

Announcements

Monday, October 01

- ▶ Please fill out the mid-semester survey under “Quizzes” on Canvas.
- ▶ WeBWork 3.7, 3.9, 4.1 are due on Wednesday at 11:59pm.
- ▶ The quiz on Friday covers §§3.7, 3.9, 4.1.
- ▶ My office is Skiles 244 and Rabinoffice hours are: Mondays, 12–1pm; Wednesdays, 1–3pm.
- ▶ I will have a new baby any day now, if it hasn't already happened. At that point various other instructors will fill in for me.

Section 4.2

One-to-one and Onto Transformations

Matrix Transformations

Reminder

Recall: Let A be an $m \times n$ matrix. The **matrix transformation** associated to A is the transformation

$$T: \mathbf{R}^n \longrightarrow \mathbf{R}^m \quad \text{defined by} \quad T(x) = Ax.$$

- ▶ The *domain* of T is \mathbf{R}^n , which is the number of *columns* of A .
- ▶ The *codomain* of T is \mathbf{R}^m , which is the number of *rows* of A .
- ▶ The *range* of T is the set of all images of T :

$$T(x) = Ax = \begin{pmatrix} | & | & \cdots & | \\ v_1 & v_2 & \cdots & v_n \\ | & | & \cdots & | \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} = x_1 v_1 + x_2 v_2 + \cdots + x_n v_n.$$

This is the *column space* of A . It is a span of vectors in the codomain.

Matrix Transformations

Example

Let $A = \begin{pmatrix} 1 & 1 \\ 0 & 1 \\ 1 & 1 \end{pmatrix}$ and let $T(x) = Ax$, so $T: \mathbf{R}^2 \rightarrow \mathbf{R}^3$.

► If $u = \begin{pmatrix} 3 \\ 4 \end{pmatrix}$ then $T(u) = \begin{pmatrix} 1 & 1 \\ 0 & 1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 3 \\ 4 \end{pmatrix} = \begin{pmatrix} 7 \\ 4 \\ 7 \end{pmatrix}$.

► Let $b = \begin{pmatrix} 7 \\ 5 \\ 7 \end{pmatrix}$. Find v in \mathbf{R}^2 such that $T(v) = b$. Is there more than one?

We want to find v such that $T(v) = Av = b$. We know how to do that:

$$\begin{pmatrix} 1 & 1 \\ 0 & 1 \\ 1 & 1 \end{pmatrix} v = \begin{pmatrix} 7 \\ 5 \\ 7 \end{pmatrix} \xrightarrow[\text{augmented matrix}]{\text{}} \left(\begin{array}{cc|c} 1 & 1 & 7 \\ 0 & 1 & 5 \\ 1 & 1 & 7 \end{array} \right) \xrightarrow[\text{reduce}]{\text{}} \left(\begin{array}{cc|c} 1 & 0 & 2 \\ 0 & 1 & 5 \\ 0 & 0 & 0 \end{array} \right).$$

This gives $x = 2$ and $y = 5$, or $v = \begin{pmatrix} 2 \\ 5 \end{pmatrix}$ (unique). In other words,

$$T(v) = \begin{pmatrix} 1 & 1 \\ 0 & 1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 2 \\ 5 \end{pmatrix} = \begin{pmatrix} 7 \\ 5 \\ 7 \end{pmatrix}.$$

Matrix Transformations

Example, continued

Let $A = \begin{pmatrix} 1 & 1 \\ 0 & 1 \\ 1 & 1 \end{pmatrix}$ and let $T(x) = Ax$, so $T: \mathbf{R}^2 \rightarrow \mathbf{R}^3$.

- Is there any c in \mathbf{R}^3 such that there is more than one v in \mathbf{R}^2 with $T(v) = c$?

Translation: is there any c in \mathbf{R}^3 such that the solution set of $Ax = c$ has more than one vector v in it?

The solution set of $Ax = c$ is a translate of the solution set of $Ax = b$ (from before), which has one vector in it. So the solution set to $Ax = c$ has only one vector. So no!

- Find c such that there is *no* v with $T(v) = c$.

Translation: Find c such that $Ax = c$ is inconsistent.

Translation: Find c not in the column space of A (i.e., the range of T).

We could draw a picture, or notice that if $c = \begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix}$, then our matrix equation translates into

$$x + y = 1 \quad y = 2 \quad x + y = 3,$$

which is obviously inconsistent.

Matrix Transformations

Non-Example

Note: All of these questions are questions about *the transformation* T ; it still makes sense to ask them in the absence of the matrix A .

The fact that T comes from a matrix means that these questions translate into questions about a matrix, which we know how to do.

Non-example: $T: \mathbf{R}^2 \rightarrow \mathbf{R}^3$ $T \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} \sin x \\ xy \\ \cos y \end{pmatrix}$

Question: Is there any c in \mathbf{R}^3 such that there is more than one v in \mathbf{R}^2 with $T(v) = c$?

Note the question still makes sense, although T has no hope of being a matrix transformation.

By the way,

$$T \begin{pmatrix} 0 \\ 0 \end{pmatrix} = \begin{pmatrix} \sin 0 \\ 0 \cdot 0 \\ \cos 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} \sin \pi \\ 0 \cdot \pi \\ \cos 0 \end{pmatrix} = T \begin{pmatrix} \pi \\ 0 \end{pmatrix},$$

so the answer is yes.

Questions About Transformations

Today we will focus on two important questions one can ask about a transformation $T: \mathbf{R}^n \rightarrow \mathbf{R}^m$:

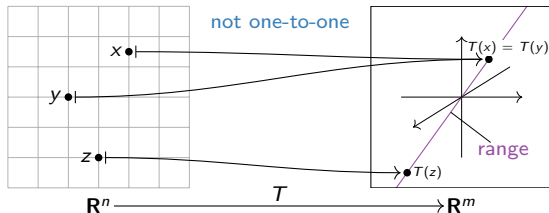
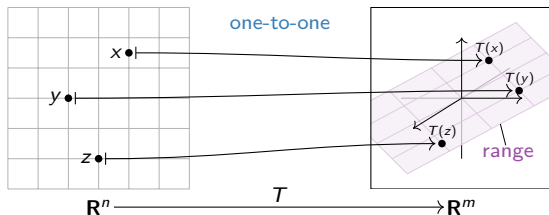
- ▶ Do there exist distinct vectors x, y in \mathbf{R}^n such that $T(x) = T(y)$?
- ▶ For every vector v in \mathbf{R}^m , does there exist a vector x in \mathbf{R}^n such that $T(x) = v$?

These are subtle because of the multiple *quantifiers* involved (“for every”, “there exists”).

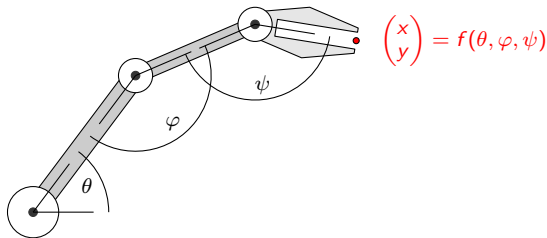
One-to-one Transformations

Definition

A transformation $T: \mathbf{R}^n \rightarrow \mathbf{R}^m$ is **one-to-one** (or **into**, or **injective**) if different vectors in \mathbf{R}^n map to different vectors in \mathbf{R}^m . In other words, for every b in \mathbf{R}^m , the equation $T(x) = b$ has *at most one* solution x . Or, different inputs have different outputs. Note that *not* one-to-one means at least two different vectors in \mathbf{R}^n have the same image.



Consider the robot hand transformation from last lecture:



Define $f: \mathbf{R}^3 \rightarrow \mathbf{R}^2$ by:

$f(\theta, \varphi, \psi)$ = position of the hand at joint angles θ, φ, ψ .

Poll

Is f one-to-one?

No: there is more than one way to move the hand to the same point.

Characterization of One-to-One Matrix Transformations

Theorem

Let $T: \mathbf{R}^n \rightarrow \mathbf{R}^m$ be a matrix transformation with matrix A . Then the following are equivalent:

- ▶ T is one-to-one
- ▶ $T(x) = b$ has one or zero solutions for every b in \mathbf{R}^m
- ▶ $Ax = b$ has a unique solution or is inconsistent for every b in \mathbf{R}^m
- ▶ $Ax = 0$ has a unique solution
- ▶ The columns of A are linearly independent
- ▶ A has a pivot in every column.

Question

If $T: \mathbf{R}^n \rightarrow \mathbf{R}^m$ is one-to-one, what can we say about the relative sizes of n and m ?

Answer: T corresponds to an $m \times n$ matrix A . In order for A to have a pivot in every column, it must have *at least as many rows as columns*: $n \leq m$.

$$\begin{pmatrix} \color{red}{1} & 0 & 0 \\ 0 & \color{red}{1} & 0 \\ 0 & 0 & \color{red}{1} \\ 0 & 0 & 0 \end{pmatrix}$$

For instance, \mathbf{R}^3 is “too big” to map *into* \mathbf{R}^2 .

One-to-One Transformations

Example

Define

$$A = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \end{pmatrix} \quad T(x) = Ax,$$

so $T: \mathbf{R}^2 \rightarrow \mathbf{R}^3$. Is T one-to-one?

The reduced row echelon form of A is

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

which has a pivot in every column. Hence T is one-to-one.

[interactive]

One-to-One Transformations

Non-Example

Define

$$A = \begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \end{pmatrix} \quad T(x) = Ax,$$

so $T: \mathbf{R}^3 \rightarrow \mathbf{R}^2$. Is T one-to-one? If not, find two different vectors x, y such that $T(x) = T(y)$.

The reduced row echelon form of A is

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

which does not have a pivot in every column. Hence A is not one-to-one. In particular, $Ax = 0$ has nontrivial solutions. The parametric form of the solutions of $Ax = 0$ are

$$\begin{array}{rcl} x & -z & = 0 \\ y + z & = 0 \end{array} \implies \begin{array}{rcl} x & = & z \\ y & = & -z. \end{array}$$

Taking $z = 1$ gives

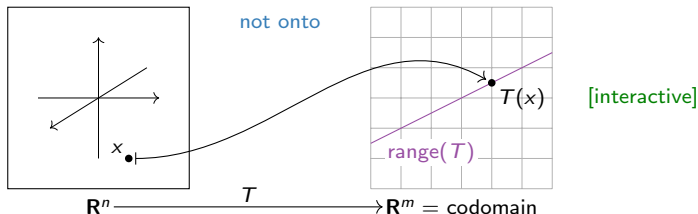
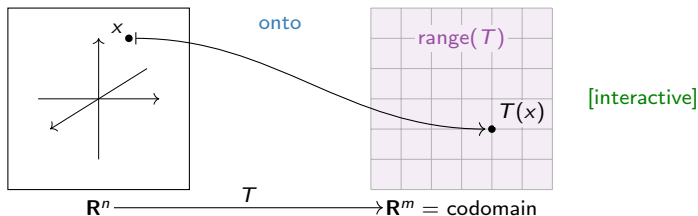
$$T \begin{pmatrix} 1 \\ -1 \\ 1 \end{pmatrix} = \begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ -1 \\ 1 \end{pmatrix} = 0 = T \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}.$$

[interactive]

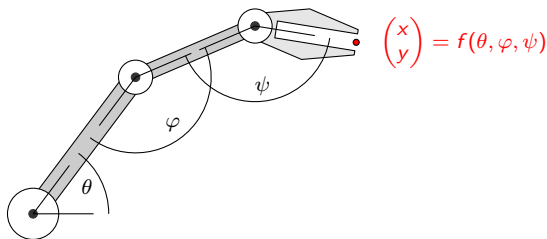
Onto Transformations

Definition

A transformation $T: \mathbf{R}^n \rightarrow \mathbf{R}^m$ is **onto** (or **surjective**) if the range of T is equal to \mathbf{R}^m (its codomain). In other words, for every b in \mathbf{R}^m , the equation $T(x) = b$ has at *least one solution*. Or, every possible output has an input. Note that *not* onto means there is some b in \mathbf{R}^m which is not the image of any x in \mathbf{R}^n .



Consider the robot hand transformation again:



Define $f: \mathbf{R}^3 \rightarrow \mathbf{R}^2$ by:

$f(\theta, \varphi, \psi) = \text{position of the hand at joint angles } \theta, \varphi, \psi.$

Poll

Is f onto?

No: it can't reach points that are far away.

Characterization of Onto Matrix Transformations

Theorem

Let $T: \mathbf{R}^n \rightarrow \mathbf{R}^m$ be a matrix transformation with matrix A . Then the following are equivalent:

- ▶ T is onto
- ▶ $T(x) = b$ has a solution for every b in \mathbf{R}^m
- ▶ $Ax = b$ is consistent for every b in \mathbf{R}^m
- ▶ The columns of A span \mathbf{R}^m
- ▶ A has a pivot in every row

Question

If $T: \mathbf{R}^n \rightarrow \mathbf{R}^m$ is onto, what can we say about the relative sizes of n and m ?

Answer: T corresponds to an $m \times n$ matrix A . In order for A to have a pivot in every row, it must have *at least as many* columns as rows: $m \leq n$.

$$\begin{pmatrix} \color{red}{1} & 0 & \star & 0 & \star \\ 0 & \color{red}{1} & \star & 0 & \star \\ 0 & 0 & 0 & \color{red}{1} & \star \end{pmatrix}$$

For instance, \mathbf{R}^2 is “too small” to map *onto* \mathbf{R}^3 .

Onto Transformations

Example

Define

$$A = \begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \end{pmatrix} \quad T(x) = Ax,$$

so $T: \mathbf{R}^3 \rightarrow \mathbf{R}^2$. Is T onto?

The reduced row echelon form of A is

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

which has a pivot in every row. Hence T is onto.

Note that T is *onto* but not *one-to-one*.

[interactive]

Onto Transformations

Non-Example

Define

$$A = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \end{pmatrix} \quad T(x) = Ax,$$

so $T: \mathbf{R}^2 \rightarrow \mathbf{R}^3$. Is T onto? If not, find a vector v in \mathbf{R}^3 such that there does not exist any x in \mathbf{R}^2 with $T(x) = v$.

The reduced row echelon form of A is

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

which does not have a pivot in every row. Hence A is not onto.

In order to find a vector v not in the range, we notice that $T\begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} a \\ b \\ a \end{pmatrix}$. In particular, the x - and z -coordinates are the same for every vector in the range, so for example, $v = \begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix}$ is not in the range.

Note that T is *one-to-one* but not *onto*.

[interactive]

One-to-One and Onto Transformations

Non-Example

Define

$$A = \begin{pmatrix} 1 & -1 & 2 \\ -2 & 2 & -4 \end{pmatrix} \quad T(x) = Ax,$$

so $T: \mathbf{R}^3 \rightarrow \mathbf{R}^2$. Is T one-to-one? Is it onto?

The reduced row echelon form of A is

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

which does not have a pivot in every row or in every column. Hence T is neither one-to-one nor onto.

[interactive]

Summary

- ▶ A transformation T is **one-to-one** if $T(x) = b$ has *at most one* solution, for every b in \mathbf{R}^m .
- ▶ A transformation T is **onto** if $T(x) = b$ has *at least one* solution, for every b in \mathbf{R}^m .
- ▶ A matrix transformation with matrix A is one-to-one if and only if the columns of A are linearly independent, if and only if A has a pivot in every column.
- ▶ A matrix transformation with matrix A is onto if and only if the columns of A span \mathbf{R}^m , if and only if A has a pivot in every row.
- ▶ Two of the most basic questions one can ask about a transformation is whether it is one-to-one or onto.