You Perturb It, You Pay According to $\mathcal{K}(A)$: Norms and Error Analysis

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MTH 499-02

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Outline

- Norms: properties, types, examples

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- Theorems, results on norms

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- Theorems, results on norms
- Relative/absolute error in perturbations, conditioning number

Definition

Let V be a vector space. A norm is a function $\|\cdot\| : V \to \mathbb{R}^+$ that has the following properties:

- $\|x\| > 0$ if $x \neq 0,\ x \in V$
- $\|\lambda x\| = |\lambda|\ \|x\|$ if $\lambda \in \mathbb{R},\ x \in V$
- $\|x + y\| \leq \|x\| + \|y\|$ for all $x, y \in V$ (triangle inequality)

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Other comments:

- Norm can be thought of as generalization of absolute value
- Interpretation: vector length in $\mathbb{R}^2$, $\mathbb{R}^3$

Types of Norms

Vector Norms:

Vector Norms:

- l_k norm

$$l_k = \|x\|_k = \left(\sum_{i=1}^{n} |x_i|^k\right)^{1/k} \text{ where } k \in \{1, 2, \dots\} \text{ and } x = (x_1, \dots, x_n)^T$$

Vector Norms:

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- Some common instances of the l_k norm:

k	l_k
1	$\|x\|_1 = \sum_{i=1}^{n} \lvert x_i \rvert$
2	$\|x\|_2 = \left(\sum_{i=1}^{n} x_i^2 \right)^{1/2}$
∞	$\|x\|_\infty = \max_{1 \le i \le n} \lvert x_i \rvert$

- Consider vectors in $\mathbb{R}^3$

$$x = (2, -1, 3)^T \qquad y = (7, 2, 5)^T \qquad z = (-3, 1, -9)^T$$

	$\|\|\cdot\|\|_1$	$\|\|\cdot\|\|_2$	$\|\|\cdot\|\|_\infty$
x			
y			
z			

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	$\|\|\cdot\|\|_1$	$\|\|\cdot\|\|_2$	$\|\|\cdot\|\|_\infty$
x	6		
y			
z			

$$||x||_1 = 2 + 1 + 3 = 6$$

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	$\|\|\cdot\|\|_1$	$\|\|\cdot\|\|_2$	$\|\|\cdot\|\|_\infty$
x	6	3.74	
y			
z			

$$||x||_2 = \sqrt{2^2 + 1^2 + 3^2} = 3.74$$

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$$||x||_\infty = 3$$

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	$\|\cdot\|_1$	$\|\cdot\|_2$	$\|\cdot\|_\infty$
x	6	3.74	3
y	14	8.83	7
z	13	9.54	9

Definition

A matrix norm subordinate to a vector norm $\|\cdot\|$ is defined as

$$\|A\| = \sup\left\{\|Au\| : u \in \mathbb{R}^n, \|u\| = 1\right\},$$

where A is an $n \times n$ matrix.

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    - Subordinate to vector norm $\|\cdot\|_\infty$ is

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      which is the maximum absolute row sum of A.

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    $$\|A\|_\infty = \max_{1\le i\le n} \sum_{j=1}^{n} |a_{ij}|,$$

    which is the maximum absolute row sum of A.
  - Subordinate to vector norm $\|\cdot\|_2$ is

    $$\begin{aligned}\|A\|_2 &= \sup_{\|x\|_2=1} \left\{\|Ax\|_2\right\} \\ &= \sqrt{\rho(A^T A)},\end{aligned}$$

    where $\rho(A^T A)$ is spectral radius of $A^T A$, largest eigenvalue of $A^T A$.

- Consider matrix $A = \begin{bmatrix} 1 & 1 \\ 2 & 1 \end{bmatrix}$

Examples of Matrix Norms

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- For $A^T A$, eigenvalues are $\sigma_1^2 = 6.8541$ and $\sigma_2^2 = 0.1459$.
- So, $\|A\|_2 = \sqrt{6.8541} \approx 2.618$.

- Consider matrix $B = \begin{bmatrix} 3 & 2 & 4 \\ 2 & 0 & 2 \\ 4 & 2 & 3 \end{bmatrix}$

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- $\|B\|_2$ is simply the maximum absolute row sum, which is 9.

Theorem (Subordinate Matrix Norm)

If $\|\cdot\|$ is any norm in $\mathbb{R}^n$, then the equation

$$\|A\| = \sup_{\|u\|=1} \{\|Au\| : u \in \mathbb{R}^n\}$$

defines a norm on the linear space of all n x n matrices.

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Proof.

TODO $\square$

Theorem (Infinity Matrix Norm)

If the vectorm norm $\|\cdot\|_\infty$ is defined by

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then its subordinate matrix norm is given by

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  - Positive definite ($x^T Ax > 0$ for all $x \in \mathbb{R}^n$, $x \neq 0_n$)

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Unicity: straightforward (assume two, show same) □

Cholesky Algorithm

function CHOLESKY$(n, (a_{ij}))$

  for $k = 1$ **to** n **do**

    $l_{kk} \leftarrow \left(a_{kk} - \sum_{s=1}^{k-1} l_{ks}^2 \right)^{1/2}$

    for $i = k+1$ **to** n **do**

      $l_{ik} \leftarrow \left(a_{ik} - \sum_{s=1}^{k-1} l_{is} l_{ks} \right) / l_{kk}$

  return (l_{ij})

where

- $A = (a_{ij})$: factored matrix
- n: order of A
- $L = (l_{ij})$: resulting lower triangular matrix

Example of Cholesky Algorithm

$$A = \begin{bmatrix} 25 & 15 & -5 \\ 15 & 18 & 0 \\ -5 & 0 & 11 \end{bmatrix}$$

$$L = \begin{bmatrix} & 0 & 0 \\ & & 0 \\ & & \end{bmatrix}$$

function $\textsc{Cholesky}(n, (a_{ij}))$
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$$k = 1 :$$

$$l_{11} = (25 - 0)^{1/2} = 5$$

Example of Cholesky Algorithm

$$A = \begin{bmatrix} 25 & 15 & -5 \\ 15 & 18 & 0 \\ -5 & 0 & 11 \end{bmatrix}$$

$$L = \begin{bmatrix} 5 & 0 & 0 \\ 3 & & 0 \\ & & \end{bmatrix}$$

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$$k = 1, \quad i = 2 :$$

$$l_{21} = (15 - 0)/5 = 3$$

Example of Cholesky Algorithm

$$A = \begin{bmatrix} 25 & 15 & -5 \\ 15 & 18 & 0 \\ -5 & 0 & 11 \end{bmatrix}$$

$$L = \begin{bmatrix} 5 & 0 & 0 \\ 3 & & 0 \\ -1 & & \end{bmatrix}$$

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  return (l_{ij})

$$k = 1, \quad i = 3:$$

$$l_{31} = (-5 - 0)/5 = -1$$

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$$k = 2:$$

$$l_{22} = (18 - 3^2)^{1/2} = 3$$

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  return (l_{ij})

$$k = 2, \quad i = 3:$$

$$l_{32} = (0 - (-1)(3))\,/3 = 1$$

$$A = \begin{bmatrix} 25 & 15 & -5 \\ 15 & 18 & 0 \\ -5 & 0 & 11 \end{bmatrix}$$

$$L = \begin{bmatrix} 5 & 0 & 0 \\ 3 & 3 & 0 \\ -1 & 1 & 3 \end{bmatrix}$$

1: **function** CHOLESKY$(n, (a_{ij}))$
2: **for** $k = 1$ **to** n **do**
3: $l_{kk} \leftarrow \left(a_{kk} - \sum_{s=1}^{k-1} l_{ks}^2 \right)^{1/2}$
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5: $l_{ik} \leftarrow \left(a_{ik} - \sum_{s=1}^{k-1} l_{is} l_{ks} \right) / l_{kk}$
6: **return** (l_{ij})

$$k = 3:$$

$$l_{33} = \left(11 - (-1)^2 - (-1)^2\right) = 3$$

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$$L = \begin{bmatrix} 5 & 0 & 0 \\ 3 & 3 & 0 \\ \text{-1} & 1 & 3 \end{bmatrix} \Longrightarrow L^T = \begin{bmatrix} 5 & 3 & \text{-1} \\ 0 & 3 & 1 \\ 0 & 0 & 3 \end{bmatrix}$$

- Verify correctness:

$$L = \begin{bmatrix} 5 & 0 & 0 \\ 3 & 3 & 0 \\ -1 & 1 & 3 \end{bmatrix} \Longrightarrow L^T = \begin{bmatrix} 5 & 3 & -1 \\ 0 & 3 & 1 \\ 0 & 0 & 3 \end{bmatrix}$$

$$LL^T = \begin{bmatrix} 5 & 0 & 0 \\ 3 & 3 & 0 \\ -1 & 1 & 3 \end{bmatrix} \begin{bmatrix} 5 & 3 & -1 \\ 0 & 3 & 1 \\ 0 & 0 & 3 \end{bmatrix} = \begin{bmatrix} 25 & 15 & -5 \\ 15 & 18 & 0 \\ -5 & 0 & 11 \end{bmatrix} = A$$

Gaussian Elimination

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- Possible row operations:
    - Interchange
    - Scaling
    - Addition
- Gaussian elimination only utilizes scaling and addition!

Gaussian Elimination Algorithm

```
function GE(n, (a_ij))
    for k = 1 to n − 1 do
        for i = k + 1 to n do
            z ← a_ik / a_kk
            a_ik ← 0
            for j = k + 1 to n do
                a_ij ← a_ij − z a_kj
    return (a_ij)
```

- Recall: row operations are equivalent to left multiplication of coefficient matrix by elementary matrices

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  - Example: scale row 2 of $A \in \mathbb{R}^{3x3}$ by 4

$$EA, \quad E = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 4 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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- Define $U = A_{s+1}$ and observe that

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- So, Gaussian elimination constructs an LU factorization (and hence is functionally equivalent to the LU factorization algorithm!)

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  - Unscaled/scaled: pertains to how the potential pivot locations are compared

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- Problem: Gaussian elimination breaks down (spectacular examples pg. 167–169)
- Solution: incorporate row interchange operations via permutation matrix (we call this pivoting)
- Types of pivoting:
  - Partial/complete: pertains to the amount of the matrix examined to find where to pivot
    - Partial: analyze one row
    - Complete: analyze entire submatrix
  - Unscaled/scaled: pertains to how the potential pivot locations are compared
    - Unscaled: compare absolute value of entries directly
    - Scaled: compare ratios of pivot entries to maximum entries in magnitude in each row

Pivoting Algorithms

function GE_PP$(n, (a_{ij}), (p_i))$

  for $k = 1$ **to** $n - 1$ **do**

    for $i = k + 1$ **to** n **do**

      $z \leftarrow a_{p_i k} / a_{p_k k}$

      $a_{p_i k} \leftarrow 0$

      for $j = k + 1$ **to** n **do**

        $a_{p_i j} \leftarrow a_{p_i j} - z a_{p_k j}$

  return (a_{ij})

Pivoting Examples

$$A_1 = \begin{bmatrix} 1 & 3 & 6 \\ 2 & 1 & 1 \\ 1 & 3 & 3 \end{bmatrix}$$

$$p = \begin{bmatrix} 1, & 2, & 3 \end{bmatrix}$$

function GE_PP$(n, (a_{ij}), (p_i))$
  for $k = 1$ **to** $n - 1$ **do**
    for $i = k + 1$ **to** n **do**
      $z \leftarrow a_{p_i k} / a_{p_k k}$
      $a_{p_i k} \leftarrow 0$
      for $j = k + 1$ **to** n **do**
        $a_{p_i j} \leftarrow a_{p_i j} - z a_{p_k j}$
  return (a_{ij})

$$\max(|1|, |2|, |1|) = 2$$

Pivoting Examples

$$A_1 = \begin{bmatrix} 1 & 3 & 6 \\ 2 & 1 & 1 \\ 1 & 3 & 3 \end{bmatrix}$$

$$p = \begin{bmatrix} 2, & 1, & 3 \end{bmatrix}$$

function GE_PP$(n, (a_{ij}), (p_i))$
    for $k = 1$ **to** $n - 1$ **do**
        for $i = k + 1$ **to** n **do**
            $z \leftarrow a_{p_i k} / a_{p_k k}$
            $a_{p_i k} \leftarrow 0$
            for $j = k + 1$ **to** n **do**
                $a_{p_i j} \leftarrow a_{p_i j} - z a_{p_k j}$
    return (a_{ij})

$$\max(|1|, |2|, |1|) = 2$$

$$R_1 \leftarrow R_1 - \frac{1}{2} R_2$$

$$R_3 \leftarrow R_3 - \frac{1}{2} R_2$$

$$R_2 \leftarrow \frac{1}{2} R_2$$

Pivoting Examples

$$A_2 = \begin{bmatrix} 0 & 2.5 & 5.5 \\ 1 & 0.5 & 0.5 \\ 0 & 2.5 & 2.5 \end{bmatrix}$$

$$p = \begin{bmatrix} 2, & 1, & 3 \end{bmatrix}$$

function $\mathrm{GE\_PP}(n, (a_{ij}), (p_i))$
  for $k = 1$ **to** $n-1$ **do**
    for $i = k+1$ **to** n **do**
      $z \leftarrow a_{p_i k} / a_{p_k k}$
      $a_{p_i k} \leftarrow 0$
      for $j = k+1$ **to** n **do**
        $a_{p_i j} \leftarrow a_{p_i j} - z a_{p_k j}$
  return (a_{ij})

$$\max(|1|, |2|, |1|) = 2$$

$$R_1 \leftarrow R_1 - \frac{1}{2} R_2$$

$$R_3 \leftarrow R_3 - \frac{1}{2} R_2$$

$$R_2 \leftarrow \frac{1}{2} R_2$$

Pivoting Examples

$$A_2 = \begin{bmatrix} 0 & 2.5 & 5.5 \\ 1 & 0.5 & 0.5 \\ 0 & 2.5 & 2.5 \end{bmatrix}$$

$$p = \begin{bmatrix} 2, & 1, & 3 \end{bmatrix}$$

function GE_PP$(n, (a_{ij}), (p_i))$
  for $k = 1$ **to** $n - 1$ **do**
    for $i = k + 1$ **to** n **do**
      $z \leftarrow a_{p_i k} / a_{p_k k}$
      $a_{p_i k} \leftarrow 0$
      for $j = k + 1$ **to** n **do**
        $a_{p_i j} \leftarrow a_{p_i j} - z a_{p_k j}$
  return (a_{ij})

$$\max(|2.5|, |2.5|) = 2.5$$

Pivoting Examples

$$A_2 = \begin{bmatrix} 0 & 2.5 & 5.5 \\ 1 & 0.5 & 0.5 \\ 0 & 2.5 & 2.5 \end{bmatrix}$$

$$p = \begin{bmatrix} 2, & 1, & 3 \end{bmatrix}$$

function GE_PP$(n, (a_{ij}), (p_i))$
    for $k = 1$ **to** $n - 1$ **do**
        for $i = k + 1$ **to** n **do**
            $z \leftarrow a_{p_i k} / a_{p_k k}$
            $a_{p_i k} \leftarrow 0$
            for $j = k + 1$ **to** n **do**
                $a_{p_i j} \leftarrow a_{p_i j} - z a_{p_k j}$
    return (a_{ij})

$$\max(|2.5|, |2.5|) = 2.5$$

$$R_3 \leftarrow R_3 - R_2$$

$$R_1 \leftarrow \frac{2}{5} R_1$$

Pivoting Examples

$$A_3 = \begin{bmatrix} 0 & 1 & 2.2 \\ 1 & 0.5 & \text{-}0.6 \\ 0 & 0 & \text{-}3 \end{bmatrix}$$

$$p = \begin{bmatrix} 2, & 1, & 3 \end{bmatrix}$$

```
function GE_PP(n, (a_ij), (p_i))
    for k = 1 to n − 1 do
        for i = k + 1 to n do
            z ← a_{p_i k} / a_{p_k k}
            a_{p_i k} ← 0
            for j = k + 1 to n do
                a_{p_i j} ← a_{p_i j} − z a_{p_k j}
    return (a_ij)
```

$$\max(|2.5|, |2.5|) = 2.5$$

$$R_3 \leftarrow R_3 - R_2$$

$$R_1 \leftarrow \frac{2}{5} R_1$$

Pivoting Examples

$$A_3 = \begin{bmatrix} 0 & 1 & 2.2 \\ 1 & 0.5 & -0.6 \\ 0 & 0 & -3 \end{bmatrix}$$

$$p = \begin{bmatrix} 2, & 1, & 3 \end{bmatrix}$$

function GE_PP$(n, (a_{ij}), (p_i))$
  for $k = 1$ **to** $n - 1$ **do**
    for $i = k + 1$ **to** n **do**
      $z \leftarrow a_{p_i k} / a_{p_k k}$
      $a_{p_i k} \leftarrow 0$
      for $j = k + 1$ **to** n **do**
        $a_{p_i j} \leftarrow a_{p_i j} - z a_{p_k j}$
  return (a_{ij})

$$R_3 \leftarrow -\frac{1}{3} R_3$$

$$A_4 = \begin{bmatrix} 0 & 1 & 2.2 \\ 1 & 0.5 & -0.6 \\ 0 & 0 & 1 \end{bmatrix}$$

$$p = \begin{bmatrix} 2, & 1, & 3 \end{bmatrix}$$

function $\mathrm{GE\_PP}(n, (a_{ij}), (p_i))$
    for $k = 1$ **to** $n - 1$ **do**
        for $i = k + 1$ **to** n **do**
            $z \leftarrow a_{p_i k} / a_{p_k k}$
            $a_{p_i k} \leftarrow 0$
            for $j = k + 1$ **to** n **do**
                $a_{p_i j} \leftarrow a_{p_i j} - z a_{p_k j}$
    return (a_{ij})

$$R_3 \leftarrow -\frac{1}{3} R_3$$