LU Decomposition Method

Major: All Engineering Majors

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Questions to have been asked and to ask?

- What is LU decomposition method?
- How do we decompose a coefficient matrix to LU?
- LU decomposition method looks so much like Naïve Gauss elimination, what gives?
- How do we use LU decomposition method to find inverse of a matrix?

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Reviewing the LU Decomposition example

$$\begin{bmatrix} 25 & 5 & 1 \\ 64 & 8 & 1 \\ 144 & 12 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 106.8 \\ 177.2 \\ 279.2 \end{bmatrix}$$

$$\begin{bmatrix} 25 & 5 & 1 \\ 64 & 8 & 1 \\ 144 & 12 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 2.56 & 1 & 0 \\ 5.76 & 3.5 & 1 \end{bmatrix} \begin{bmatrix} 25 & 5 & 1 \\ 0 & -4.8 & -1.56 \\ 0 & 0 & 0.7 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 & 0 \\ 2.56 & 1 & 0 \\ 5.76 & 3.5 & 1 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} = \begin{bmatrix} 106.8 \\ 177.2 \\ 279.2 \end{bmatrix} \text{ gives } \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} = \begin{bmatrix} 106.8 \\ -96.208 \\ 0.76 \end{bmatrix}$$

$$\begin{bmatrix} 25 & 5 & 1 \\ 0 & -4.8 & -1.56 \\ 0 & 0 & 0.7 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 106.8 \\ -96.208 \\ 0.76 \end{bmatrix} \text{ gives } \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0.290472 \\ 19.6905 \\ 1.08571 \end{bmatrix}$$

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LU Decomposition Method

[A][X] = [C]

1. Decompose [A] into [L] and [U]
2. Solve [L][Z] = [C] for [Z] by using forward substitution
3. Solve [U][X] = [Z] for [X] by using back substitution

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LU decomposition method for solving a set of equations of form uses the following steps

$[L][X] = [Z]$ followed by $[U][Z] = [C]$

$[L][Z] = [C]$ followed by $[U][X] = [Z]$

$[U][Z] = [C]$ followed by $[L][X] = [Z]$

$[U][X] = [Z]$ followed by $[L][Z] = [C]$

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To solve a set of equations $[A][X] = [C]$ by LU decomposition, the first set of equations to be solved are $[L][Z] = [C]$. The vector $[Z]$ is _______. (Check all that apply)

Same as $[L]^{-1}[C]$

Same as the solution vector $[X]$

Same as the right-hand side vector one gets at the end of the forward elimination steps of Naive Gauss Elimination for $[A][X] = [C]$

Same as the vector $[C]$

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Every A matrix that has inverse can be decomposed to LU or PLU

$$\begin{bmatrix} 25 & 5 & 1 \\ 64 & 8 & 1 \\ 144 & 12 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 2.56 & 1 & 0 \\ 5.76 & 3.5 & 1 \end{bmatrix} \begin{bmatrix} 25 & 5 & 1 \\ 0 & -4.8 & -1.56 \\ 0 & 0 & 0.7 \end{bmatrix}$$

$$A = PLU$$

$$\begin{bmatrix} 0 & 1 & 0 \\ -8 & 8 & 1 \\ 2 & -2 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -4 & 0 & 1 \end{bmatrix} \begin{bmatrix} 2 & -2 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

P is a so-called permutation matrix

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THE END

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Is LU Decomposition better than Gaussian Elimination?

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Naïve Gaussian Elimination

[A][X] = [C]

1.Conduct forward elimination to get [U][X] = [Z]

2. Conduct back substitution to solve [U][X] = [Z] for [X]

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LU Decomposition Method

[A][X] = [C]

1. Decompose [A] into [L] and [U]
2. Solve [L][Z] = [C] for [Z] by using forward substitution
3. Solve [U][X] = [Z] for [X] by using back substitution

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Is LU Decomposition Method better than Gaussian Elimination Method?

Solve $[A][X] = [B]$

T = clock cycle time
$n \times n$ = size of the matrix
CT= computational time

Naive Gauss Elimination Method	LU Decomposition Methods
Forward Elimination $CT\|_{FE} = T\left(\frac{8n^3}{3} + 8n^2 - \frac{32n}{3}\right)$	**Decomposition to LU** $CT\|_{DE} = T\left(\frac{8n^3}{3} + 4n^2 - \frac{20n}{3}\right)$
Back Substitution $CT\|_{BS} = T(4n^2 + 12n)$	**Forward Substitution** $CT\|_{FS} = T(4n^2 - 4n)$
	Back Substitution $CT\|_{BS} = T(4n^2 + 12n)$

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Is LU Decomposition better than Gaussian Elimination?

To solve $[A][X] = [B]$

Time taken by methods

Gaussian Elimination	LU Decomposition
$T\left(\frac{8n^3}{3} + 12n^2 + \frac{4n}{3}\right)$	$T\left(\frac{8n^3}{3} + 12n^2 + \frac{4n}{3}\right)$

T = clock cycle time and $n \times n$ = size of the matrix

So both methods are equally efficient.

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THE END

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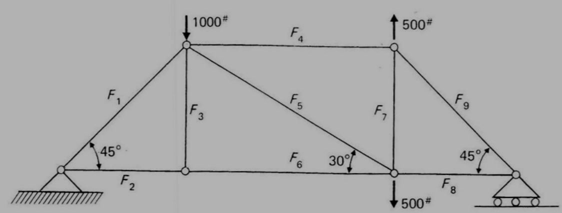
Truss Problem

$$\begin{bmatrix} 0.7071 & 0 & 0 & -1 & -0.8660 & 0 & 0 & 0 & 0 \\ 0.7071 & 0 & 1 & 0 & 0.5 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0.7071 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -0.7071 \\ 0 & 0 & 0 & 0 & 0.8660 & 1 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & -0.5 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0.7071 \end{bmatrix} F = \begin{bmatrix} 0 \\ -1000 \\ 0 \\ 0 \\ 500 \\ 0 \\ 0 \\ -500 \\ 0 \end{bmatrix}$$



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Finding the inverse of a square matrix

[B] is inverse of a square matrix [*A*] if

$$[A][B] = [I] \quad \textbf{OR} \quad [B][A] = [I]$$

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Two ways to show what inverse means?

$$\begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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Finding the inverse of a square matrix

How can LU Decomposition be used to find the inverse?

$$[A][B] = [I]$$

First Column of [B]

$$[A] \begin{bmatrix} b_{11} \\ b_{21} \\ \vdots \\ b_{n1} \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

Second Column of [B] ....

$$[A] \begin{bmatrix} b_{12} \\ b_{22} \\ \vdots \\ b_{n2} \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ \vdots \\ 0 \end{bmatrix}$$

Last Column of [B]

$$[A] \begin{bmatrix} b_{1n} \\ b_{2n} \\ \vdots \\ b_{nn} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 1 \end{bmatrix}$$

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Example: Inverse of a Matrix

Find the inverse of a square matrix [*A*]

$$[A]=\begin{bmatrix}25 & 5 & 1\\ 64 & 8 & 1\\ 144 & 12 & 1\end{bmatrix}$$

Using the decomposition procedure, the [*L*] and [*U*] matrices are found to be

$$[A]=[L][U]=\begin{bmatrix}1 & 0 & 0\\ 2.56 & 1 & 0\\ 5.76 & 3.5 & 1\end{bmatrix}\begin{bmatrix}25 & 5 & 1\\ 0 & -4.8 & -1.56\\ 0 & 0 & 0.7\end{bmatrix}$$

Solving for each column of [*B*] requires two steps

1) Solve [*L*] [*Z*] = [*C*] for [*Z*]
2) Solve [*U*] [*X*] = [*Z*] for [*X*]

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Finding 1st column of inverse: LZ=C

$$\begin{bmatrix}25 & 5 & 1\\ 64 & 8 & 1\\ 144 & 12 & 1\end{bmatrix}\begin{bmatrix}b_{11}\\ b_{21}\\ b_{31}\end{bmatrix}=\begin{bmatrix}1\\ 0\\ 0\end{bmatrix}$$

$$Step\ 1\colon [L][Z]=[C]\rightarrow\begin{bmatrix}1 & 0 & 0\\ 2.56 & 1 & 0\\ 5.76 & 3.5 & 1\end{bmatrix}\begin{bmatrix}z_1\\ z_2\\ z_3\end{bmatrix}=\begin{bmatrix}1\\ 0\\ 0\end{bmatrix}$$

$$\begin{aligned}z_1&=1\\ 2.56z_1+z_2&=0\\ 5.76z_1+3.5z_2+z_3&=0\end{aligned}$$

$$\begin{aligned}z_1&=1\\ z_2&=0-2.56z_1\\ &=0-2.56(1)\\ &=-2.56\\ z_3&=0-5.76z_1-3.5z_2\\ &=0-5.76(1)-3.5(-2.56)\\ &=3.2\end{aligned}$$

$$[Z]=\begin{bmatrix}z_1\\ z_2\\ z_3\end{bmatrix}=\begin{bmatrix}1\\ -2.56\\ 3.2\end{bmatrix}$$

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Finding 1st column of inverse: UX=Z

$$Step\ 2\colon [U][X]=[Z]\rightarrow\begin{bmatrix}25 & 5 & 1\\ 0 & -4.8 & -1.56\\ 0 & 0 & 0.7\end{bmatrix}\begin{bmatrix}b_{11}\\ b_{21}\\ b_{31}\end{bmatrix}=\begin{bmatrix}1\\ -2.56\\ 3.2\end{bmatrix}$$

$$\begin{aligned}25b_{11}+5b_{21}+b_{31}&=1\\ -4.8b_{21}-1.56b_{31}&=-2.56\\ 0.7b_{31}&=3.2\end{aligned}$$

$$\begin{aligned}b_{31}&=\frac{3.2}{0.7}\\ &=4.571\\ b_{21}&=\frac{-2.56+1.560b_{31}}{-4.8}\\ &=\frac{-2.56+1.560(4.571)}{-4.8}\\ &=-0.9524\\ b_{11}&=\frac{1-5b_{21}-b_{31}}{25}\\ &=\frac{1-5(-0.9524)-4.571}{25}\\ &=0.04762\end{aligned}$$

$$\begin{bmatrix}b_{11}\\ b_{21}\\ b_{31}\end{bmatrix}=\begin{bmatrix}0.04762\\ -0.9524\\ 4.571\end{bmatrix}$$

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Inverse of a Matrix

$$\begin{bmatrix}25 & 5 & 1\\ 64 & 8 & 1\\ 144 & 12 & 1\end{bmatrix}\begin{bmatrix}b_{11} & b_{12} & b_{13}\\ b_{21} & b_{22} & b_{23}\\ b_{31} & b_{32} & b_{33}\end{bmatrix}=\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix}$$

First Column	Second Column	Third Column
$\begin{bmatrix}25 & 5 & 1\\ 64 & 8 & 1\\ 144 & 12 & 1\end{bmatrix}\begin{bmatrix}b_{11}\\ b_{21}\\ b_{31}\end{bmatrix}=\begin{bmatrix}1\\ 0\\ 0\end{bmatrix}$	$\begin{bmatrix}25 & 5 & 1\\ 64 & 8 & 1\\ 144 & 12 & 1\end{bmatrix}\begin{bmatrix}b_{12}\\ b_{22}\\ b_{32}\end{bmatrix}=\begin{bmatrix}0\\ 1\\ 0\end{bmatrix}$	$\begin{bmatrix}25 & 5 & 1\\ 64 & 8 & 1\\ 144 & 12 & 1\end{bmatrix}\begin{bmatrix}b_{13}\\ b_{23}\\ b_{33}\end{bmatrix}=\begin{bmatrix}0\\ 0\\ 1\end{bmatrix}$
$\begin{bmatrix}b_{11}\\ b_{21}\\ b_{31}\end{bmatrix}=\begin{bmatrix}0.04762\\ -0.9524\\ 4.571\end{bmatrix}$	$\begin{bmatrix}b_{12}\\ b_{22}\\ b_{32}\end{bmatrix}=\begin{bmatrix}-0.08333\\ 1.417\\ -5.000\end{bmatrix}$	$\begin{bmatrix}b_{13}\\ b_{23}\\ b_{33}\end{bmatrix}=\begin{bmatrix}0.03571\\ -0.4643\\ 1.429\end{bmatrix}$

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Example: Inverse of a Matrix

$$\begin{bmatrix} b_{11} \\ b_{21} \\ b_{31} \end{bmatrix} = \begin{bmatrix} 0.04762 \\ -0.9524 \\ 4.571 \end{bmatrix} \quad \begin{bmatrix} b_{12} \\ b_{22} \\ b_{32} \end{bmatrix} = \begin{bmatrix} -0.08333 \\ 1.417 \\ -5.000 \end{bmatrix} \quad \begin{bmatrix} b_{13} \\ b_{23} \\ b_{33} \end{bmatrix} = \begin{bmatrix} 0.03571 \\ -0.4643 \\ 1.429 \end{bmatrix}$$

$$[A]^{-1} = \begin{bmatrix} 0.04762 & -0.08333 & 0.03571 \\ -0.9524 & 1.417 & -0.4643 \\ 4.571 & -5.000 & 1.429 \end{bmatrix}$$

To check your work, check the following

$$[A][A]^{-1} = [I] = [A]^{-1}[A]$$

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To find inverse of [A]

Time taken by Gaussian Elimination

$$= n(CT|_{FE} + CT|_{BS})$$

$$= n \times T\left(\frac{8n^3}{3} + 8n^2 - \frac{32n}{3}\right) + n \times T(4n^2 + 12n)$$

$$= T\left(\frac{8n^4}{3} + 12n^3 + \frac{4n^2}{3}\right)$$

Time taken by LU Decomposition

$$= CT|_{DE} + n \times CT|_{FS} + n \times CT|_{BS}$$

$$= T\left(\frac{8n^3}{3} + 4n^2 - \frac{20n}{3}\right) + n \times T(4n^2 - 4n) + n \times T(4n^2 + 12n)$$

$$= T\left(\frac{32n^3}{3} + 12n^2 - \frac{20n}{3}\right)$$

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To find inverse of [A]

Time taken by Gaussian Elimination

$$T\left(\frac{8n^4}{3} + 12n^3 + \frac{4n^2}{3}\right)$$

Time taken by LU Decomposition

$$T\left(\frac{32n^3}{3} + 12n^2 - \frac{20n}{3}\right)$$

Table 1 Comparing computational times of finding inverse of a matrix using LU decomposition and Naive Gauss elimination.

n	10	100	1000	10000
$\frac{CT_{\text{inverse GE}}}{CT_{\text{inverse LU}}}$	3.288	25.84	250.8	2501

For large n, $\frac{CT_{\text{inverse GE}}}{CT_{\text{inverse LU}}} \approx \frac{n}{4}$

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Time Taken by Back Substitution

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\ 0 & a'_{22} & a'_{23} & \cdots & a'_{2n} \\ 0 & 0 & a''_{33} & \cdots & a''_{3n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & 0 & 0 & a_{nn}^{(n-1)} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} b_1 \\ b'_2 \\ b''_3 \\ \vdots \\ b_n^{(n-1)} \end{bmatrix}$$

$$x_n = \frac{b_n^{(n-1)}}{a_{nn}^{(n-1)}}$$

$$x_i = \frac{b_i^{(i-1)} - \sum_{j=i+1}^{n} a_{ij}^{(i-1)} x_j}{a_{ii}^{(i-1)}} \text{ for } i = n-1, \ldots, 1$$

```
n = length(B);
X(n)=B(n)/A(n,n)
for i=n-1:-1:1
X(i) = B(i);
    for j=(i+1):1:n
        X(i) = X(i) - A(i, j)*X(j);
    end
X(i) = X(i)/A(i, i);
end
```

Back Substitution CT

$$CT|_{BS} = T(4n^2 + 12n)$$

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Time Taken by Back Substitution

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\ 0 & a'_{22} & a'_{23} & \cdots & a'_{2n} \\ 0 & 0 & a''_{33} & \cdots & a''_{3n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & 0 & 0 & a_{nn}^{(n-1)} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} b_1 \\ b'_2 \\ b''_3 \\ \vdots \\ b_n^{(n-1)} \end{bmatrix}$$

$$x_n = \frac{b_n^{(n-1)}}{a_{nn}^{(n-1)}}$$

$$x_i = \frac{b_i^{(i-1)} - \sum_{j=i+1}^{n} a_{ij}^{(i-1)} x_j}{a_{ii}^{(i-1)}} \text{ for } i = n-1, \ldots, 1$$

```
n = length(B);
X(n)=B(n)/A(n,n)
for i=n-1:-1:1
X(i) = B(i);
   for j=(i+1):1:n
      X(i) = X(i) - A(i, j)*X(j);
   end
X(i) = X(i)/A(i, i);
end
```

Back Substitution CT

$$CT|_{BS} = T(4n^2 + 12n)$$

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How many times does the variable 'a' get assigned the value of 2?

```
for j=4:1:11
    a=2
end
```

4

7

8

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How many times does the variable 'a' get assigned the value of 2?

```
for j=i+1:1:n
    a=2
end
```

n-i

n-i-1

n

i+1

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How many times does the variable 'a' get assigned the value of 2?

```
for i=3: -1: 1
    for j=i+1: 1: 4
       a=2
    end
end
```

6

7

8

12

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What is the sum of 5+6+7+...+122?

Hint: $S = \frac{n}{2}(a_1 + a_n)$

" 7493 "

" 7493.00000 "

" 7493! "

" 7493 "

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Time Taken by Back Substitution

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\ 0 & a'_{22} & a'_{23} & \cdots & a'_{2n} \\ 0 & 0 & a''_{33} & \cdots & a''_{3n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & 0 & 0 & a_{nn}^{(n-1)} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} b_1 \\ b'_2 \\ b''_3 \\ \vdots \\ b_n^{(n-1)} \end{bmatrix}$$

$$x_n = \frac{b_n^{(n-1)}}{a_{nn}^{(n-1)}}$$

$$x_i = \frac{b_i^{(i-1)} - \sum_{j=i+1}^{n} a_{ij}^{(i-1)} x_j}{a_{ii}^{(i-1)}} \text{ for } i = n-1, \ldots, 1$$

```
n = length(B);
X(n)=B(n)/A(n,n)
for i=n-1:-1:1
X(i) = B(i);
   for j=(i+1):1:n
      X(i) = X(i) - A(i, j)*X(j);
   end
X(i) = X(i)/A(i, i);
end
```

Back Substitution CT

$CT|_{BS} = T(4n^2 + 12n)$

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Time Taken by Back Substitution

```
n = length(B);
X(n)=B(n)/A(n,n)
for i=n-1:-1:1
X(i) = B(i);
    for j=(i+1):1:n
        X(i) = X(i) - A(i, j)*X(j);
    end
X(i) = X(i)/A(i, i);
end
```

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THE END

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Two ice cubes are floating in the water in a glass. After the ice melts, will the water level be:

- Higher
- Lower
- Same

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Increasing the precision of numbers from single to double in the Naive Gaussian elimination method

- avoids division by zero
- decreases round-off error
- allows equations with a noninvertible coefficient matrix to be solved

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Someone is asking you to use LU decomposition method to solve m sets of (n equations, n unknowns) of the form [A][X]=[C]. If the coefficient matrix [A] stays the same in all sets, how many times does one need to decompose the matrix [A]?

1
m
n
mn

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There are two parts in Naive Gaussian Elimination - forward elimination and back substitution. If we are solving n equations for n unknowns, how many steps are in the forward elimination part?

n
n-1
n+1

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Naive Gaussian elimination has these inherent numerical methods errors (Check all that apply)

Round off errors
Truncation errors

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LU decomposition method is computationally more efficient than Naive Gauss elimination for (Check all that apply)

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Using 3 significant digits with *chopping* at all stages, the result for the following calculation is

$$x_1 = \frac{6.095 - 3.456 \times 1.99}{8}$$

-0.0988

-0.0978

-0.0969

-0.0962

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Division by zero during the forward elimination part in *Naïve Gaussian* elimination for [A][X]=[C] implies the coefficient matrix [A] ____________

is invertible

is not invertible

cannot be determined to be invertible or not

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THE END

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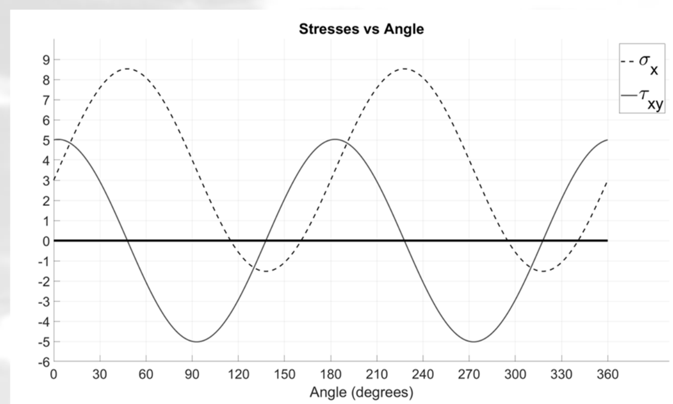

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