

§1.1: Systems of Linear Equations

Linear Algebra is the study of linear equations.

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Example: $x_2 = \sqrt{2}(\sqrt{6} - x_1) + x_3 \longrightarrow \sqrt{2}x_1 + (1)x_2 + (-1)x_3 = 2\sqrt{3}$

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$$xy + x = e^5$$

The problem is that the variables are not only multiplied by numbers.

In general, a **linear equation** is an equation of the form

$$a_1x_1 + a_2x_2 + \cdots + a_nx_n = b.$$

x_1, x_2, \dots, x_n are the **variables**.

a_1, a_2, \dots, a_n are the **coefficients**.

A linear equation has the form $a_1x_1 + a_2x_2 + \dots + a_nx_n = b$.

Definition: A *system of linear equations* (or a *linear system*) is a collection of linear equations involving the same set of variables.

Example:
$$\begin{array}{rclcl} x & +y & & = & 3 \\ 3x & & +2z & = & -2 \end{array}$$
 is a system of 2 equations in 3 variables, x, y, z . Notice that not every variable appears in every equation.

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Definition: A *solution* of a linear system is a list (s_1, s_2, \dots, s_n) of numbers that makes each equation a true statement when the values s_1, s_2, \dots, s_n are substituted for x_1, x_2, \dots, x_n respectively.

Definition: The *solution set* of a linear system is the set of all possible solutions.

Example: One solution to the above system is $(x, y, z) = (2, 1, -4)$, because $2 + 1 = 3$ and $3(2) + 2(-4) = -2$.

Question: Is there another solution? How many solutions are there?

Definition: A linear system is *consistent* if it has a solution,
and *inconsistent* if it does not have a solution.

Fact: (which we will prove in the next class) A linear system has either

- exactly one solution consistent
- infinitely many solutions consistent
- no solutions inconsistent

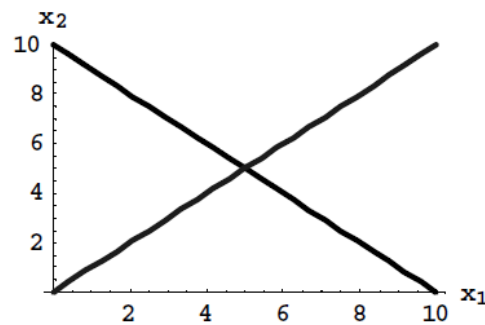
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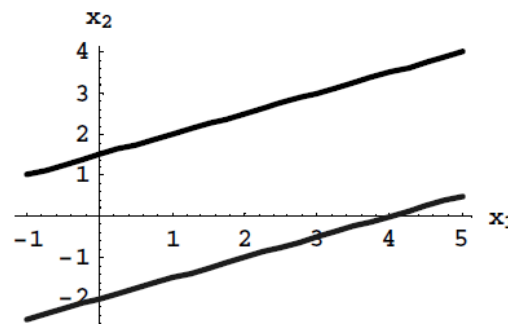
EXAMPLE Two equations in two variables:

$$\begin{aligned}x_1 + x_2 &= 10 \\ -x_1 + x_2 &= 0\end{aligned}$$



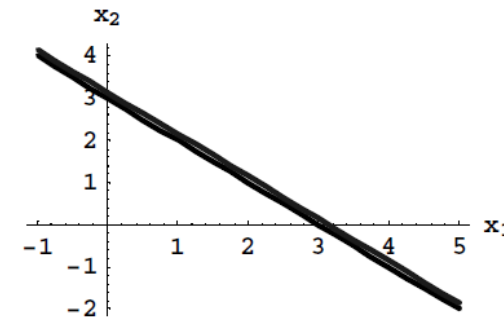
one unique solution
consistent

$$\begin{aligned}x_1 - 2x_2 &= -3 \\ 2x_1 - 4x_2 &= 8\end{aligned}$$



no solution
inconsistent

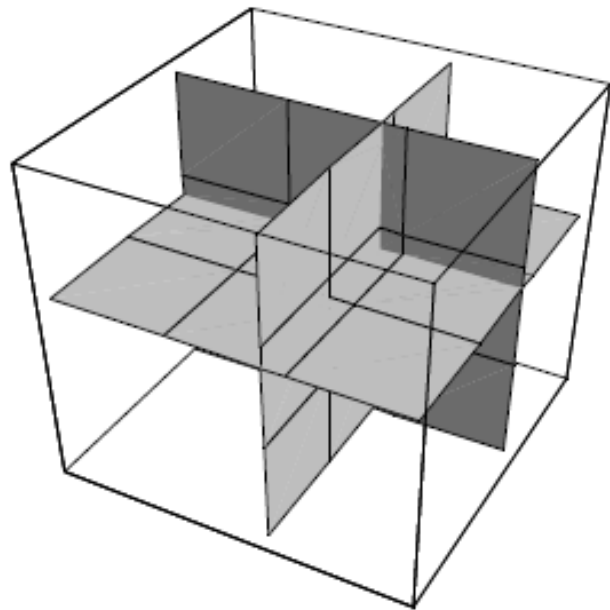
$$\begin{aligned}x_1 + x_2 &= 3 \\ -2x_1 - 2x_2 &= -6\end{aligned}$$



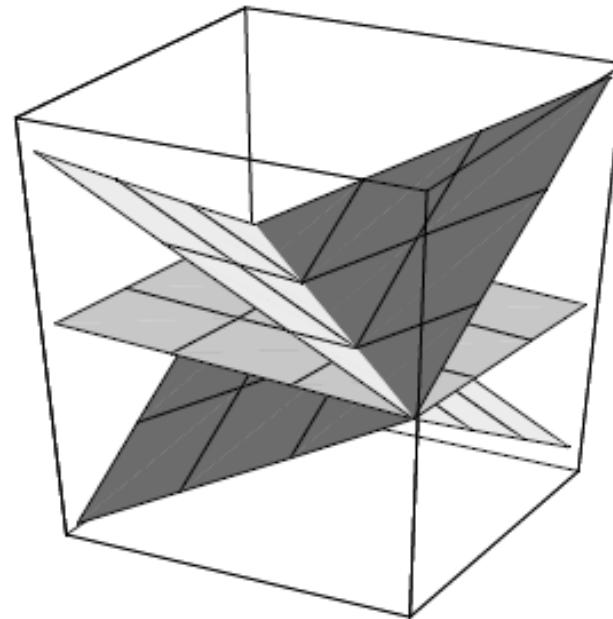
infinitely many solutions
consistent

EXAMPLE: Three equations in three variables. Each equation determines a plane in 3-space.

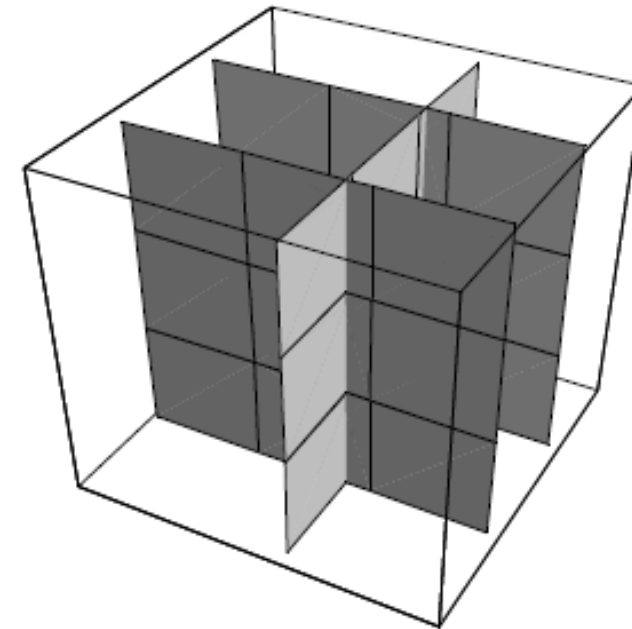
i) The planes intersect in one point. (*one solution*)



ii) The planes intersect in one line. (*infinitely many solutions*)



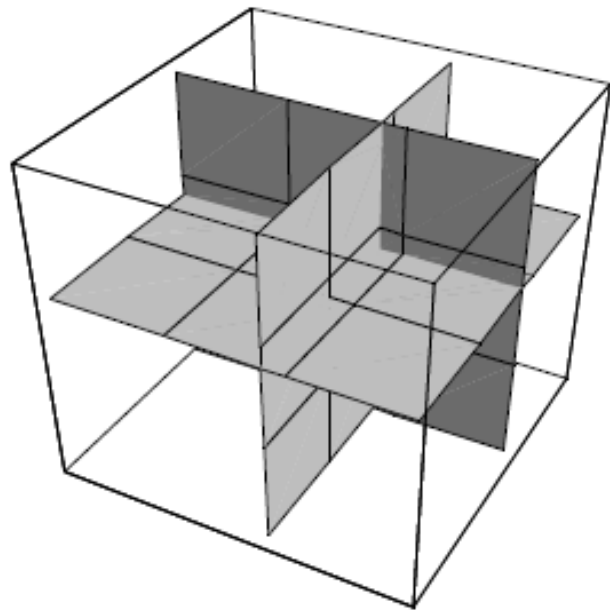
iii) There is no point in common to all three planes. (*no solution*)



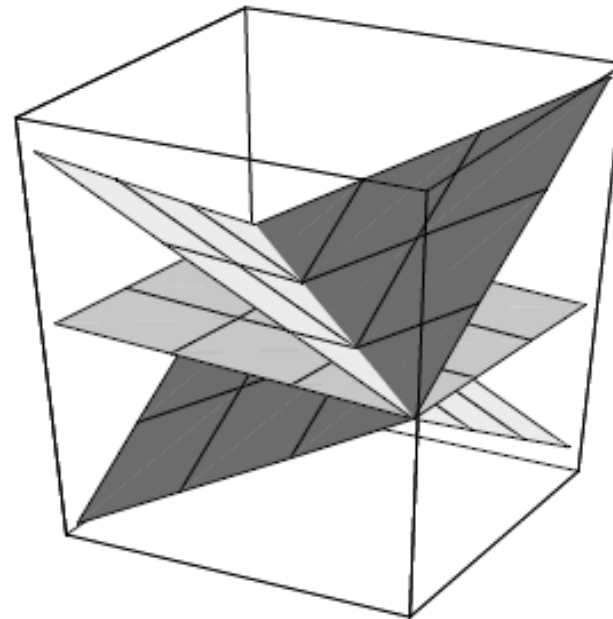
Which of these cases are consistent?

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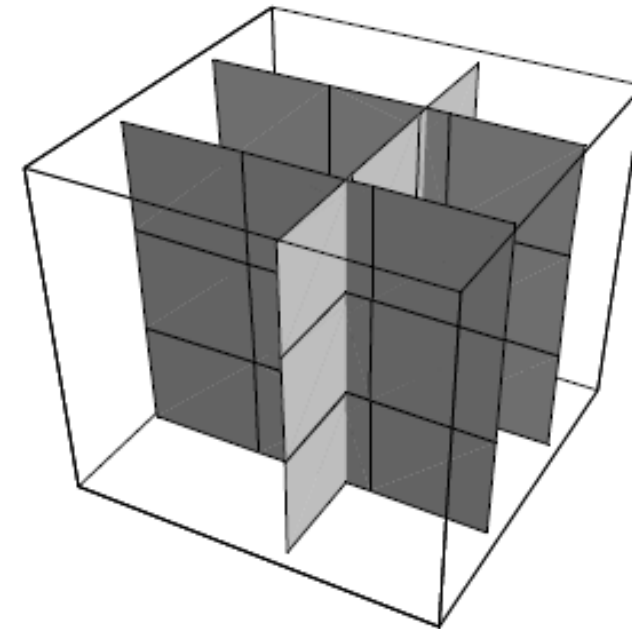
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Which of these cases are consistent?

consistent

consistent

inconsistent

Our goal for this week is to develop an efficient algorithm to solve a linear system.

Example:

$$x_1 - 2x_2 = -1$$

$$-x_1 + 3x_2 = 3$$

$$x_2 = 2$$

add the two equations to
eliminate x_1

$$x_1 = 3$$

substitute for x_2 in the
first equation to find x_1

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Example:

$$\begin{array}{rcl} \begin{array}{rcl} x_1 & - & 2x_2 = -1 \\ -x_1 & + & 3x_2 = 3 \end{array} & \rightarrow & \begin{array}{rcl} x_1 & - & 2x_2 = -1 \\ & & x_2 = 2 \end{array} \quad \rightarrow \quad \begin{array}{rcl} x_1 & & = 3 \\ & & x_2 = 2 \end{array} \\ & & \text{add the two equations to} & & \text{substitute for } x_2 \text{ in the} \\ & & \text{eliminate } x_1 & & \text{first equation to find } x_1 \end{array}$$

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Example:

$$R_1 \quad x_1 - 2x_2 = -1$$

$$R_2 \quad -x_1 + 3x_2 = 3$$

$$\rightarrow \quad x_1 - 2x_2 = -1 \quad R_1 \xrightarrow{+ 2R_2} \quad x_1 = 3$$

$$R_2 + R_1 \rightarrow \quad x_2 = 2 \quad x_2 = 2$$

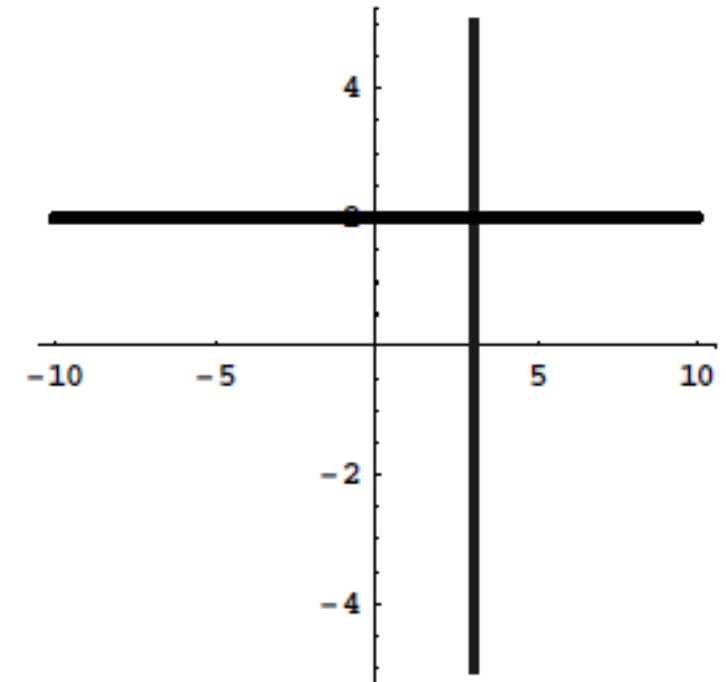
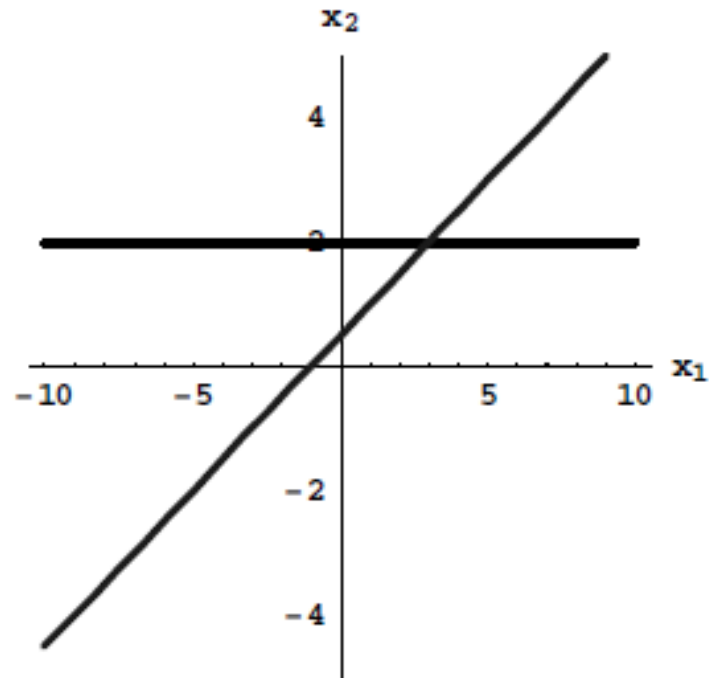
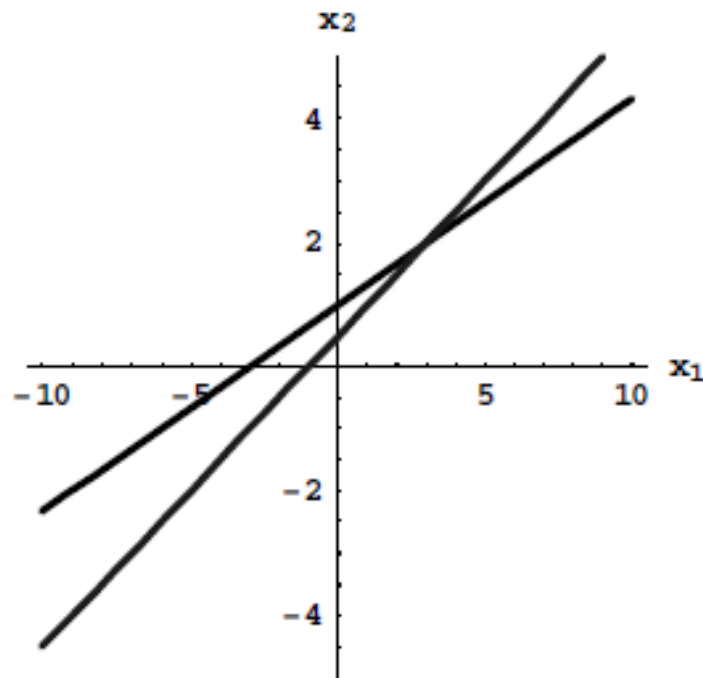
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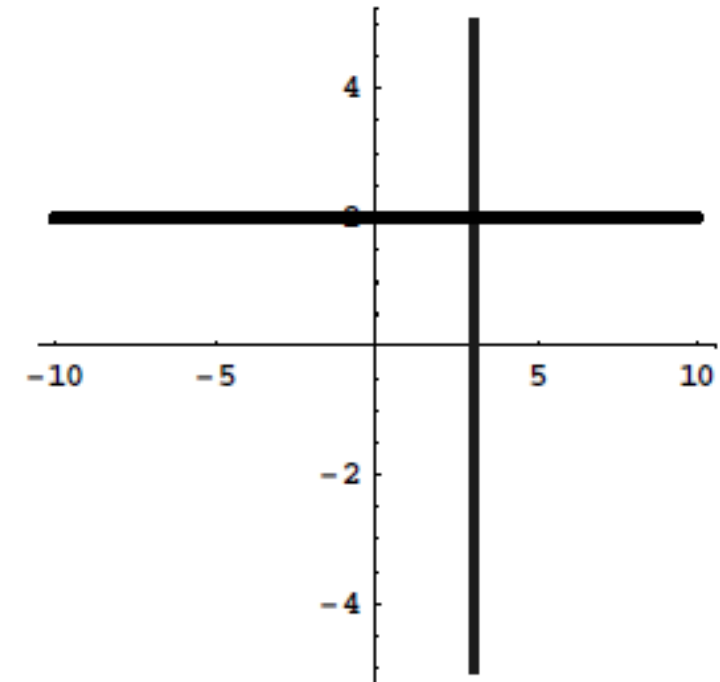
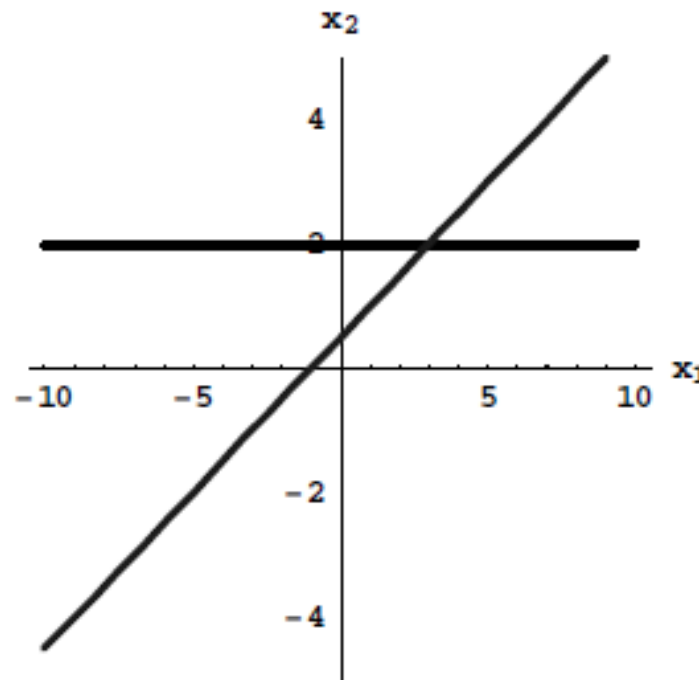
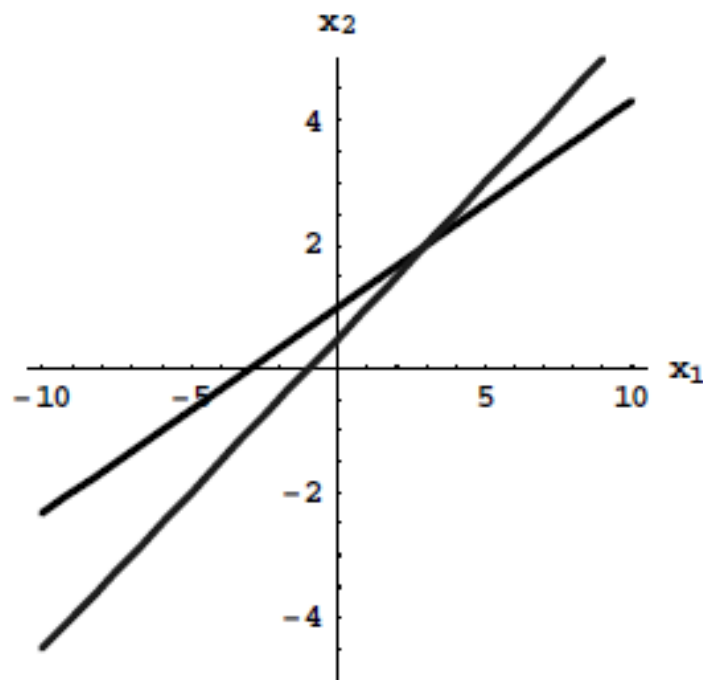
$$\begin{array}{lcl}
 R_1 & x_1 - 2x_2 = -1 & \rightarrow x_1 - 2x_2 = -1 \\
 R_2 & -x_1 + 3x_2 = 3 & \rightarrow R_2 + R_1 \rightarrow x_2 = 2
 \end{array}
 \quad
 \begin{array}{lcl}
 R_1 \rightarrow R_1 + 2R_2 & \rightarrow & x_1 = 3 \\
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 \end{array}$$



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 \begin{array}{lcl}
 & x_1 & = 3 \\
 & x_2 & = 2
 \end{array}$$



Definition: Two linear systems are *equivalent* if they have the same solution set.

So the three linear systems above are different but equivalent.

A general strategy for solving a linear system: replace one system with an equivalent system that is easier to solve.

We simplify the writing by using **matrix notation**, recording only the coefficients and not the variables

$$\begin{array}{lcl}
 R_1 & x_1 - 2x_2 = -1 & \\
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$$\left[\begin{array}{cc|c} 1 & -2 & -1 \\ -1 & 3 & 3 \end{array} \right] \longrightarrow \left[\begin{array}{cc|c} 1 & -2 & -1 \\ 0 & 1 & 2 \end{array} \right] \longrightarrow \left[\begin{array}{cc|c} 1 & 0 & 3 \\ 0 & 1 & 2 \end{array} \right]$$

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The **augmented matrix** of a linear system contains the right hand side:

$$\left[\begin{array}{cc|c} 1 & -2 & -1 \\ -1 & 3 & 3 \end{array} \right]$$

The **coefficient matrix** of a linear system is the left hand side only:

$$\left[\begin{array}{cc} 1 & -2 \\ -1 & 3 \end{array} \right]$$

(The textbook does not put a vertical line between the coefficient matrix and the right hand side, but I recommend that you do to avoid confusion.)

$$\begin{array}{rcl}
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In this example, we solved the linear system by applying **elementary row operations** to the augmented matrix (we only used 1. above, the others will be useful later):

1. **Replacement**: add a multiple of one row to another row. $R_i \rightarrow R_i + cR_j$
2. **Interchange**: interchange two rows. $R_i \rightarrow R_j, R_j \rightarrow R_i$
3. **Scaling**: multiply all entries in a row by a nonzero constant. $R_i \rightarrow cR_i, c \neq 0$

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Definition: Two matrices are **row equivalent** if one can be transformed into the other by a sequence of elementary row operations.

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Definition: Two matrices are **row equivalent** if one can be transformed into the other by a sequence of elementary row operations.

Fact: If the augmented matrices of two linear systems are row equivalent, then the two systems have the same solution set, i.e. they are equivalent linear systems.

Warning: Do not do multiple elementary row operations at the same time, **except** adding multiples of **the same** row to several rows.

$$x_1 - 2x_2 = 1$$

$$-x_1 + 3x_2 = 3$$

$$\left[\begin{array}{cc|c} 1 & -2 & -1 \\ -1 & 3 & 3 \end{array} \right] \rightarrow$$

$$x_2 = 2$$

$$x_2 = 2$$

$$\left[\begin{array}{cc|c} 0 & 1 & 2 \\ 0 & 1 & 2 \end{array} \right]$$

$$\leftarrow R_1 + R_2$$

$$\leftarrow R_2 + R_1$$

These are NOT equivalent systems: in the system on the right, x_1 can take any value, which is not true for the system on the left.

$$x_1 - 2x_2 = -3$$

$$x_2 = 16$$

$$x_3 = 3$$

$$\left[\begin{array}{ccc|c} 1 & -2 & 0 & -3 \\ 0 & 1 & 0 & 16 \\ 0 & 0 & 1 & 3 \end{array} \right]$$

$$\leftarrow R_1 - R_3$$

$$\leftarrow R_2 + 4R_3$$

$$x_1 = 29$$

$$x_2 = 16$$

$$x_3 = 3$$

$$\left[\begin{array}{ccc|c} 1 & 0 & 0 & 29 \\ 0 & 1 & 0 & 16 \\ 0 & 0 & 1 & 3 \end{array} \right]$$

Sometimes we are not interested in the exact value of the solutions, just the number of solutions. In other words:

1. **Existence** of solutions: is the system consistent?
2. **Uniqueness** of solutions: if a solution exists, is it the only one?

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1. **Existence** of solutions: is the system consistent?
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Answering this requires less work than finding the solution.

Example:

$$\begin{array}{rrcr} x_1 & - & 2x_2 & + & x_3 & = & 0 \\ & & 2x_2 & - & 8x_3 & = & 8 \\ -4x_1 & + & 5x_2 & + & 9x_3 & = & -9 \end{array} \quad \left[\begin{array}{ccc|c} 1 & -2 & 1 & 0 \\ & 0 & 2 & -8 \\ -4 & 5 & 9 & -9 \end{array} \right]$$

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We can stop here:
back-substitution shows
that we can find a unique
solution.

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echelon form

$$\begin{array}{rrcr} x_1 & - & 2x_2 & = & -3 \\ & & x_2 & = & 16 \\ & & & & x_3 & = & 3 \end{array} \quad \left[\begin{array}{ccc|c} 1 & -2 & 0 & -3 \\ 0 & 1 & 0 & 16 \\ 0 & 0 & 1 & 3 \end{array} \right]$$

$$\begin{array}{rrcr} x_1 & & & = & 29 \\ & & x_2 & = & 16 \\ & & & & x_3 & = & 3 \end{array} \quad \left[\begin{array}{ccc|c} 1 & 0 & 0 & 29 \\ 0 & 1 & 0 & 16 \\ 0 & 0 & 1 & 3 \end{array} \right]$$

reduced echelon form

Here is the example from p8. Notice that we use row operations to first put the matrix into echelon form, and then into reduced echelon form.

Can we always do this for any linear system?

Theorem: Any matrix A is row-equivalent to exactly one reduced echelon matrix, which is called its **reduced echelon form** and written $\text{rref}(A)$.

So our general strategy for solving a linear system is: apply row operations to its augmented matrix to obtain its rref.

And our general strategy for determining existence/uniqueness of solutions is: apply row operations to its augmented matrix to obtain an **echelon form**, i.e. a row-equivalent echelon matrix.

These processes of row operations (to get to echelon or reduced echelon form) are called **row reduction**.

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And our general strategy for determining existence/uniqueness of solutions is: apply row operations to its augmented matrix to obtain an **echelon form**, i.e. a row-equivalent echelon matrix.

Warning: an echelon form is not unique. Its entries depend on the row operations we used. But its pattern of \blacksquare and $*$ is unique.

These processes of row operations (to get to echelon or reduced echelon form) are called **row reduction**.

Row reduction:

augmented matrix of linear
system



echelon
form



reduced
echelon
form

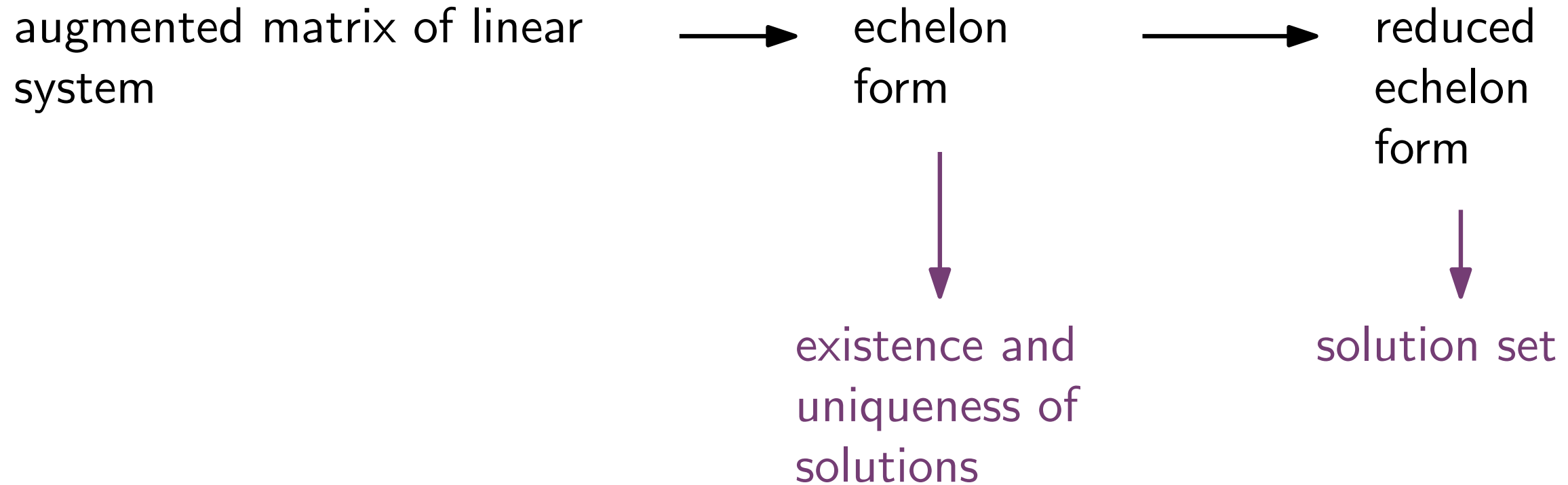


existence and
uniqueness of
solutions



solution set

Row reduction:



The rest of this section:

- The row reduction algorithm
- Getting the solution, existence/uniqueness from the (reduced) echelon form


Important terms in the row reduction algorithm:

- **pivot position**: the position of a leading entry in a row-equivalent echelon matrix.
- **pivot**: a nonzero entry of the matrix that is used in a pivot position to create zeroes below it.
- **pivot column**: a column containing a pivot position.





The black squares are the pivot positions.

$$\begin{bmatrix} 0 & \blacksquare & * & * & * & * & * & * & * & * & * \\ 0 & 0 & 0 & \blacksquare & * & * & * & * & * & * & * \\ 0 & 0 & 0 & 0 & \blacksquare & * & * & * & * & * & * \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \blacksquare & * & * & * \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \blacksquare & * & * \end{bmatrix}$$

Check your answer: www.wolframalpha.com

 **WolframAlpha**[®] computational knowledge engine

rref{{0 , 3 , -6 , 6 , 4 , -5},{3 , -7 , 8 , -5 , 8 , 9},{1 , -3 , 4 , -3 , 2 , 5}}



Web Apps

Examples

Random

Input:

row reduce

$$\begin{pmatrix} 0 & 3 & -6 & 6 & 4 & -5 \\ 3 & -7 & 8 & -5 & 8 & 9 \\ 1 & -3 & 4 & -3 & 2 & 5 \end{pmatrix}$$

Result:

$$\begin{pmatrix} 1 & 0 & -2 & 3 & 0 & -24 \\ 0 & 1 & -2 & 2 & 0 & -7 \\ 0 & 0 & 0 & 0 & 1 & 4 \end{pmatrix}$$

Step-by-step solution

Getting the solution set from the reduced echelon form:

A **basic variable** is a variable corresponding to a pivot column.
All other variables are **free variables**.

6. Write each row of the augmented matrix as a linear equation.

Example:

$$\left[\begin{array}{ccccc|c} 1 & 0 & -2 & 3 & 0 & -24 \\ 0 & 1 & -2 & 2 & 0 & -7 \\ 0 & 0 & 0 & 0 & 1 & 4 \end{array} \right] \quad \begin{array}{rcl} x_1 & -2x_3 + 3x_4 & = -24 \\ x_2 & -2x_3 + 2x_4 & = -7 \\ & & x_5 = 4 \end{array}$$

basic variables: x_1, x_2, x_5 , free variables: x_3, x_4 .

The free variables can take any value. These values then uniquely determine the basic variables.

Example:

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$$\begin{aligned} x_1 - 2x_3 + 3x_4 &= -24 \\ x_2 - 2x_3 + 2x_4 &= -7 \\ x_5 &= 4 \end{aligned}$$

basic variables: x_1, x_2, x_5 , free variables: x_3, x_4 .

The free variables can take any value. These values then uniquely determine the basic variables.

7. Take the free variables in the equations to the right hand side, and add equations of the form “free variable = itself”, so we have equations for each variable in terms of the free variables.

Example:

$$x_1 = -24 + 2x_3 - 3x_4$$

$$x_2 = -7 + 2x_3 - 2x_4$$

$$x_3 = x_3$$

$$x_4 = x_4$$

$$x_5 = 4$$

Example:

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So the solution set is

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{pmatrix} = \begin{pmatrix} -24 + 2s - 3t \\ -7 + 2s - 2t \\ s \\ t \\ 4 \end{pmatrix}$$

where s and t can take any value.

Example: Suppose we found that the reduced echelon form of the augmented matrix is

$$\left[\begin{array}{ccc|c} 1 & 0 & 2 & 1 \\ 0 & 1 & -4 & 8 \\ 0 & 0 & 0 & 15 \end{array} \right]$$

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The last equation says $0x_1 + 0x_2 + 0x_3 = 15$, so this system is inconsistent.

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The last equation says $0x_1 + 0x_2 + 0x_3 = 15$, so this system is inconsistent.

Theorem 2: Existence and Uniqueness:

A linear system is consistent if and only if an echelon form of its augmented matrix has **no** row of the form $[0 \dots 0 | *]$ with $* \neq 0$.

If a linear system is consistent, then:

- it has a unique solution if there are no free variables;
- it has infinitely many solutions if there are free variables.

In particular, this proves the fact we saw earlier, that a linear system has either a unique solution, infinitely many solutions, or no solutions.

Warning: In general, the existence of solutions is unrelated to the uniqueness of solutions. (We will meet an important exception in §2.3.)