Math 311-504

Topics in Applied Mathematics

Lecture 5: Gaussian elimination. Row echelon form.

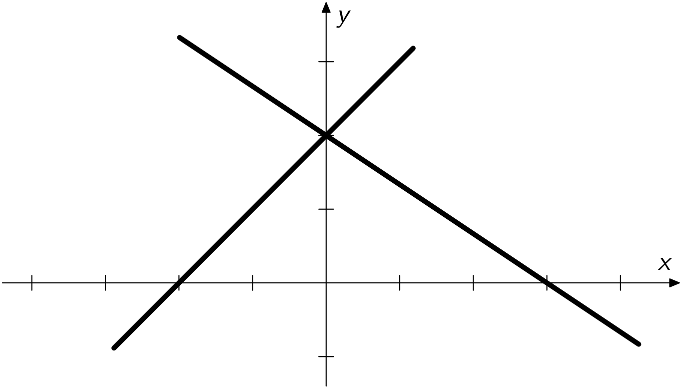
System of linear equations

$$\begin{cases} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n = b_1 \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n = b_2 \\ \cdots\cdots\cdots \\ a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n = b_m \end{cases}$$

Here $x_1, x_2, \ldots, x_n$ are variables and a_{ij}, b_j are constants.

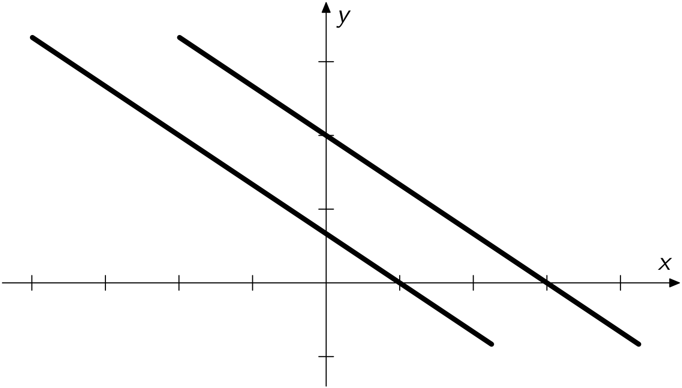
A *solution* of the system is a common solution of all equations in the system.

A system of linear equations can have **one** solution, **infinitely many** solutions, or **no** solution at all.



$$\begin{cases} x - y = -2 \\ 2x + 3y = 6 \end{cases}$$

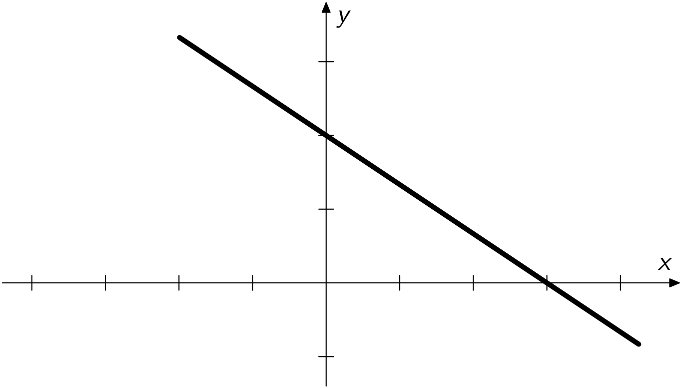
$$x = 0,\ y = 2$$



$$\begin{cases} 2x + 3y = 2 \\ 2x + 3y = 6 \end{cases}$$

inconsistent system

(no solutions)



$$\begin{cases} 4x + 6y = 12 \\ 2x + 3y = 6 \end{cases} \iff 2x + 3y = 6$$

Solving systems of linear equations

Elimination method always works for systems of linear equations.

Algorithm: (1) pick a variable, solve one of the equations for it, and eliminate it from the other equations; (2) put aside the equation used in the elimination, and return to step (1).

$$x - y = 2 \implies x = y + 2$$

$$2x - y - z = 5 \implies 2(y+2) - y - z = 5$$

After the elimination is completed, the system is solved by *back substitution*.

$$y = 1 \implies x = y + 2 = 3$$

Gaussian elimination

Gaussian elimination is a modification of the elimination method that allows only so-called *elementary operations*.

Elementary operations for systems of linear equations:

(1) to multiply an equation by a nonzero scalar;
(2) to add an equation multiplied by a scalar to another equation;
(3) to interchange two equations.

Theorem Applying elementary operations to a system of linear equations does not change the solution set of the system.

Operation 1: multiply the ith equation by $r \neq 0$.

$$\begin{cases} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n = b_1 \\ \cdots\cdots\cdots\cdots\cdots \\ a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n = b_i \\ \cdots\cdots\cdots\cdots\cdots \\ a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n = b_m \end{cases}$$

$$\Longrightarrow \begin{cases} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n = b_1 \\ \cdots\cdots\cdots\cdots\cdots \\ (ra_{i1})x_1 + (ra_{i2})x_2 + \cdots + (ra_{in})x_n = rb_i \\ \cdots\cdots\cdots\cdots\cdots \\ a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n = b_m \end{cases}$$

To undo the operation, multiply the ith equation by r^{-1}.

Operation 2: add r times the ith equation to the jth equation.

$$\begin{cases} \cdots\cdots\cdots\cdots \\ a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n = b_i \\ \cdots\cdots\cdots\cdots \\ a_{j1}x_1 + a_{j2}x_2 + \cdots + a_{jn}x_n = b_j \\ \cdots\cdots\cdots\cdots \end{cases} \Longrightarrow$$

$$\begin{cases} \cdots\cdots\cdots\cdots \\ a_{i1}x_1 + \cdots + a_{in}x_n = b_i \\ \cdots\cdots\cdots\cdots \\ (a_{j1} + ra_{i1})x_1 + \cdots + (a_{jn} + ra_{in})x_n = b_j + rb_i \\ \cdots\cdots\cdots\cdots \end{cases}$$

To undo the operation, add $-r$ times the ith equation to the jth equation.

Operation 3: interchange the *i*th and *j*th equations.

$$\begin{cases} \cdots\cdots\cdots\cdots\cdots \\ a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n = b_i \\ \cdots\cdots\cdots\cdots\cdots \\ a_{j1}x_1 + a_{j2}x_2 + \cdots + a_{jn}x_n = b_j \\ \cdots\cdots\cdots\cdots\cdots \end{cases}$$

$$\Longrightarrow \begin{cases} \cdots\cdots\cdots\cdots\cdots \\ a_{j1}x_1 + a_{j2}x_2 + \cdots + a_{jn}x_n = b_j \\ \cdots\cdots\cdots\cdots\cdots \\ a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n = b_i \\ \cdots\cdots\cdots\cdots\cdots \end{cases}$$

To undo the operation, apply it once more.

Example.

$$\begin{cases} x - y = 2 \\ 2x - y - z = 3 \\ x + y + z = 6 \end{cases}$$

Add -2 times the 1st equation to the 2nd equation:

$$\begin{cases} x - y = 2 \\ y - z = -1 \\ x + y + z = 6 \end{cases} \qquad \boxed{R2 := R2 - 2 * R1}$$

Add -1 times the 1st equation to the 3rd equation:

$$\begin{cases} x - y = 2 \\ y - z = -1 \\ 2y + z = 4 \end{cases}$$

Add -1 times the 1st equation to the 3rd equation:

$$\left\{\begin{array}{rcrcrcr} x & - & y & & & = & 2 \\ & & y & - & z & = & -1 \\ & & 2y & + & z & = & 4 \end{array}\right.$$

Add -2 times the 2nd equation to the 3rd equation:

$$\left\{\begin{array}{rcrcrcr} x & - & y & & & = & 2 \\ & & y & - & z & = & -1 \\ & & & & 3z & = & 6 \end{array}\right.$$

The elimination is completed, and we can solve the system by back substitution. However we can as well proceed with elementary operations.

Multiply the 3rd equation by $1/3$:

Multiply the 3rd equation by 1/3:

$$\begin{cases} x - y = 2 \\ y - z = -1 \\ z = 2 \end{cases}$$

Add the 3rd equation to the 2nd equation:

$$\begin{cases} x - y = 2 \\ y = 1 \\ z = 2 \end{cases}$$

Add the 2nd equation to the 1st equation:

$$\begin{cases} x = 3 \\ y = 1 \\ z = 2 \end{cases}$$

System of linear equations:

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

Solution: $(x, y, z) = (3, 1, 2)$

Another example.

$$\left\{\begin{array}{rcrcrcl} x & + & y & - & 2z & = & 1 \\ & & y & - & z & = & 3 \\ -x & + & 4y & - & 3z & = & 1 \end{array}\right.$$

Add the 1st equation to the 3rd equation:

$$\left\{\begin{array}{rcrcrcl} x & + & y & - & 2z & = & 1 \\ & & y & - & z & = & 3 \\ & & 5y & - & 5z & = & 2 \end{array}\right.$$

Add -5 times the 2nd equation to the 3rd equation:

$$\left\{\begin{array}{rcrcrcr} x & + & y & - & 2z & = & 1 \\ & & y & - & z & = & 3 \\ & & & & 0 & = & -13 \end{array}\right.$$

System of linear equations:

$$\begin{cases} x + y - 2z = 1 \\ y - z = 3 \\ -x + 4y - 3z = 1 \end{cases}$$

Solution: no solution (*inconsistent system*).

Yet another example.

$$\left\{\begin{array}{rcrcrcr} x & + & y & - & 2z & = & 1 \\ & & y & - & z & = & 3 \\ -x & + & 4y & - & 3z & = & 14 \end{array}\right.$$

Add the 1st equation to the 3rd equation:

$$\left\{\begin{array}{rcrcrcr} x & + & y & - & 2z & = & 1 \\ & & y & - & z & = & 3 \\ & & 5y & - & 5z & = & 15 \end{array}\right.$$

Add -5 times the 2nd equation to the 3rd equation:

$$\left\{\begin{array}{rcrcrcr} x & + & y & - & 2z & = & 1 \\ & & y & - & z & = & 3 \\ & & & & 0 & = & 0 \end{array}\right.$$

Add -5 times the 2nd equation to the 3rd equation:

$$\left\{\begin{array}{rcrcrcr} x & + & y & - & 2z & = & 1 \\ & & y & - & z & = & 3 \\ & & & & 0 & = & 0 \end{array}\right.$$

Add -1 times the 2nd equation to the 1st equation:

$$\left\{\begin{array}{rcrcrcr} x & & & - & z & = & -2 \\ & & y & - & z & = & 3 \\ & & & & 0 & = & 0 \end{array}\right. \iff \left\{\begin{array}{l} x = z - 2 \\ y = z + 3 \end{array}\right.$$

Here z is a *free variable*.

It follows that $\left\{\begin{array}{l} x = t - 2 \\ y = t + 3 \\ z = t \end{array}\right.$ for some $t \in \mathbb{R}$.

System of linear equations:

$$\begin{cases} x + y - 2z = 1 \\ y - z = 3 \\ -x + 4y - 3z = 14 \end{cases}$$

Solution: $(x, y, z) = (t - 2, t + 3, t), \ \ t \in \mathbb{R}.$

In vector form, $(x, y, z) = (-2, 3, 0) + t(1, 1, 1).$

The set of all solutions is a line in $\mathbb{R}^3$ passing through the point $(-2, 3, 0)$ in the direction $(1, 1, 1)$.

Matrices

Definition. A *matrix* is a rectangular array of numbers.

Examples: $\begin{pmatrix} 2 & 7 \\ -1 & 0 \\ 3 & 3 \end{pmatrix}$, $\begin{pmatrix} 2 & 7 & 0.2 \\ 4.6 & 1 & 1 \end{pmatrix}$,

$\begin{pmatrix} 3/5 \\ 5/8 \\ 4 \end{pmatrix}$, $(\sqrt{2}, 0, -\sqrt{3}, 5)$, $\begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$.

dimensions $=$ **(# of rows)** $\times$ **(# of columns)**

n-by-*n*: **square matrix**

n-by-1: **column vector**

1-by-*n*: **row vector**

System of linear equations:

$$\begin{cases} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n = b_1 \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n = b_2 \\ \cdots\cdots\cdots \\ a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n = b_m \end{cases}$$

Coefficient matrix and column vector of the right-hand sides:

$$\begin{pmatrix} a_{11} & a_{12} & \ldots & a_{1n} \\ a_{21} & a_{22} & \ldots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \ldots & a_{mn} \end{pmatrix} \qquad \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{pmatrix}$$

System of linear equations:

$$\begin{cases} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n = b_1 \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n = b_2 \\ \cdots\cdots\cdots \\ a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n = b_m \end{cases}$$

Augmented matrix:

$$\left(\begin{array}{cccc|c} a_{11} & a_{12} & \ldots & a_{1n} & b_1 \\ a_{21} & a_{22} & \ldots & a_{2n} & b_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ a_{m1} & a_{m2} & \ldots & a_{mn} & b_m \end{array}\right)$$

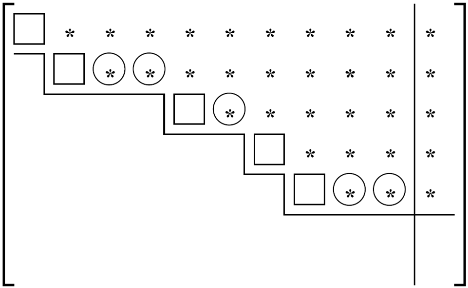
Elementary operations for systems of linear equations correspond to *elementary row operations* for augmented matrices:

(1) to multiply a row (as a vector) by a nonzero scalar;

(2) to add (as a vector) the ith row multiplied (as a vector) by some $r \in \mathbb{R}$ to the jth row;

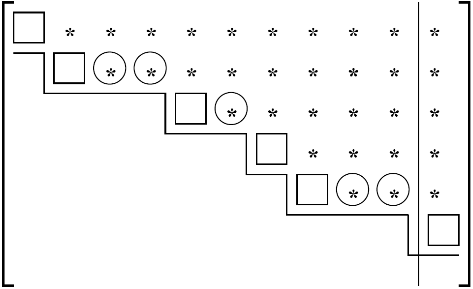
(3) to interchange two rows.

The goal of the Gaussian elimination is to convert the augmented matrix into **row echelon form**:



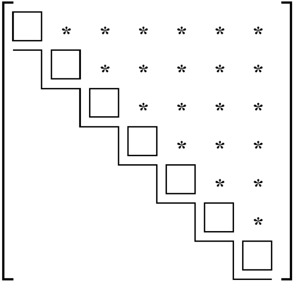
- all the entries below the staircase line are zero;
- boxed entries, called **pivotal** or **lead entries**, are nonzero;
- each circled star correspond to a free variable.

The original system of linear equations is *consistent* if there is no leading entry in the rightmost column of the augmented matrix (in row echelon form).



Inconsistent system

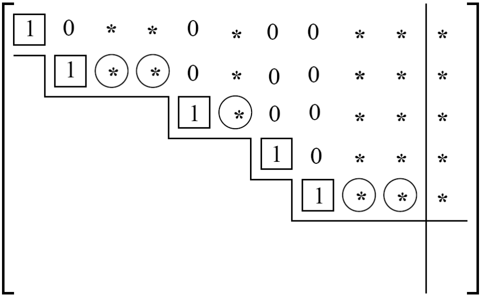
Strict triangular form is a particular case of row echelon form that can occur for systems of *n* equations in *n* variables:



Matrix of coefficients

Strict triangular form implies that the system of linear equations has a unique solution for **any** right-hand sides.

The matrix is in **reduced row echelon form** if (i) each leading entry is 1, and (ii) each leading entry is the only nonzero entry in its column.



Theorem Any matrix can be converted into reduced row echelon form by a sequence of elementary operations.

Example.

$$\begin{cases} x - y = 2 \\ 2x - y - z = 3 \\ x + y + z = 6 \end{cases} \qquad \left(\begin{array}{rrr|r} 1 & -1 & 0 & 2 \\ 2 & -1 & -1 & 3 \\ 1 & 1 & 1 & 6 \end{array}\right)$$

Row echelon form (also strict triangular):

$$\begin{cases} x - y = 2 \\ y - z = -1 \\ 3z = 6 \end{cases} \qquad \left(\begin{array}{rrr|r} \boxed{1} & -1 & 0 & 2 \\ 0 & \boxed{1} & -1 & -1 \\ 0 & 0 & \boxed{3} & 6 \end{array}\right)$$

Reduced row echelon form:

$$\begin{cases} x = 3 \\ y = 1 \\ z = 2 \end{cases} \qquad \left(\begin{array}{rrr|r} \boxed{1} & 0 & 0 & 3 \\ 0 & \boxed{1} & 0 & 1 \\ 0 & 0 & \boxed{1} & 2 \end{array}\right)$$

Another example.

$$\left\{\begin{array}{rcrcrcl} x & + & y & - & 2z & = & 1 \\ & & y & - & z & = & 3 \\ -x & + & 4y & - & 3z & = & 1 \end{array}\right. \qquad \left(\begin{array}{rrr|r} 1 & 1 & -2 & 1 \\ 0 & 1 & -1 & 3 \\ -1 & 4 & -3 & 1 \end{array}\right)$$

Row echelon form:

$$\left\{\begin{array}{rcrcrcr} x & + & y & - & 2z & = & 1 \\ & & y & - & z & = & 3 \\ & & & & 0 & = & -13 \end{array}\right. \qquad \left(\begin{array}{rrr|r} \boxed{1} & 1 & -2 & 1 \\ 0 & \boxed{1} & -1 & 3 \\ 0 & 0 & 0 & \boxed{-13} \end{array}\right)$$

Reduced row echelon form:

$$\left\{\begin{array}{rcrcrcl} x & & & - & z & = & 0 \\ & & y & - & z & = & 0 \\ & & & & 0 & = & 1 \end{array}\right. \qquad \left(\begin{array}{rrr|r} \boxed{1} & 0 & -1 & 0 \\ 0 & \boxed{1} & -1 & 0 \\ 0 & 0 & 0 & \boxed{1} \end{array}\right)$$

Yet another example.

$$\begin{cases} x + y - 2z = 1 \\ y - z = 3 \\ -x + 4y - 3z = 14 \end{cases} \qquad \left(\begin{array}{rrr|r} 1 & 1 & -2 & 1 \\ 0 & 1 & -1 & 3 \\ -1 & 4 & -3 & 14 \end{array}\right)$$

Row echelon form:

$$\begin{cases} x + y - 2z = 1 \\ y - z = 3 \\ 0 = 0 \end{cases} \qquad \left(\begin{array}{rrr|r} \boxed{1} & 1 & -2 & 1 \\ 0 & \boxed{1} & -1 & 3 \\ 0 & 0 & 0 & 0 \end{array}\right)$$

Reduced row echelon form:

$$\begin{cases} x - z = -2 \\ y - z = 3 \\ 0 = 0 \end{cases} \qquad \left(\begin{array}{rrr|r} \boxed{1} & 0 & -1 & -2 \\ 0 & \boxed{1} & -1 & 3 \\ 0 & 0 & 0 & 0 \end{array}\right)$$