

VECTOR & MATRIX NORMS

- Inner products
- Vector norms
- Matrix norms
- Introduction to singular values
- Expressions of some matrix norms.

Properties of Inner Product:

- $(x, y) = \overline{(y, x)}$.
- $(\alpha x + \beta y, z) = \alpha(x, z) + \beta(y, z)$ [Linearity]
- $(x, x) \geq 0$ is always real and non-negative.
- $(x, x) = 0$ iff $x = 0$ (for finite dimensional spaces).
- Given $A \in \mathbb{C}^{m \times n}$ then

$$(Ax, y) = (x, A^H y) \quad \forall x \in \mathbb{C}^n, \forall y \in \mathbb{C}^m$$

Inner products and Norms

Inner product of 2 vectors

- Inner product of 2 vectors x and y in \mathbb{R}^n :

$$x_1 y_1 + x_2 y_2 + \dots + x_n y_n \text{ in } \mathbb{R}^n$$

Notation: (x, y) or $y^T x$

- For complex vectors

$$(x, y) = x_1 \bar{y}_1 + x_2 \bar{y}_2 + \dots + x_n \bar{y}_n \text{ in } \mathbb{C}^n$$

Note: $(x, y) = y^H x$

- On notation: Sometimes you will find $\langle \cdot, \cdot \rangle$ for (\cdot, \cdot) and A^* instead of A^H

Vector norms

Norms are needed to measure lengths of vectors and closeness of two vectors. Examples of use: Estimate convergence rate of an iterative method; Estimate the error of an approximation to a given solution; ...

- A vector norm on a vector space \mathbb{X} is a real-valued function on \mathbb{X} , which satisfies the following three conditions:

1. $\|x\| \geq 0$, $\forall x \in \mathbb{X}$, and $\|x\| = 0$ iff $x = 0$.
2. $\|\alpha x\| = |\alpha| \|x\|$, $\forall x \in \mathbb{X}$, $\forall \alpha \in \mathbb{C}$.
3. $\|x + y\| \leq \|x\| + \|y\|$, $\forall x, y \in \mathbb{X}$.

- Third property is called the **triangle inequality**.

Important example: Euclidean norm on $\mathbb{X} = \mathbb{C}^n$,

$$\|x\|_2 = (x, x)^{1/2} = \sqrt{|x_1|^2 + |x_2|^2 + \dots + |x_n|^2}$$

Ex1 Show that when Q is orthogonal then $\|Qx\|_2 = \|x\|_2$

➤ Most common vector norms in numerical linear algebra: special cases of the Hölder norms (for $p \geq 1$):

$$\|x\|_p = \left(\sum_{i=1}^n |x_i|^p \right)^{1/p}.$$

Ex2 Find out (online search) how to show that these are indeed norms for any $p \geq 1$ (Not easy for 3rd requirement!)

Property: ➤ Limit of $\|x\|_p$ when $p \rightarrow \infty$ exists:

$$\lim_{p \rightarrow \infty} \|x\|_p = \max_{i=1}^n |x_i|$$

➤ Defines a norm denoted by $\|\cdot\|_\infty$.

➤ The cases $p = 1$, $p = 2$, and $p = \infty$ lead to the most important norms $\|\cdot\|_p$ in practice. These are:

$$\begin{aligned} \|x\|_1 &= |x_1| + |x_2| + \dots + |x_n|, \\ \|x\|_2 &= [|x_1|^2 + |x_2|^2 + \dots + |x_n|^2]^{1/2}, \\ \|x\|_\infty &= \max_{i=1, \dots, n} |x_i|. \end{aligned}$$

➤ The Cauchy-Schwartz inequality (important) is:

$$|(x, y)| \leq \|x\|_2 \|y\|_2.$$

Ex3 When do you have equality in the above relation?

Ex4 Expand $(x + y, x + y)$. What does the Cauchy-Schwarz inequality imply?

➤ The Hölder inequality (less important for $p \neq 2$) is:

$$|(x, y)| \leq \|x\|_p \|y\|_q, \text{ with } \frac{1}{p} + \frac{1}{q} = 1$$

Ex5 Second triangle inequality: $|\|x\| - \|y\|| \leq \|x - y\|$.

Ex6 Consider the metric $d(x, y) = \max_i |x_i - y_i|$. Show that any norm in \mathbb{R}^n is a continuous function with respect to this metric.

Equivalence of norms:

In finite dimensional spaces ($\mathbb{R}^n, \mathbb{C}^n, \dots$) all norms are 'equivalent': if ϕ_1 and ϕ_2 are two norms then there exists positive constants α, β such that:

$$\beta \phi_2(x) \leq \phi_1(x) \leq \alpha \phi_2(x).$$

Ex7 How can you prove this result? [Hint: Show for $\phi_2 = \|\cdot\|_\infty$]

➤ We can bound one norm in terms of any other norm.

Ex8 Show that for any x : $\frac{1}{\sqrt{n}} \|x\|_1 \leq \|x\|_2 \leq \|x\|_1$

Ex9 What are the "unit balls" $B_p = \{x \mid \|x\|_p \leq 1\}$ associated with the norms $\|\cdot\|_p$ for $p = 1, 2, \infty$, in \mathbb{R}^2 ?

Convergence of vector sequences

A sequence of vectors $x^{(k)}$, $k = 1, \dots, \infty$ converges to a vector x with respect to the norm $\|\cdot\|$ if, by definition,

$$\lim_{k \rightarrow \infty} \|x^{(k)} - x\| = 0$$

► **Important point:** because all norms in \mathbb{R}^n are equivalent, the convergence of $x^{(k)}$ w.r.t. a given norm implies convergence w.r.t. any other norm.

► **Notation:**

$$\lim_{k \rightarrow \infty} x^{(k)} = x$$

2-9

GvL 2.2-2.3; – Norms

Example: The sequence

$$x^{(k)} = \begin{pmatrix} 1 + 1/k \\ \frac{k}{k + \log_2 k} \\ \frac{1}{k} \end{pmatrix}$$

converges to

$$x = \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix}$$

► **Note:** Convergence of $x^{(k)}$ to x is the same as the convergence of each individual component $x_i^{(k)}$ of $x^{(k)}$ to the corresponding component x_i of x .

2-10

GvL 2.2-2.3; – Norms

Matrix norms

► Can define matrix norms by considering $m \times n$ matrices as vectors in \mathbb{R}^{mn} . These norms satisfy the usual properties of vector norms, i.e.,

1. $\|A\| \geq 0$, $\forall A \in \mathbb{C}^{m \times n}$, and $\|A\| = 0$ iff $A = 0$
2. $\|\alpha A\| = |\alpha| \|A\|$, $\forall A \in \mathbb{C}^{m \times n}$, $\forall \alpha \in \mathbb{C}$
3. $\|A + B\| \leq \|A\| + \|B\|$, $\forall A, B \in \mathbb{C}^{m \times n}$.

► However, these will lack (in general) the right properties for composition of operators (product of matrices).

► The case of $\|\cdot\|_2$ yields the Frobenius norm of matrices.

2-11

GvL 2.2-2.3; – Norms

► Given a matrix A in $\mathbb{C}^{m \times n}$, define the set of **matrix norms**

$$\|A\|_p = \max_{x \in \mathbb{C}^n, x \neq 0} \frac{\|Ax\|_p}{\|x\|_p}.$$

► These norms satisfy the usual properties of vector norms (see previous page).

► The matrix norm $\|\cdot\|_p$ is **induced** by the vector norm $\|\cdot\|_p$.

► Again, important cases are for $p = 1, 2, \infty$.

► Show that $\|A\|_p = \max_{x \in \mathbb{C}^n, \|x\|_p=1} \|Ax\|_p$

2-12

GvL 2.2-2.3; – Norms

Consistency / sub-multiplicativity of matrix norms

- A fundamental property of matrix norms is **consistency**

$$\|AB\|_p \leq \|A\|_p \|B\|_p.$$

[Also termed “sub-multiplicativity”]

- Consequence: (for square matrices) $\|A^k\|_p \leq \|A\|_p^k$
- A^k converges to zero if **any** of its p -norms is < 1

[Note: sufficient but not necessary condition]

- ☞10 Compute the Frobenius norms of the matrices

$$\begin{pmatrix} 1 & 1 \\ 1 & 0 \\ 3 & 2 \end{pmatrix} \quad \begin{pmatrix} 1 & 2 & -1 \\ -1 & \sqrt{5} & 0 \\ -1 & 1 & \sqrt{2} \end{pmatrix}$$

- ☞11 Prove that the Frobenius norm is consistent [Hint: Use Cauchy-Schwartz]
- ☞12 Define the ‘vector 1-norm’ of a matrix A as the 1-norm of the vector of stacked columns of A . Is this norm a consistent matrix norm?

[Hint: Result is true – Use Cauchy-Schwarz to prove it.]

Frobenius norms of matrices

- The **Frobenius norm** of a matrix is defined by

$$\|A\|_F = \left(\sum_{j=1}^n \sum_{i=1}^m |a_{ij}|^2 \right)^{1/2}.$$

- Same as the 2-norm of the column vector in \mathbb{C}^{mn} consisting of all the columns (respectively rows) of A .
- This norm is also consistent [but not induced from a vector norm]

Expressions of standard matrix norms

- Recall the notation: (for square $n \times n$ matrices)

$\rho(A) = \max |\lambda_i(A)|$; $\text{Tr}(A) = \sum_{i=1}^n a_{ii} = \sum_{i=1}^n \lambda_i(A)$ where $\lambda_i(A)$, $i = 1, 2, \dots, n$ are all eigenvalues of A

$$\begin{aligned} \|A\|_1 &= \max_{j=1, \dots, n} \sum_{i=1}^m |a_{ij}|, \\ \|A\|_\infty &= \max_{i=1, \dots, m} \sum_{j=1}^n |a_{ij}|, \\ \|A\|_2 &= [\rho(A^H A)]^{1/2} = [\rho(AA^H)]^{1/2}, \\ \|A\|_F &= [\text{Tr}(A^H A)]^{1/2} = [\text{Tr}(AA^H)]^{1/2}. \end{aligned}$$

Ex 13 Compute the p -norm for $p = 1, 2, \infty, F$ for the matrix

$$A = \begin{pmatrix} 0 & 2 \\ 0 & 1 \end{pmatrix}$$

Ex 14 Show that $\rho(A) \leq \|A\|$ for any matrix norm.

Ex 15 Is $\rho(A)$ a norm?

1. $\rho(A) = \|A\|_2$ when A is Hermitian ($A^H = A$). True for this particular case...

2. ... However, not true in general. For $A = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$, we have $\rho(A) = 0$ while $A \neq 0$. Also, triangle inequality not satisfied for the pair A , and $B = A^T$. Indeed, $\rho(A + B) = 1$ while $\rho(A) + \rho(B) = 0$.

Ex 16 Given a function $f(t)$ (e.g., e^t) how would you define $f(A)$? [Was seen earlier. Here you need to fully justify answer. Assume A is diagonalizable]

Assume we have r nonzero singular values (with $r \leq \min\{m, n\}$):

$$\sigma_1 \geq \sigma_2 \geq \dots \geq \sigma_r > 0$$

Then:

$$\begin{aligned} \bullet \|A\|_2 &= \sigma_1 \\ \bullet \|A\|_F &= [\sum_{i=1}^r \sigma_i^2]^{1/2} \end{aligned}$$

More generally: Schatten p -norm ($p \geq 1$) defined by

$$\|A\|_{*,p} = [\sum_{i=1}^r \sigma_i^p]^{1/p}$$

Note: $\|A\|_{*,p} = p$ -norm of vector $[\sigma_1; \sigma_2; \dots; \sigma_r]$

In particular: $\|A\|_{*,1} = \sum \sigma_i$ is called the nuclear norm and is denoted by $\|A\|_*$. (Common in machine learning).

Singular values and matrix norms

Let $A \in \mathbb{R}^{m \times n}$ or $A \in \mathbb{C}^{m \times n}$

Eigenvalues of $A^H A$ & $A A^H$ are real ≥ 0 . Ex 17 Show this.

Let
$$\begin{cases} \sigma_i = \sqrt{\lambda_i(A^H A)} & i = 1, \dots, n \text{ if } n \leq m \\ \sigma_i = \sqrt{\lambda_i(A A^H)} & i = 1, \dots, m \text{ if } m < n \end{cases}$$

The σ_i 's are called singular values of A .

Note: a total of $\min(m, n)$ singular values.

Always sorted decreasingly: $\sigma_1 \geq \sigma_2 \geq \sigma_3 \geq \dots \sigma_k \geq \dots$

We will see a lot more on singular values later

A few properties of the 2-norm and the F-norm

Let $A = uv^T$. Then $\|A\|_2 = \|u\|_2 \|v\|_2$

Ex 18 Prove this result

Ex 19 In this case $\|A\|_F = ??$

For any $A \in \mathbb{C}^{m \times n}$ and unitary matrix $Q \in \mathbb{C}^{m \times m}$ we have $\|QA\|_2 = \|A\|_2$; $\|QA\|_F = \|A\|_F$.

Ex 20 Show that the result is true for any orthogonal matrix Q (Q has orthonormal columns), i.e., when $Q \in \mathbb{C}^{p \times m}$ with $p > m$

Ex 21 Let $Q \in \mathbb{C}^{n \times n}$, unitary. Do we have $\|AQ\|_2 = \|A\|_2$? $\|AQ\|_F = \|A\|_F$? What if $Q \in \mathbb{C}^{n \times p}$, with $p < n$ (and $Q^H Q = I$)?