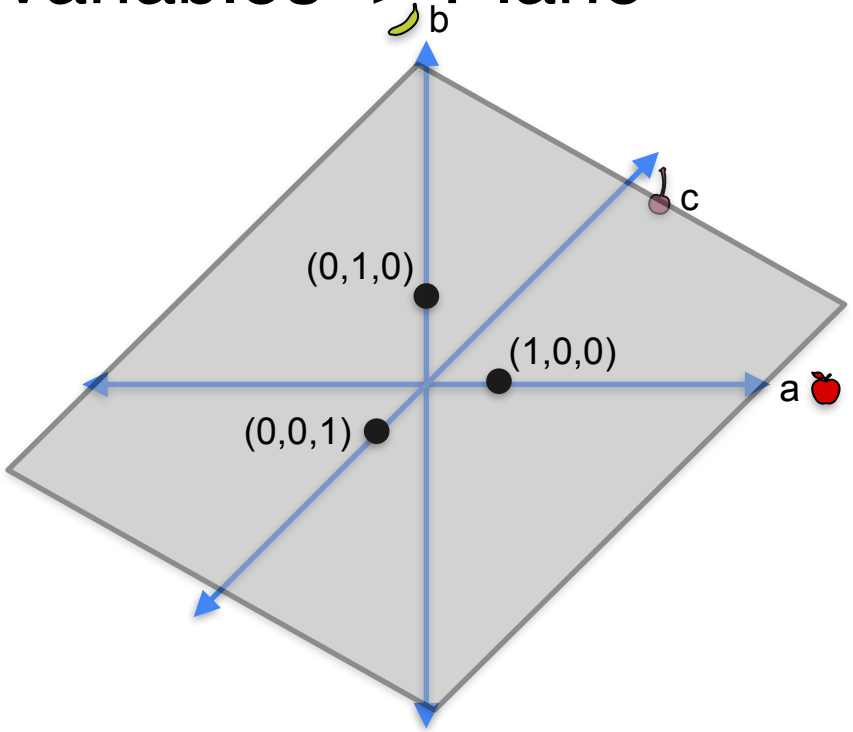
Linear equation in 3 variables -> Plane

$a + b + c = 1$

$1 + 0 + 0 = 1$

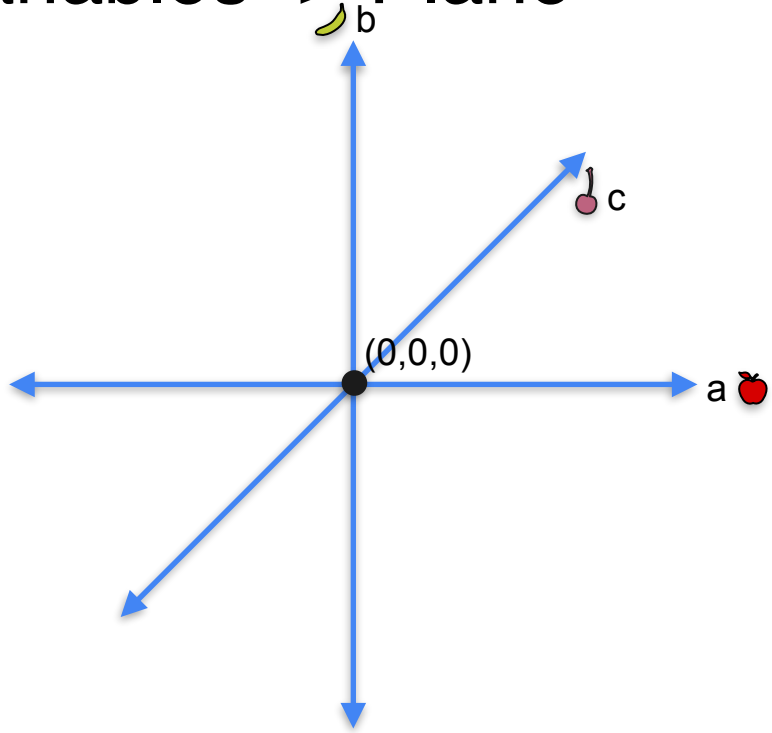
$0 + 1 + 0 = 1$

$0 + 0 + 1 = 1$



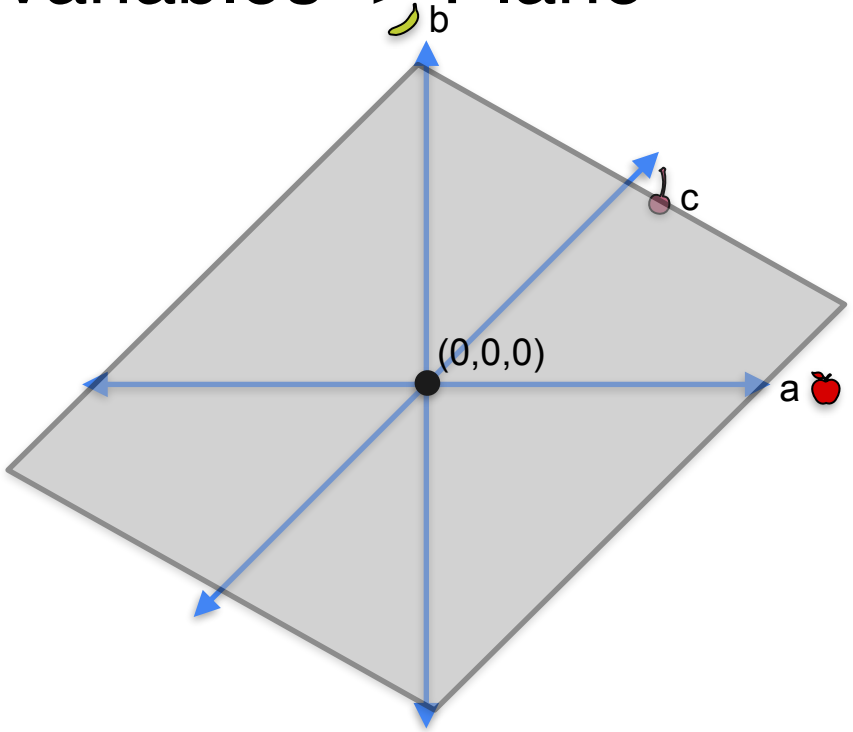
Linear equation in 3 variables -> Plane

$3a - 5b + 2c = \mathbf{0}$



Linear equation in 3 variables -> Plane

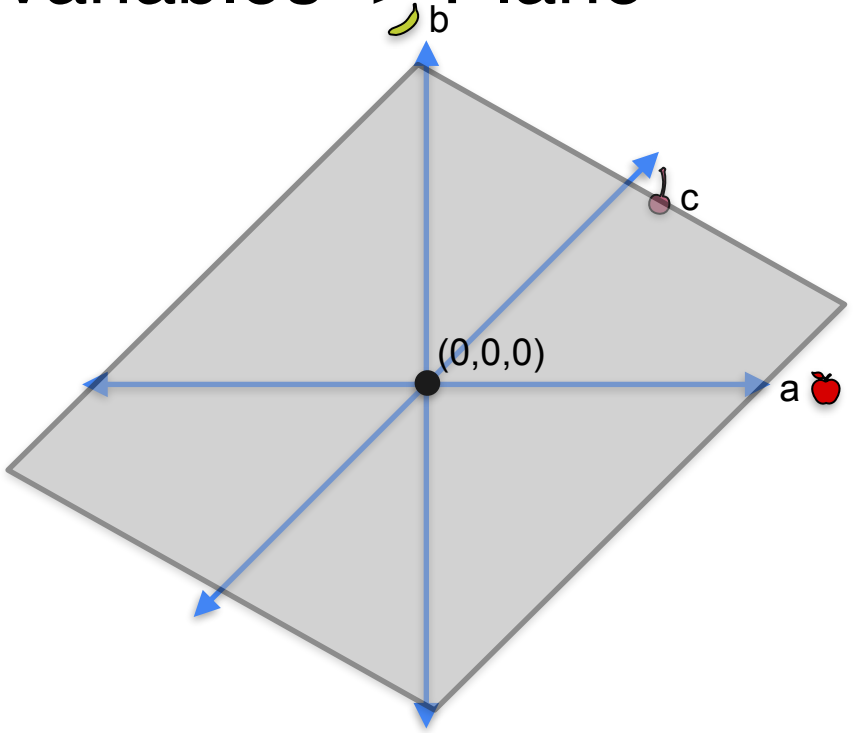
$3a - 5b + 2c = \mathbf{0}$



Linear equation in 3 variables -> Plane

$3a - 5b + 2c = 0$

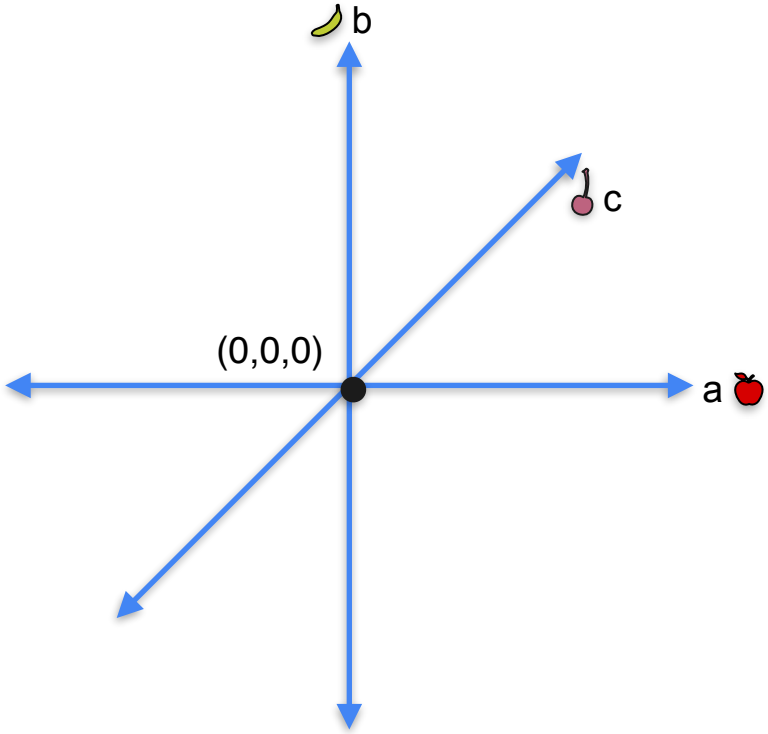
$3(0) + 5(0) + 2(0) = 0$



System 1

System 1

- a + b + c = **0**
- a + 2b + c = **0**
- a + b + 2c = **0**



System 1

System 1

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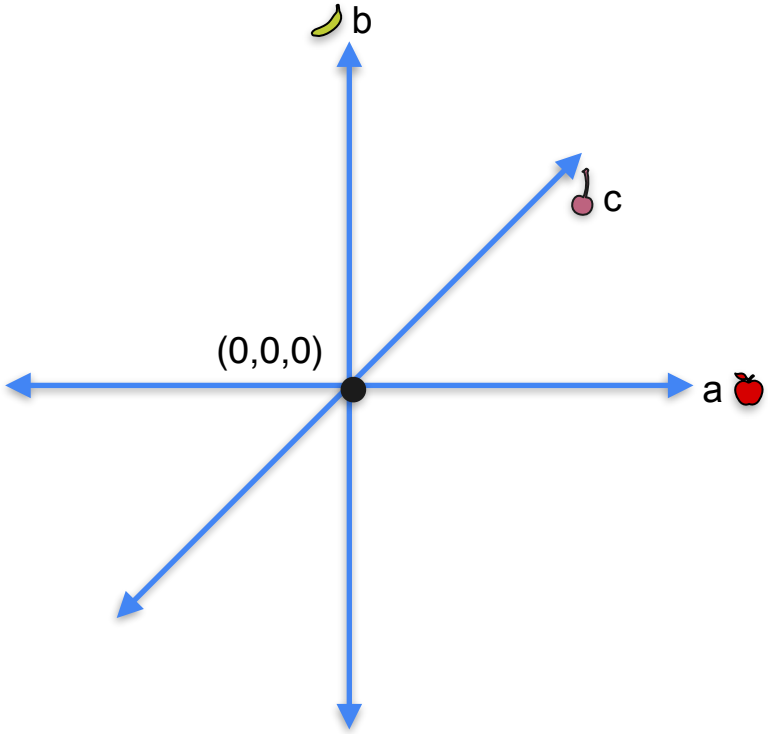
- $a + 2b + c = 0$
- $a + b + 2c = 0$



System 1

System 1

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- $a + 2b + c = 0$
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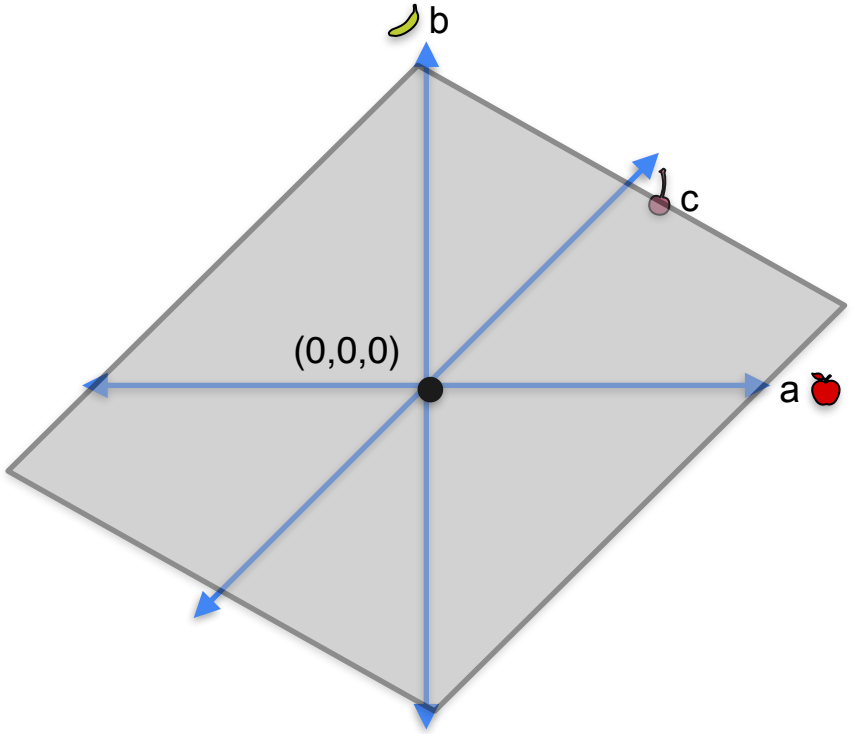
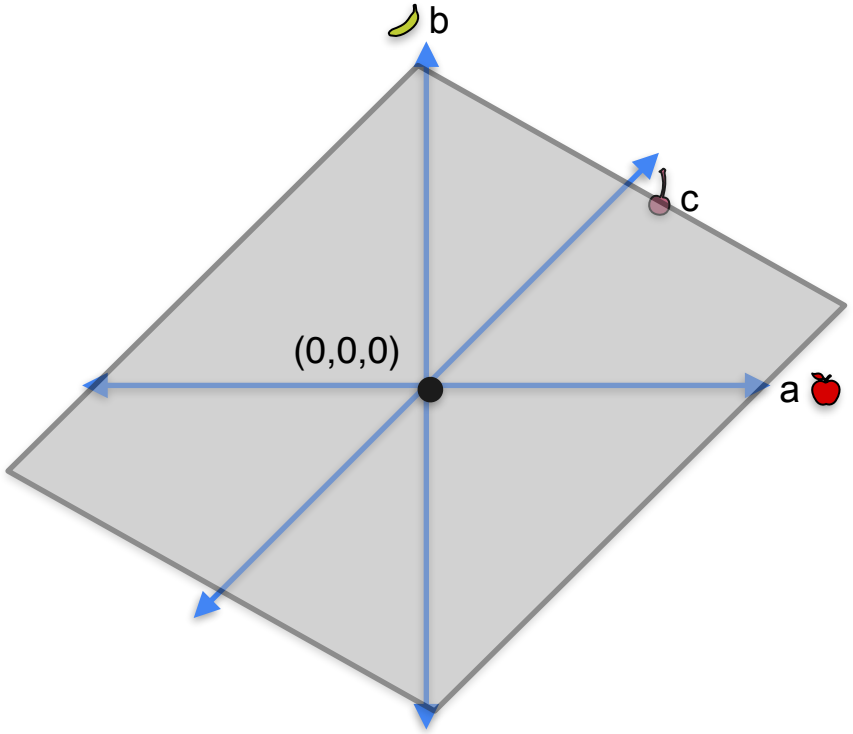


System 1

System 1

- a + b + c = **0**
- a + 2b + c = **0**
- a + b + 2c = **0**



System 1

System 1

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- a + 2b + c = **0**
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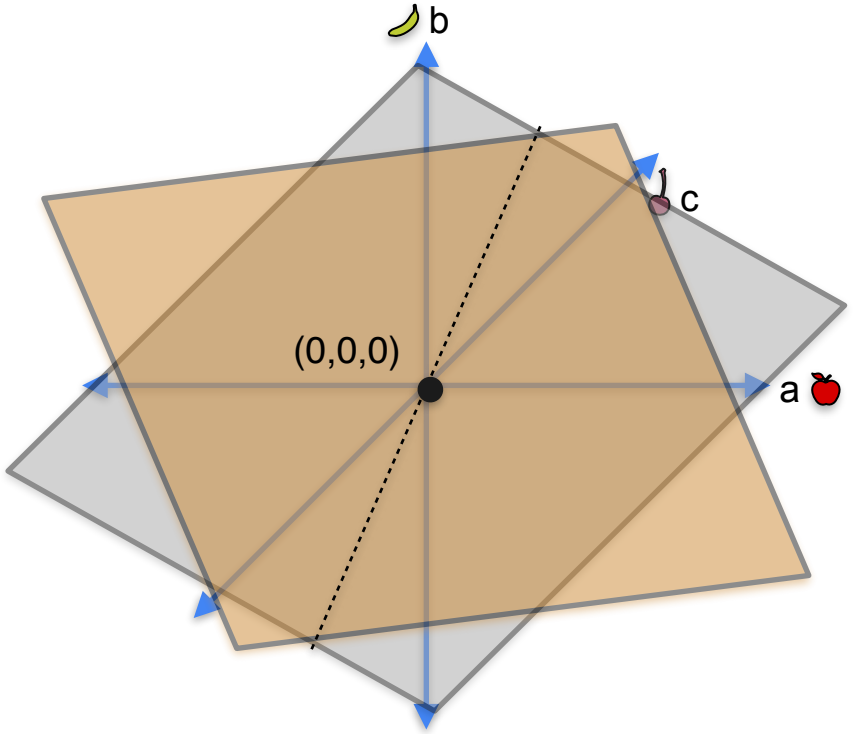

System 1

System 1

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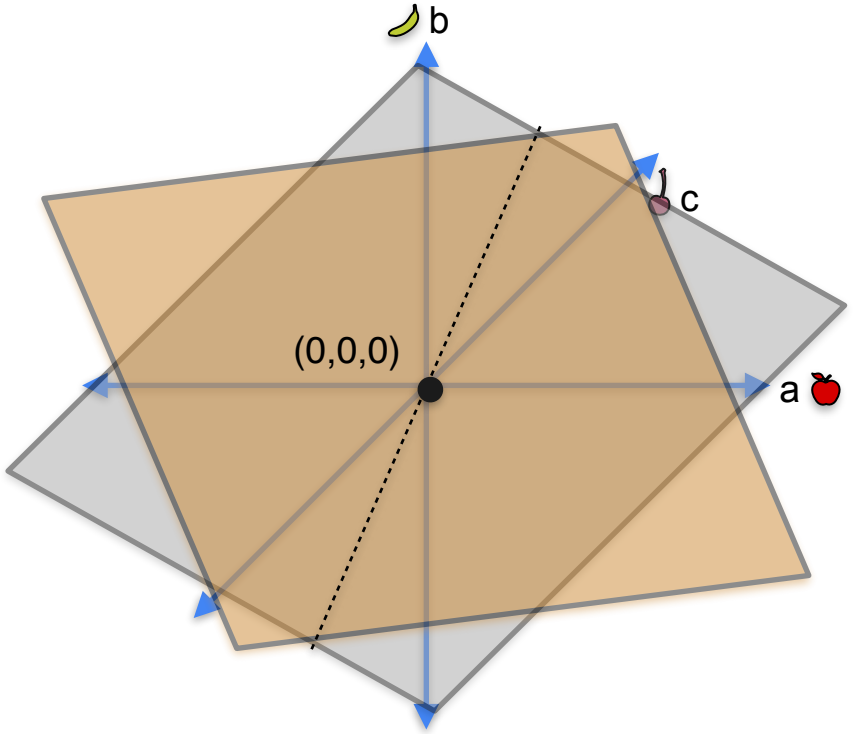
- $a + 2b + c = 0$
- $a + b + 2c = 0$



System 1

System 1

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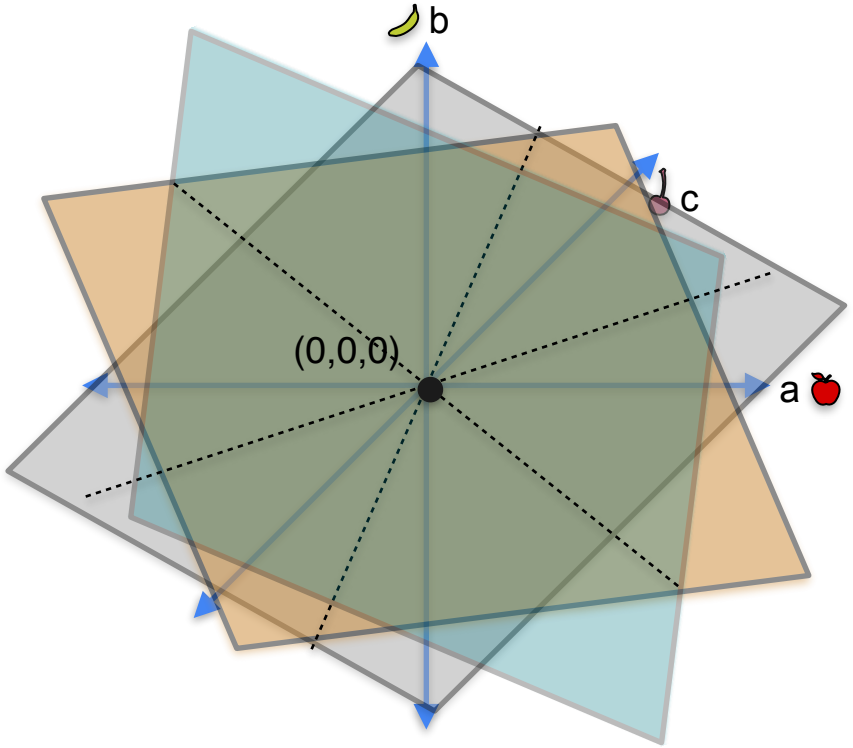
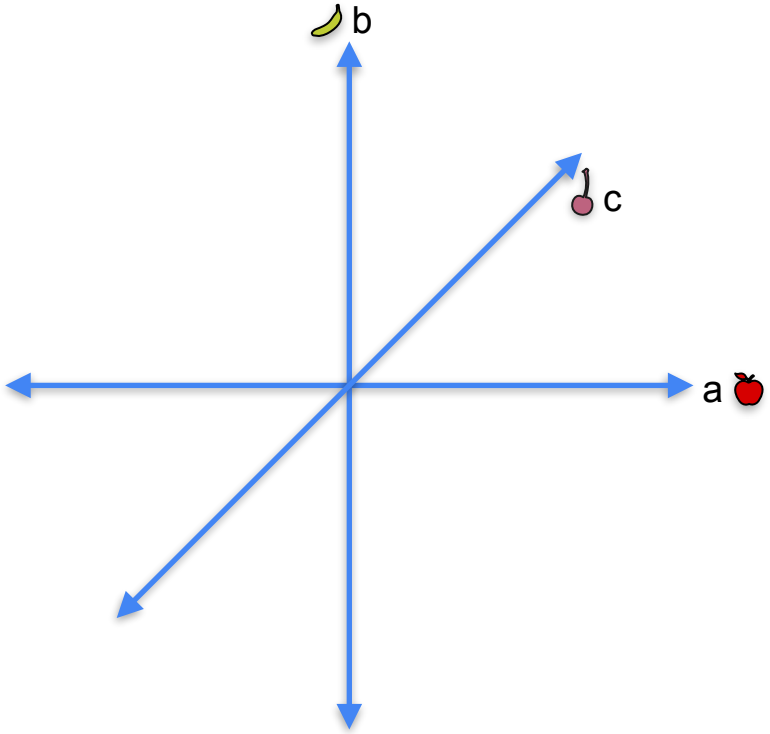


System 2

System 2

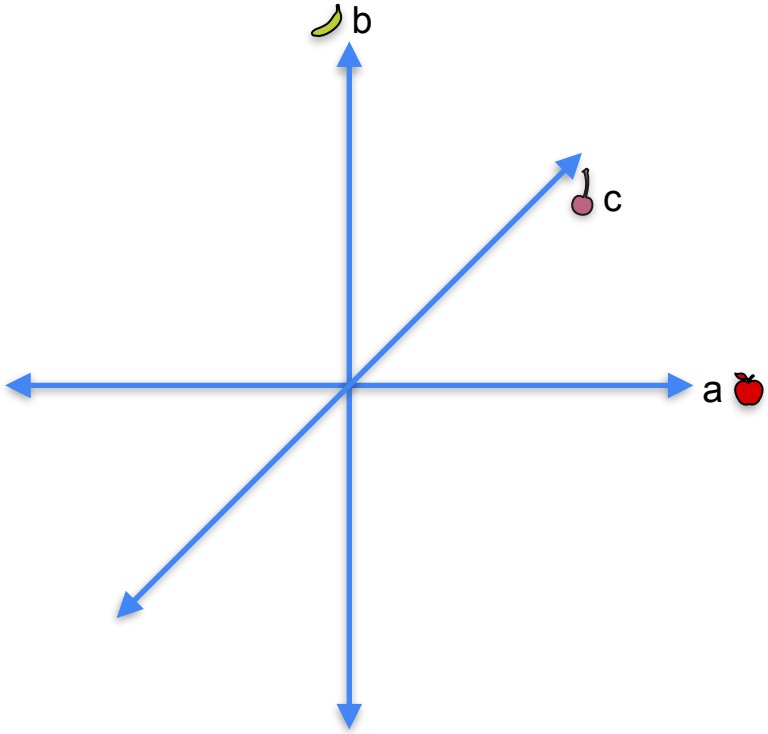
- a + b + c = **0**
- a + b + 2c = **0**
- a + b + 3c = **0**



System 2

System 2

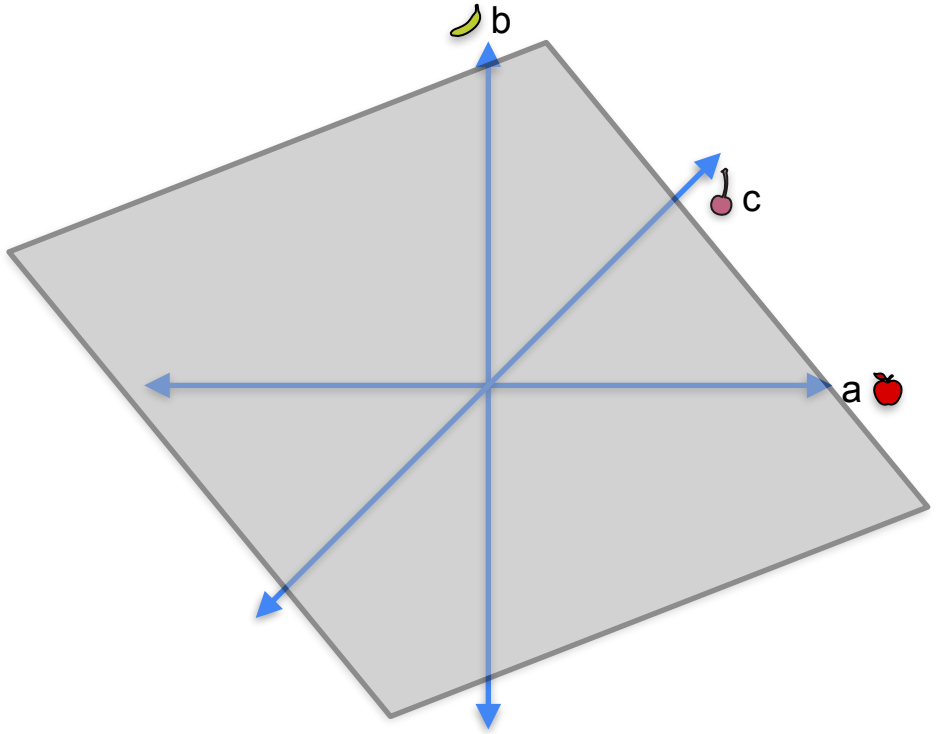
- $a + b + c = 0$
- $a + b + 2c = 0$
- $a + b + 3c = 0$



System 2

System 2

- $a + b + c = 0$
- $a + b + 2c = 0$
- $a + b + 3c = 0$



System 2

System 2

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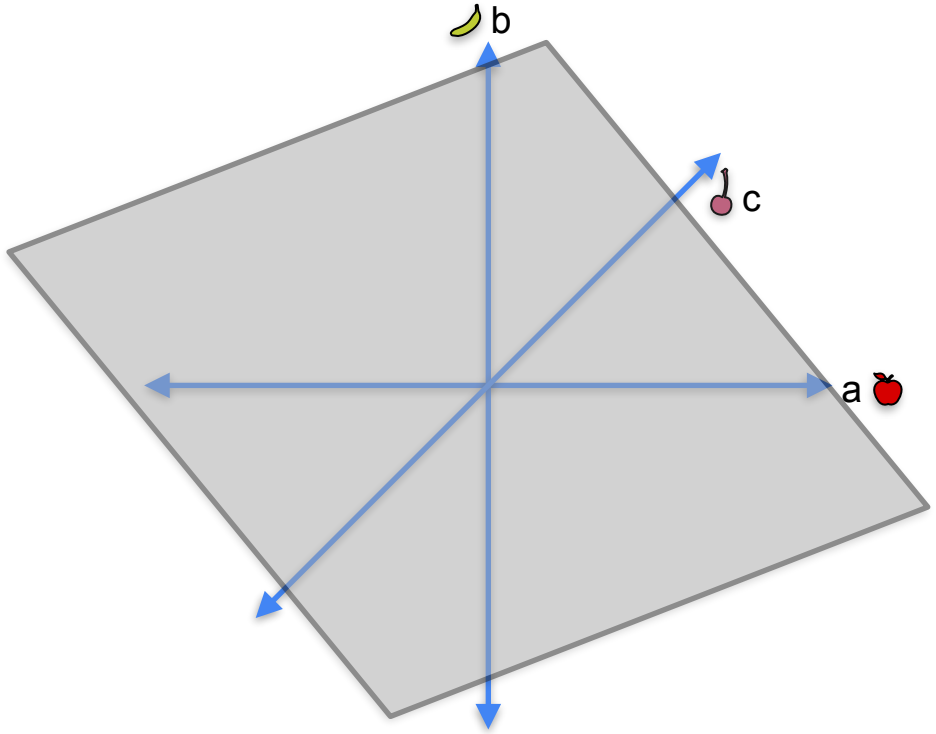
- $a + b + 2c = 0$
- $a + b + 3c = 0$



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System 2

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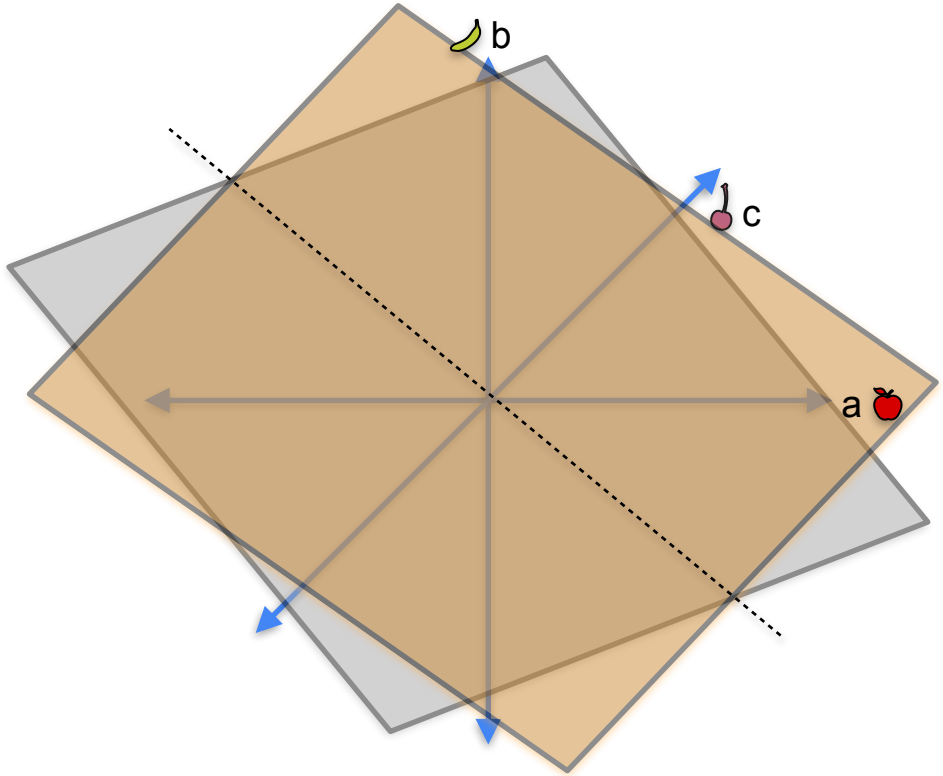

System 2

System 2

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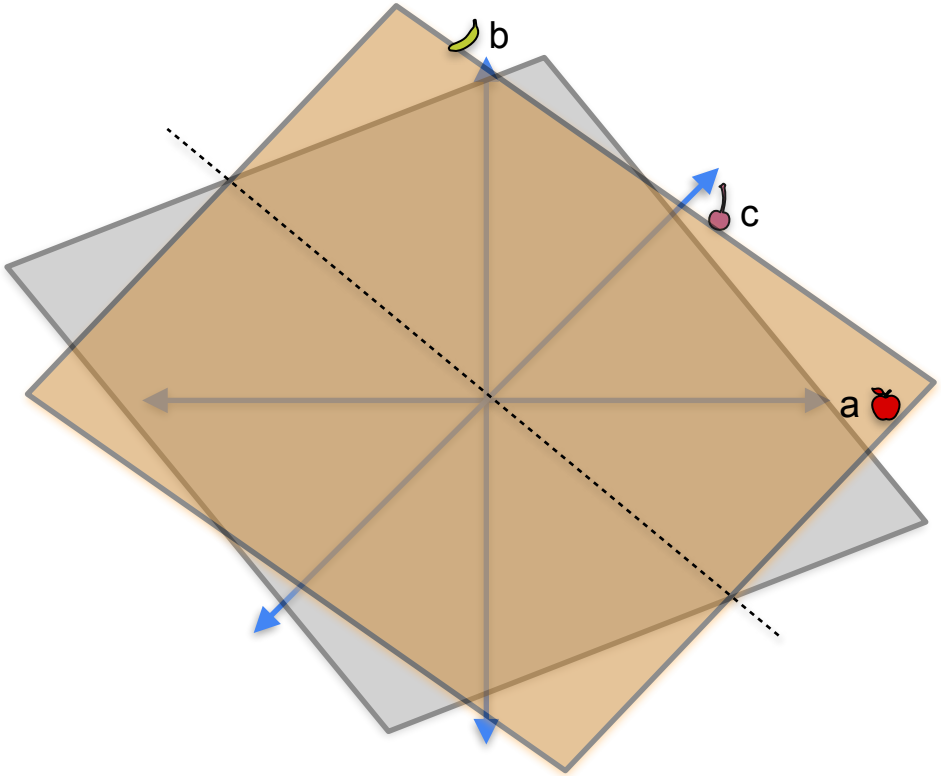
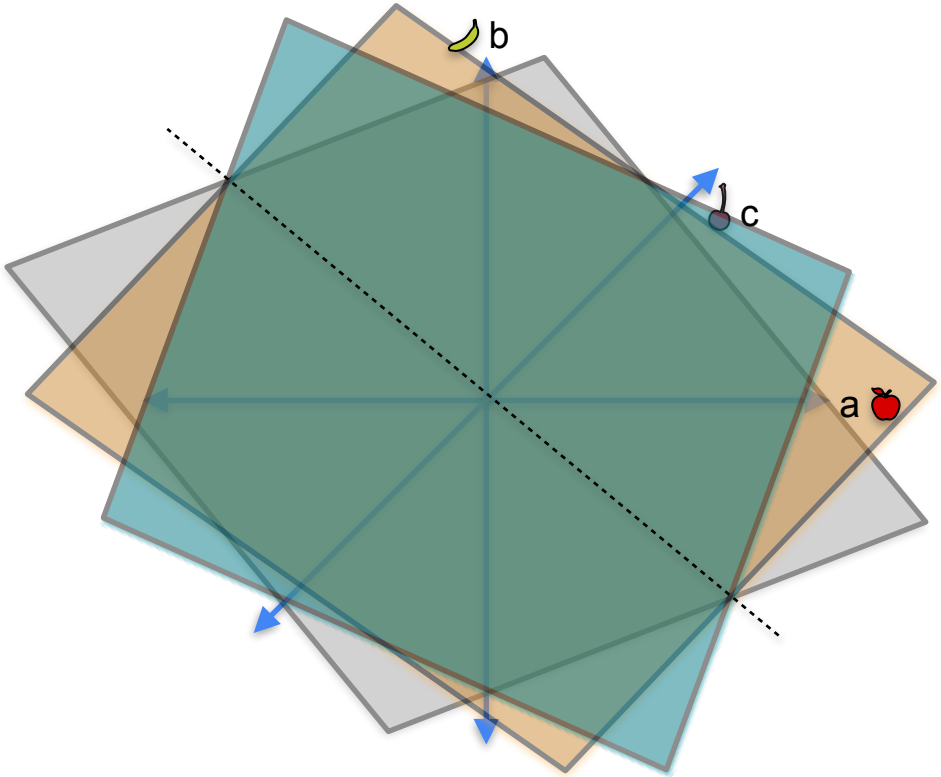
- a + b + 3c = **0**



System 2

System 2

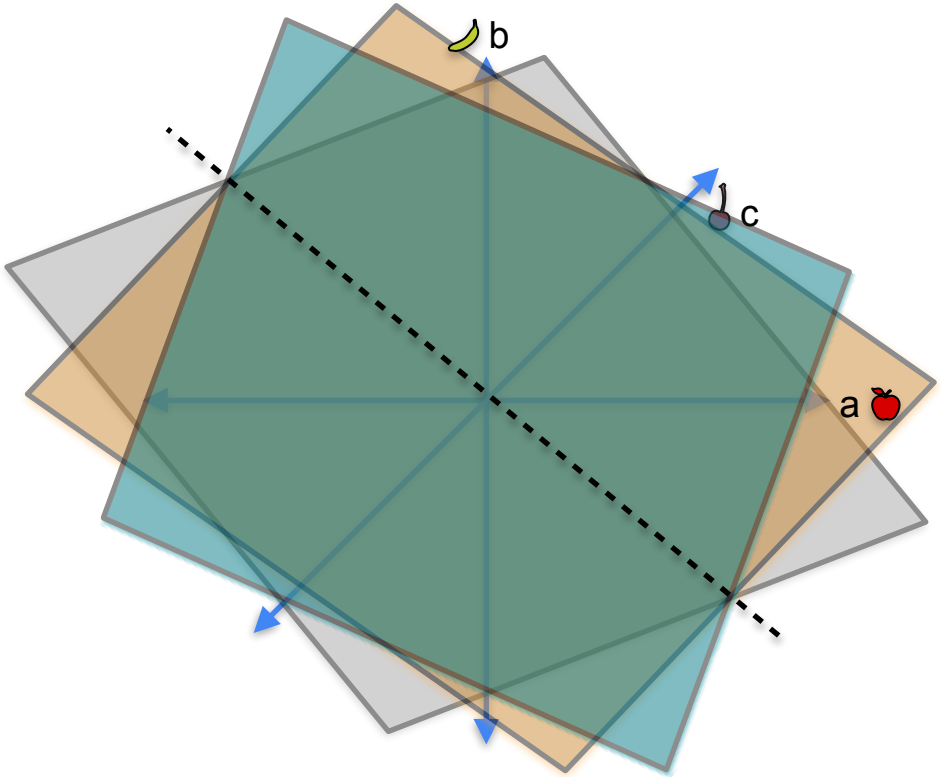
- a + b + c = **0**
- a + b + 2c = **0**
- a + b + 3c = **0**



System 2

System 2

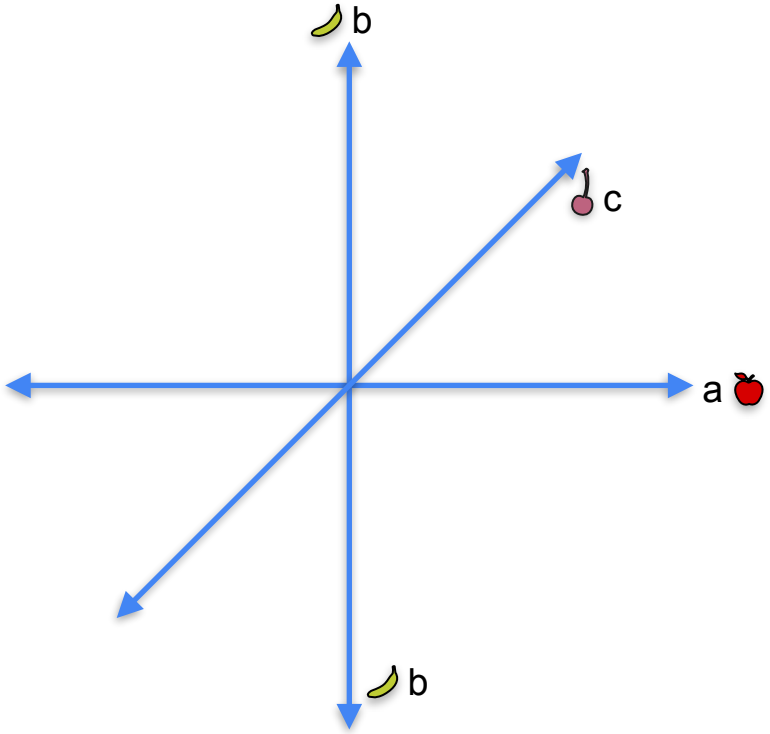
- a + b + c = **0**
- a + b + 2c = **0**
- a + b + 3c = **0**



System 3

System 3

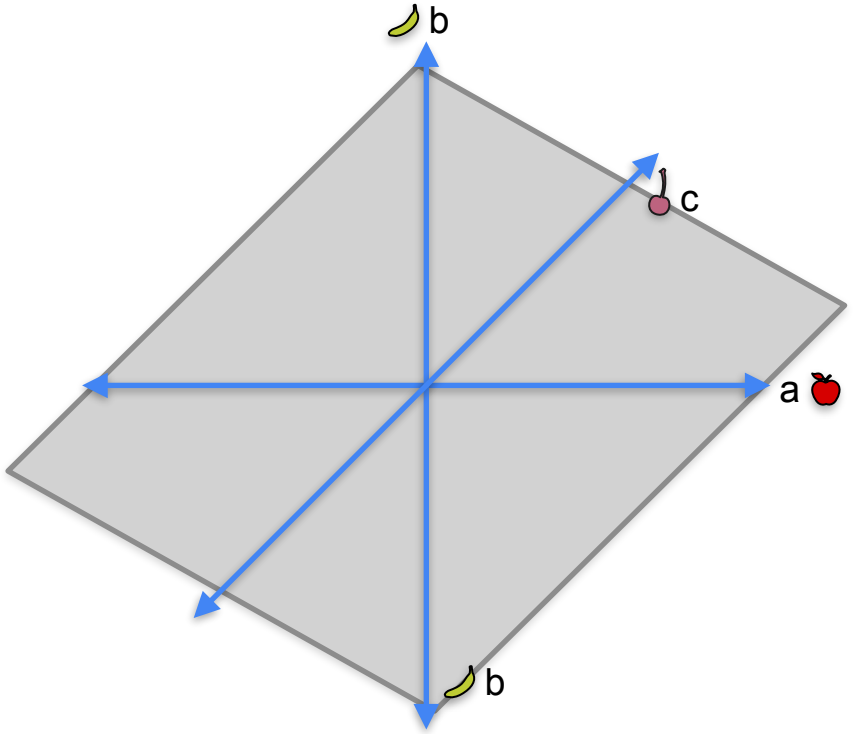
- a + b + c = **0**
- 2a + 2b + 2c = **0**
- 3a + 3b + 3c = **0**



System 3

System 3

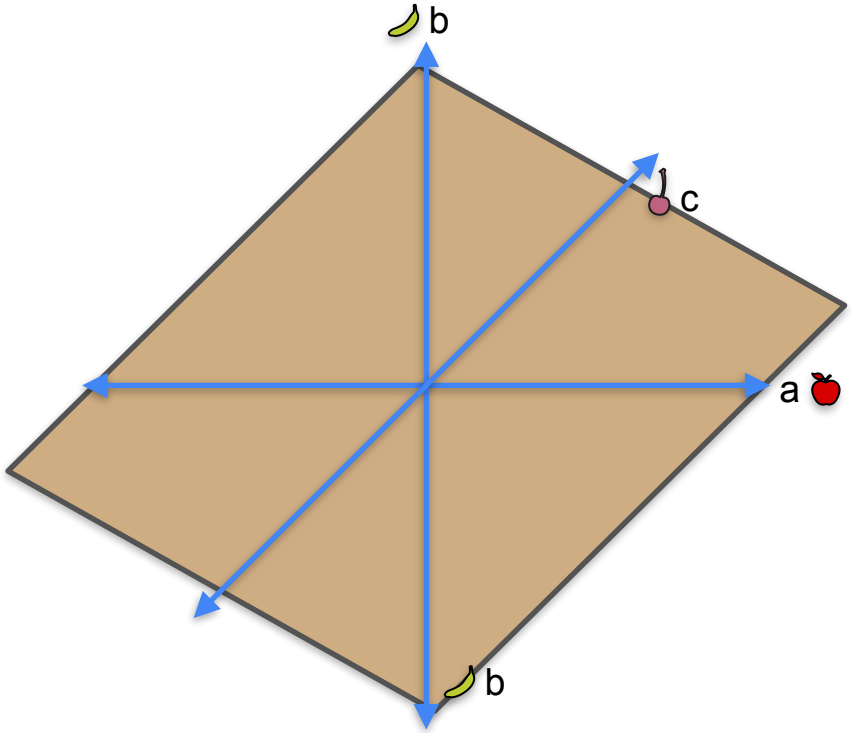
- $a + b + c = 0$
- $2a + 2b + 2c = 0$
- $3a + 3b + 3c = 0$



System 3

System 3

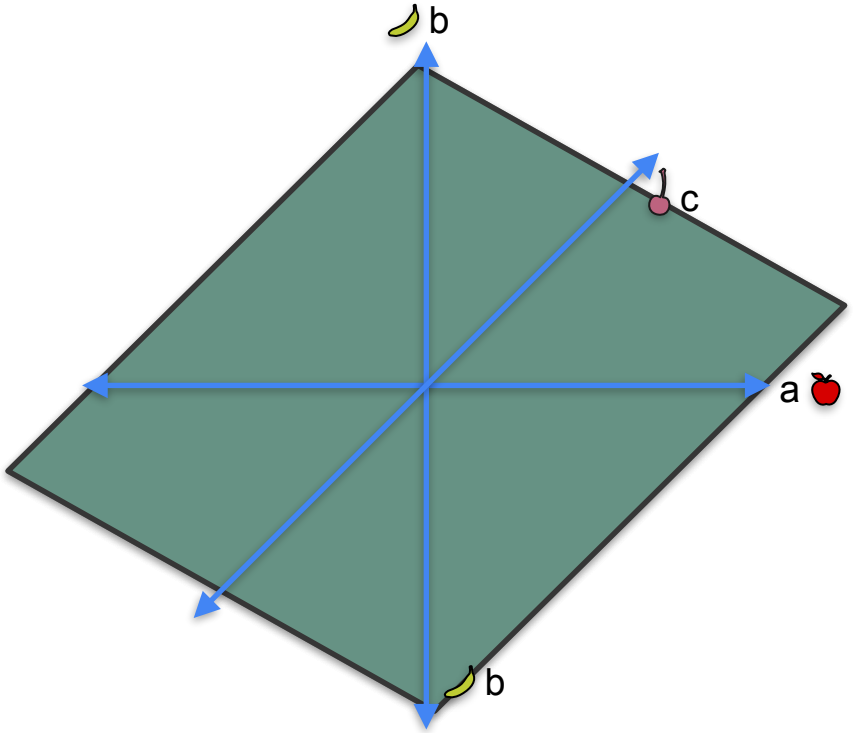
- $a + b + c = 0$
- $2a + 2b + 2c = 0$
- $3a + 3b + 3c = 0$



System 3

System 3

- $a + b + c = 0$
- $2a + 2b + 2c = 0$
- $3a + 3b + 3c = 0$ ⇦



DeepLearning.AI

System of Linear Equations

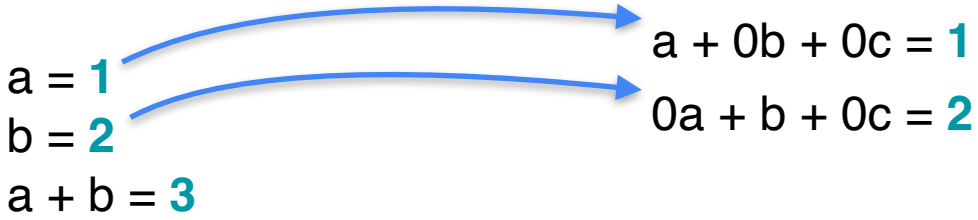
Linear dependence and independence (3x3)

Linear dependence and independence

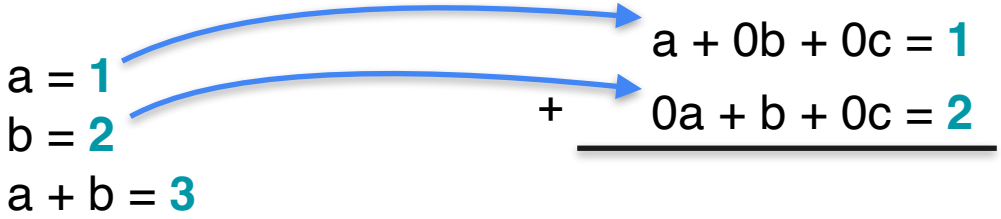
a = **1**
b = **2**
a + b = **3**

Linear dependence and independence

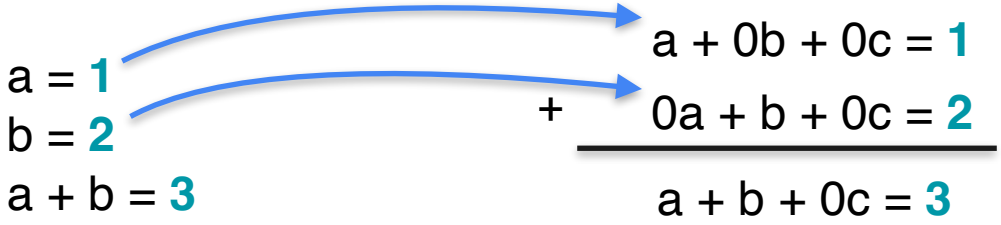
Linear dependence and independence



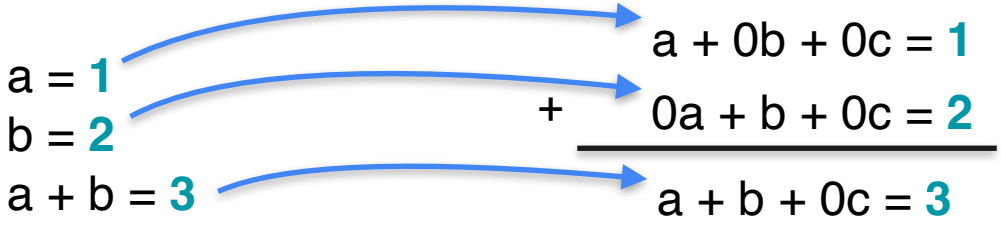
Linear dependence and independence



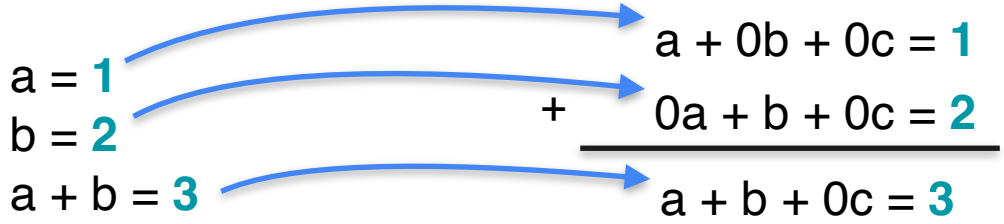
Linear dependence and independence



Linear dependence and independence

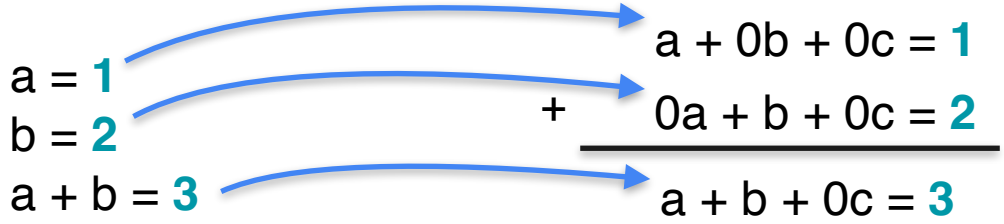


Linear dependence and independence



1	0	0
0	1	0
1	1	0

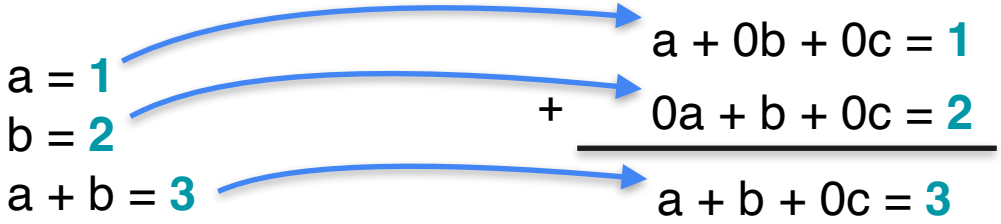
Linear dependence and independence



1	0	0
0	1	0
1	1	0

Row 1 + Row 2 = Row 3

Linear dependence and independence

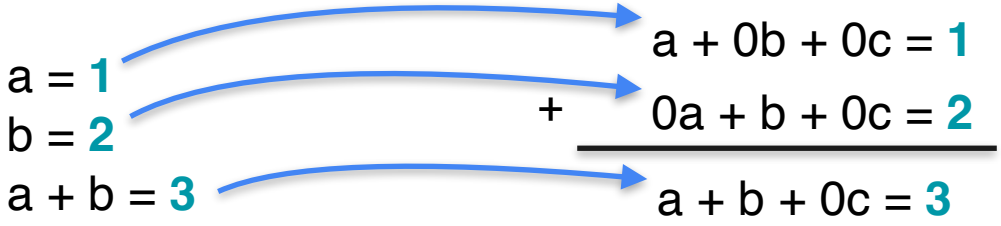


1	0	0
0	1	0
1	1	0

Row 1 + Row 2 = Row 3

Row 3 **depends** on rows 1 and 2

Linear dependence and independence



1	0	0
0	1	0
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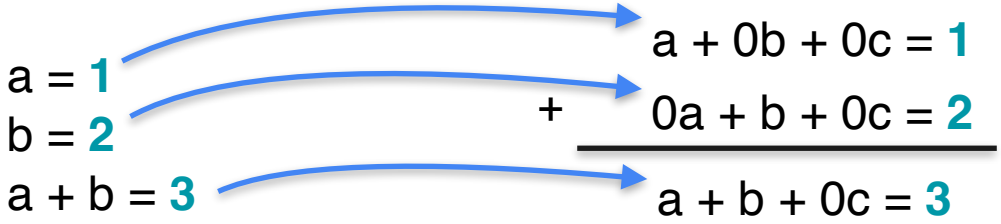
Row 1 + Row 2 = Row 3

Row 3 **depends** on rows 1 and 2

Rows are **linearly dependent**

Linear dependence and independence



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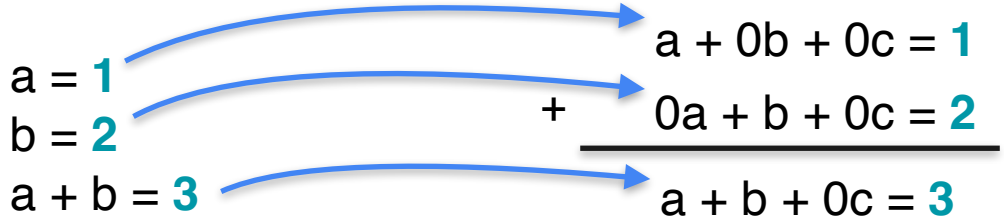
Linear dependence and independence



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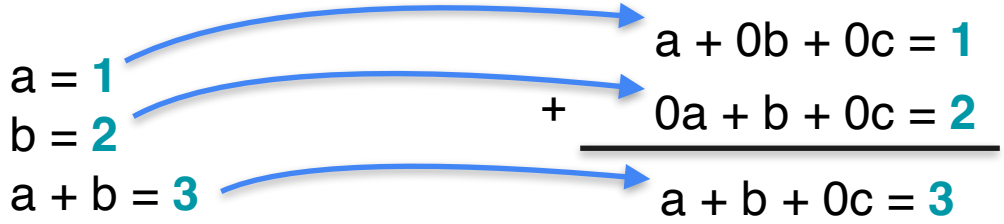

1	0	0
0	1	0
1	1	0

Row 1 + Row 2 = Row 3

Row 3 **depends** on rows 1 and 2

Rows are **linearly dependent**

Linear dependence and independence

$a + b + c = 0$
$2a + 2b + 2c = 0$
$3a + 3b + 3c = 0$

1	1	1
2	2	2
3	3	3

Linear dependence and independence

$a + b + c = 0$

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

$3a + 3b + 3c = 0$

$a + b + c = 0$

1	1	1
2	2	2
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Linear dependence and independence

$a + b + c = 0$
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Linear dependence and independence

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$$3a + 3b + 3c = 0$$

$$a + b + c = 0$$
$$+ \quad 2a + 2b + 2c = 0$$

1	1	1
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Linear dependence and independence

$$a + b + c = 0$$
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$$a + b + c = 0$$
$$+ \quad 2a + 2b + 2c = 0$$
$$3a + 3b + 3c = 0$$

1	1	1
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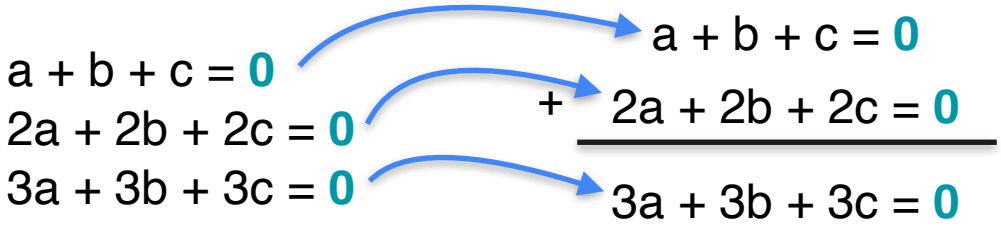
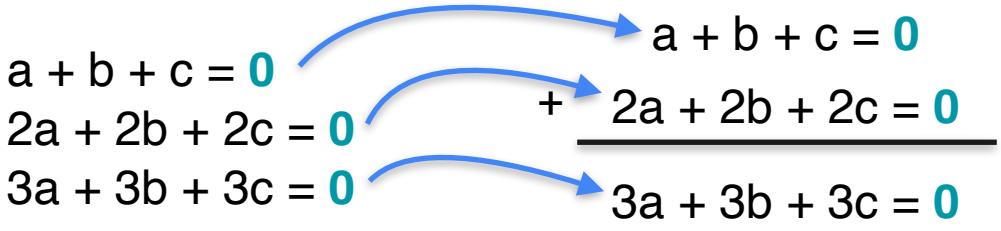
3	3	3

Linear dependence and independence



1	1	1
2	2	2
3	3	3

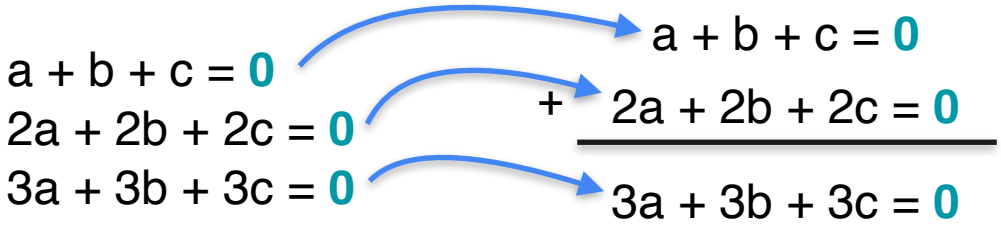
Linear dependence and independence



1	1	1
2	2	2
3	3	3

Row 1 + Row 2 = Row 3

Linear dependence and independence



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2	2	2
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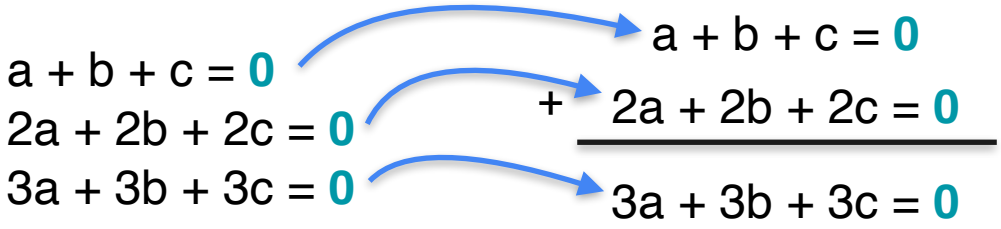
Row 1 + Row 2 = Row 3

Row 3 **depends** on rows 1 and 2

Linear dependence and independence



1	1	1
2	2	2
3	3	3

Row 1 + Row 2 = Row 3

Row 3 **depends** on rows 1 and 2

Rows are **linearly dependent**

Linear dependence and independence

$a + b + c = \mathbf{0}$
$a + b + 2c = \mathbf{0}$
$a + b + 3c = \mathbf{0}$

1	1	1
1	1	2
1	1	3

Linear dependence and independence

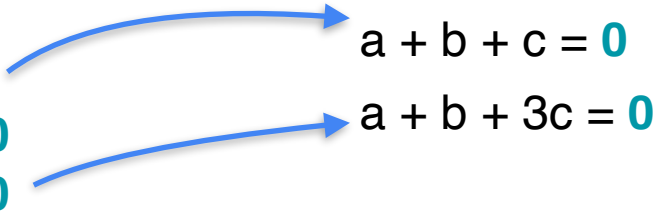
$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$

$a + b + c = 0$

1	1	1
1	1	2
1	1	3

Linear dependence and independence

$a + b + c = 0$
$a + b + 2c = 0$
$a + b + 3c = 0$



1	1	1
1	1	2
1	1	3

Linear dependence and independence

$$
\begin{aligned}
a + b + c &= 0 \\
a + b + 2c &= 0 \\
a + b + 3c &= 0
\end{aligned}
$$

$$
\begin{aligned}
a + b + c &= 0 \\
+\quad a + b + 3c &= 0 \\
\hline
\end{aligned}
$$

1	1	1
1	1	2
1	1	3

Linear dependence and independence

$$a + b + c = 0$$
$$a + b + 2c = 0$$
$$a + b + 3c = 0$$

$$a + b + c = 0$$
$$+ \quad a + b + 3c = 0$$
$$2a + 2b + 4c = 0$$

1	1	1
1	1	2
1	1	3

Linear dependence and independence

$$a + b + c = 0$$
$$a + b + 2c = 0$$
$$a + b + 3c = 0$$

$$a + b + c = 0$$
$$+ \quad a + b + 3c = 0$$
$$2a + 2b + 4c = 0$$
$$\div 2$$

1	1	1
1	1	2
1	1	3

Linear dependence and independence

$$a + b + c = 0$$
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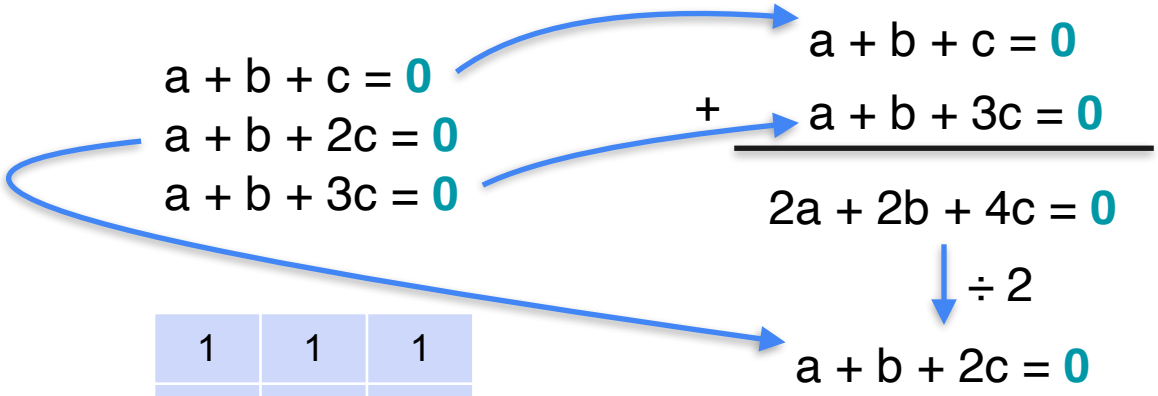
$$a + b + 3c = 0$$

$$a + b + c = 0$$
$$+ \quad a + b + 3c = 0$$
$$2a + 2b + 4c = 0$$
$$\div 2$$
$$a + b + 2c = 0$$

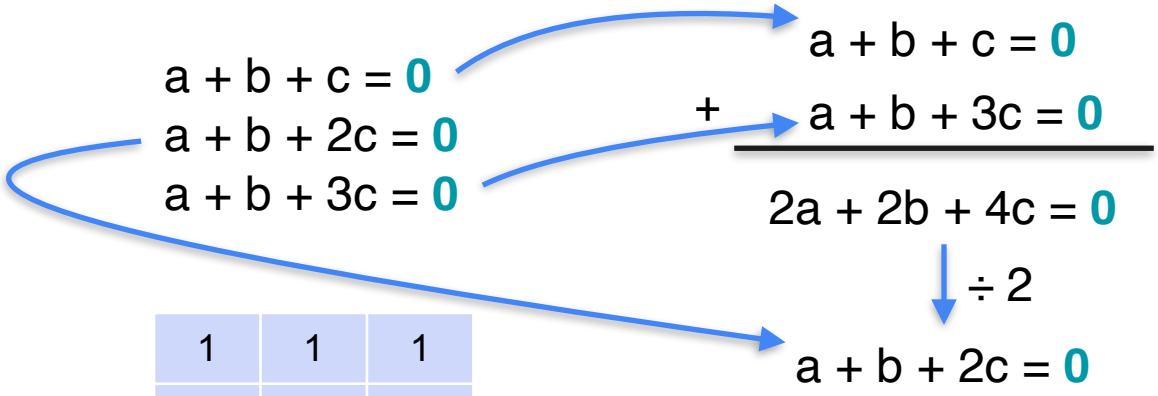
1	1	1
1	1	2
1	1	3

Linear dependence and independence



1	1	1
1	1	2
1	1	3

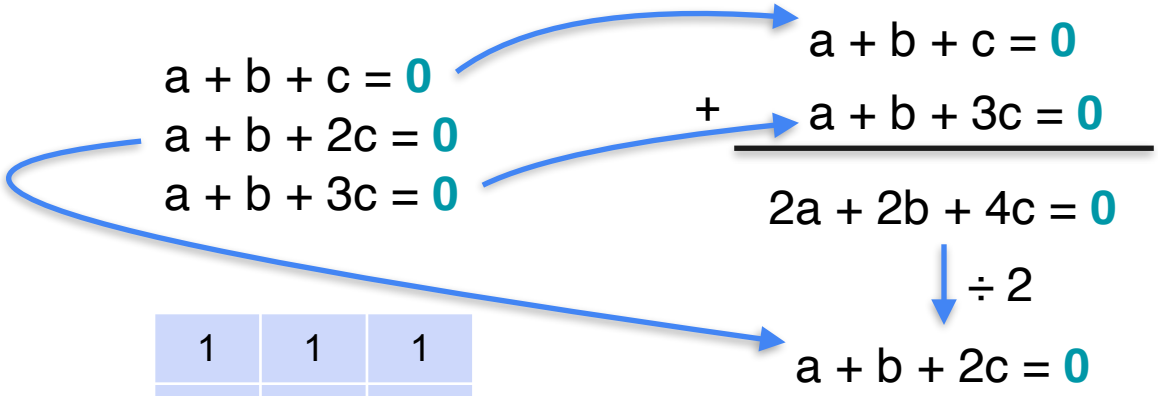
Linear dependence and independence



1	1	1
1	1	2
1	1	3

Average of Row 1 and Row 3 is Row 2
Row 2 **depends** on rows 1 and 3

Linear dependence and independence



1	1	1
1	1	2
1	1	3

Average of Row 1 and Row 3 is Row 2
Row 2 **depends** on rows 1 and 3

Rows are **linearly dependent**

Linear dependence and independence

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

1	1	1
1	2	1
1	1	2

Linear dependence and independence

$a + b + c = 0$
$a + 2b + c = 0$ → No relations between equations
$a + b + 2c = 0$

1	1	1
1	2	1
1	1	2

Linear dependence and independence

$a + b + c = 0$
$a + 2b + c = 0$ → No relations between equations
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1	1	1
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1	1	2

No relations between rows

Linear dependence and independence

$a + b + c = 0$
$a + 2b + c = 0$ → No relations between equations
$a + b + 2c = 0$

1	1	1
1	2	1
1	1	2

No relations between rows

Rows are **linearly independent**

Quiz: Linear dependence and independence

Problem: Determine if the following matrices have linearly dependent or independent rows

1	0	1
0	1	0
3	2	3

1	1	1
1	1	2
0	0	-1

1	1	1
0	2	2
0	0	3

1	2	5
0	3	-2
2	4	10

Solution: Linear dependence and independence

Problem: Determine if the following matrices have linear dependent or independent rows

1	0	1
0	1	0
3	2	3

1	1	1
1	1	2
0	0	-1

1	1	1
0	2	2
0	0	3

1	2	5
0	3	-2
2	4	10

Solution: Linear dependence and independence

Problem: Determine if the following matrices have linear dependent or independent rows

1	0	1
0	1	0
3	2	3

1	1	1
1	1	2
0	0	-1

1	1	1
0	2	2
0	0	3

1	2	5
0	3	-2
2	4	10

3Row1 + 2Row2 = Row3

Dependent (singular)

Solution: Linear dependence and independence

Problem: Determine if the following matrices have linear dependent or independent rows

1	0	1
0	1	0
3	2	3

3Row1 + 2Row2 = Row3

Dependent (singular)

1	1	1
1	1	2
0	0	-1

Row1 - Row2 = Row3

Dependent (singular)

1	1	1
0	2	2
0	0	3

1	2	5
0	3	-2
2	4	10

Solution: Linear dependence and independence

Problem: Determine if the following matrices have linear dependent or independent rows

1	0	1
0	1	0
3	2	3

3Row1 + 2Row2 = Row3

Dependent (singular)

1	1	1
1	1	2
0	0	-1

Row1 - Row2 = Row3

Dependent (singular)

1	1	1
0	2	2
0	0	3

No relations

Independent (Non-singular)

1	2	5
0	3	-2
2	4	10

Solution: Linear dependence and independence

Problem: Determine if the following matrices have linear dependent or independent rows

1	0	1
0	1	0
3	2	3

3Row1 + 2Row2 = Row3

Dependent (singular)

1	1	1
1	1	2
0	0	-1

Row1 - Row2 = Row3

Dependent (singular)

1	1	1
0	2	2
0	0	3

No relations

Independent (Non-singular)

1	2	5
0	3	-2
2	4	10

2Row1 = Row3

Dependent (singular)

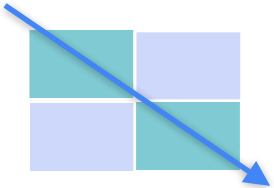
DeepLearning.AI

System of Linear Equations

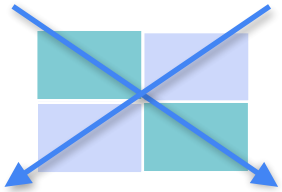
The determinant (3x3)

Diagonals in a 3x3 matrix

Diagonals in a 3x3 matrix



Diagonals in a 3x3 matrix



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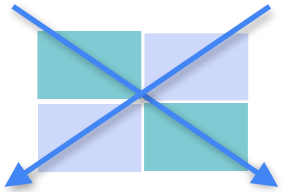

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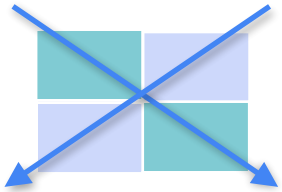

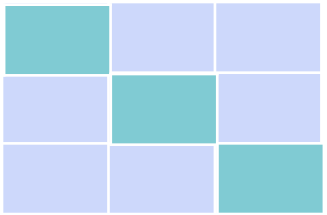

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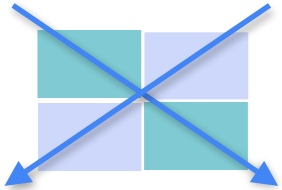
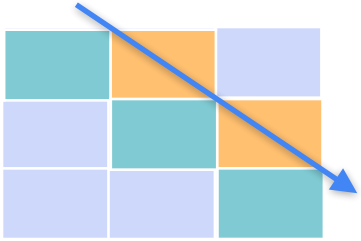
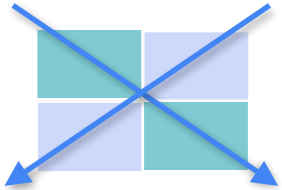
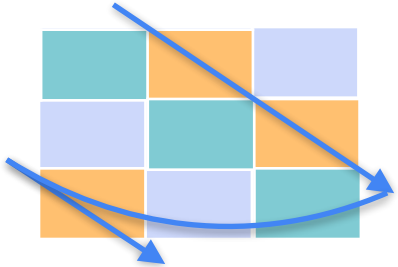




Diagonals in a 3x3 matrix





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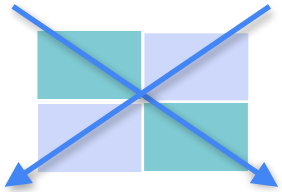

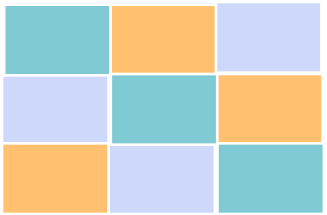

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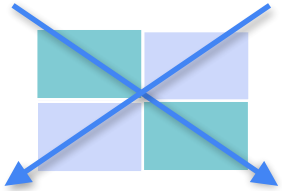
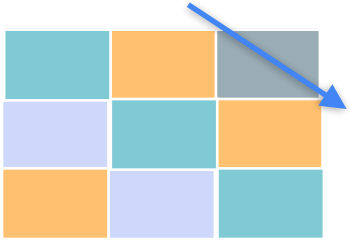
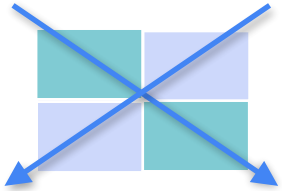
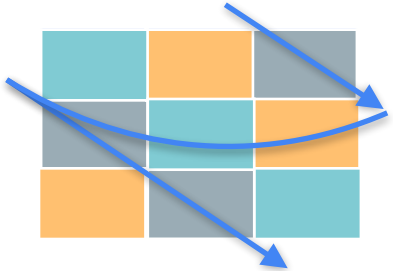




Diagonals in a 3x3 matrix





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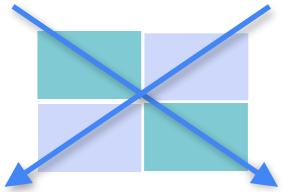
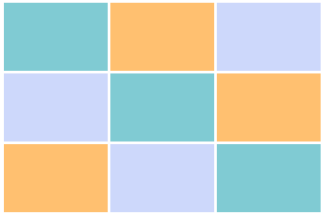


Determinant

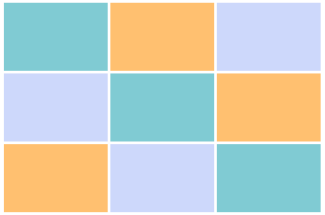
Determinant

Add

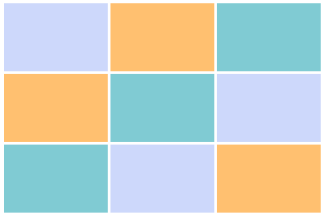


Determinant

Add



Subtract



The determinant

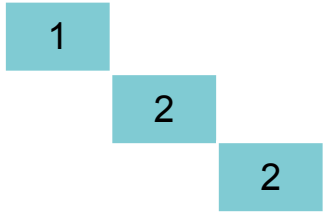
1	1	1
1	2	1
1	1	2

The determinant

1	1	1
1	2	1
1	1	2

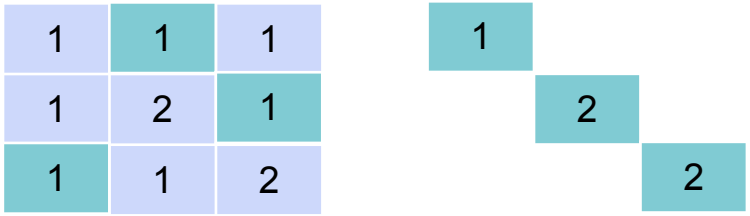
The determinant

1	1	1
1	2	1
1	1	2



$$+ \quad 1 \cdot 2 \cdot 2$$

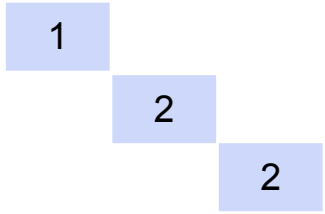
The determinant



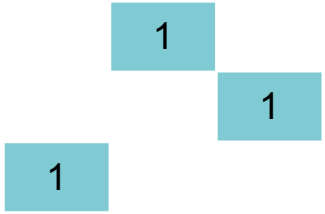
$$+ \quad 1 \cdot 2 \cdot 2$$

The determinant

1	1	1
1	2	1
1	1	2

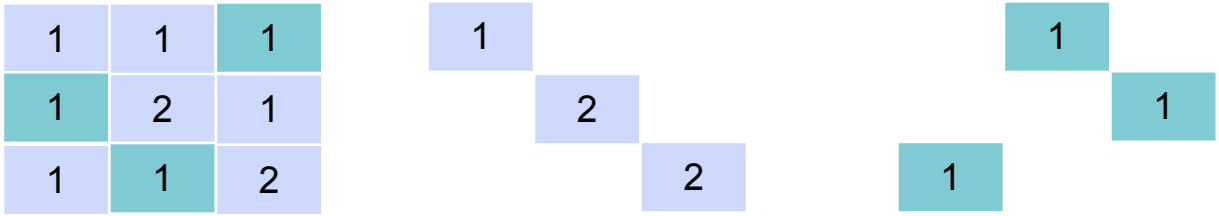


$+ \ 1 \cdot 2 \cdot 2$



$+ \ 1 \cdot 1 \cdot 1$

The determinant

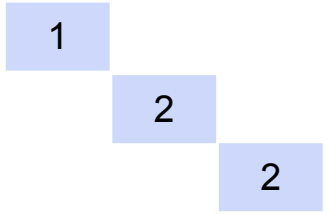


$+ \quad 1 \cdot 2 \cdot 2$

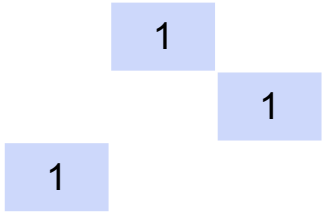
$+ \quad 1 \cdot 1 \cdot 1$

The determinant

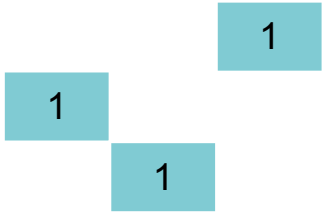
1	1	1
1	2	1
1	1	2



$+ \ 1 \cdot 2 \cdot 2$

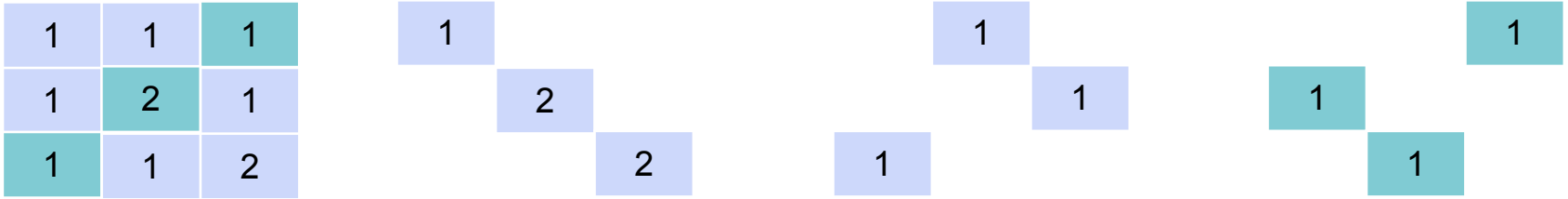


$+ \ 1 \cdot 1 \cdot 1$



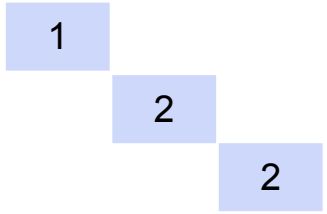
$+ \ 1 \cdot 1 \cdot 1$

The determinant

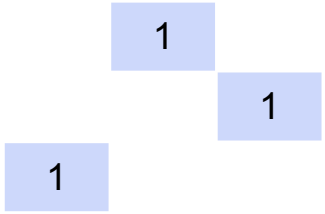


The determinant

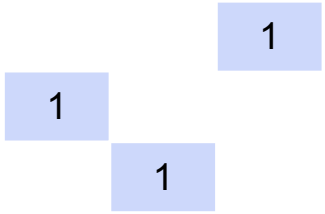
1	1	1
1	2	1
1	1	2



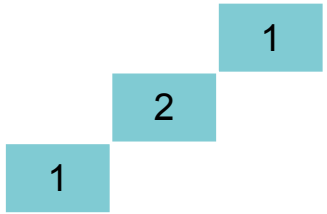
$+ \ 1 \cdot 2 \cdot 2$



$+ \ 1 \cdot 1 \cdot 1$

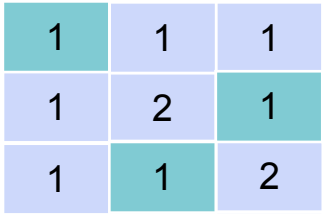


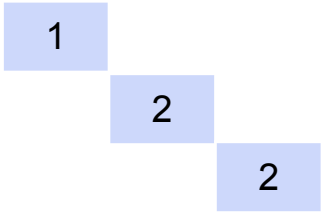
$+ \ 1 \cdot 1 \cdot 1$



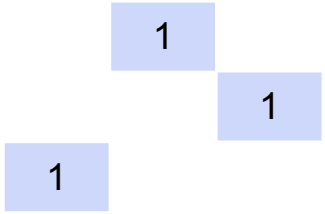
$- \ 1 \cdot 2 \cdot 1$

The determinant

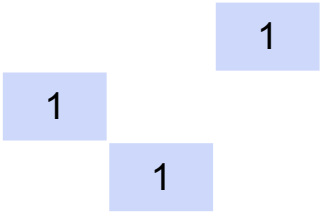




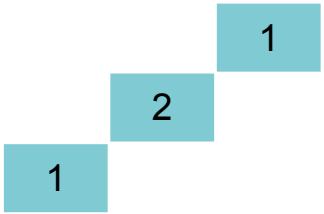
$+ \ 1 \cdot 2 \cdot 2$



$+ \ 1 \cdot 1 \cdot 1$

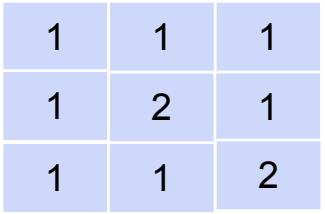


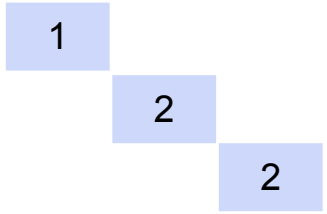
$+ \ 1 \cdot 1 \cdot 1$



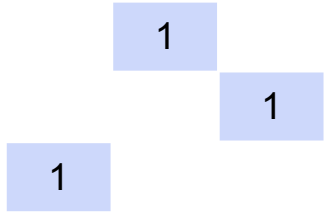
$- \ 1 \cdot 2 \cdot 1$

The determinant

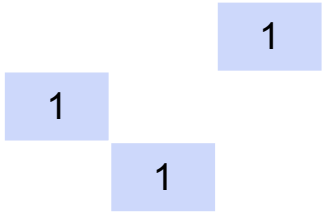




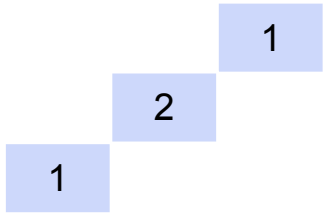
$+ \ 1 \cdot 2 \cdot 2$



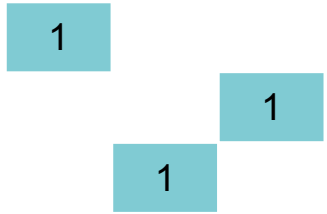
$+ \ 1 \cdot 1 \cdot 1$



$+ \ 1 \cdot 1 \cdot 1$

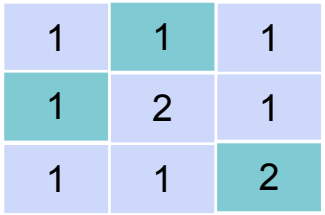


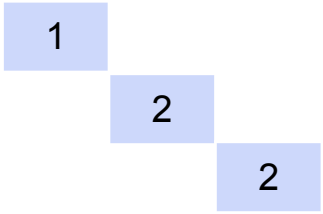
$- \ 1 \cdot 2 \cdot 1$



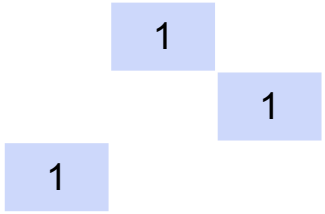
$- \ 1 \cdot 1 \cdot 1$

The determinant

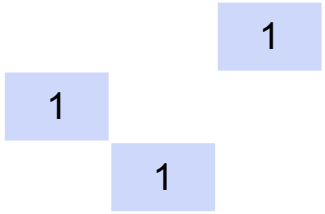




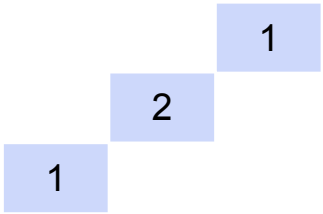
$+ \ 1 \cdot 2 \cdot 2$



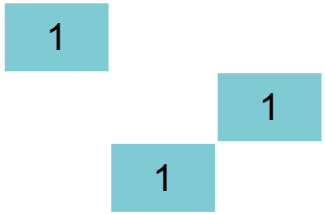
$+ \ 1 \cdot 1 \cdot 1$



$+ \ 1 \cdot 1 \cdot 1$



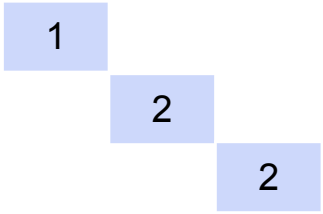
$- \ 1 \cdot 2 \cdot 1$



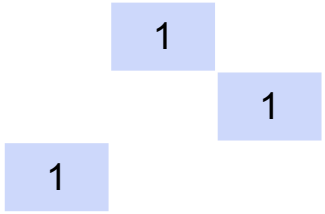
$- \ 1 \cdot 1 \cdot 1$

The determinant

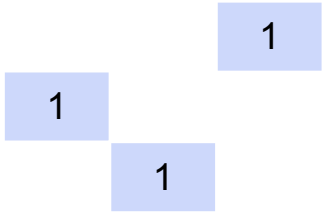
1	1	1
1	2	1
1	1	2



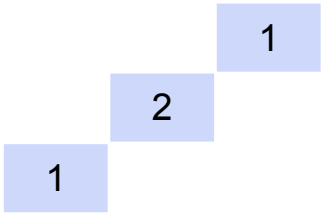
$+ \ 1 \cdot 2 \cdot 2$



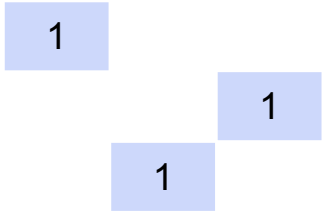
$+ \ 1 \cdot 1 \cdot 1$



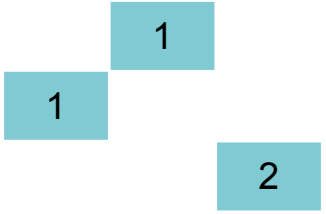
$+ \ 1 \cdot 1 \cdot 1$



$- \ 1 \cdot 2 \cdot 1$



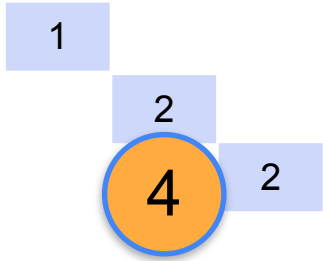
$- \ 1 \cdot 1 \cdot 1$



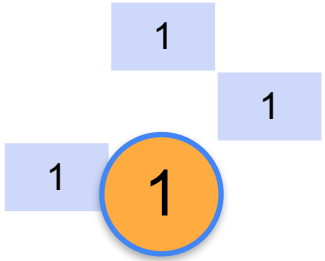
$- \ 1 \cdot 1 \cdot 2$

The determinant

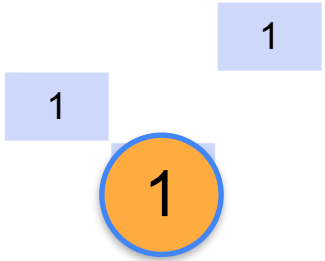
1	1	1
1	2	1
1	1	2



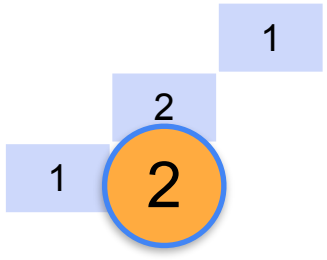
$+ \ 1 \cdot 2 \cdot 2$



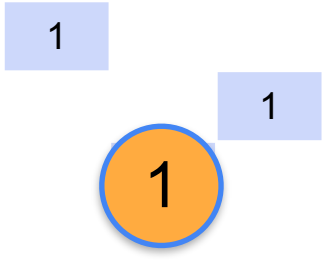
$+ \ 1 \cdot 1 \cdot 1$



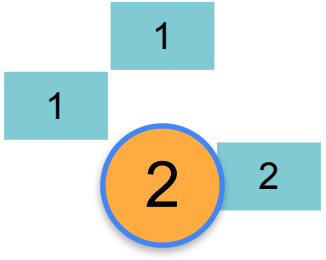
$+ \ 1 \cdot 1 \cdot 1$



$- \ 1 \cdot 2 \cdot 1$



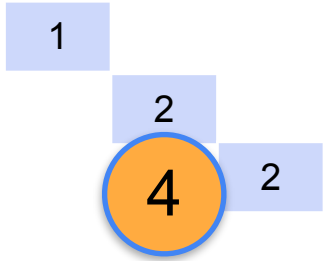
$- \ 1 \cdot 1 \cdot 1$



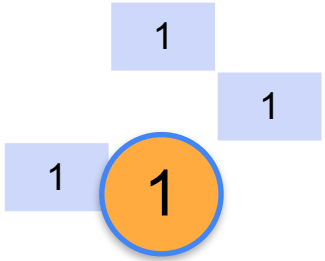
$- \ 1 \cdot 1 \cdot 2$

The determinant

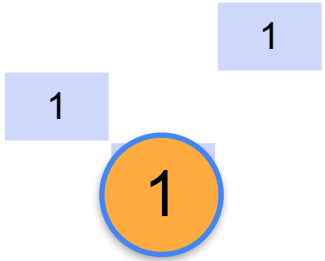
1	1	1
1	2	1
1	1	2



$+ \ 1 \cdot 2 \cdot 2$

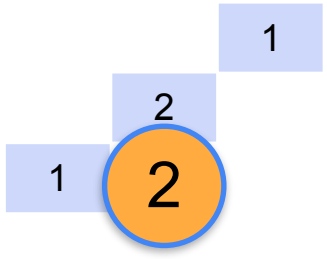


$+ \ 1 \cdot 1 \cdot 1$

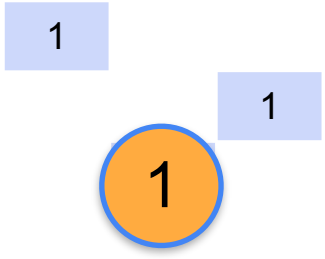


$+ \ 1 \cdot 1 \cdot 1$

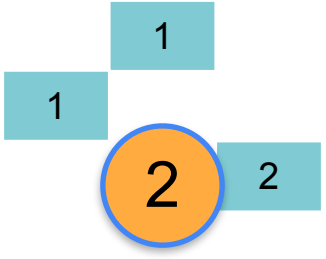
Det = 4+1+1
-2-1-2



$- \ 1 \cdot 2 \cdot 1$



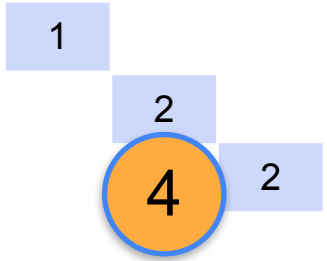
$- \ 1 \cdot 1 \cdot 1$



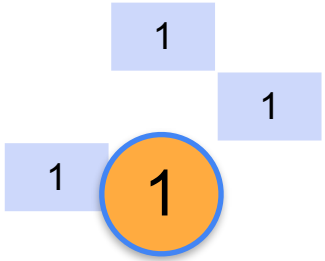
$- \ 1 \cdot 1 \cdot 2$

The determinant

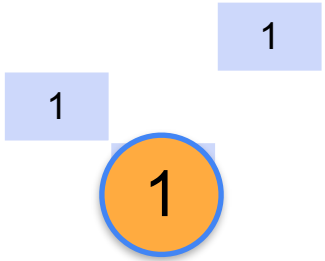
1	1	1
1	2	1
1	1	2



$+ \quad 1 \cdot 2 \cdot 2$



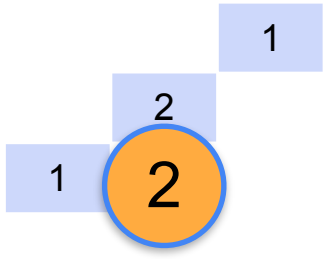
$+ \quad 1 \cdot 1 \cdot 1$



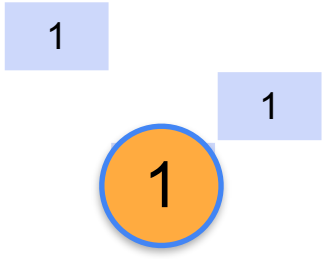
$+ \quad 1 \cdot 1 \cdot 1$

Det = 4+1+1
-2-1-2

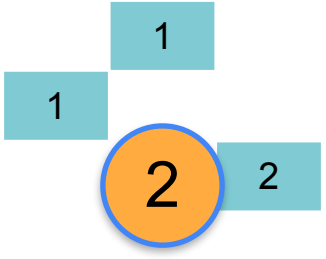
= 1



$- \quad 1 \cdot 2 \cdot 1$



$- \quad 1 \cdot 1 \cdot 1$



$- \quad 1 \cdot 1 \cdot 2$

Quiz: Determinants

Problem: Find the determinant of the following matrices (from the previous quiz). Verify that those with determinant 0 are precisely the singular matrices.

1	0	1
0	1	0
3	3	3

1	1	1
1	1	2
0	0	-1

1	1	1
0	2	2
0	0	3

1	2	5
0	3	-2
2	4	10

Solution: Determinants

Problem: Find the determinant of the following matrices (from the previous quiz). Verify that those with determinant 0 are precisely the singular matrices.

1	0	1
0	1	0
3	3	3

1	1	1
1	1	2
0	0	-1

1	1	1
0	2	2
0	0	3

1	2	5
0	3	-2
2	4	10

Solution: Determinants

Problem: Find the determinant of the following matrices (from the previous quiz). Verify that those with determinant 0 are precisely the singular matrices.

1	0	1
0	1	0
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1	1	1
1	1	2
0	0	-1

1	1	1
0	2	2
0	0	3

1	2	5
0	3	-2
2	4	10

Determinant = 0

Singular

Solution: Determinants

Problem: Find the determinant of the following matrices (from the previous quiz). Verify that those with determinant 0 are precisely the singular matrices.

1	0	1
0	1	0
3	3	3

Determinant = 0

Singular

1	1	1
1	1	2
0	0	-1

Determinant = 0

Singular

1	1	1
0	2	2
0	0	3

1	2	5
0	3	-2
2	4	10

Solution: Determinants

Problem: Find the determinant of the following matrices (from the previous quiz). Verify that those with determinant 0 are precisely the singular matrices.

1	0	1
0	1	0
3	3	3

Determinant = 0

Singular

1	1	1
1	1	2
0	0	-1

Determinant = 0

Singular

1	1	1
0	2	2
0	0	3

Determinant = 6

Non-singular

1	2	5
0	3	-2
2	4	10

Solution: Determinants

Problem: Find the determinant of the following matrices (from the previous quiz). Verify that those with determinant 0 are precisely the singular matrices.

1	0	1
0	1	0
3	3	3

Determinant = 0

Singular

1	1	1
1	1	2
0	0	-1

Determinant = 0

Singular

1	1	1
0	2	2
0	0	3

Determinant = 6

Non-singular

1	2	5
0	3	-2
2	4	10

Determinant = 0

Singular

The determinant

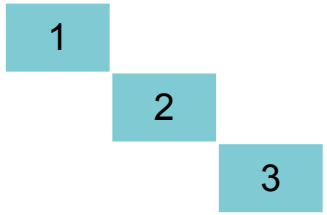
1	1	1
0	2	2
0	0	3

Det = 6+0+0-0-0-0

= 6

The determinant

1	1	1
0	2	2
0	0	3

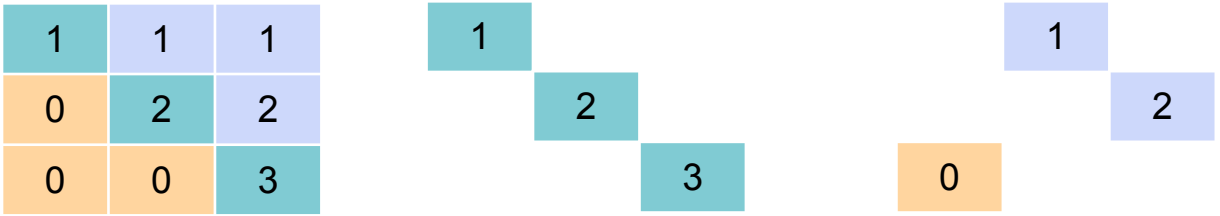


$$+ \quad 1 \cdot 2 \cdot 3$$

Det = 6+0+0-0-0-0

= 6

The determinant



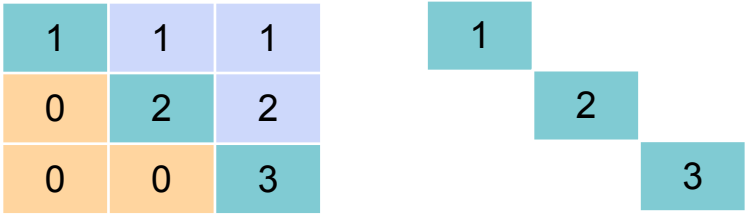
$+ \ 1 \cdot 2 \cdot 3$

$+ \ 1 \cdot 2 \cdot 0$

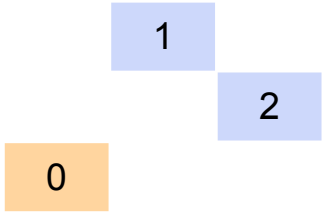
Det = 6+0+0-0-0-0

= 6

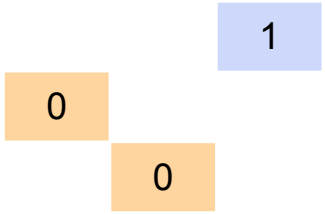
The determinant



$+ \ 1 \cdot 2 \cdot 3$



$+ \ 1 \cdot 2 \cdot 0$



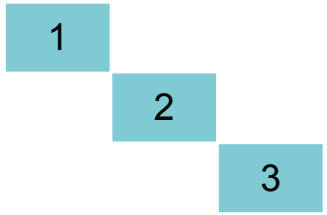
$+ \ 1 \cdot 0 \cdot 0$

Det = 6+0+0-0-0-0

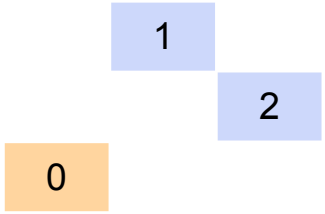
= 6

The determinant

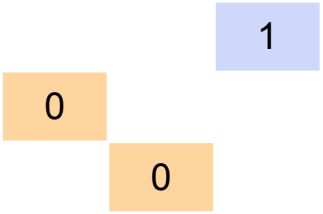
1	1	1
0	2	2
0	0	3



$+ \ 1 \cdot 2 \cdot 3$



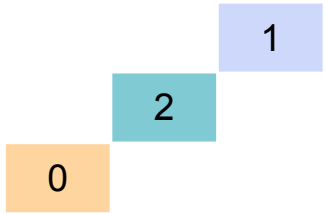
$+ \ 1 \cdot 2 \cdot 0$



$+ \ 1 \cdot 0 \cdot 0$

Det = 6+0+0-0-0-0

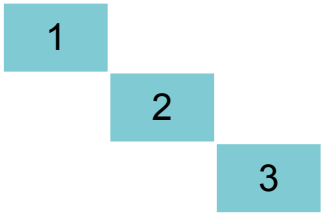
= 6



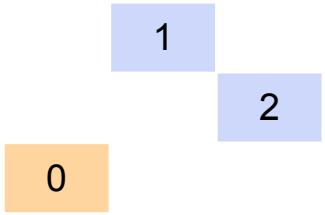
$- \ 1 \cdot 2 \cdot 0$

The determinant

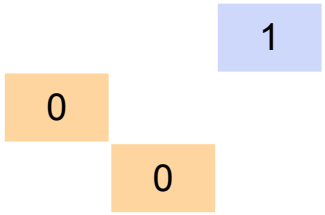
1	1	1
0	2	2
0	0	3



$+ \ 1 \cdot 2 \cdot 3$



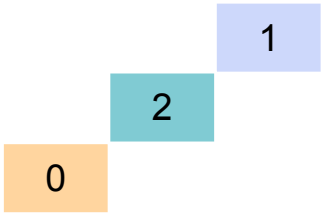
$+ \ 1 \cdot 2 \cdot 0$



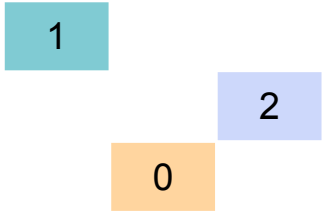
$+ \ 1 \cdot 0 \cdot 0$

Det = 6+0+0-0-0-0

= 6



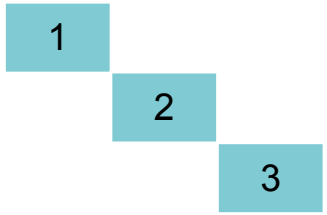
$- \ 1 \cdot 2 \cdot 0$



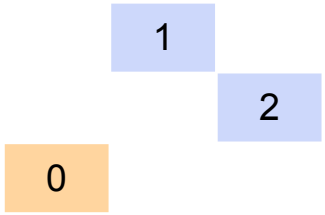
$- \ 1 \cdot 2 \cdot 0$

The determinant

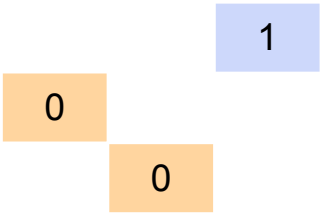
1	1	1
0	2	2
0	0	3



$+ \ 1 \cdot 2 \cdot 3$



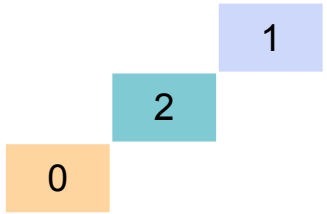
$+ \ 1 \cdot 2 \cdot 0$



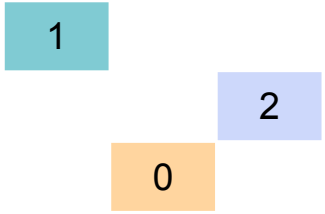
$+ \ 1 \cdot 0 \cdot 0$

Det = 6+0+0-0-0-0

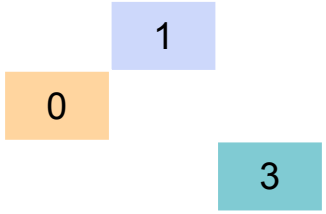
= 6



$- \ 1 \cdot 2 \cdot 0$

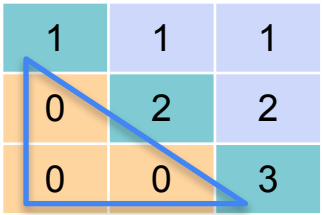


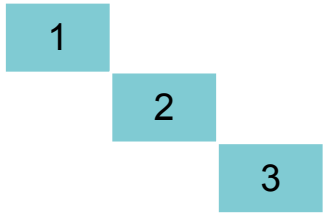
$- \ 1 \cdot 2 \cdot 0$



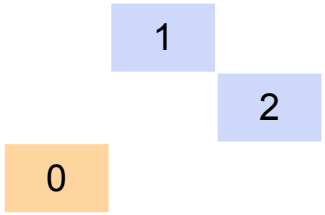
$- \ 1 \cdot 0 \cdot 3$

The determinant

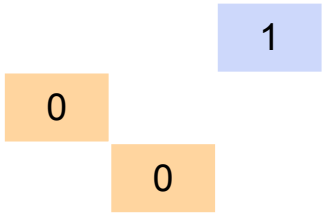




$+ \ 1 \cdot 2 \cdot 3$



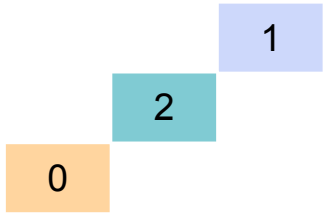
$+ \ 1 \cdot 2 \cdot 0$



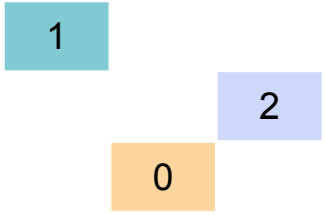
$+ \ 1 \cdot 0 \cdot 0$

Det = 6+0+0-0-0-0

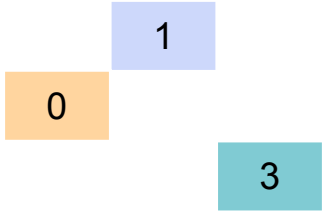
= 6



$- \ 1 \cdot 2 \cdot 0$

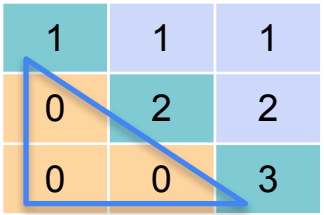


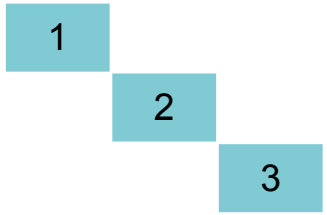
$- \ 1 \cdot 2 \cdot 0$



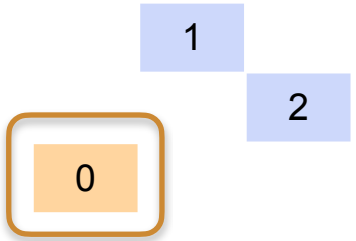
$- \ 1 \cdot 0 \cdot 3$

The determinant

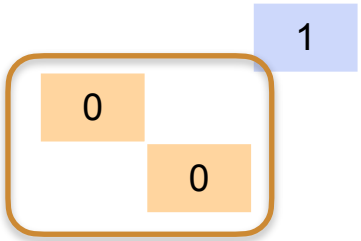




$+ \ 1 \cdot 2 \cdot 3$



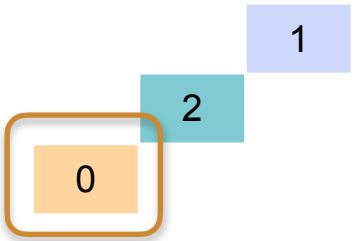
$+ \ 1 \cdot 2 \cdot 0$



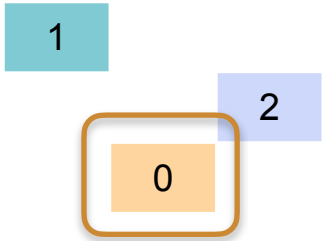
$+ \ 1 \cdot 0 \cdot 0$

Det = 6+0+0-0-0-0

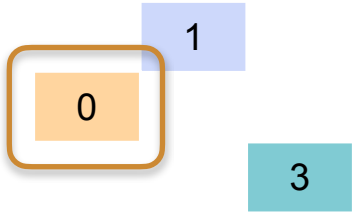
= 6



$- \ 1 \cdot 2 \cdot 0$

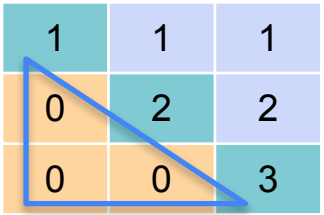


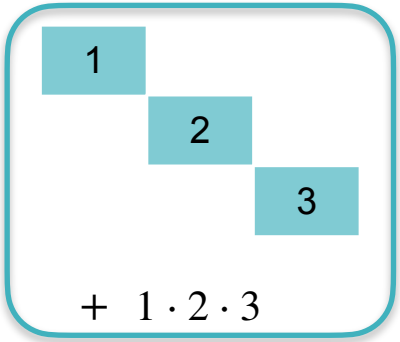
$- \ 1 \cdot 2 \cdot 0$

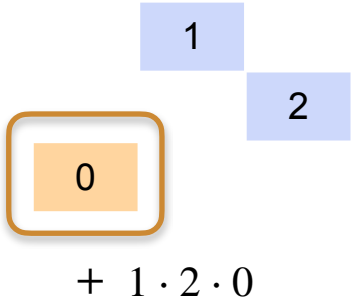


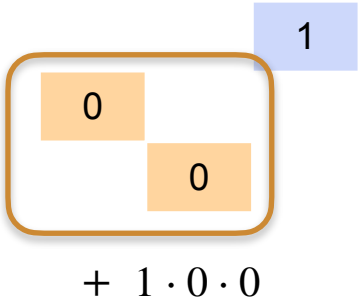
$- \ 1 \cdot 0 \cdot 3$

The determinant



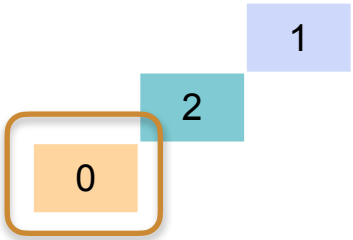


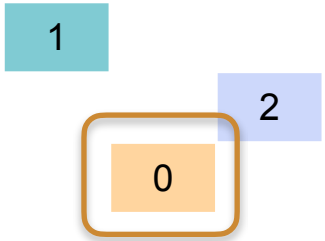


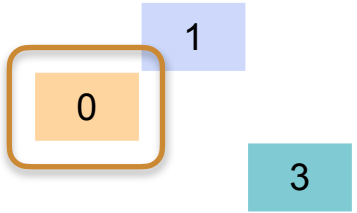


Det = 6+0+0-0-0-0

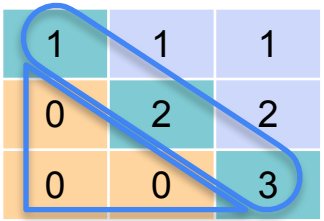
= 6

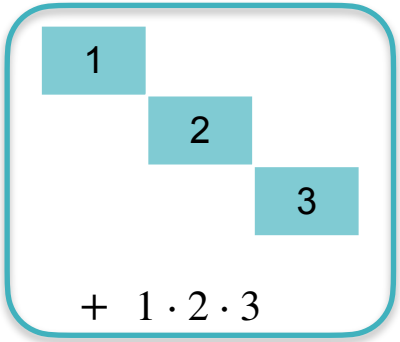


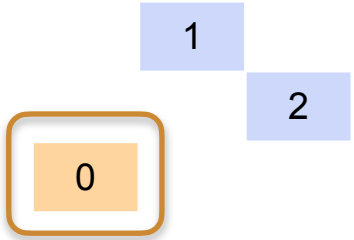


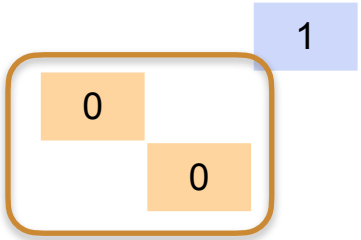


The determinant



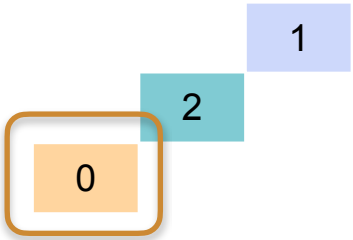


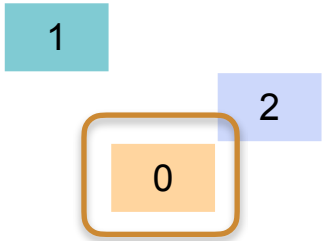


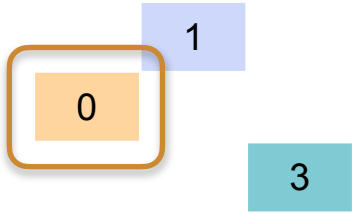


Det = 6+0+0-0-0-0

= 6





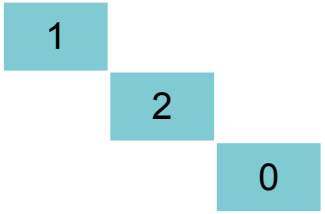


The determinant

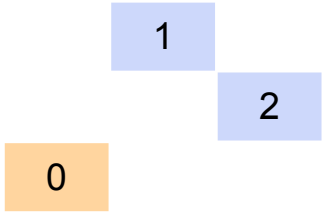
1	1	1
0	2	2
0	0	0

The determinant

1	1	1
0	2	2
0	0	0



$+ \ 1 \cdot 2 \cdot 0$



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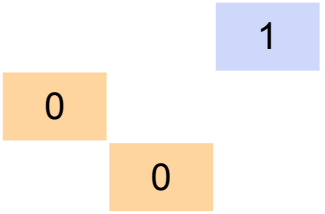

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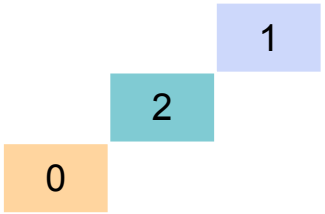

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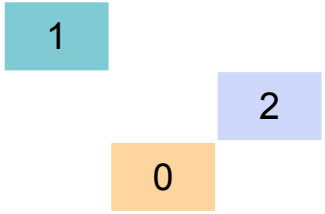

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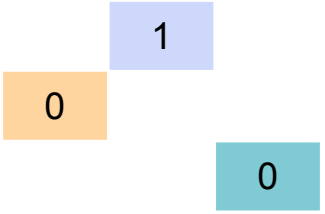

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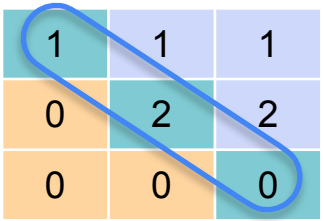
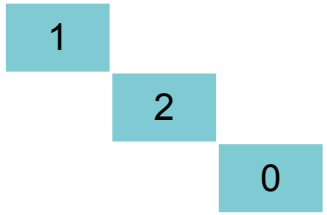
The determinant





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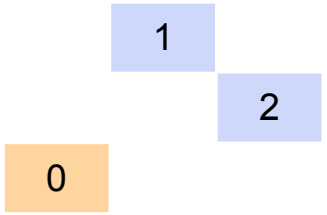

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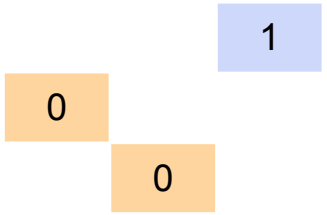

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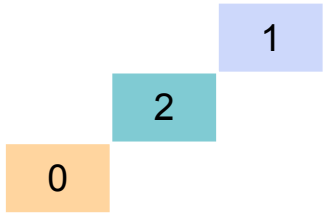

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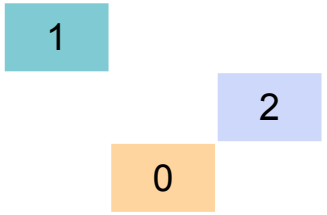

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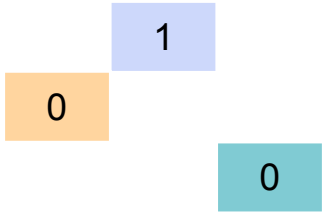

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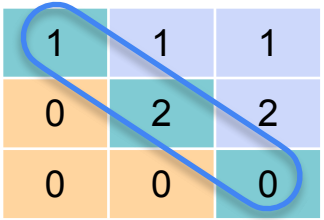
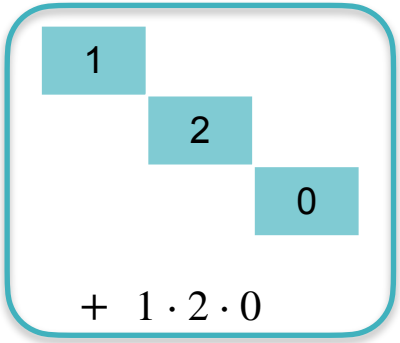
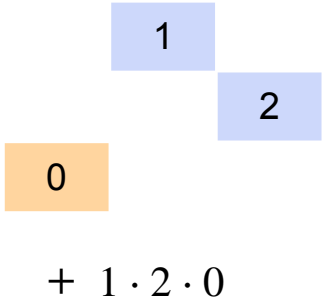
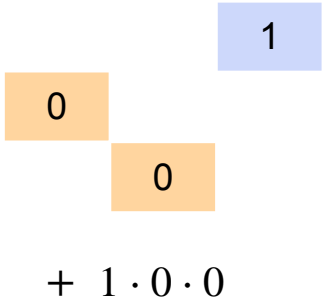
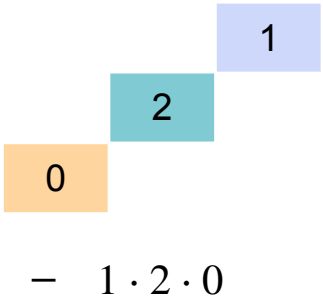
The determinant

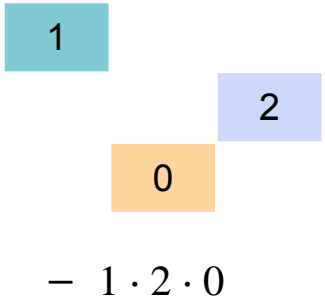


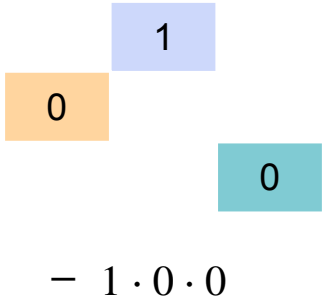




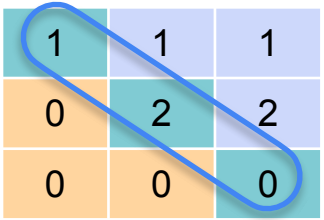


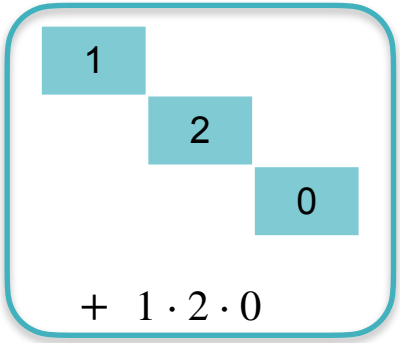


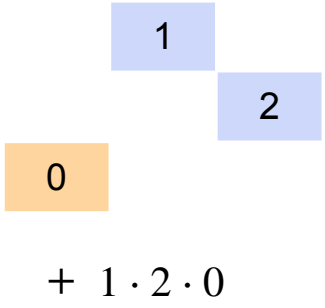


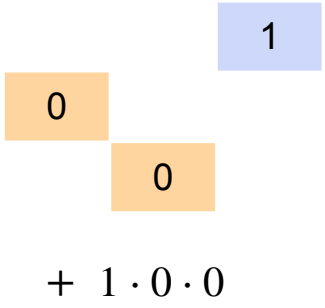


The determinant

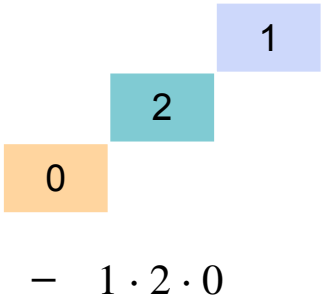


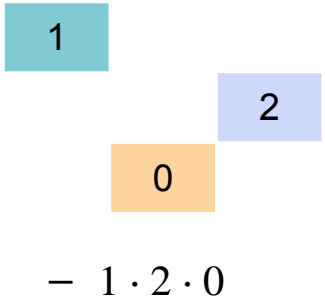


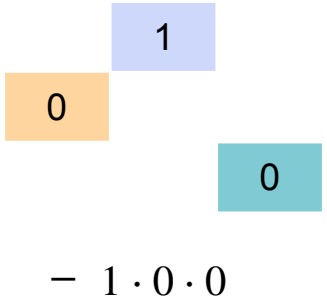




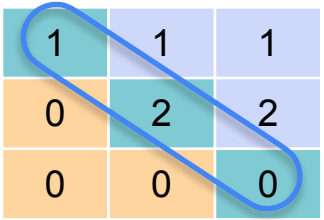
Det = 0+0+0-0-0-0

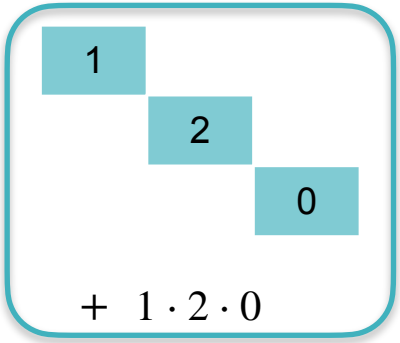


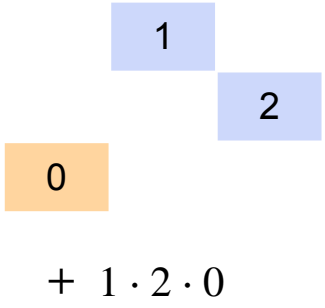


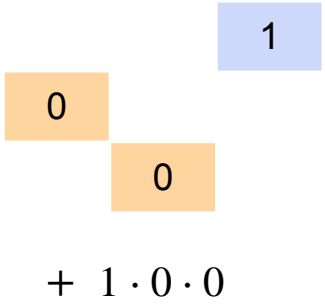


The determinant



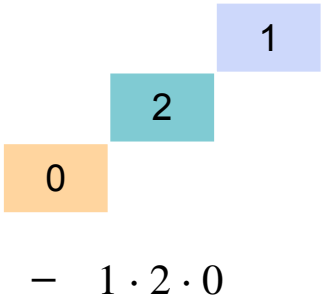


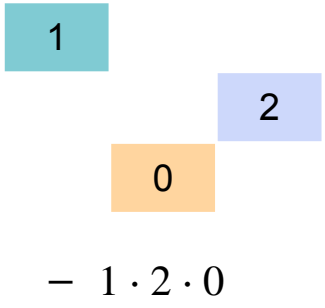


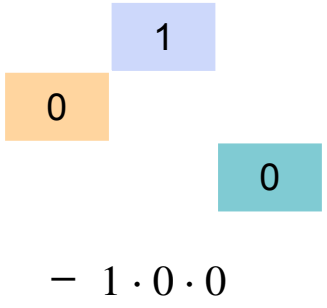


Det = 0+0+0-0-0-0

= 0







DeepLearning.AI

System of Linear Equations

Conclusion