

Solving Systems of Equations

Example

Solve the system of equations

$$\begin{aligned}x + 2y + 3z &= 6 \\2x - 3y + 2z &= 14 \\3x + y - z &= -2\end{aligned}$$

This is the kind of problem we'll talk about for the first half of the course.

- ▶ A **solution** is a list of numbers x, y, z, \dots that makes *all* of the equations true.
- ▶ The **solution set** is the collection of all solutions.
- ▶ **Solving** the system means finding the solution set in a "parameterized" form.

What is a *systematic* way to solve a system of equations?

Solving Systems of Equations

Example

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$$x + 2y + 3z = 6$$

$$2x - 3y + 2z = 14$$

$$3x + y - z = -2$$

What strategies do you know?

- ▶ Substitution
- ▶ Elimination

Both are perfectly valid, but only elimination scales well to large numbers of equations.

Solving Systems of Equations

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Solve the system of equations

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$$3x + y - z = -2$$

Elimination method: in what ways can you manipulate the equations?

- ▶ Multiply an equation by a nonzero number. (scale)
- ▶ Add a multiple of one equation to another. (replacement)
- ▶ Swap two equations. (swap)

Solving Systems of Equations

Example

Solve the system of equations

$$x + 2y + 3z = 6$$

$$2x - 3y + 2z = 14$$

$$3x + y - z = -2$$

Multiply first by -3

~~~~~→

$$-3x - 6y - 9z = -18$$

$$2x - 3y + 2z = 14$$

$$3x + y - z = -2$$

Add first to third

~~~~~→

$$-3x - 6y - 9z = -18$$

$$2x - 3y + 2z = 14$$

$$-5y - 10z = -20$$

Now I've eliminated x from the last equation!

... but there's a long way to go still. Can we make our lives easier?

Solving Systems of Equations

Better notation

It sure is a pain to have to write x, y, z , and $=$ over and over again.

Matrix notation: write just the numbers, in a box, instead!

$$\begin{array}{rcl} x + 2y + 3z = & 6 \\ 2x - 3y + 2z = & 14 \\ 3x + y - z = & -2 \end{array} \quad \begin{array}{l} \text{becomes} \\ \rightsquigarrow \end{array} \quad \left(\begin{array}{ccc|c} 1 & 2 & 3 & 6 \\ 2 & -3 & 2 & 14 \\ 3 & 1 & -1 & -2 \end{array} \right)$$

This is called an **(augmented) matrix**. Our equation manipulations become **elementary row operations**:

- ▶ Multiply all entries in a row by a nonzero number. **(scale)**
- ▶ Add a multiple of each entry of one row to the corresponding entry in another. **(row replacement)**
- ▶ Swap two rows. **(swap)**

Example

Solve the system of equations

$$\begin{aligned}x + 2y + 3z &= 6 \\2x - 3y + 2z &= 14 \\3x + y - z &= -2\end{aligned}$$

Start:

$$\left(\begin{array}{ccc|c} 1 & 2 & 3 & 6 \\ 2 & -3 & 2 & 14 \\ 3 & 1 & -1 & -2 \end{array} \right)$$

Goal: we want our elimination method to eventually produce a system of equations like

$$\begin{array}{rcl} x & = & A \\ y & = & B \\ z & = & C \end{array} \quad \text{or in matrix form,} \quad \left(\begin{array}{ccc|c} 1 & 0 & 0 & A \\ 0 & 1 & 0 & B \\ 0 & 0 & 1 & C \end{array} \right)$$

So we need to do row operations that make the start matrix look like the end one.

Strategy (preliminary): fiddle with it so we only have ones and zeros. [\[animated\]](#)

Row Operations

Continued

$$\left(\begin{array}{ccc|c} 1 & 2 & 3 & 6 \\ 2 & -3 & 2 & 14 \\ 3 & 1 & -1 & -2 \end{array} \right)$$

We want these to be zero.
So we subtract multiples of the first row.

$$\left(\begin{array}{ccc|c} 1 & 2 & 3 & 6 \\ 0 & -7 & -4 & 2 \\ 0 & -5 & -10 & -20 \end{array} \right)$$

We want these to be zero.

It would be nice if this were a 1.
We could divide by -7 , but that
would produce ugly fractions.

Let's swap the last two rows first.

$$\begin{array}{l} R_2 = R_2 - 2R_1 \\ \hline \end{array}$$

$$\begin{array}{l} R_3 = R_3 - 3R_1 \\ \hline \end{array}$$

$$\begin{array}{l} R_2 \leftrightarrow R_3 \\ \hline \end{array}$$

$$\begin{array}{l} R_2 = R_2 \div -5 \\ \hline \end{array}$$

$$\begin{array}{l} R_3 = R_3 + 7R_2 \\ \hline \end{array}$$

$$\begin{array}{l} R_1 = R_1 - 2R_2 \\ \hline \end{array}$$

$$\left(\begin{array}{ccc|c} 1 & 2 & 3 & 6 \\ 0 & -7 & -4 & 2 \\ 3 & 1 & -1 & -2 \end{array} \right)$$

$$\left(\begin{array}{ccc|c} 1 & 2 & 3 & 6 \\ 0 & -7 & -4 & 2 \\ 0 & -5 & -10 & -20 \end{array} \right)$$

$$\left(\begin{array}{ccc|c} 1 & 2 & 3 & 6 \\ 0 & -5 & -10 & -20 \\ 0 & -7 & -4 & 2 \end{array} \right)$$

$$\left(\begin{array}{ccc|c} 1 & 2 & 3 & 6 \\ 0 & 1 & 2 & 4 \\ 0 & -7 & -4 & 2 \end{array} \right)$$

$$\left(\begin{array}{ccc|c} 1 & 2 & 3 & 6 \\ 0 & 1 & 2 & 4 \\ 0 & 0 & 10 & 30 \end{array} \right)$$

$$\left(\begin{array}{ccc|c} 1 & 0 & -1 & -2 \\ 0 & 1 & 2 & 4 \\ 0 & 0 & 10 & 30 \end{array} \right)$$

Row Operations

Continued

$$\left(\begin{array}{ccc|c} 1 & 0 & -1 & -2 \\ 0 & 1 & 2 & 4 \\ 0 & 0 & 10 & 30 \end{array} \right)$$

We want these to be zero.

Let's make this a 1 first.

$$R_3 = R_3 \div 10$$

$$R_2 = R_2 - 2R_3$$

$$R_1 = R_1 + R_3$$

translates into

$$\left(\begin{array}{ccc|c} 1 & 0 & -1 & -2 \\ 0 & 1 & 2 & 4 \\ 0 & 0 & 1 & 3 \end{array} \right)$$

$$\left(\begin{array}{ccc|c} 1 & 0 & -1 & -2 \\ 0 & 1 & 0 & -2 \\ 0 & 0 & 1 & 3 \end{array} \right)$$

$$\left(\begin{array}{ccc|c} 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & -2 \\ 0 & 0 & 1 & 3 \end{array} \right)$$

$$x = 1$$

$$y = -2$$

$$z = 3$$

Success!

Check:

$$x + 2y + 3z = 6$$

$$2x - 3y + 2z = 14$$

$$3x + y - z = -2$$

substitute solution

$$1 + 2 \cdot (-2) + 3 \cdot 3 = 6$$

$$2 \cdot 1 - 3 \cdot (-2) + 2 \cdot 3 = 14$$

$$3 \cdot 1 + (-2) - 3 = -2$$



Important

The process of doing row operations to a matrix does not change the solution set of the corresponding linear equations!

Definition

Two matrices are called **row equivalent** if one can be obtained from the other by doing some number of elementary row operations.

So the linear equations of row-equivalent matrices have the *same solution set*.

A Bad Example

Example

Solve the system of equations

$$x + y = 2$$

$$3x + 4y = 5$$

$$4x + 5y = 9$$

Let's try doing row operations: [\[interactive row reducer\]](#)

First clear these by subtracting multiples of the first row.

$$\left(\begin{array}{cc|c} 1 & 1 & 2 \\ 3 & 4 & 5 \\ 4 & 5 & 9 \end{array} \right) \begin{array}{l} R_2 = R_2 - 3R_1 \\ R_3 = R_3 - 4R_1 \end{array} \rightarrow \left(\begin{array}{cc|c} 1 & 1 & 2 \\ 0 & 1 & -1 \\ 4 & 5 & 9 \end{array} \right)$$
$$\left(\begin{array}{cc|c} 1 & 1 & 2 \\ 0 & 1 & -1 \\ 0 & 1 & 1 \end{array} \right)$$

Now clear this by subtracting the second row.

$$\left(\begin{array}{cc|c} 1 & 1 & 2 \\ 0 & 1 & -1 \\ 0 & 1 & 1 \end{array} \right) \begin{array}{l} R_3 = R_3 - R_2 \end{array} \rightarrow \left(\begin{array}{cc|c} 1 & 1 & 2 \\ 0 & 1 & -1 \\ 0 & 0 & 2 \end{array} \right)$$

A Bad Example

Continued

$$\left(\begin{array}{cc|c} 1 & 1 & 2 \\ 0 & 1 & -1 \\ 0 & 0 & 2 \end{array} \right) \xrightarrow{\text{translates into}} \begin{array}{l} x + y = 2 \\ y = -1 \\ 0 = 2 \end{array}$$

In other words, the original equations

$$\begin{array}{l} x + y = 2 \\ 3x + 4y = 5 \\ 4x + 5y = 9 \end{array} \quad \text{have the same solutions as} \quad \begin{array}{l} x + y = 2 \\ y = -1 \\ 0 = 2 \end{array}$$

But the latter system obviously has no solutions (there is no way to make them all true), so our original system has no solutions either.

Definition

A system of equations is called **inconsistent** if it has no solution. It is **consistent** otherwise.

Section 2.2

Row Reduction

Row Echelon Form

Let's come up with an *algorithm* for turning an arbitrary matrix into a "solved" matrix. What do we mean by "solved"?

A matrix is in **row echelon form** if

1. All zero rows are at the bottom.
2. Each leading nonzero entry of a row is to the *right* of the leading entry of the row above.
3. Below a leading entry of a row, all entries are *zero*.

Picture:

$$\begin{pmatrix} \boxed{\star} & \star & \star & \star & \star \\ 0 & \boxed{\star} & \star & \star & \star \\ 0 & 0 & 0 & \boxed{\star} & \star \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

\star = any number

$\boxed{\star}$ = any nonzero number

Definition

A **pivot** $\boxed{\star}$ is the first nonzero entry of a row of a matrix. A **pivot column** is a column containing a pivot of a matrix *in row echelon form*.

Reduced Row Echelon Form

A matrix is in **reduced row echelon form** if it is in row echelon form, and in addition,

4. The pivot in each nonzero row is equal to 1.
5. Each pivot is the only nonzero entry in its column.

Picture:

$$\begin{pmatrix} 1 & 0 & * & 0 & * \\ 0 & 1 & * & 0 & * \\ 0 & 0 & 0 & 1 & * \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad \begin{array}{l} * = \text{any number} \\ 1 = \text{pivot} \end{array}$$

Note: Echelon forms do not care whether or not a column is augmented. Just ignore the vertical line.

Question

Can every matrix be put into reduced row echelon form only using row operations?

Answer: Yes! Stay tuned.

Reduced Row Echelon Form

Continued

Why is this the “solved” version of the matrix?

$$\left(\begin{array}{ccc|c} 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & -2 \\ 0 & 0 & 1 & 3 \end{array} \right)$$

is in reduced row echelon form. It translates into

$$\begin{aligned} x &= 1 \\ y &= -2 \\ z &= 3, \end{aligned}$$

which is clearly the solution.

But what happens if there are fewer pivots than rows?

$$\left(\begin{array}{ccc|c} 1 & 2 & 0 & 1 \\ 0 & 0 & 1 & 3 \\ 0 & 0 & 0 & 0 \end{array} \right)$$

... parametrized solution set (later).

Poll

Which of the following matrices are in reduced row echelon form?

A. $\begin{pmatrix} 1 & 0 \\ 0 & 2 \end{pmatrix}$ B. $\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$

C. $\begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}$ D. $(0 \ 1 \ 0 \ 0)$ E. $(0 \ 1 \ 8 \ 0)$

F. $\left(\begin{array}{cc|c} 1 & 17 & 0 \\ 0 & 0 & 1 \end{array} \right)$

Answer: B, D, E, F.

Note that A is in row echelon form though.

Summary

- ▶ Solving a system of equations means producing all values for the unknowns that make all the equations true simultaneously.
- ▶ It is easier to solve a system of linear equations if you put all the coefficients in an **augmented matrix**.
- ▶ Solving a system using the elimination method means doing **elementary row operations** on an augmented matrix.
- ▶ Two systems or matrices are **row-equivalent** if one can be obtained from the other by doing a sequence of elementary row operations. Row-equivalent systems have the *same solution set*.
- ▶ A linear system with no solutions is called **inconsistent**.
- ▶ The (reduced) row echelon form of a matrix is its “solved” row-equivalent version.