MS-252 Linear Algebra

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1. Systems of Linear Equations

Preliminaries

- Attendance will be marked at the beginning. If you miss it, I will NOT mark it later.
- Quizzes can be announced as well as unannounced. **No retakes irrespective of your reason for missing a quiz.**
- There is no such thing as a stupid question.
- We will be following the book *Elementary Linear Algebra – Applications Version* by *Howard Anton and Chris Rorres*.
- Office Hours: Wednesday 4:00 pm till 5:00 pm or set a time via email (nazarkhan at pucit.edu.pk).
- Course webpage: `http://faculty.pucit.edu.pk/nazarkhan/teaching/MS252/MS252.html`

Introduction

- A huge number of problems can be modelled by a 2 dimensional array of numbers.
- This 2D array is called a matrix.
- This course deals with solving problems involving matrices.
- These include
  - Google's PageRank algorithm
  - Face recognition
  - Computer graphics
  - and many many many more . . .

Algebra

- The word algebra comes from the Arabic ‘al-jabr’which literally means ‘the reunion of broken parts’).
- It was used in the title of the book *Ilm al-jabr wal-muqabala* by Muhammad ibn Musa al-Khwarizmi.

Algebra

- Muhammad ibn Musa al-Khwarizmi was a Persian mathematician, astronomer, and geographer in the 9^{th} century.
- Born in Khwarizm (modern-day Uzbekistan).
- Algebra was a revolutionary move away from geometry-driven Greek mathematics.
- It truly gave mathematics 'wings' and an ability to touch what you can't see or even imagine.

Algebra

- Introduced the Hindu-Arabic numeral system to the Islamic world. Later spread to Europe, revolutionizing mathematics.
- His works were translated into Latin and influenced European scholars during the Middle Ages.
- Contributed to astronomy by refining Ptolemy's works and creating astronomical tables.
- The word algorithm also stems from 'Algoritmi', a Latinized version of al-Khwarizmi.

Linear Equations

- A 2D line in the xy plane can be represented as $y = mx + c$.
- Alternatively as $-mx + 1y = c$ or $a_1x + a_2y = b$.
- Such equations are called *linear equations*.
- Linear equation in n *variables*[1] $x_1, x_2, \dots, x_n$ can be expressed as

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

where $a_1, a_2, \dots, a_n, b_n$ are constant, real[2] numbers.

Linear	Non-linear
Power 1 only.	Other powers, products, roots or trigonometric functions.
$x + 3y = 7$	$x + 3y^2 = 7$
$y = \frac{1}{2}x + 3z + 1$	$3x + 2y - z + xz = 7$
	$y - \sin x = 0$
	$\sqrt{x} + 2x_2 + x_3 = 1$

[1] Also called *unknowns*.

[2] Numbers we typically use, like 3,-0.64, 3/4

Systems of Linear Equations

- Finite set of linear equations.

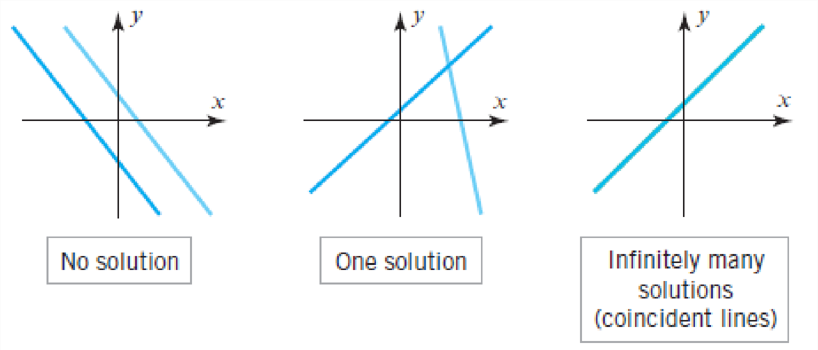
$$
\begin{aligned}
4x_1 - x_2 + 3x_3 &= -1 \\
3x_1 + x_2 + 9x_3 &= -4
\end{aligned}
$$

- System is *consistent* if a solution exists that satisfies all equations.
- Otherwise, the system is *inconsistent*.

$$
\begin{aligned}
x + y &= 3 \\
x + y &= 4
\end{aligned}
$$

Systems of Linear Equations

- Every system of linear equations has
  1. either no solutions,
  2. or exactly one solution,
  3. or infinitely many solutions.



Systems of Linear Equations

- A general system of 3 linear equations in 4 unknowns

$$
\begin{aligned}
a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + a_{14}x_4 &= b_1 \\
a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + a_{24}x_4 &= b_2 \\
a_{31}x_1 + a_{32}x_2 + a_{33}x_3 + a_{34}x_4 &= b_3
\end{aligned}
$$

- Notation: Coefficient a_{ij} lies in equation i and multiplies with unknown x_j.

Systems of Linear Equations

Augmented Matrix

- The system of equations

$$\begin{aligned} x_1 + x_2 + 2x_3 &= 9 \\ 2x_1 + 4x_2 - 3x_3 &= 1 \\ 3x_1 + 6x_2 - 5x_3 &= 0 \end{aligned}$$

can be abbreviated via the *augmented matrix*

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

- How can we solve for x_1, x_2 and x_3?

Elementary Row Operations

1. Multiply an equation by a nonzero constant.
2. Interchange two equations.
3. Add a multiple of one equation to another.

$$\begin{aligned} x + y + 2z &= 9 \\ 2x + 4y - 3z &= 1 \\ 3x + 6y - 5z &= 0 \end{aligned}$$

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

Add -2 times the first equation to the second to obtain

$$\begin{aligned} x + y + 2z &= 9 \\ 2y - 7z &= -17 \\ 3x + 6y - 5z &= 0 \end{aligned}$$

Add -2 times the first row to the second to obtain

$$\begin{bmatrix} 1 & 1 & 2 & 9 \\ 0 & 2 & -7 & -17 \\ 3 & 6 & -5 & 0 \end{bmatrix}$$

Add -3 times the first equation to the third to obtain

$$\begin{aligned} x + y + 2z &= 9 \\ 2y - 7z &= -17 \\ 3y - 11z &= -27 \end{aligned}$$

Add -3 times the first row to the third to obtain

$$\begin{bmatrix} 1 & 1 & 2 & 9 \\ 0 & 2 & -7 & -17 \\ 0 & 3 & -11 & -27 \end{bmatrix}$$

Multiply the second equation by $\frac{1}{2}$ to obtain

$$\begin{aligned} x + y + 2z &= 9 \\ y - \tfrac{7}{2}z &= -\tfrac{17}{2} \\ 3y - 11z &= -27 \end{aligned}$$

Multiply the second row by $\frac{1}{2}$ to obtain

$$\begin{bmatrix} 1 & 1 & 2 & 9 \\ 0 & 1 & -\frac{7}{2} & -\frac{17}{2} \\ 0 & 3 & -11 & -27 \end{bmatrix}$$

Add -3 times the second equation to the third to obtain

$$\begin{aligned} x + y + 2z &= 9 \\ y - \tfrac{7}{2}z &= -\tfrac{17}{2} \\ -\tfrac{1}{2}z &= -\tfrac{3}{2} \end{aligned}$$

Add -3 times the second row to the third to obtain

$$\begin{bmatrix} 1 & 1 & 2 & 9 \\ 0 & 1 & -\frac{7}{2} & -\frac{17}{2} \\ 0 & 0 & -\frac{1}{2} & -\frac{3}{2} \end{bmatrix}$$

Multiply the third equation by -2 to obtain

$$\begin{aligned} x + y + 2z &= 9 \\ y - \tfrac{7}{2}z &= -\tfrac{17}{2} \\ z &= 3 \end{aligned}$$

Multiply the third row by -2 to obtain

$$\begin{bmatrix} 1 & 1 & 2 & 9 \\ 0 & 1 & -\frac{7}{2} & -\frac{17}{2} \\ 0 & 0 & 1 & 3 \end{bmatrix}$$

Add -1 times the second equation to the first to obtain

$$\begin{aligned} x + \tfrac{11}{2}z &= \tfrac{35}{2} \\ y - \tfrac{7}{2}z &= -\tfrac{17}{2} \\ z &= 3 \end{aligned}$$

Add -1 times the second row to the first to obtain

$$\begin{bmatrix} 1 & 0 & \frac{11}{2} & \frac{35}{2} \\ 0 & 1 & -\frac{7}{2} & -\frac{17}{2} \\ 0 & 0 & 1 & 3 \end{bmatrix}$$

Add $-\frac{11}{2}$ times the third equation to the first and $\frac{7}{2}$ times the third equation to the second to obtain

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

Add $-\frac{11}{2}$ times the third row to the first and $\frac{7}{2}$ times the third row to the second to obtain

$$\begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 2 \\ 0 & 0 & 1 & 3 \end{bmatrix}$$

Reduced Row-Echelon Form

- The augmented matrix in the last problem was reduced from
$$\begin{bmatrix}1 & 1 & 2 & 9\\ 2 & 4 & -3 & 1\\ 3 & 6 & -5 & 0\end{bmatrix} \text{ to } \begin{bmatrix}1 & 0 & 0 & 1\\ 0 & 1 & 0 & 2\\ 0 & 0 & 1 & 3\end{bmatrix}$$
- This is an example of a matrix that is in *reduced row-echelon form*.
- A matrix in this form must have the following properties:
  1. If a row does not consist entirely of zeros, then the first nonzero number in the row is a 1. We call this a *leading 1*.
  2. If there are any rows that consist entirely of zeros, then they are grouped together at the bottom of the matrix.
  3. In any two successive rows that do not consist entirely of zeros, the leading 1 in the lower row occurs farther to the right than the leading 1 in the higher row.
  4. Each column that contains a leading 1 has zeros everywhere else in that column.

Row-Echelon Form

- A matrix that has the first three properties is said to be in row echelon form.
- Thus, a matrix in reduced row echelon form is also in row echelon form, but not conversely.

The following matrices are in reduced row echelon form.

$$\begin{bmatrix} 1 & 0 & 0 & 4 \\ 0 & 1 & 0 & 7 \\ 0 & 0 & 1 & -1 \end{bmatrix}, \quad \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad \begin{bmatrix} 0 & 1 & -2 & 0 & 1 \\ 0 & 0 & 0 & 1 & 3 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

The following matrices are in row echelon form but not reduced row echelon form.

$$\begin{bmatrix} 1 & 4 & -3 & 7 \\ 0 & 1 & 6 & 2 \\ 0 & 0 & 1 & 5 \end{bmatrix}, \quad \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \begin{bmatrix} 0 & 1 & 2 & 6 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

- We now look at a systematic procedure for obtaining row-echelon form. It is called *Gaussian elimination*.

Gaussian Elimination

$$\begin{bmatrix} 0 & 0 & -2 & 0 & 7 & 12 \\ 2 & 4 & -10 & 6 & 12 & 28 \\ 2 & 4 & -5 & 6 & -5 & -1 \end{bmatrix}$$

Step 1. Locate the leftmost column that does not consist entirely of zeros.

$$\begin{bmatrix} 0 & 0 & -2 & 0 & 7 & 12 \\ 2 & 4 & -10 & 6 & 12 & 28 \\ 2 & 4 & -5 & 6 & -5 & -1 \end{bmatrix}$$

Leftmost nonzero column

Step 2. Interchange the top row with another row, if necessary, to bring a nonzero entry to the top of the column found in Step 1.

$$\begin{bmatrix} 2 & 4 & -10 & 6 & 12 & 28 \\ 0 & 0 & -2 & 0 & 7 & 12 \\ 2 & 4 & -5 & 6 & -5 & -1 \end{bmatrix} \longleftarrow$$

The first and second rows in the preceding matrix were interchanged.

Step 3. If the entry that is now at the top of the column found in Step 1 is a, multiply the first row by $1/a$ in order to introduce a leading 1.

$$\begin{bmatrix} 1 & 2 & -5 & 3 & 6 & 14 \\ 0 & 0 & -2 & 0 & 7 & 12 \\ 2 & 4 & -5 & 6 & -5 & -1 \end{bmatrix} \longleftarrow$$

The first row of the preceding matrix was multiplied by $\frac{1}{2}$.

Gaussian Elimination

Step 4. Add suitable multiples of the top row to the rows below so that all entries below the leading 1 become zeros.

$$\begin{bmatrix} 1 & 2 & -5 & 3 & 6 & 14 \\ 0 & 0 & -2 & 0 & 7 & 12 \\ 0 & 0 & 5 & 0 & -17 & -29 \end{bmatrix}$$

←— -2 times the first row of the preceding matrix was added to the third row.

Step 5. Now cover the top row in the matrix and begin again with Step 1 applied to the submatrix that remains. Continue in this way until the *entire* matrix is in row echelon form.

$$\begin{bmatrix} 1 & 2 & -5 & 3 & 6 & 14 \\ 0 & 0 & -2 & 0 & 7 & 12 \\ 0 & 0 & 5 & 0 & -17 & -29 \end{bmatrix}$$

Leftmost nonzero column in the submatrix

$$\begin{bmatrix} 1 & 2 & -5 & 3 & 6 & 14 \\ 0 & 0 & 1 & 0 & -\frac{7}{2} & -6 \\ 0 & 0 & 5 & 0 & -17 & -29 \end{bmatrix}$$

←— The first row in the submatrix was multiplied by $-\frac{1}{2}$ to introduce a leading 1.

Gaussian Elimination

$$\begin{bmatrix} 1 & 2 & -5 & 3 & 6 & 14 \\ 0 & 0 & 1 & 0 & -\frac{7}{2} & -6 \\ 0 & 0 & 0 & 0 & \frac{1}{2} & 1 \end{bmatrix}$$

-5 times the first row of the submatrix was added to the second row of the submatrix to introduce a zero below the leading 1.

$$\begin{bmatrix} 1 & 2 & -5 & 3 & 6 & 14 \\ 0 & 0 & 1 & 0 & -\frac{7}{2} & -6 \\ 0 & 0 & 0 & 0 & \frac{1}{2} & 1 \end{bmatrix}$$

The top row in the submatrix was covered, and we returned again to Step 1.

Leftmost nonzero column in the new submatrix

$$\begin{bmatrix} 1 & 2 & -5 & 3 & 6 & 14 \\ 0 & 0 & 1 & 0 & -\frac{7}{2} & -6 \\ 0 & 0 & 0 & 0 & 1 & 2 \end{bmatrix}$$

The first (and only) row in the new submatrix was multiplied by 2 to introduce a leading 1.

The *entire* matrix is now in row echelon form. To find the reduced row echelon form we need the following additional step.

Gauss-Jordan Elimination for Reduced Row-Echelon Form

Step 6. Beginning with the last nonzero row and working upward, add suitable multiples of each row to the rows above to introduce zeros above the leading 1's.

$$\begin{bmatrix} 1 & 2 & -5 & 3 & 6 & 14 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 2 \end{bmatrix} \longleftarrow$$

$\frac{7}{2}$ times the third row of the preceding matrix was added to the second row.

$$\begin{bmatrix} 1 & 2 & -5 & 3 & 0 & 2 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 2 \end{bmatrix} \longleftarrow$$

-6 times the third row was added to the first row.

$$\begin{bmatrix} 1 & 2 & 0 & 3 & 0 & 7 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 2 \end{bmatrix} \longleftarrow$$

5 times the second row was added to the first row.

The last matrix is in reduced row echelon form.

Free Variables and Infinite Solutions

- Consider the following linear system $\begin{bmatrix} 1 & 3 & -2 & 0 & 3 \\ 2 & 6 & -5 & -2 & 7 \\ 0 & 0 & 5 & 10 & -5 \end{bmatrix}$
- The row echelon form is $\begin{bmatrix} 1 & 3 & -2 & 0 & 3 \\ 0 & 0 & 1 & 2 & -1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$
- Therefore, x_1 and x_3 are *leading variables* and x_2 and x_4 are *free variables*.
- Any free variables imply that there are infinite solutions.
- Setting $x_2 = s$ and $x_4 = t$, we obtain $x_3 = -1 - 2t$ and $x_1 = 3 - 3s + 2(-1 - 2t)$.
- For $s = 1$ and $t = 1$, we get

$$x_1 = -6, x_2 = 1, x_3 = -3, x_4 = 1 \qquad \text{(Verify)}$$

- Since s and t can take an infinite range of values, there are infinite solutions.
  Find solution for $s = 2$ and $t = -1$ and verify.

Homogeneous Systems

- When the constant terms in all equations are 0, the linear system is called *homogeneous*.
- The system of equations

$$\begin{aligned} x_1 + x_2 + 2x_3 &= 0 \\ 2x_1 + 4x_2 - 3x_3 &= 0 \\ 3x_1 + 6x_2 - 5x_3 &= 0 \end{aligned}$$

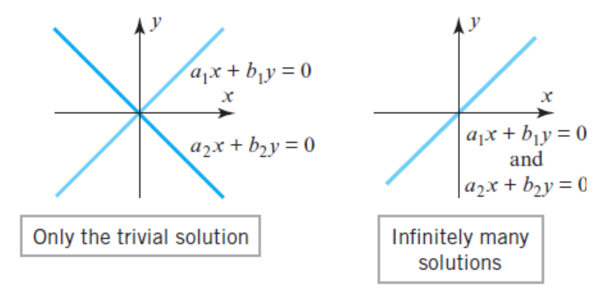
abbreviated via the augmented matrix

$$\begin{bmatrix} 1 & 1 & 2 & 0 \\ 2 & 4 & -3 & 0 \\ 3 & 6 & -5 & 0 \end{bmatrix}$$

is homogeneous.

Homogeneous Systems

- Setting all unknowns to 0 *always satisfies* any homogeneous system. So a homogeneous system can never be inconsistent.
- It has either the all-zeros (*trivial*) solution or infinitely many solutions.



- We are usually interested in *non-trivial solutions*.

When are there infinite solutions?

- For both homogeneous as well as consistent non-homogeneous systems, *if number of equations is less than number of unknowns, there must be infinite solutions*.
- This is because the row-echelon form will necessarily contain free variables.
- Consider the homogeneous linear system $\begin{bmatrix} 1 & 3 & -2 & 0 & 0 \\ 2 & 6 & -5 & -2 & 0 \\ 0 & 0 & 5 & 11 & 0 \end{bmatrix}$
- The row echelon form $\begin{bmatrix} 1 & 3 & -2 & 0 & 0 \\ 0 & 0 & 1 & 2 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}$ contains 3 leading 1s.
- Since there are 3 rows, number of leading 1s can never exceed 3 and there must be atleast 1 free variable.
- Since x_2 is a free variable here, there are infinite solutions.

Take Home Points

- Linear equation
- Linear system
- Solution set
- Consistent system
- Augmented matrix
- Elementary row operations
- Row echelon form – Gaussian elimination
- Reduced row echelon form – Gauss-Jordan elimination
- Back substitution
- Homogeneous system
- Trivial solution

Questions

- Exercise 1.1
  - $1, 2, 5 - 8, 12, 21, 24$, all true-false questions.
- Exercise 1.2
  - $1 - 3, 6, 10, 23, 36 - 38$, all true-false questions.