# CE 311K: Linear System of Equations

Krishna Kumar

University of Texas at Austin

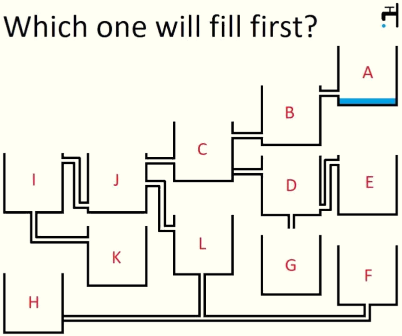
krishnak@utexas.edu

December 2, 2019



1. Linear System of Equations

## Linear System of Equations

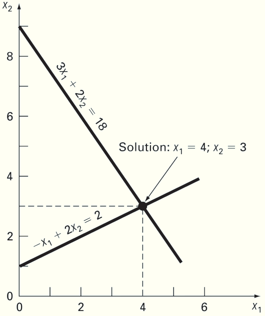





## Solving Linear System of Equations

$$
\begin{aligned}
3x_1 + 2x_2 &= 18 \\
-x_1 + 2x_2 &= 2
\end{aligned}
$$

# Solving Linear System of Equations






# Singularity and Ill-conditioned

## Solving Linear System of Equations

1. Direct Methods
    1. Gauss Elimination
    2. Gauss-Jordan Elimination
    3. LU decomposition
2. Iterative Methods
    1. Jacobi iterative
    2. Gauss-Seidel



## Direct methods

Consider a system of 3 linear equations for simplicity:

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

Matrix form is:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}$$

Concise form: $Ax = b$

## Systems that can be solved easily

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ 0 & a_{22} & a_{23} \\ 0 & 0 & a_{33} \end{bmatrix} \quad \begin{bmatrix} a_{11} & 0 & 0 \\ a_{21} & a_{22} & 0 \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \quad \begin{bmatrix} a_{11} & 0 & 0 \\ 0 & a_{22} & 0 \\ 0 & 0 & a_{33} \end{bmatrix}$$



## Solve by "back substitution' Upper triangle system (U)

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ 0 & a_{22} & a_{23} \\ 0 & 0 & a_{33} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}$$

## Gauss Elimination

Consider a system of 3 linear equations:

$$\begin{bmatrix} 2 & 4 & 6 \\ 4 & 11 & 21 \\ 6 & 21 & 52 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \begin{bmatrix} 24 \\ 72 \\ 158 \end{bmatrix}$$



## Gauss Elimination: Limitations

1. Prone to round off errors, when we have many ($> 100$) equations.
2. If coefficient matrix is sparse (lots of zeros), elimination methods are very inefficient.

## Gauss Seidel Iterative approach

For conciseness, we limit to $3 \times 3$ equations. If diagonal elements are all non-zero, then the equations can be solved as:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}$$



## Gauss Seidel Iterative approach

Using Gauss-Seidel solve for [x]

$$\begin{aligned} 4x_1 + x_2 + 2x_3 &= 4 \\ 3x_1 + 5x_2 + x_3 &= 7 \\ x_1 + x_2 + 3x_3 &= 3 \end{aligned}$$

## Gauss Seidel Convergence criteria

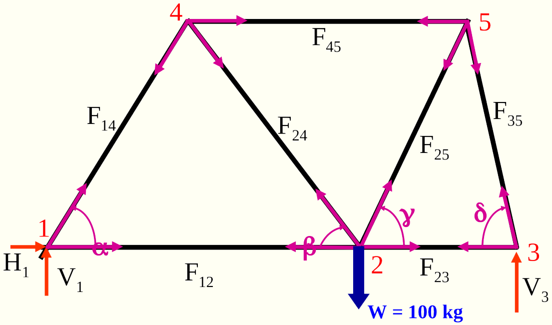
Convergence can be checked using the relative error.

$$|\varepsilon_{a,i}| = \left| \frac{x_i^k - x_i^{k-1}}{x_i^k} * 100\% \right| < \varepsilon_s$$

where $k$, and $k-1$ represents the current and previous iterations



## Truss analysis



## Truss analysis: Force balance

**Node 1**

$$\begin{cases}\sum F_{y,1} = V_1 + F_{14}\sin\alpha = 0\\ \sum F_{x,1} = H_1 + F_{12} + F_{14}\sin\alpha = 0\end{cases}$$

**Node 2**

$$\begin{cases}\sum F_{y,2} = F_{24}\sin\beta + F_{25}\sin\gamma = 100\\ \sum F_{x,2} = -F_{12} + F_{23} - F_{24}\cos\beta + F_{25}\cos\gamma = 0\end{cases}$$

**Node 3**

$$\begin{cases}\sum F_{y,3} = V_3 + F_{35}\sin\delta = 0\\ \sum F_{x,3} = -F_{23} - F_{35}\cos\delta = 0\end{cases}$$

**Node 4**

$$\begin{cases}\sum F_{y,4} = -F_{14}\sin\alpha - F_{24}\sin\beta = 0\\ \sum F_{x,4} = -F_{14}\cos\alpha + F_{24}\cos\beta + F_{45} = 0\end{cases}$$

**Node 5**

$$\begin{cases}\sum F_{y,5} = -F_{25}\sin\gamma - F_{35}\sin\delta = 0\\ \sum F_{x,5} = -F_{25}\cos\gamma + F_{35}\cos\delta - F_{45} = 0\end{cases}$$



## Truss analysis: Matrix formulation

$$\begin{bmatrix} 1 & 0 & 0 & 0 & \sin\alpha & 0 & 0 & 0 & 0 & 0\\ 0 & 1 & 0 & 1 & \cos\alpha & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & \sin\beta & \sin\gamma & 0 & 0\\ 0 & 0 & 0 & -1 & 0 & 1 & \cos\beta & \cos\gamma & 0 & 0\\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & \sin\delta & 0\\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & -\cos\delta & 0\\ 0 & 0 & 0 & 0 & -\sin\alpha & 0 & -\sin\beta & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & -\cos\alpha & 0 & \cos\beta & 0 & 0 & 1\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\sin\gamma & \sin\delta & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cos\gamma & \cos\delta & -1 \end{bmatrix} \begin{Bmatrix} V_1\\ H_1\\ V_3\\ F_{12}\\ F_{14}\\ F_{23}\\ F_{24}\\ F_{25}\\ F_{35}\\ F_{45} \end{Bmatrix} = \begin{Bmatrix} 0\\ 0\\ 100\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0 \end{Bmatrix}$$