MA 200: Multivariable Calculus

Naman Mishra

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Chapter 1

Linear algebra

Definition 1.1 (homogeneous function)**.** Let V be a vector space over $\mathbb{R}$. A function $f\colon V \setminus \{0\} \to \mathbb{R}$ is called a *homogeneous function* of degree k if

$$f(rx) = r^k f(x)$$

for each $x \in V \setminus \{0\}$ and $r > 0$.

Remarks.

- If f and g are homogeneous functions of degree k and l respectively, then $f \cdot g$ is homogeneous of degree $k + l$ and f/g is homogeneous of degree $k - l$ (provided g is never zero).
- $f \equiv 0$ is homogeneous of any degree.

Definition 1.2 (norm)**.** Let V be a vector space over $\mathbb{R}$. A norm $\|\cdot\|$ on V is a function from V to $\mathbb{R}$ that satisfies

(N1) (Positivity) $\|x\| \geq 0$ for any $x \in V$.

(N2) (Definiteness) $\|x\| = 0$ iff $x = 0$.

(N3) (Homogeneity) $\|rx\| = |r|\|x\|$ for any $x \in V$ and $r \in \mathbb{R}$.

(N4) (Triangle inequality) $\|x + y\| \leq \|x\| + \|y\|$ for any $x, y \in V$.

Definition 1.3 (normed linear space)**.** A vector space V equipped with a norm $\|\cdot\|$ is called a *normed linear space*.

Remark. Any normed linear space $(V, \|\cdot\|)$ can be given a metric space structure by defining the distance $d(x, y)$ between $x, y \in V$ as $\|x - y\|$.

The set $B(x, r) \coloneqq \{y \in V \mid \|x - y\| < r\}$ is called the open ball of radius r centered at x.

The set $S(x, r) \coloneqq \{y \in V \mid \|x - y\| = r\}$ is called the sphere of radius r centered at x.

Exercise 1.4 (reverse triangle inequality)**.** *Let V be a normed linear space. Show that*

$$\Big| \|x\| - \|y\| \Big| \leq \|x - y\|$$

for any $x, y \in V$.

Proof. First observe from homogeneity (N3) that $\|x\| = \|-x\|$ for any $x \in V$. Next, from the triangle inequality (N4) we have

$$\|x\| \leq \|x - y\| + \|y\|$$

so that

$$\|x\| - \|y\| \leq \|x - y\|.$$

Similarly,

$$\|y\| \leq \|y - x\| + \|x\|$$

so that

$$-\|x - y\| \leq \|x\| - \|y\|.$$

Combining these gives the result. ■

This shows that $f = x \mapsto \|x\|$ is a (Lipschitz) continuous function on V.

Definition 1.5 (metric space)**.** A *metric space* is a set X equipped with a function $d\colon X \times X \to \mathbb{R}$ called a *metric* that satisfies the following properties:

(M1) $d(x, y) \geq 0$ for any $x, y \in X$.

(M2) $d(x, y) = 0$ iff $x = y$.

(M3) $d(x, y) = d(y, x)$ for any $x, y \in X$.

(M4) $d(x, z) \leq d(x, y) + d(y, z)$ for any $x, y, z \in X$.

Exercise 1.6 (self)**.** *Show that any normed linear space $(V, \|\cdot\|)$ is a metric space under the distance $d(x, y) = \|x - y\|$.*

Proof. (M1) and (M2) are immediate from (N1) and (N2). (N3) implies (M3) by scaling by -1. Triangle implies triangle. ■

Definition 1.7 (continuity)**.** Let (X, d) and (Y, ρ) be metric spaces. A function $f\colon X \to Y$ is called *continuous* at $a \in X$ iff

$$\begin{aligned} x_n \to a &\implies f(x_n) \to f(a), \text{ or} \\ d(x_n, a) \to 0 &\implies \rho(f(x_n), f(a)) \to 0 \end{aligned}$$

Exercise 1.8 (product metric spaces)**.** *Let (X_1, d_1) and (X_2, d_2) be metric spaces. Let $d\colon X_1 \times X_2 \to \mathbb{R}$ be defined by*

$$d((x_1, x_2), (y_1, y_2)) := d_1(x_1, y_1) + d_2(x_2, y_2).$$

Show that d is a metric on $X_1 \times X_2$.

Let $(z_n)_{n\in\mathbb{N}} = ((x_n, y_n))_{n\in\mathbb{N}}$ be a sequence in $X_1 \times X_2$. Show that $z_n \to (x, y)$ iff $x_n \to x$ and $y_n \to y$.

Proof. Suppose $x_n \to x$ and $y_n \to y$. That is, $d_1(x_n, x) \to 0$ and $d_2(y_n, y) \to 0$. Thus $d_1(x_n, x) + d_2(y_n, y) \to 0$.

Conversely if $d_1(x_n, x) + d_2(y_n, y) \to 0$ and each is nonnegative, then $d_1(x_n, x) \to 0$ and $d_2(y_n, y) \to 0$. ∎

Remark. $\widetilde{d}$ given by

$$\widetilde{d}((x_1, x_2), (y_1, y_2)) := \min\{d_1(x_1, y_1), d_2(x_2, y_2)\}$$

is *not* a metric on $X_1 \times X_2$ as it fails definiteness.

However, $\max\{d_1, d_2\}$ *is* a metric.

Exercise 1.9. *Let $(V, \|\cdot\|)$ be a normed linear space.*

- *The addition map $(x, y) \mapsto x + y$ is a continuous map from $V \times V$ to V.*
- *The scalar multiplication map $(\alpha, x) \mapsto \alpha x$ is continuous from $\mathbb{R} \times V$ to V.*

Solution.

- $\|x' + y' - (x + y)\| \le \|x' - x\| + \|y' - y\| = \|(x', y') - (x, y)\|$.
- $\|\alpha' x' - \alpha x\| \le \|\alpha' x' - \alpha x'\| + \|\alpha x' - \alpha x\| = |\alpha' - \alpha|\|x'\| + |\alpha|\|x' - x\|$. Thus choosing $\delta = \varepsilon / \max\{|\alpha|, \|x\|\}$ gives

  $$\|\alpha' x' - \alpha x\| \le \max\{|\alpha|, \|x\|\}(|\alpha' - \alpha| + \|x' - x\|) < \varepsilon$$

  whenever $|\alpha' - \alpha| + \|x' - x\| < \delta$. ∎

Examples.

- (ℓ^p norm) $\mathbb{R}^n$ with $p \in [1, \infty]$ and

  $$\|x\|_p := \left(|x_1|^p + \cdots + |x_n|^p\right)^{1/p}$$

  where

  $$\|x\|_\infty := \max\{|x_1|, \ldots, |x_n|\}$$

  is the limit of the l^p norms as $p \to \infty$.

Exercise 1.10. *See problem 1.6.*

Definition 1.11 (norm equivalence)**.** Let $\|\cdot\|_a$ and $\|\cdot\|_b$ be two norms on V. We say that $\|\cdot\|_a$ and $\|\cdot\|_b$ are *equivalent* if these exist $c_1, c_2 > 0$ such that

$$c_1\|x\|_a \leq \|x\|_b \leq c_2\|x\|_a$$

for all $x \in V$. We write $\|\cdot\|_a \sim \|\cdot\|_b$.

Exercise 1.12. *Check that $\sim$ is an equivalence relation.*

Solution. Reflexivity is obvious. Symmetry is since

$$c_1\|x\|_a \leq \|x\|_b \leq c_2\|x\|_a \implies \frac{1}{c_2}\|x\|_b \leq \|x\|_a \leq \frac{1}{c_1}\|x\|_b.$$

For transitivity, let

$$\begin{aligned} c_1\|x\|_a \leq \|x\|_b \leq c_2\|x\|_a, \\ c_3\|x\|_b \leq \|x\|_c \leq c_4\|x\|_b. \end{aligned}$$

Then

$$c_1c_3\|x\|_a \leq \|x\|_c \leq c_2c_4\|x\|_a. \qquad \blacksquare$$

Lecture 2. Monday August 5

Proposition 1.13. *Equivalent norms induce the same topology. That is, let $\|\cdot\|_a \sim \|\cdot\|_b$. Then a set is open (resp. compact) under $\|\cdot\|_a$ iff it is open (resp. compact) under $\|\cdot\|_b$.*

Proof. Suppose $c_1\|x\|_a \leq \|x\|_b \leq c_2\|x\|_a$.

Let $U \subseteq V$ be open under $\|\cdot\|_a$. Let $x \in U$. There exists $\varepsilon > 0$ such that $\|y - x\|_a < \varepsilon \implies y \in U$. But then $\|y - x\|_b < c_1\varepsilon \implies y \in U$. Thus U is open under $\|\cdot\|_b$.

Compactness follows from openness. $\blacksquare$

Proposition 1.14. *Every ℓ^p norm is equivalent to ℓ^∞.*

Proof. Let $x \in \mathbb{R}^n$. Then $\|x\|_\infty \leq \|x\|_p \leq n^{\frac{1}{p}}\|x\|_\infty$. $\blacksquare$

The usual topology on $\mathbb{R}^n$ is the one induced by the Euclidean norm. This norm itself is induced by the inner product $\langle x, y\rangle = \sum_{i=1}^n x_i y_i$. Using Cauchy-Schwarz, we can define the angle between two vectors $x, y \in \mathbb{R}^n$ to be

$$\cos^{-1}\left(\frac{\langle x, y\rangle}{\|x\|\|y\|}\right).$$

Proposition 1.15. *Let $\|\cdot\|$ be any norm on $\mathbb{R}^n$. Then the function $x \mapsto \|x\|$ is Lipschitz continuous with respect to the Euclidean topology.*

Proof.

$$\begin{aligned}\|x\| &= \left\|\sum x_i e_i\right\| \\ &\le \sum |x_i|\|e_i\| \\ &\le M\|x\|_2\end{aligned}$$

where $M = \sum \|e_i\|$.

The reverse triangle inequality exercise 1.4 gives

$$\begin{aligned}\big|\|x\| - \|y\|\big| &\le \|x - y\| \\ &\le M\|x - y\|_2.\end{aligned}$$

■

Theorem 1.16. *Any two norms on $\mathbb{R}^n$ are equivalent.*

Proof. Let $\|\cdot\|$ be any norm on $\mathbb{R}^n$. Then $x \mapsto \|x\|$ is continuous with respect to $\|\cdot\|_2$. Let

$$S(0,1)_{\|\cdot\|_2} = \{x \in \mathbb{R}^n : \|x\|_2 = 1\} = S^{n-1}.$$

$\|\cdot\|$ attains a minimum and a maximum on S^{n-1}. Thus there exist positive constants c_1, c_2 such that

$$c_1 \le \|x\| \le c_2$$

for all $x \in S^{n-1}$.

Now for any $x \in \mathbb{R}^n \setminus \{0\}$, dividing by $\|x\|_2$ gives a point that lies on S^{n-1}. Thus

$$c_1 \le \left\|\frac{x}{\|x\|_2}\right\| \le c_2.$$

By homogeneity (N3),

$$c_1\|x\|_2 \le \|x\| \le c_2\|x\|_2.$$

This is also trivially true for $x = 0$.

Thus $\|\cdot\| \sim \|\cdot\|_2$. ■

Remark. The idea of the proof is as follows.

Any homogenous function is determined by its value on the unit sphere. A homogenous function of degree *zero* is essentially nothing but a function on the unit sphere ($f(v) = f(\hat{v})$).

The function $x \mapsto \frac{\|x\|}{\|x\|_2}j$ is a continuous homogenous function on degree 0. The unit sphere is known to be compact under the Euclidean norm (and every other, but not before we complete the proof). Thus

$$c_1 \le \frac{\|x\|}{\|x\|_2} \le c_2$$

for some positive constants c_1, c_2.

Definiteness and $\triangle$ are required for the ratio to be continuous. Homogeneity is required for it to be homogenous. Is positivity required?

Remark. We technically only need to show $c_1\|x\|_2 \leq \|x\|$, since the other inequality is proven in the previous proof. It is nonetheless clearer to show both inequalities.

Exercise 1.17 (Self)**.** *Show that (N1) follows from (N3) and (N4).*

Solution. Let $v \in V$. By triangle inequality, $\|v\| = \|-v + 2v\| \leq \|-v\| + \|2v\|$. By homogeneity, this is $3\|v\|$. Thus $\|v\| \leq 3\|v\|$, so $\|v\| \geq 0$. ■

Remarks (Finite-dimensional vector spaces).

- Let V be a vector space over $\mathbb{R}$ with dimension $n < \infty$. Using a basis for V, any norm on V induces a norm on $\mathbb{R}^n$, and vice versa. Norms on V are in a one-to-one correspondence with norms on $\mathbb{R}^n$.
- Thus any two norms on V are equivalent.
- Any two inner products on V will also be equivalent due to this.
- Any finite-dimensional vector space over $\mathbb{R}$ is complete.

Exercise 1.18. *Let $f\colon \mathbb{R} \setminus \{0\} \to \mathbb{R}$ be given by $f(x) = \frac{1}{x}$. Show that f is continuous. What is the key idea of your proof?*

Solution. Let $x_0 \in \mathbb{R} \setminus \{0\}$ and $\varepsilon > 0$. Choose $\delta = \min\{\varepsilon \cdot \frac{1}{2}|x_0|^2, \frac{1}{2}|x_0|\}$. Then for any x in the δ-neighbourhood of x_0,

$$\begin{aligned} |f(x) - f(x_0)| &= \left|\frac{1}{x} - \frac{1}{x_0}\right| \\ &= \frac{|x_0 - x|}{|x||x_0|} \\ &< \frac{\delta}{|x||x_0|} \\ &< \frac{2\delta}{|x_0|^2} \\ &\leq \varepsilon. \end{aligned}$$

■

Remark. The proof works by bounding $\frac{1}{|x|}$. The rest goes to zero as $x \to a$. We will do a similar proof in proposition 1.36.

On $\mathbb{R}^n$, we will always fix the ℓ^2-norm

Lecture 3. Wednesday August 7

Notation.

$$L(\mathbb{R}^n, \mathbb{R}^m) = \{T\colon \mathbb{R}^n \to \mathbb{R}^m \mid T \text{ is linear}\}$$

and

$$M_{m\times n}(\mathbb{R}) = L(\mathbb{R}^n, \mathbb{R}^m)$$

using the isomorphism $A \mapsto T_A$ where

$$\begin{aligned} T_A\colon \mathbb{R}^n &\to \mathbb{R}^m \\ v &\mapsto Av, \end{aligned}$$

where v is interpreted as a column vector. We will also write $L(\mathbb{R}^n)$ for $L(\mathbb{R}^n, \mathbb{R}^n)$.

Definition 1.19 (O notation)**.** Let $f\colon \mathbb{R}^n \to \mathbb{R}^m$ and $g\colon \mathbb{R}^n \to \mathbb{R}^k$. We say that

(i) $f(x) = o(g(x))$ as $x \to a$ if

$$\lim_{x\to a} \frac{\|f(x)\|}{\|g(x)\|} = 0,$$

(ii) $f(x) = O(g(x))$ as $x \to a$ if

$$\limsup_{x\to a} \frac{\|f(x)\|}{\|g(x)\|} < c$$

for some $c > 0$.

where the assumption is that g is non-zero in some neighbourhood of a.

Exercise 1.20. *Show that the definition of O is equivalent to the following:*

We say that $f(x) = O(g(x))$ as $x \to a$ if there exists an open neighbourhood V of a such that $\frac{\|f(x)\|}{\|g(x)\|}$ is bounded on V.

Exercise 1.21.

1.1 Matrix norms

Definition 1.22 (Hilbert-Schmidt norm)**.** For a matrix $A \in M_{m\times n}(\mathbb{R})$, we define the *Hilbert-Schmidt* or *Frobenius* norm by

$$\|A\|_{HS} = \Big(\sum_{i,j} a_{ij}^2\Big)^{1/2}$$

Exercise 1.23. *Show that* $\|A\|_{HS}^2 = \mathrm{Tr}(A^\top A) = \mathrm{Tr}(AA^\top)$.

Since the trace is independent of the basis, so is the Hilbert-Schmidt norm.

Proposition 1.24. *Any linear transformation is continuous.*

Proof. Let $T \in L(\mathbb{R}^n, \mathbb{R}^m)$. Then

$$\begin{aligned}
\|Tx\| &= \left\|T\left(\sum x_i e_i\right)\right\| \\
&= \left\|\sum x_i T e_i\right\| \\
&\le \sum |x_i| \|Te_i\| \\
&\le \|x\| \sum \|Te_i\| \\
&= M\|x\| \qquad (1.1)
\end{aligned}$$

where $M = \|Te_1\| + \cdots + \|Te_n\|$.

Now

$$\|Tx - Ty\| = \|T(x-y)\| \le M\|x-y\|$$

says that T is Lipschitz continuous with Lipschitz constant M. ■

We temporarity define two norms on $M_{m\times n}(\mathbb{R})$:

$$\begin{aligned}
\|T\|_S &= \sup_{\|x\|=1} \|Tx\| \\
\|T\|_B &= \sup_{\|x\|\le 1} \|Tx\|
\end{aligned}$$

Lemma 1.25. $\|T\|_S = \|T\|_B$.

Proof. From the definition it is obvious that $\|T\|_S \le \|T\|_B$. Now for any $x \in \mathbb{R}^n \setminus \{0\}$, let $y = x/\|x\|$.

$$\begin{aligned}
\|Ty\| &\le \|T\|_S \\
\frac{\|Tx\|}{\|x\|} &\le \|T\|_S \\
\implies \|Tx\| &\le \|T\|_S \|x\|
\end{aligned}$$

Thus for $\|x\| \le 1$, we have $\|Tx\| \le \|T\|_S$ (check 0 separately). So $\|T\|_B \le \|T\|_S$. ■

Definition 1.26 (Operator norm)**.** For any $T \in L(\mathbb{R}^n, \mathbb{R}^m)$, we define the *operator norm* by

$$\|T\| = \sup_{\|x\|=1} \|Tx\|$$

From the previous lemma, we can also write

$$\|T\| = \sup_{\|x\|\le 1} \|Tx\| = \sup_{x\neq 0} \frac{\|Tx\|}{\|x\|}.$$

From equation (1.1), we have

$$\|T\| \le \|Te_1\| + \cdots + \|Te_n\|.$$

So the operator norm is finite.

Proposition 1.27. *The operator norm is a norm on* $L(\mathbb{R}^n, \mathbb{R}^m)$.

Proof. Let $T, S \in L(\mathbb{R}^n, \mathbb{R}^m)$.

(N1) Positivity is by positivity of the vector norm.

(N2) Suppose T is not identically zero. Let $v \neq 0$ be such that $\|Tv\| \neq 0$. Then
$$\|T\| = \sup_{x \neq 0} \frac{\|Tx\|}{\|x\|} \geq \frac{\|Tv\|}{\|v\|} > 0.$$

(N3) $|\lambda T| = \sup_{\|x\|=1} \|\lambda T x\| = |\lambda| \sup_{\|x\|=1} \|Tx\| = |\lambda| \|T\|$.

(N4)
$$\begin{aligned} \|T + S\| &= \sup_{\|x\|=1} \|(T+S)x\| \\ &\leq \sup_{\|x\|=1} \|Tx\| + \|Sx\| \\ &\leq \sup_{\|x\|=1} \|Tx\| + \sup_{\|x\|=1} \|Sx\| \\ &= \|T\| + \|S\|. \end{aligned}$$
■

Proposition 1.28. *Let* $T_2 \in L(\mathbb{R}^m, \mathbb{R}^n)$ *and* $T_1 \in L(\mathbb{R}^n, \mathbb{R}^k)$. *Then*
$$\|T_1 \circ T_2\| \leq \|T_1\| \|T_2\|$$

Proof. Let $x \in \mathbb{R}^m$ with $\|x\| = 1$. Then
$$\|T_1 T_2 x\| \leq \|T_1\| \|T_2 x\| \leq \|T_1\| \|T_2\|.$$
■

Since $M_{m\times n}(\mathbb{R}) \cong \mathbb{R}^{mn}$, we can conclude that the Hilbert-Schmidt norm and the operator norm are equivalent, as are any two norms on $M_{m\times n}(\mathbb{R})$. Thus we can talk about openness and continuity without specifying the norm.

Proposition 1.29. $\mathrm{GL}_n(\mathbb{R})$ *is open in* $M_n(\mathbb{R})$.

Proof. $\det\colon M_n(\mathbb{R}) \to \mathbb{R}$ is continuous because it is a polynomial in the entries of the matrix. Note that $\mathrm{GL}_n(\mathbb{R}) = \det^{-1}(\mathbb{R} \setminus \{0\})$, so it is the preimage of an open set, which is open by proposition 1.34. ■

Rudin's proof. $\mathrm{GL}_n(\mathbb{R})$ is open in $M_n(\mathbb{R})$ iff for any $X \in \mathrm{GL}_n(\mathbb{R})$, there is some $r_X > 0$ such that
$$\|X - A\| < r_X \implies A \in \mathrm{GL}_n(\mathbb{R}).$$

Let us do this for $X = I$.

A reasonable guess is $r_I = 1$ (intuiting from the 1D case). Let $A \in M_n(\mathbb{R})$ with $\|A - I\| < 1$.

Suppose $Av = 0$ for some $v \neq 0$. Then $\|(A - I)v\| = \|v\|$. But $\|A - I\| < 1$ implies that $\|(A - I)v\| < \|v\|$, a contradiction. Thus A is invertible. ∎

The subclaim $\|A - I\| < 1 \implies A \in \mathrm{GL}_n(\mathbb{R})$ can be proven by borrowing the following result from $\mathbb{C}$.

$$\frac{1}{1-z} = 1 + z + z^2 + \dots \quad \text{for} \quad |z| < 1.$$

Lemma 1.30. *Let $Z \in M_n(\mathbb{R})$ be such that $\|Z\| < 1$. Then*

(i) $\sum_{n=0}^{\infty} Z^n$ *converges.*

(ii) $I - Z$ *is invertible.*

(iii) $(I - Z)^{-1} = \sum_{n=0}^{\infty} Z^n$.

Proof. By $\|A \circ B\| \leq \|A\|\|B\|$, $\|Z^k\| \leq \|Z\|^k$.

It is easy to see that the series converges by the Cauchy criterion. For any $\varepsilon > 0$, there is some n such that

$$\left\| \sum_{k=n}^{m} Z^k \right\| \leq \sum_{k=n}^{m} \|Z^k\| < \varepsilon$$

for all $m > n$.

To see that $I - Z$ is invertible, note that

$$\|I - Z\| \geq \Big| \|I\| - \|Z\| \Big| = 1 - \|Z\| > 0.$$

Finally, let $S_n = \sum_{k=0}^{n} Z^k$ and $S_\infty = \lim_{n\to\infty} S_n$. Then $(I - Z)S_n = I - Z^{n+1}$ and so $(I - Z)S_n \to I$ as $n \to \infty$. Since matrix multiplication is continuous, we can take the limit inside the product and get $(I - Z)S_\infty = I$. ∎

Remark. For infinite-dimensional spaces, we also need to show $S_\infty(I - Z) = I$, which will be done in the exact same way.

Proposition 1.31. $A \mapsto A^{-1}$ *is continuous on* $\mathrm{GL}_n(\mathbb{R})$.

Proof. Let $A \in \mathrm{GL}_n(\mathbb{R})$. Then $A^{-1} = \frac{1}{\det A} \operatorname{adj} A$. Each entry of A^{-1} is a rational function in the entries of A, so $A \mapsto A^{-1}$ is continuous by exercise 1.32. ∎

Lecture 4. Friday August 9

Exercise 1.32. *Let $U \subseteq \mathbb{R}^n$ be an open set. Let $f\colon U \to \mathbb{R}^m$ be such that*

$$f(x) := (f_1(x), f_2(x), \dots, f_n(x)), \quad x \in U$$

Show that f is continuous at $a \in U$ iff each f_i is continuous at a.

Lecture 4: Topology?

Solution. Consider the ℓ^1 norm on $\mathbb{R}^m$.

Suppose f is continuous. Since $|f_1(x) - f_1(y)| \leq \|f(x) - f(y)\|$, so is each f_i.

Suppose each f_i is continuous at a. For any $\varepsilon > 0$, there exists $\delta_i > 0$ such that $|f_i(x) - f_i(a)| < \frac{1}{m}\varepsilon$ in a δ_i-neighbourhood of a. Let $\delta = \min\{\delta_1, \delta_2, \ldots, \delta_n\}$. ■

Exercise 1.33. *Let $f(x) = o(g(x))$ and $g(x) = O(h(x))$. Then show that $f(x) = o(h(x))$.*

Solution.

$$\limsup_{x\to a} \frac{\|f(x)\|}{\|h(x)\|} < c \quad \text{and} \quad \lim_{x\to a} \frac{\|g(x)\|}{\|h(x)\|} = 0$$

Thus

$$\limsup_{x\to a} \frac{\|f(x)\|}{\|h(x)\|} = 0.$$ ■

Proposition 1.34. *Suppose X and Y are metric spaces. Then the following are equivalent.*

(i) f is continuous.

(ii) $f^{-1}(V)$ is open whenever V is open in Y.

Solution. Suppose f is continuous. Let $V \subseteq Y$ be open.

Let $x \in f^{-1}(V)$. Then $f(x) \in V$. There is some $\varepsilon > 0$ such that $B(f(x), \varepsilon) \subseteq V$. But by continuity, there is some $\delta > 0$ such that $f(B(x, \delta)) \subseteq B(f(x), \varepsilon) \subseteq V$. Thus $B(x, \delta) \subseteq f^{-1}(V)$.

Conversely, suppose $f^{-1}(V)$ is open whenever V is open. Then for any $x \in X$ and $\varepsilon > 0$, we have that $f^{-1}(B(f(x), \varepsilon))$ is open. So some δ-neighbourhood of x in X that is contained in $f^{-1}(B(f(x), \varepsilon))$. ■

Assignment 1

up August 2
due August 12
quiz August 14

Problem 1.1. *Let* $(V, \|\cdot\|)$ *be a normed linear space.*

(i) Show that the addition map $(u, v) \mapsto u + v$ *is continuous.*

(ii) Show that the scalar multiplication map $(\alpha, u) \mapsto \alpha u$ *is continuous.*

Proof.

(i) $\|u_2 + v_2 - (u_1 + v_1)\| \le \|u_2 - u_1\| + \|v_2 - v_1\|$.

(ii) $\|\alpha_2 u_2 - \alpha_1 u_1\| = \|\alpha_2 u_2 - \alpha_1 u_2 + \alpha_1 u_2 - \alpha_1 u_1\| = \|(\alpha_2 - \alpha_1)u_2 + \alpha_1(u_2 - u_1)\| \le |\alpha_2 - \alpha_1|\|u_2\| + |\alpha_1|\|u_2 - u_1\|$. ∎

Problem 1.2. *Let* $(V, \|\cdot\|)$ *be a normed linear space. Prove that*

$$\Big|\|x\| - \|y\|\Big| \le \|x - y\|$$

for all $x, y \in V$*. Show that the function* $x \mapsto \|x\|$ *from* V *to* $\mathbb{R}$ *is continuous.*

Proof. By the $\triangle$ inequality,

$$\|x\| = \|x - y + y\| \le \|x - y\| + \|y\| \implies \|x\| - \|y\| \le \|x - y\|.$$

Similarly

$$\|y\| = \|y - x + x\| \le \|y - x\| + \|x\| \implies \|x\| - \|y\| \ge -\|x - y\|.$$

Thus

$$\Big|\|x\| - \|y\|\Big| \le \|x - y\|.$$

To show that $\|\cdot\|$ is continuous, do what exactly? Notice

$$\Big|\|x\| - \|y\|\Big| \le \|x - y\|?$$ ∎

Problem 1.3. *For* $x, y \in \mathbb{R}^n$*, show that*

$$|\langle x,\, y\rangle| \le \|x\|_2 \|y\|_2 \tag{1.2}$$

Also show that the two sides in equation (1.2) *are equal if and only if* x *and* y *are linearly dependent over* $\mathbb{R}$.

Proof. If either of x or y is 0, both sides are 0.

Suppose $x, y \neq 0$. Let $\widehat{x} = \dfrac{x}{\|x\|_2}$ and $\widehat{y} = \dfrac{y}{\|y\|_2}$. Then proving equation (1.2) amounts to proving

$$|\langle \widehat{x},\, \widehat{y}\rangle| \le 1$$

because of homogeneity of the inner product.

$$\begin{aligned} 0 &\leq \sum_{i=1}^{n} (\widehat{x}_i - \widehat{y}_i)^2 \\ 0 &\leq \sum_{i=1}^{n} \widehat{x}_i^2 - 2\widehat{x}_i\widehat{y}_i + \widehat{y}_i^2 \\ 2\sum_{i=1}^{n} \widehat{x}_i\widehat{y}_i &\leq \sum_{i=1}^{n} \widehat{x}_i^2 + \sum_{i=1}^{n} \widehat{y}_i^2 \\ \langle \widehat{x},\, \widehat{y}\rangle &\leq 1. \end{aligned}$$

Similarly $\langle -\widehat{x},\, \widehat{y}\rangle \leq 1$, which gives $\langle \widehat{x},\, \widehat{y}\rangle \geq -1$. ■

Problem 1.4. *Let $\{x_k\}_{k\in\mathbb{N}} \subseteq \mathbb{R}^n$ and $x \in \mathbb{R}^n$. Show that $\{x_k\}_{k\in\mathbb{N}}$ converges to x if and only if $\{\langle x_k,\, y\rangle\}$ converges to $\langle x,\, y\rangle$ for all $y \in \mathbb{R}^n$.*

Proof. Suppose $x_k \to x$. Let $y \in \mathbb{R}^n$. Then

$$|\langle x_k,\, y\rangle - \langle x,\, y\rangle| = |\langle x_k - x,\, y\rangle| \leq \|x_k - x\|\|y\| \to 0.$$

Conversely, suppose $\langle x_k,\, y\rangle \to \langle x,\, y\rangle$ for all $y \in \mathbb{R}^n$. Then $\langle x_k,\, e_i\rangle \to \langle x,\, e_i\rangle$ for all i. Thus $x_k \to x$ componentwise. ■

Problem 1.5. *Let $1 < p, q < \infty$ be such that $\frac{1}{p} + \frac{1}{q} = 1$. Show that for any $a \geq 0$ and $x \geq 0$ the following holds:*

$$xa \leq \frac{a^p}{p} + \frac{x^q}{q}. \tag{1.3}$$

Show that in equation (1.3) equality holds if and only if $x^q = a^p$.

Proof. Let $a \geq 0$ be fixed. Define $f(x) = xa - \frac{a^p}{p} - \frac{x^q}{q}$. This is differentiable on $[0, \infty)$ since $q > 0$. $f'(x) = a - x^{q-1}$. Thus

$$\begin{aligned} f'(x) \leq 0 &\iff x^{q-1} \leq a \\ &\iff x^{q/p} \leq a \\ &\iff x^q \leq a^p. \end{aligned}$$

Thus f is decreasing on $[a^{p/q}, \infty)$ and increasing on $[0, a^{p/q}]$. Thus $f(x) \geq f(a^{p/q}) = 0$. Moreover, since $f'(x) \neq 0$ for $x^q \neq a^p$, we have $f(x) = 0 \iff x^q = a^p$.

Thus $xa \leq \frac{a^p}{p} + \frac{x^q}{q}$ with equality only if $x^q = a^p$. ■

Problem 1.6. *For $1 \leq p \leq \infty$ and $x = (x_1, x_2, \ldots, x_n)$, we define*

$$\|x\|_p = \begin{cases} \left(|x_1|^p + |x_2|^p + \cdots + |x_n|^p\right)^{\frac{1}{p}} & 1 \leq p < \infty \\ \max\limits_{1\leq i\leq n} |x_i| & p = \infty \end{cases}$$

(i) Let $1 \leq q \leq \infty$ *be such that* $\dfrac{1}{p} + \dfrac{1}{q} = 1$*. For any* $x, y \in \mathbb{R}^n$*, show that*

$$|\langle x,\, y\rangle| \leq \|x\|_p \|y\|_q \text{ and } \|x+y\|_p \leq \|x\|_p + \|y\|_p. \tag{1.4}$$

(ii) Show that $\|\cdot\|_p$ *defines a norm on* $\mathbb{R}^n$*.*

(iii) Show that $\|x\|_\infty = \lim_{p\to\infty} \|x\|_p$ *for any* $x \in \mathbb{R}^n$*.*

Proof. We first deal with the case $p = \infty$ for parts (a) and (b).

(i) $q = 1$.

$$\begin{aligned} |\langle x,\, y\rangle| &= |x_1 y_1 + x_2 y_2 + \cdots + x_n y_n| \\ &\leq |x_1||y_1| + |x_2||y_2| + \cdots + |x_n||y_n| \\ &= \max_{1\leq i\leq n} |x_i| (|y_1| + |y_2| + \cdots + |y_n|) \\ &= \|x\|_\infty \|y\|_1 \end{aligned}$$

and

$$\begin{aligned} \|x+y\|_\infty &= \max_{1\leq i\leq n} |x_i + y_i| \\ &\leq \max_{1\leq i\leq n} (|x_i| + |y_i|) \\ &\leq \max_{1\leq i,j\leq n} (|x_i| + |y_j|) \\ &= \max_{1\leq i\leq n} |x_i| + \max_{1\leq j\leq n} |y_j| \\ &= \|x\|_\infty + \|y\|_\infty. \end{aligned}$$

(ii) We have positivity by definition. $\|x\|_p = 0 \iff \max_{1\leq i\leq n}|x_i| = 0 \iff |x_1| = |x_2| = \cdots = |x_n| = 0 \iff x = 0$, so definiteness holds. Homogeneity is since

$$\|\alpha x\|_\infty = \max_{1\leq i\leq n} |\alpha x_i| = |\alpha| \max_{1\leq i\leq n} |x_i| = |\alpha| \|x\|_\infty.$$

Triangle inequality is proven above.

Thus $\|\cdot\|_\infty$ is a norm.

Now we deal with the case $1 \leq p < \infty$.

(i) For $|\langle x,\, y\rangle| \leq \|x\|_p \|y\|_q$, we only concern ourselves with $1 < p, q < \infty$. The case $p = 1$ requires $q = \infty$, which is covered above with p and q interchanged. We will show that the ratio of the two sides is bounded by 1.

$$\begin{aligned}
\frac{|\langle x,\, y\rangle|}{\|x\|_p \|y\|_q} &= \left|\frac{x_1y_1 + x_2y_2 + \cdots + x_ny_n}{\|x\|_p\|y\|_q}\right| \\
&\le \sum_{i=1}^{n} \frac{|x_i||y_i|}{\|x\|_p\|y\|_q} \\
&\le \sum_{i=1}^{n} \left(\frac{1}{p}\frac{|x_i|^p}{\|x\|_p^p} + \frac{1}{q}\frac{|y_i|^q}{\|y\|_q^q}\right) && \text{(by equation (1.3))} \\
&= \frac{1}{p}\frac{\sum_i |x_i|^p}{\|x\|_p^p} + \frac{1}{q}\frac{\sum_i |y_i|^q}{\|y\|_q^q} \\
&= \frac{1}{p} + \frac{1}{q} \\
&= 1.
\end{aligned}$$

We use this result to prove the triangle inequality. (We did this in a UM 204 assignment last semester, with ample of hints and time to spare.)

$$\begin{aligned}
\|x+y\|_p^p &= \sum_{i=1}^{n} |x_i + y_i|^p \\
&= \sum_{i=1}^{n} |x_i + y_i||x_i + y_i|^{p-1} \\
&\le \sum_{i=1}^{n} |x_i||x_i + y_i|^{p-1} + \sum_{i=1}^{n} |y_i||x_i + y_i|^{p-1}
\end{aligned}$$

Let $X = (|x_1|, |x_2|, \ldots, |x_n|)$ and $Z = (|x_1+y_1|^{p-1}, |x_2+y_2|^{p-1}, \ldots, |x_n+y_n|^{p-1})$. Then by equation (1.3),

$$\begin{aligned}
\sum_{i=1}^{n} |x_i||x_i + y_i|^{p-1} &= |\langle X,\, Z\rangle| \\
&\le \|X\|_p \|Z\|_q
\end{aligned}$$

where $q = \frac{p}{p-1}$

$$\begin{aligned}
&\le \|x\|_p (|x_1 + y_1|^p + \cdots + |x_n + y_n|^p)^{\frac{p}{p-1}} \\
&= \|x\|_p \|x+y\|_p^{p-1}.
\end{aligned}$$

Similarly,

$$\sum_{i=1}^{n} |y_i||x_i + y_i|^{p-1} \le \|y\|_p \|x+y\|_p^{p-1}.$$

This gives

$$\begin{aligned}\|x+y\|_p^p &\le (\|x\|_p + \|y\|_p)\|x+y\|_p^{p-1}\\ \|x+y\|_p &\le \|x\|_p + \|y\|_p.\end{aligned}$$

(ii) Positivity is again by definition. $\|x\|_p = 0 \iff |x_i|^p = 0$ for all i, which is iff $x = 0$. Homogeneity is trivial to check.

$$\begin{aligned}\|\alpha x\|_p &= (|\alpha x_1|^p + |\alpha x_2|^p + \cdots + |\alpha x_n|^p)^{\frac{1}{p}}\\ &= (|\alpha|^p|x_1|^p + |\alpha|^p|x_2|^p + \cdots + |\alpha|^p|x_n|^p)^{\frac{1}{p}}\\ &= |\alpha|\|x\|_p.\end{aligned}$$

Triangle inequality is proven above.

Thus $\|\cdot\|_p$ is a norm.

We now prove part (c). The case $x = 0$ is trivial since $\|x\|_p = \|x\|_\infty = 0$ for any p.

WLOG let $\|x\|_\infty = |x_1| > 0$. Then for $1 \le p < \infty$,

$$\begin{aligned}\|x\|_p &= |x_1|\left(1 + \frac{|x_2|^p}{|x_1|^p} + \cdots + \frac{|x_n|^p}{|x_1|^p}\right)^{\frac{1}{p}}\\ &\le |x_1| \cdot n^{\frac{1}{p}}\end{aligned}$$

Further,

$$\|x\|_p = (|x_1|^p + |x_2|^p + \cdots + |x_n|^p)^{\frac{1}{p}} \ge (|x_1|^p)^{\frac{1}{p}} = |x_1|.$$

Thus

$$|x_1| \le \|x\|_p \le n^{\frac{1}{p}}|x_1|.$$

As $p \to \infty$, $n^{\frac{1}{p}} \to 1$. Thus by the squeeze theorem, $\|x\|_p \to |x_1| = \|x\|_\infty$. ■

Problem 1.7. *Let $C[a,b]$ be the set of all complex-valued continuous functions on $[a,b]$.*

(i) Let $f \in C[a,b]$ be such that f is non-negative and $\int_a^b f(x)\,\mathrm{d}x = 0$. Show that $f \equiv 0$.

(ii) For $f \in C[a,b]$, define

$$\|f\|_\infty := \sup_{x\in[a,b]} |f(x)|, \qquad \|f\|_1 := \int_a^b |f(x)|\,\mathrm{d}x.$$

Show that $\|\cdot\|_\infty$ and $\|\cdot\|_1$ are norms on $C[a,b]$.

(iii) Are the above two norms on $C[a,b]$ equivalent? Are they comparable?

Solution.

(i) Suppose f is non-zero at some point $c \in [a, b]$. By continuity, $f(x) \geq \frac{f(c)}{2}$ in some neighbourhood $[c - \delta, c + \delta]$. Then f is lower bounded by the step function

$$g(x) = \begin{cases} \frac{f(c)}{2} & x \in [c - \delta, c + \delta] \\ 0 & \text{otherwise} \end{cases}$$

which has positive integral. This would force $\int_a^b f(x)\,\mathrm{d}x > 0$. Contradiction! Such a c cannot exist.

(ii) Clearly both are non-negative. $\|f\|_\infty = 0 \iff |f(x)| \leq 0$ for all $x \in [a, b]$, which is iff $f \equiv 0$. Definiteness of $\|\cdot\|_1$ is by the previous part. Homogeneity is obvious. Triangle inequality is an extension of the triangle inequality for complex numbers.

(iii) They are *not* equivalent. Consider $[a, b] = [0, 1]$ and $f(x) = e^{-\lambda x}$. Then $\|f\|_\infty = 1$ and $\|f\|_1 = \frac{1-e^{-\lambda}}{\lambda}$. One can choose λ to make $\|f\|_1$ arbitrarily close to 0. Thus there are no constants $c_1, c_2 > 0$ such that

$$c_1\|f\|_\infty \leq \|f\|_1 \leq c_2\|f\|_\infty.$$

However, we *can* compare the norms as

$$\|f\|_1 \leq (b - a)\|f\|_\infty.$$

This is simply by noticing that the constant function $x \mapsto \|f\|_\infty$ upper bounds $|f(x)|$ and has integral $(b - a)\|f\|_\infty$ over $[a, b]$. ■

Problem 1.8. *For $A \in L(\mathbb{R}^n, \mathbb{R}^m)$, let $\|A\|$ denote the operator norm of A. Show that*

$$\|A\| = \inf\{M : \|Ax\| \leq M\|x\| \text{ for all } x \in \mathbb{R}^n\}.$$

Proof. $\|Ax\| \leq M\|x\|$ is trivially true for $x = 0$ no matter what M is. Thus

$$\begin{aligned} &\inf\{M : \|Ax\| \leq M\|x\| \text{ for all } x \in \mathbb{R}^n\} \\ &\qquad = \inf\{M : \|Ax\| \leq M\|x\| \text{ for all } x \in \mathbb{R}^n \setminus \{0\}\} \\ &\qquad = \inf\left\{M : \left\|A\frac{x}{\|x\|}\right\| \leq M \text{ for all } x \in \mathbb{R}^n \setminus \{0\}\right\} \\ &\qquad = \inf\{M : \|Ay\| \leq M \text{ for all } y \in S^{n-1}\} \\ &\qquad = \inf\{\text{upper bounds of } \{\|Ay\| : y \in S^{n-1}\}\} \\ &\qquad = \sup\{\|Ay\| : y \in S^{n-1}\} \\ &\qquad = \|A\|. \end{aligned}$$

■

Problem 1.9. *Let A be a real symmetric $n \times n$ matrix.*

(i) Show that all eigenvalues of A are real.

(ii) For $1 \le i \le n$, let λ_i denote the eigenvalues of A. Show that

$$\|A\| = \max_{1\le i\le n} |\lambda_i|.$$

Solution.

(i) View A as a linear operator on $\mathbb{C}^n$. Let λ be an eigenvalue of A and v be the corresponding eigenvector. Then

$$\lambda\langle v,\, v\rangle = \langle Av,\, v\rangle = \langle v,\, Av\rangle = \bar{\lambda}\langle v,\, v\rangle.$$

Thus $\lambda = \bar{\lambda}$ is real.

(ii) (assuming spectral theorem) WLOG let $\lambda_1 = \max_{1\le i\le n}|\lambda_i|$. Write any vector $x \in \mathbb{R}^n$ as a linear combination of orthonormal eigenvectors $x = \sum_{i=1}^n c_i v_i$, where v_i is the eigenvector corresponding to λ_i. Then $Ax = \sum_{i=1}^n c_i \lambda_i v_i$.

$$\begin{aligned}\|Ax\|^2 &= \sum_{i=1}^n c_i^2 \lambda_i^2 \\ &\le \lambda_1^2 \sum_{i=1}^n c_i^2 \\ &= \lambda_1^2 \|x\|^2.\end{aligned}$$

Thus $\|A\| \le \lambda_1$. Moreover, $\|Av_1\| = |\lambda_1|\|v_1\|$. Thus $\|A\| \ge \lambda_1$. ■

Problem 1.10. *Let $A \in L(\mathbb{R}^n, \mathbb{R}^m)$ and $B \in L(\mathbb{R}^k, \mathbb{R}^n)$. Show that*

$$\|A\| \le \|A\|_{HS} \le \sqrt{n}\|A\| \quad \text{and} \quad \|AB\|_{HS} \le \|A\|_{HS}\|B\|_{HS}.$$

Proof. $\|A\|_{HS} = \sqrt{\mathrm{Tr}(A^\top A)}$. Recall that the trace of a matrix is the sum of its eigenvalues.

Let $v_1, v_2, \dots, v_n$ be orthonormal eigenvectors of $A^\top A$ with eigenvalues $\lambda_1 \ge \lambda_2 \ge \cdots \ge \lambda_n$ (spectral theorem). Each λ_i is non-negative, since $\langle A^\top Ax,\, x\rangle = \langle Ax,\, Ax\rangle \ge 0$.

Then for any $x = \sum_{i=1}^n c_i v_i$ with $\|x\| = 1$,

$$\|Ax\|^2 = \langle Ax,\, Ax\rangle = \langle A^\top Ax,\, x\rangle = \sum_{i=1}^n c_i^2 \lambda_i \le \lambda_1$$

where the equality holds for $x = v_1$. Thus $\|A\| = \sqrt{\lambda_1}$. Since $\|A\|_{HS}^2 = \sum_{i=1}^n \lambda_i$, we have $\lambda_1 \le \|A\|_{HS}^2 \le n\lambda_1$. This gives $\|A\| \le \|A\|_{HS} \le \sqrt{n}\|A\|$.

For $1 \le i \le m$ and $1 \le j \le k$ let

$$a_i = \begin{pmatrix} A_{i1} & A_{i2} & \cdots & A_{in}\end{pmatrix}^\top, \qquad b_j = \begin{pmatrix} B_{1j} \\ B_{2j} \\ \vdots \\ B_{nj}\end{pmatrix}.$$

Then

$$AB = \begin{pmatrix} \langle a_1,\, b_1\rangle & \langle a_1,\, b_2\rangle & \cdots & \langle a_1,\, b_k\rangle \\ \langle a_2,\, b_1\rangle & \langle a_2,\, b_2\rangle & \cdots & \langle a_2,\, b_k\rangle \\ \vdots & \vdots & \ddots & \vdots \\ \langle a_m,\, b_1\rangle & \langle a_m,\, b_2\rangle & \cdots & \langle a_m,\, b_k\rangle \end{pmatrix}$$

so by Cauchy-Schwarz,

$$\begin{aligned} \|AB\|_{HS}^2 &= \sum_{i=1}^m \sum_{j=1}^k \langle a_i,\, b_j\rangle^2 \\ &\le \sum_{i=1}^m \sum_{j=1}^k \|a_i\|^2 \|b_j\|^2 \\ &= \left(\sum_{i=1}^m \|a_i\|^2\right)\left(\sum_{j=1}^k \|b_j\|^2\right) \\ &= \|A\|_{HS}^2 \|B\|_{HS}^2. \end{aligned}$$

■

Remark. A far simpler proof that I missed is the following.

$$\begin{aligned} \|Ax\|^2 &\le \sum_i \langle A_i,\, x\rangle^2 \\ &\le \sum_i \|a_i\|^2 \|x\|^2 \\ &= \|A\|_{HS}^2 \|x\|^2 \end{aligned} \qquad \begin{aligned} \|A\|_{HS}^2 &= \sum_j \sum_i a_{ij}^2 \\ &= \sum_j \|Ae_j\|^2 \\ &\le \sum_j \|A\|^2 \\ &= n\|A\|^2. \end{aligned}$$

Lecture 5. Monday August 12

Exercise 1.35. *Let Z be as in $(I-Z)^{-1} = I+Z+O(Z^2)$ and also $(I-Z)^{-1} = I+Z+o(Z^2)$.*

Proposition 1.36. *Let $A \in M_n(\mathbb{R})$ be such that $\|I-A\| < 1$. Then $A \in \mathrm{GL}_n(\mathbb{R})$.*

Let $A \in \mathrm{GL}_n(\mathbb{R})$ be fixed and let $B \in M_n(\mathbb{R})$ be such that $\|B-A\| < \|A^{-1}\|^{-1}$. Then $B \in \mathrm{GL}_n(\mathbb{R})$.

$A \mapsto A^{-1}$ is continuous on $\mathrm{GL}_n(\mathbb{R})$.

Proof. We proved the first part earlier. For the second part, let $A \in \mathrm{GL}_n(\mathbb{R})$ be fixed and let $\|B-A\| < \|A^{-1}\|^{-1}$.

We can write $B-A$ as $A(A^{-1}B-I)$. Now

$$\begin{aligned}\|A^{-1}B-I\| &= \|A^{-1}(B-A)\| \\ &\le \|A^{-1}\|\|B-A\| \\ &< 1.\end{aligned}$$

Then by the first part, $A^{-1}B \in \mathrm{GL}_n(\mathbb{R})$, so that $B \in \mathrm{GL}_n(\mathbb{R})$.

For the last part, we want $B^{-1} \to A^{-1}$ as $B \to A$.

$$B^{-1} - A^{-1} = A^{-1}(A-B)B^{-1} \tag{1.5}$$

We need to bound $\|B^{-1}\|$. let W be an open neighbourhood of A of radius $\frac{1}{2}\|A^{-1}\|^{-1}$. Then $W \subseteq \mathrm{GL}_n(\mathbb{R})$.

For any $B \in W$, $\|A-B\|\|A^{-1}\| < \frac{1}{2}$ and

$$\begin{aligned}\|B^{-1}\| - \|A^{-1}\| &\le \|B^{-1} - A^{-1}\| \\ &\le \|B^{-1}\|\|A-B\|\|A^{-1}\| && \text{(by equation (1.5))} \\ &\le \frac{1}{2}\|B^{-1}\|.\end{aligned}$$

This bounds $\|B^{-1}\|$ above by $2\|A^{-1}\|$. Using equation (1.5) again, we have

$$\begin{aligned}\|B^{-1} - A^{-1}\| &\le \|A^{-1}\|\|A-B\|\|B^{-1}\| \\ &\le 2\|A^{-1}\|^2 \cdot \|A-B\|.\end{aligned}$$

As $B \to A$, $B^{-1} \to A^{-1}$. ■

Remark. This is similar in spirit to exercise 1.18.

- Equation (1.5) is similar to taking the common denominator in $\frac{1}{x} - \frac{1}{a}$.
- The choice of W is similar to choosing $\delta \le \frac{1}{2}|a|$.

Chapter 2

Differentiation

Definition 2.1. Let $f\colon \mathbb{R} \to \mathbb{R}$ be a function. We say that f is *differentiable* at $a \in \mathbb{R}$ if
$$\lim_{h\to 0} \frac{f(a+h)-f(a)}{h}$$
exists. We denote this limit by $f'(a)$ and call it the *derivative* of f at a.

This doesn't make sense for $f\colon \mathbb{R}^n \to \mathbb{R}^m$ when $n > 2$ (for $n = 2$ we can identify $\mathbb{R}^2$ with $\mathbb{C}$).

Theorem 2.2 (Hurwitz' theorem)**.** $\mathbb{R}^n$ *is a*

We will redefine differentiability for real functions.

Proposition 2.3. *Let U be an open subset of $\mathbb{R}$ and $f\colon U \to \mathbb{R}$. Let $a \in U$. Then f is differentiable at a if and only if there exists a linear map $T \in L(\mathbb{R}, \mathbb{R})$ such that*
$$f(a+h) - f(a) = Th + o(h).$$

Proof. Suppose f is differentiable at $a \in U$.
$$\lim_{h\to 0} \frac{f(a+h)-f(a)}{h} = f'(a)$$
We can rewrite this as
$$\begin{aligned} &\lim_{h\to 0} \frac{f(a+h)-f(a)-f'(a)h}{h} = 0 \\ \implies &\lim_{h\to 0} \frac{|f(a+h)-f(a)-T_{f'(a)}h|}{|h|} = 0 \end{aligned}$$
where $T_\alpha \in L(\mathbb{R}, \mathbb{R})$ is the linear map $x \mapsto \alpha x$.

Conversely, suppose there exists a linear map T such that $f(a+h) -$

$f(a) - Th = o(h)$. Then

$$\begin{aligned} \lim_{h\to 0} \frac{|f(a+h) - f(a) - Th|}{|h|} &= 0 \\ \implies \lim_{h\to 0} \left| \frac{f(a+h) - f(a)}{h} - T(1) \right| &= 0 \\ \implies \lim_{h\to 0} \frac{f(a+h) - f(a)}{h} &= T(1). \end{aligned}$$

■

Lecture 6. Monday August 19

Definition 2.4. Let $U \subseteq \mathbb{R}^n$ be an open set containing a. Let $f: U \to \mathbb{R}^m$. We say that f is *differentiable* at a if there exists a linear map $T \in L(\mathbb{R}^n, \mathbb{R}^m)$ such that

$$\lim_{h\to 0} \frac{\|f(a+h) - f(a) - Th\|}{\|h\|} = 0.$$

We say that T is the *derivative* of f at a and write $f'(a) = T$.

If f is differentiable at every point in U, we say that f is differentiable on U.

Writing $f'(a)$ requires the derivative to be unique.

Proposition 2.5. *Let $T_1, T_2 \in L(\mathbb{R}^n, \mathbb{R}^m)$ be satisftying the definition of differentiability at a for $f: U \to \mathbb{R}^m$. Then $T_1 = T_2$.*

Proof. Let $T = T_1 - T_2$. Then

$$\begin{aligned} Th &= T_1 h - T_2 h \\ &= (f(a+h) - f(a) - T_2 h) - (f(a+h) - f(a) - T_1 h) \\ &= o(h) - o(h) = o(h). \end{aligned}$$

We have $\lim\limits_{h\to 0} \frac{\|Th\|}{\|h\|} = 0$. Let $v \in \mathbb{R}^n \setminus \{0\}$. As $t \to 0$, $tv \to 0$. Thus

$$\begin{aligned} \lim_{t\to 0} \frac{\|T(tv)\|}{\|tv\|} &= \lim_{t\to 0} \frac{|t|\|Tv\|}{|t|\|v\|} \\ &= \frac{\|Tv\|}{\|v\|} = 0. \end{aligned}$$

Thus $Tv = 0$ for all $v \in \mathbb{R}^n$. ■

Proposition 2.6. *Differentiability at a point implies continuity at that point.*

Proof. Suppose f is differentiable at a with $f'(a) = T$. Let

$$q(h) = f(a+h) - f(a) - Th.$$

$$\begin{aligned}\|f(a+h)-f(a)\| &= \|f(a+h)-f(a)-Th+Th\| \\ &\le \|q(h)\|+\|Th\| \\ &\le \frac{\|q(h)\|}{\|h\|}\|h\|+\|T\|\|h\|.\end{aligned}$$

As $h \to 0$, each term goes to 0. ■

For *finding* the derivative, it is helpful to do the following:

- Use little-o notation.
- Identify the linear map T.
- Ignore the little-o terms.

If $f(a+h) = f(a) + Th + o(h)$, then $f'(a) = T$.

Examples.

- Let $f\colon \mathbb{R}^n \to \mathbb{R}^m$ be given by $f(x) = c$ for some constant $c \in \mathbb{R}^m$. For any $a \in \mathbb{R}^n$, we can write $f(a+h) = f(a) + 0 + 0$. Thus $f'(a) = 0$.
- Let $f \in L(\mathbb{R}^n, \mathbb{R}^m)$. Then $f(a+h) = f(a) + f(h) + 0$. Thus $f'(a) = f$.
- Let $f\colon \mathbb{R} \to \mathbb{R}$ be given by $f(x) = x$. This is a special case of the previous example. $f'(a) = \mathrm{id}$.

Even though we are developing calculus on $\mathbb{R}^n$, it is trivially extended to all finite-dimensional normed linear spaces over $\mathbb{R}$ via the natural identification with $\mathbb{R}^n$.