

Announcements

Wednesday, October 10

- ▶ The second midterm is on **Friday, October 19**.
 - ▶ That is one week from this Friday.
 - ▶ The exam covers §§3.5, 3.6, 3.7, 3.9, 4.1, 4.2, 4.3, 4.4 (through today's material).
- ▶ WeBWork 4.2, 4.3 are due today at 11:59pm.
- ▶ The quiz on Friday covers §§4.2, 4.3
- ▶ You can go to other instructors' office hours; see Canvas announcements.



Section 4.4

Matrix Multiplication

Motivation

Recall: we can turn any system of linear equations into a matrix equation

$$Ax = b.$$

This notation is suggestive. Can we solve the equation by “dividing by A”?

$$x \stackrel{??}{=} \frac{b}{A}$$

Answer: Sometimes, but you have to know what you're doing.

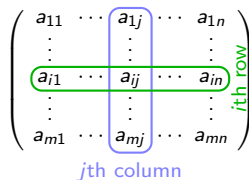
Today we'll study *matrix algebra*: adding and multiplying matrices.

These are not so hard to do. The important thing to understand today is the relationship between *matrix multiplication* and *composition of transformations*.

More Notation for Matrices

Let A be an $m \times n$ matrix.

We write a_{ij} for the entry in the i th row and the j th column. It is called the **ij th entry** of the matrix.



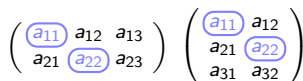
The diagram shows a general $m \times n$ matrix A with entries a_{ij} . A green horizontal oval highlights the i th row, with the label " i th row" written vertically to its right. A blue vertical oval highlights the j th column, with the label " j th column" written below it. The intersection of these two ovals is the entry a_{ij} .

$$\begin{pmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{i1} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & & \vdots & & \vdots \\ a_{m1} & \cdots & a_{mj} & \cdots & a_{mn} \end{pmatrix}$$

The entries $a_{11}, a_{22}, a_{33}, \dots$ are the **diagonal entries**; they form the **main diagonal** of the matrix.

A **diagonal matrix** is a *square* matrix whose only nonzero entries are on the main diagonal.

The $n \times n$ **identity matrix** I_n is the diagonal matrix with all diagonal entries equal to 1. It is special because $I_n \mathbf{v} = \mathbf{v}$ for all \mathbf{v} in \mathbf{R}^n .



The diagram shows a 3×3 matrix with entries a_{ij} . The diagonal entries a_{11}, a_{22}, a_{33} are each circled in blue.

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}$$

$$\begin{pmatrix} a_{11} & 0 & 0 \\ 0 & a_{22} & 0 \\ 0 & 0 & a_{33} \end{pmatrix}$$

$$I_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

More Notation for Matrices

Continued

The **zero matrix** (of size $m \times n$) is the $m \times n$ matrix 0 with all zero entries.

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

The **transpose** of an $m \times n$ matrix A is the $n \times m$ matrix A^T whose rows are the columns of A . In other words, the ij entry of A^T is a_{ji} .

$$\begin{matrix} & A & & A^T \\ \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{pmatrix} & \rightsquigarrow & \begin{pmatrix} a_{11} & a_{21} \\ a_{12} & a_{22} \\ a_{13} & a_{23} \end{pmatrix} \end{matrix}$$

Addition and Scalar Multiplication

You add two matrices component by component, like with vectors.

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{pmatrix} + \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \end{pmatrix} = \begin{pmatrix} a_{11} + b_{11} & a_{12} + b_{12} & a_{13} + b_{13} \\ a_{21} + b_{21} & a_{22} + b_{22} & a_{23} + b_{23} \end{pmatrix}$$

Note you can only add two matrices *of the same size*.

You multiply a matrix by a scalar by multiplying each component, like with vectors.

$$c \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{pmatrix} = \begin{pmatrix} ca_{11} & ca_{12} & ca_{13} \\ ca_{21} & ca_{22} & ca_{23} \end{pmatrix}.$$

These satisfy the expected rules, like with vectors:

$$\begin{array}{ll} A + B = B + A & (A + B) + C = A + (B + C) \\ c(A + B) = cA + cB & (c + d)A = cA + dA \\ (cd)A = c(dA) & A + 0 = A \end{array}$$

Matrix Multiplication

Beware: matrix multiplication is more subtle than addition and scalar multiplication.

Let A be an $m \times n$ matrix and let B be an $n \times p$ matrix with columns v_1, v_2, \dots, v_p :

$$B = \begin{pmatrix} | & | & \cdots & | \\ v_1 & v_2 & \cdots & v_p \\ | & | & \cdots & | \end{pmatrix}.$$

The **product** AB is the $m \times p$ matrix with columns Av_1, Av_2, \dots, Av_p :

The equality is
a definition

$$AB \stackrel{\text{def}}{=} \begin{pmatrix} | & | & \cdots & | \\ Av_1 & Av_2 & \cdots & Av_p \\ | & | & \cdots & | \end{pmatrix}.$$

In order for Av_1, Av_2, \dots, Av_p to make sense, the number of **columns** of A has to be the same as the number of **rows** of B . Note the **sizes** of the product!

Example

$$\begin{aligned} \begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix} \begin{pmatrix} 1 & -3 \\ 2 & -2 \\ 3 & -1 \end{pmatrix} &= \left(\begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix} \quad \begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix} \cdot \begin{pmatrix} -3 \\ -2 \\ -1 \end{pmatrix} \right) \\ &= \begin{pmatrix} 14 & -10 \\ 32 & -28 \end{pmatrix} \end{aligned}$$

The Row-Column Rule for Matrix Multiplication

Recall: A row vector of length n times a column vector of length n is a scalar:

$$(a_1 \quad \cdots \quad a_n) \begin{pmatrix} b_1 \\ \vdots \\ b_n \end{pmatrix} = a_1 b_1 + \cdots + a_n b_n.$$

Another way of multiplying a matrix by a vector is:

$$Ax = \begin{pmatrix} -r_1- \\ \vdots \\ -r_m- \end{pmatrix} x = \begin{pmatrix} r_1 x \\ \vdots \\ r_m x \end{pmatrix}.$$

On the other hand, you multiply two matrices by

$$AB = A \begin{pmatrix} | & & | \\ c_1 & \cdots & c_p \\ | & & | \end{pmatrix} = \begin{pmatrix} | & & | \\ Ac_1 & \cdots & Ac_p \\ | & & | \end{pmatrix}.$$

It follows that

$$AB = \begin{pmatrix} -r_1- \\ \vdots \\ -r_m- \end{pmatrix} \begin{pmatrix} | & & | \\ c_1 & \cdots & c_p \\ | & & | \end{pmatrix} = \begin{pmatrix} r_1 c_1 & r_1 c_2 & \cdots & r_1 c_p \\ r_2 c_1 & r_2 c_2 & \cdots & r_2 c_p \\ \vdots & \vdots & & \vdots \\ r_m c_1 & r_m c_2 & \cdots & r_m c_p \end{pmatrix}$$

The Row-Column Rule for Matrix Multiplication

The ij entry of $C = AB$ is the i th row of A times the j th column of B :

$$c_{ij} = (AB)_{ij} = a_{i1}b_{1j} + a_{i2}b_{2j} + \cdots + a_{in}b_{nj}.$$

This is how everybody on the planet actually computes AB . Diagram ($AB = C$):

$$\begin{pmatrix} a_{11} & \cdots & a_{1k} & \cdots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{i1} & \cdots & a_{ik} & \cdots & a_{in} \\ \vdots & & \vdots & & \vdots \\ a_{m1} & \cdots & a_{mk} & \cdots & a_{mn} \end{pmatrix} \cdot \begin{pmatrix} b_{11} & \cdots & b_{1j} & \cdots & b_{1p} \\ \vdots & & \vdots & & \vdots \\ b_{k1} & \cdots & b_{kj} & \cdots & b_{kp} \\ \vdots & & \vdots & & \vdots \\ b_{n1} & \cdots & b_{nj} & \cdots & b_{np} \end{pmatrix} = \begin{pmatrix} c_{11} & \cdots & c_{1j} & \cdots & c_{1p} \\ \vdots & & \vdots & & \vdots \\ c_{i1} & \cdots & c_{ij} & \cdots & c_{ip} \\ \vdots & & \vdots & & \vdots \\ c_{m1} & \cdots & c_{mj} & \cdots & c_{mp} \end{pmatrix}$$

j th column ij entry

Example

$$\begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix} \begin{pmatrix} 1 & -3 \\ 2 & -2 \\ 3 & -1 \end{pmatrix} = \begin{pmatrix} 1 \cdot 1 + 2 \cdot 2 + 3 \cdot 3 & \square \\ \square & \square \end{pmatrix} = \begin{pmatrix} 14 & \square \\ \square & \square \end{pmatrix}$$

$$\begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix} \begin{pmatrix} 1 & -3 \\ 2 & -2 \\ 3 & -1 \end{pmatrix} = \begin{pmatrix} \square & \square \\ 4 \cdot 1 + 5 \cdot 2 + 6 \cdot 3 & \square \end{pmatrix} = \begin{pmatrix} \square & \square \\ 32 & \square \end{pmatrix}$$

Composition of Transformations

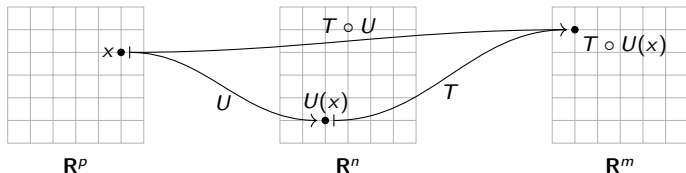
Why is this the correct definition of matrix multiplication?

Definition

Let $T: \mathbf{R}^n \rightarrow \mathbf{R}^m$ and $U: \mathbf{R}^p \rightarrow \mathbf{R}^n$ be transformations. The **composition** is the transformation

$$T \circ U: \mathbf{R}^p \rightarrow \mathbf{R}^m \quad \text{defined by} \quad T \circ U(x) = T(U(x)).$$

This makes sense because $U(x)$ (the output of U) is in \mathbf{R}^n , which is the domain of T (the inputs of T). [\[interactive\]](#)



Fact: If T and U are linear then so is $T \circ U$.

Guess: If A is the matrix for T , and B is the matrix for U , what is the matrix for $T \circ U$?

Composition of Linear Transformations

Let $T: \mathbf{R}^n \rightarrow \mathbf{R}^m$ and $U: \mathbf{R}^p \rightarrow \mathbf{R}^n$ be *linear* transformations. Let A and B be their matrices:

$$A = \left(\begin{array}{c|c|c|c} & & & \\ T(e_1) & T(e_2) & \cdots & T(e_n) \\ & & & \end{array} \right) \quad B = \left(\begin{array}{c|c|c|c} & & & \\ U(e_1) & U(e_2) & \cdots & U(e_p) \\ & & & \end{array} \right)$$

Question

$U(e_1) = Be_1$ is the first column of B

What is the matrix for $T \circ U$?

the first column of AB is $A(Be_1)$

We find the matrix for $T \circ U$ by plugging in the unit coordinate vectors:

$$T \circ U(e_1) = T(U(e_1)) \cong T(Be_1) = A(Be_1) \cong (AB)e_1.$$

For any other i , the same works:

$$T \circ U(e_i) = T(U(e_i)) = T(Be_i) = A(Be_i) = (AB)e_i.$$

This says that the i th column of the matrix for $T \circ U$ is the i th column of AB .

The matrix of the composition is the product of the matrices!

Composition of Linear Transformations

Remark

We can also add and scalar multiply linear transformations:

$$T, U: \mathbf{R}^n \rightarrow \mathbf{R}^m \rightsquigarrow T + U: \mathbf{R}^n \rightarrow \mathbf{R}^m \quad (T + U)(x) = T(x) + U(x).$$

In other words, add transformations “pointwise”.

$$T: \mathbf{R}^n \rightarrow \mathbf{R}^m \quad c \text{ in } \mathbf{R} \rightsquigarrow cT: \mathbf{R}^n \rightarrow \mathbf{R}^m \quad (cT)(x) = c \cdot T(x).$$

In other words, scalar-multiply a transformation “pointwise”.

If T has matrix A and U has matrix B , then:

- ▶ $T + U$ has matrix $A + B$.
- ▶ cT has matrix cA .

So, transformation algebra is the same as matrix algebra.

Composition of Linear Transformations

Example

Let $T: \mathbf{R}^3 \rightarrow \mathbf{R}^2$ and $U: \mathbf{R}^2 \rightarrow \mathbf{R}^3$ be the matrix transformations

$$T(x) = \begin{pmatrix} 1 & -1 & 0 \\ 0 & 1 & 1 \end{pmatrix} x \quad U(x) = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 1 \end{pmatrix} x.$$

Then the matrix for $T \circ U$ is

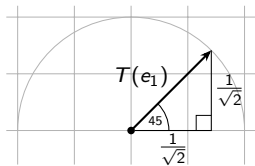
$$\begin{pmatrix} 1 & -1 & 0 \\ 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 1 \end{pmatrix} = \begin{pmatrix} 1 & -1 \\ 1 & 2 \end{pmatrix}$$

[interactive]

Composition of Linear Transformations

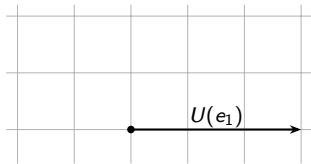
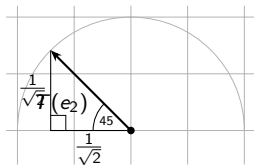
Another Example

Let $T: \mathbf{R}^2 \rightarrow \mathbf{R}^2$ be rotation by 45° , and let $U: \mathbf{R}^2 \rightarrow \mathbf{R}^2$ scale the x-coordinate by 1.5. Let's compute their standard matrices A and B :



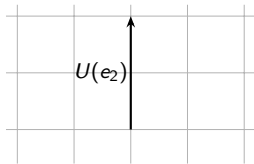
$$T(e_1) = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$$T(e_2) = \frac{1}{\sqrt{2}} \begin{pmatrix} -1 \\ 1 \end{pmatrix}$$



$$U(e_1) = \begin{pmatrix} 1.5 \\ 0 \end{pmatrix}$$

$$U(e_2) = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$



$$\Rightarrow A = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \quad B = \begin{pmatrix} 1.5 & 0 \\ 0 & 1 \end{pmatrix}$$

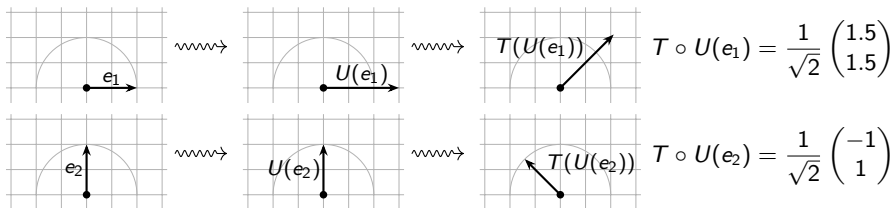
Composition of Linear Transformations

Another example, continued

So the matrix C for $T \circ U$ is

$$\begin{aligned} C = AB &= \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 1.5 & 0 \\ 0 & 1 \end{pmatrix} \\ &= \left(\frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 1.5 \\ 0 \end{pmatrix} \quad \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right) = \frac{1}{\sqrt{2}} \begin{pmatrix} 1.5 & -1 \\ 1.5 & 1 \end{pmatrix}. \end{aligned}$$

Check: [\[interactive: \$e_1\$ \]](#) [\[interactive: \$e_2\$ \]](#)

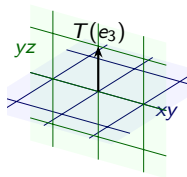
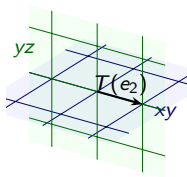
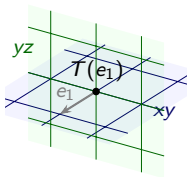


$$\Rightarrow C = \frac{1}{\sqrt{2}} \begin{pmatrix} 1.5 & -1 \\ 1.5 & 1 \end{pmatrix} \quad \checkmark$$

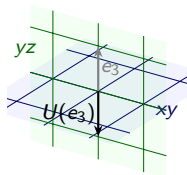
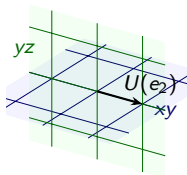
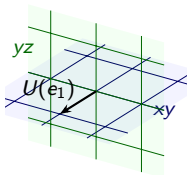
Composition of Linear Transformations

Another example

Let $T: \mathbf{R}^3 \rightarrow \mathbf{R}^3$ be projection onto the yz -plane, and let $U: \mathbf{R}^3 \rightarrow \mathbf{R}^3$ be reflection over the xy -plane. Let's compute their standard matrices A and B :



$$A = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



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

Composition of Linear Transformations

Another example, continued

So the matrix C for $T \circ U$ is

$$C = AB = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}.$$

Check: we did this last time



[interactive: e_1]

[interactive: e_2]

[interactive: e_3]

Poll

Do there exist *nonzero* matrices A and B with $AB = 0$?

Yes! Here's an example:

$$\begin{pmatrix} 1 & 0 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 1 & 1 \end{pmatrix} = \left(\begin{pmatrix} 1 & 0 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right) = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}.$$

Properties of Matrix Multiplication

Mostly matrix multiplication works like you'd expect. Suppose A has size $m \times n$, and that the other matrices below have the right size to make multiplication work.

$$\begin{array}{ll} A(BC) = (AB)C & A(B + C) = (AB + AC) \\ (B + C)A = BA + CA & c(AB) = (cA)B \\ c(AB) = A(cB) & I_m A = A \\ AI_n = A & \end{array}$$

Most of these are easy to verify.

Associativity is $A(BC) = (AB)C$. It is a pain to verify using the row-column rule! Much easier: use associativity of linear transformations:

$$S \circ (T \circ U) = (S \circ T) \circ U.$$

This is a good example of an instance where having a conceptual viewpoint saves you a lot of work.

Recommended: Try to verify all of them on your own.

Properties of Matrix Multiplication

Caveats

Warnings!

- ▶ AB is usually not equal to BA .

$$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 2 & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & -1 \\ 2 & 0 \end{pmatrix} \quad \begin{pmatrix} 2 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} = \begin{pmatrix} 0 & -2 \\ 1 & 0 \end{pmatrix}$$

In fact, AB may be defined when BA is not.

- ▶ $AB = AC$ does not imply $B = C$, even if $A \neq 0$.

$$\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 2 \\ 3 & 4 \end{pmatrix} = \begin{pmatrix} 1 & 2 \\ 0 & 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 2 \\ 5 & 6 \end{pmatrix}$$

- ▶ $AB = 0$ does not imply $A = 0$ or $B = 0$.

$$\begin{pmatrix} 1 & 0 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 1 & 1 \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}$$

Powers of a Matrix

Suppose A is a *square* matrix.

Then $A \cdot A$ makes sense, and has the same size.

Then $A \cdot (A \cdot A)$ also makes sense and has the same size.

Definition

Let n be a positive whole number and let A be a square matrix. The **n th power** of A is the product

$$A^n = \underbrace{A \cdot A \cdots A}_{n \text{ times}}$$

Example

$$\begin{aligned} A &= \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} & A^2 &= \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & 2 \\ 0 & 1 \end{pmatrix} \\ & & A^3 &= \begin{pmatrix} 1 & 2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & 3 \\ 0 & 1 \end{pmatrix} \\ & & \dots & A^n = \begin{pmatrix} 1 & n-1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & n \\ 0 & 1 \end{pmatrix} \end{aligned}$$

Summary

- ▶ The product of an $m \times n$ matrix and an $n \times p$ matrix is an $m \times p$ matrix. I showed you two ways of computing the product.
- ▶ Composition of linear transformations corresponds to multiplication of matrices.
- ▶ You have to be careful when multiplying matrices together, because things like commutativity and cancellation fail.
- ▶ You can take powers of square matrices.