Simultaneous Linear Equations

Holistic Numerical Methods Institute

Topic: LU Decomposition

Major: Industrial Engineering

LU Decomposition

LU Decomposition is another method to solve a set of simultaneous linear equations

Which is better, Gauss Elimination or LU Decomposition?

To answer this, a closer look at LU decomposition is needed.

LU Decomposition

Method

For most non-singular matrix $[A]$ that one could conduct Naïve Gauss Elimination forward elimination steps, one can always write it as

$$[A]=[L][U]$$

Where

$[L]$ = lower triangular martix

$[U]$ = upper triangular martix

LU Decomposition

Proof

If solving a set of linear equations $[A][X]=[C]$

If $[A]=[L][U]$ Then $[L][U][X]=[C]$

Multiply by $[L]^{-1}$

Which gives $[L]^{-1}[L][U][X]=[L]^{-1}[C]$

Remember $[L]^{-1}[L]=[I]$ which leads to $[I][U][X]=[L]^{-1}[C]$

Now, if $[I][U]=[U]$ then $[U][X]=[L]^{-1}[C]$

Now, let $[L]^{-1}[C]=[Z]$

Which ends with $[L][Z]=[C]$ (1)

and $[U][X]=[Z]$ (2)

LU Decomposition

How can this be used?

Given $[A][X]=[C]$

Decompose $[\mathrm{A}]$ into $[L]$ and $[U]$

Then solve $[L][Z]=[\mathrm{C}]$ for $[Z]$

And then solve $[U][\mathrm{X}]=[Z]$ for $[X]$

LU Decomposition

How is this better or faster than Gauss Elimination?

Let's look at computational time.

n = number of equations

To decompose [A], time is proportional to $\frac{n^3}{3}$

To solve $[U][X]=[C]$ and $[\mathrm{L}][\mathrm{Z}]=[\mathrm{C}]$

time proportional to $\frac{n^2}{2}$

LU Decomposition

Therefore, total computational time for LU Decomposition is proportional to

$$\frac{n^3}{3} + 2\left(\frac{n^2}{2}\right) \quad \text{or} \quad \frac{n^3}{3} + n^2$$

Gauss Elimination computation time is proportional to

$$\frac{n^3}{3} + \frac{n^2}{2}$$

How is this better?

LU Decomposition

What about a situation where the [C] vector changes?

In LU Decomposition, LU decomposition of [A] is independent of the [C] vector, therefore it only needs to be done once.

Let m = the number of times the [C] vector changes

The computational times are proportional to

LU decomposition = $m\left(\frac{n^3}{3}+\frac{n^2}{2}\right)$ Gauss Elimination= $\frac{n^3}{3}+m(n^2)$

Consider a 100 equation set with 50 right hand side vectors

LU Decomposition = 8.33×10^5 Gauss Elimination = 1.69×10^7

LU Decomposition

Another Advantage

Finding the Inverse of a Matrix

LU Decomposition

$$\frac{n^3}{3} + n(n^2) = \frac{4n^3}{3}$$

Gauss Elimination

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

For large values of n

$$\frac{n^4}{3} + \frac{n^3}{2} \rangle\rangle \frac{4n^3}{3}$$

LU Decomposition

Method: [A] Decompose to [L] and [U]

$$[A] = [L][U] = \begin{bmatrix} 1 & 0 & 0 \\ \ell_{21} & 1 & 0 \\ \ell_{31} & \ell_{32} & 1 \end{bmatrix} \begin{bmatrix} u_{11} & u_{12} & u_{13} \\ 0 & u_{22} & u_{23} \\ 0 & 0 & u_{33} \end{bmatrix}$$

[U] is the same as the coefficient matrix at the end of the forward elimination step.

[L] is obtained using the *multipliers* that were used in the forward elimination process

Example: Production Optimization

To find the number of toys a company should manufacture per day to optimally use their injection-molding machine and the assembly line, one needs to solve the following set of equations. The unknowns are the number of toys for boys, *x1*, number of toys for girls, *x2*, and the number of unisexual toys, *x3*.

$$\begin{bmatrix} 0.3333 & 0.1667 & 0.6667 \\ 0.1667 & 0.6667 & 0.3333 \\ 1.05 & -1.00 & 0.00 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{Bmatrix} 756 \\ 1260 \\ 0 \end{Bmatrix}$$

Find the values of *x1, x2,* and *x3* using Naïve Guass Elimination.

Example: Production Optimization

Finding the [*U*] matrix

Using the Forward Elimination Procedure of Gauss Elimination

$$\begin{bmatrix} 0.3333 & 0.1667 & 0.6667 \\ 0.1667 & 0.6667 & 0.3333 \\ 1.05 & -1.00 & 0.00 \end{bmatrix}$$

$$Row2 - \left[\frac{Row1}{0.3333}\right] \times (0.1667) = \begin{bmatrix} 0.3333 & 0.1667 & 0.6667 \\ 0 & 0.5833 & -0.0002 \\ 1.05 & -1.00 & 0.00 \end{bmatrix}$$

$$Row3 - \left[\frac{Row1}{0.3333}\right] \times (1.05) = \begin{bmatrix} 0.3333 & 0.1667 & 0.6667 \\ 0 & 0.5833 & -0.0002 \\ 0 & -1.52516 & -2.1003 \end{bmatrix}$$

Example: Production Optimization

Finding the [*U*] matrix

Using the Forward Elimination Procedure of Gauss Elimination

$$\begin{bmatrix} 0.3333 & 0.1667 & 0.6667 \\ 0 & 0.5833 & -0.0002 \\ 0 & -1.52516 & -2.1003 \end{bmatrix}$$

$$Row3 - \left[\frac{Row2}{0.5833}\right] \times (-1.52516) = \begin{bmatrix} 0.3333 & 0.1667 & 0.6667 \\ 0 & 0.5833 & -0.0002 \\ 0 & 0 & -2.1008 \end{bmatrix}$$

$$[U] = \begin{bmatrix} 0.3333 & 0.1667 & 0.6667 \\ 0 & 0.5833 & -0.0002 \\ 0 & 0 & -2.1008 \end{bmatrix}$$

Example: Production Optimization

Finding the [*L*] matrix

Using the multipliers used during the Forward Elimination Procedure

From the first step of forward elimination

$$\begin{bmatrix} 1 & 0 & 0 \\ \ell_{21} & 1 & 0 \\ \ell_{31} & \ell_{32} & 1 \end{bmatrix}$$

$$\ell_{21} = \frac{a_{21}}{a_{11}} = \frac{0.1667}{0.3333} = 0.50015$$

$$\ell_{31} = \frac{a_{31}}{a_{11}} = \frac{1.05}{0.3333} = 3.1503$$

From the second step of forward elimination

$$\begin{bmatrix} 0.3333 & 0.1667 & 0.6667 \\ 0 & 0.5833 & -0.0002 \\ 0 & -1.52516 & -2.1003 \end{bmatrix}$$

$$\ell_{32} = \frac{a_{32}}{a_{22}} = \frac{-1.52516}{0.5833} = -2.6147$$

Example: Production Optimization

$$[L]=\begin{bmatrix} 1 & 0 & 0 \\ 0.50015 & 1 & 0 \\ 3.1503 & -2.6147 & 1 \end{bmatrix}$$

Does $[L][U]=[A]$?

$$[L][U]=\begin{bmatrix} 1 & 0 & 0 \\ 0.50015 & 1 & 0 \\ 3.1503 & -2.6147 & 1 \end{bmatrix}\begin{bmatrix} 0.3333 & 0.1667 & 0.6667 \\ 0 & 0.5833 & -0.0002 \\ 0 & 0 & -2.1008 \end{bmatrix}$$

Example: Production Optimization

Example: Solving simultaneous linear equations using LU Decomposition

Set $[L][Z]=[C]$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0.50015 & 1 & 0 \\ 3.1503 & -2.6147 & 1 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} = \begin{bmatrix} 756 \\ 1260 \\ 0 \end{bmatrix}$$

Solve for $[Z]$

$$z_1 = 756$$

$$0.50015 z_1 + z_2 = 1260$$

$$3.1503 z_1 + (-2.6147) + z_3 = 0$$

Example: Production Optimization

Example: Solving simultaneous linear equations using LU Decomposition

Complete the forward substitution to solve for $[Z]$

$$z_1 = 756$$

$$\begin{aligned} z_2 &= 1260 - 0.50015 z_1 \\ &= 1260 - 0.50015 \times 756 \\ &= 881.89 \end{aligned}$$

$$\begin{aligned} z_3 &= 0 - 3.1503 z_1 - (-2.6147) z_2 \\ &= 0 - 3.1503 \times 756 - (-2.6147) \times 881.89 \\ &= -75.749 \end{aligned}$$

$$[Z] = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} = \begin{bmatrix} 756 \\ 881.89 \\ -75.749 \end{bmatrix}$$

Example: Production Optimization

Example: Solving simultaneous linear equations using LU Decomposition

Set $[U][X]=[Z]$

$$\begin{bmatrix} 0.3333 & 0.1667 & 0.6667 \\ 0 & 0.5833 & -0.0002 \\ 0 & 0 & -2.1008 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}=\begin{bmatrix} 756 \\ 881.89 \\ -75.749 \end{bmatrix}$$

Solve for $[X]$

The 3 equations become

$$0.3333x_1 + 0.1667x_2 + 0.6667x_3 = 756$$

$$0.5833x_2 + (-0.0002)x_3 = 881.89$$

$$-2.1008x_3 = -75.749$$

Example: Production Optimization

Example: Solving simultaneous linear equations using LU Decomposition

From the 3rd equation

$$-2.1008x_3 = -75.749$$

$$x_3 = \frac{-75.749}{-2.1008}$$

$$= 36.0572$$

Substituting in x_3 and using the second equation

$$0.5833x_2 + (-0.0002)x_3 = 881.89$$

$$x_2 = \frac{881.89 - (-0.0002)x_3}{0.5833}$$

$$= \frac{881.89 - (-0.0002) \times 36.0572}{0.5833}$$

$$= 1511.91$$

Example: Production Optimization

Example: Solving simultaneous linear equations using LU Decomposition

Substituting in x_3 and x_2 using the first equation

$$0.3333x_1 + 0.1667x_2 + 0.6667x_3 = 756$$

$$x_1 = \frac{756 - 0.1667x_2 - 0.6667x_3}{0.3333}$$

$$= \frac{756 - 0.1667 \times 1511.91 - 0.6667 \times 36.0572}{0.3333}$$

$$= 1439.89$$

Hence the Solution Vector is:

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 1439.89 \\ 1511.91 \\ 36.0572 \end{bmatrix}$$

Example: Production Optimization

Solution:

The solution vector is

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 1439.92 \\ 1511.91 \\ 36.0586 \end{bmatrix}$$

1440 toys for boys should be produced

1512 toys for girls should be produced

36 unisexual toys should be produced

LU Decomposition

Finding the inverse of a square matrix

Remember, the relative computational time comparison of LU decomposition and Gauss elimination is:

$$\frac{n^4}{3} + \frac{n^3}{2} \rangle\rangle \frac{4n^3}{3}$$

Review: The inverse [B] of a square matrix [*A*] is defined as

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

LU Decomposition

Finding the inverse of a square matrix

How can LU Decomposition be used to find the inverse?

Assume the first column of [*B*] to be $\begin{bmatrix} b_{11} & b_{12} & \ldots & b_{n1} \end{bmatrix}^T$

Using this and the definition of matrix multiplication

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*]

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

The remaining columns in [*B*] can be found in the same manner

LU Decomposition

Example: Finding the inverse of a square matrix

Find the inverse of [*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

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

LU Decomposition

Example: Finding the inverse of a square matrix

Solving for the each column of [*B*] requires to steps

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

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

This generates the equations:

$$z_1 = 1$$
$$2.56 z_1 + z_2 = 0$$
$$5.76 z_1 + 3.5 z_2 + z_3 = 0$$

LU Decomposition

Example: Finding the inverse of a square matrix

Solving for [*Z*]

$$z_1 = 1$$

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

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

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

LU Decomposition

Example: Finding the inverse of a square matrix

Solving for [*U*] [*X*] = [*Z*] for [*X*]

$$\begin{bmatrix} 25 & 5 & 1 \\ 0 & -4.8 & -1.56 \\ 0 & 0 & 0.7 \end{bmatrix}\begin{bmatrix} b_{11} \\ b_{21} \\ b_{31} \end{bmatrix} = \begin{bmatrix} 1 \\ -2.56 \\ 3.2 \end{bmatrix}$$

$$25b_{11} + 5b_{21} + b_{31} = 1$$

$$-4.8b_{21} - 1.56b_{31} = -2.56$$

$$0.7b_{31} = 3.2$$

LU Decomposition

Example: Finding the inverse of a square matrix

Using Backward Substitution

$$b_{31} = \frac{3.2}{0.7} = 4.571$$

$$b_{21} = \frac{-2.56 + 1.560 b_{31}}{-4.8}$$

$$= \frac{-2.56 + 1.560(4.571)}{-4.8} = -0.9524$$

$$b_{11} = \frac{1 - 5b_{21} - b_{31}}{25}$$

$$= \frac{1 - 5(-0.9524) - 4.571}{25} = 0.04762$$

So the first column of the inverse of [*A*] is:

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

LU Decomposition

Example: Finding the inverse of a square matrix

Repeating for the second and third columns of the inverse

Second Column

$$\begin{bmatrix} 25 & 5 & 1 \\ 64 & 8 & 1 \\ 144 & 12 & 1 \end{bmatrix} \begin{bmatrix} b_{12} \\ b_{22} \\ b_{32} \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} b_{12} \\ b_{22} \\ b_{32} \end{bmatrix} = \begin{bmatrix} -0.08333 \\ 1.417 \\ -5.000 \end{bmatrix}$$

Third Column

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

$$\begin{bmatrix} b_{13} \\ b_{23} \\ b_{33} \end{bmatrix} = \begin{bmatrix} 0.03571 \\ -0.4643 \\ 1.429 \end{bmatrix}$$

LU Decomposition

Example: Finding the inverse of a square matrix

The inverse of [A] is

$$[A]^{-1} = \begin{bmatrix} 0.4762 & 0.08333 & 0.0357 \\ -0.9524 & 1.417 & -0.4643 \\ 4.571 & -5.050 & 1.429 \end{bmatrix}$$

To check your work do the following operation

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