Contents

Chapter 1

Multivariable Calculus

1.1 Linear Algebra

1.1.1 Vector Spaces

Definition (Normed vector space): Let V be a vector space. A **norm** is a real valued function $\|\cdot\| : V \to \mathbb{R}$ which has the following properties

1. $\forall x \in V,\ \|x\| > 0.$
2. $\|x\| = 0 \implies x = 0.$
3. $\forall x \in V\ \forall \alpha \in \mathbb{F},\ \|\alpha x\| = |\alpha|\,\|x\|.$
4. $\forall x, y \in V\ \ \|x + y\| \leq \|x\| + \|y\|.$

Each normed vector space induces a metric space (V, d) where $d(x, y) = \|y - x\|$.

Theorem 1.1. *In every normed space* $(V, \|\cdot\|)$ *we have*

$$|\|v\| - \|w\|| \leq \|v - w\|$$

Hence the norm is Lipschitz continuous.

Definition: Assume V is a vector space and let $\|\cdot\|_1$, $\|\cdot\|_2$ be two norms for V. They are said to be equivalent when

$$\exists c_1, c_2 > 0\ \forall x : \qquad c_1 \|x\|_1 \leq \|x\|_2 \leq c_2 \|x\|$$

To check if the above definition is indeed an equivalence relation, we must show that following:

Reflexive $\|\cdot\|_1 \sim \|\cdot\|_1$.

Symmetric $\|\cdot\|_1 \sim \|\cdot\|_2 \implies \|\cdot\|_2 \sim \|\cdot\|_1$.

Transitive $\|\cdot\|_1 \sim \|\cdot\|_2$, $\|\cdot\|_2 \sim \|\cdot\|_3 \implies \|\cdot\|_1 \sim \|\cdot\|_3$.

Remark 1. Equivalent norms induce equivalent metrics, hence they induce the same topology.

Theorem 1.2. *All norms defined on a finite dimensional vector space V are equivalent.*

Proof. Let $\|\cdot\|$ be an arbitrary norm on V and $\{e_1, e_2, \ldots, e_n\}$ be a basis of V. Let $\|\cdot\|_2$ be L_2-norm (Euclidean norm). It will suffice to show $\|\cdot\| \sim \|\cdot\|_2$. Let

$$M = \max(\|e_1\|, \ldots, \|e_n\|)$$

Take $x \in V$, writing $x = \sum_{i=1}^{n} \xi_i e_i$ we have:

$$\|x\| = \left\| \sum_{i=i}^{n} \xi_i e_i \right\| \leq \sum_{i=1}^{n} |\xi_i| \|e_i\| \leq M\sqrt{n} \|x\|_2$$

Taking $c_2 = M\sqrt{n}$ proves the right inequality. For the left inequality we need the following lemma

Lemma 1.3. *If V is a normed vector space with $\|\cdot\|_2$, as defined above, is viewed as metric space $(V, \|\cdot\|_2)$ then $\|\cdot\| : V \to \mathbb{R}$ is continuous.*

Proof. Let $x_0 \in V$ and M be defined as above. For any $\epsilon > 0$ consider $\delta = \frac{\epsilon}{M\sqrt{n}}$ then if $\|x - x_0\|_2 < \delta$

$$|\|x\| - \|x_0\|| \leq \|x - x_0\| \leq M\sqrt{n} \|x - x_0\| \leq \epsilon$$

Now consider the sphere of radius $r = 1$ centered at 0, $S_1(0) = S_1 = \{x \in V : \|x\|_2 = 1\}$. One can show that S is compact. Therefore, $\|x\|$ assumes its minimum on S. Let $a = \|x_0\|$ be the minimum. Since $0 \notin S$ then $a > 0$. By letting $y = x/\|x\|_2$, we have $y \in S$ and thus $a \leq \|y\|$ which is

$$a \|x\|_2 \leq \|x\|$$

Taking $c_1 = a$ proves the theorem. ∎

Example 1.1. The closed unit ball in the infinite dimensional vector space $C([0,1], \mathbb{R})$ with $\|f\| = \max f(x)$ is not compact. Take $f_n(x) = x^n$. Obviously $\|f_n\| = 1$, however f_n doesn't uniformly converge and hence f_n doesn't have a limit in $C([0,1], \mathbb{R})$ with the max norm. Consider the following norm

$$\|f\|_I = \int_0^1 |f(x)| \, \mathrm{d}x$$

Note that $\|\cdot\|_I$ and $\|\cdot\|_{\max}$ are not equivalent. Let $g(x) = 0$ for all $x \in [0,1]$. Then

$$\|f_n - g\|_I = \frac{1}{n+1} \to 0 \quad \text{as} n \to \infty.$$

Definition (Banach space): A normed vector space V that is complete is a **Banach space**. A **Hilbert Space** is a Banach space whose norm is induced by an inner product.

Proposition 1.4. *A normed finite dimensional vecotr space V, is Banach space.*

Proof.

1.1.2 Linear Maps

Let V and W be a vector spaces over $\mathbb{F}$. A map $T : V \to W$ is **linear** if

$$T(x + \lambda y) = T(x) + \lambda T(y)$$

for all $x, y \in V$ and $\lambda \in \mathbb{F}$.

Definition: Let $(V, \|\cdot\|_V)$ and $(W, \|\cdot\|_W)$ be normed spaces then, a linear transformation $T : V \to W$ is **bounded** if there exists a constant $C > 0$ such that

$$\|Tv\|_W \leq C\,\|v\|_V$$

for all $v \in V$. We denote the set of all linear map from $V \to W$ as $\mathcal{L}(V, W)$ and the set of all bounded linear maps as $\mathcal{B}(V, W)$. If $T \in \mathcal{L}(V, W)$ is bijective such that $T^{-1} \in \mathcal{L}(V, W)$, then T is called an **isomorphism** and V, W are **isomorphic**. An operator $T \in \mathcal{L}(V, W)$ is called **isometric** if $\|Tv\|_W = \|v\|_V$ for all $v \in V$.

Definition: If $(V, \|\cdot\|_V), (W, \|\cdot\|_W)$ are normed spaces then the **operator norm** of a linear transformation $T : V \to W$ is

$$\|T\| = \sup\left\{ \frac{\|Tv\|_W}{\|v\|_V} \middle| v \neq 0 \right\}$$

Proposition 1.5. *Let $T : U \to V$ and $T' : V \to W$ be two linear transformations.*

$$\|T' \circ T\| \leq \|T\|\,\|T'\|$$

Proof. for an arbitrary non-zero $x \in U$

$$\|T' \circ T(x)\|_W \leq \|T'\|\,\|Tx\|_V \leq \|T'\|\,\|T\|\,\|x\|_U$$

which implies

$$\|T' \circ T\| \leq \|T\|\,\|T'\|$$

Theorem 1.6. *Let $(V, \|\cdot\|_V)$ and $(W, \|\cdot\|_W)$ be normed spaces and $T : V \to W$ be a linear transformation. The following are equivalent*

1. *$\|T\|$ is finite.*
2. *T is bounded.*
3. *T is Lipschitz continuous.*
4. *T is continuous at a point.*
5. *$\sup_{\|v\|_V = 1} \|Tv\|_W < \infty$.*

Proof. item 1 $\Rightarrow$ item 2: Obviously

$$\frac{\|Tv\|_W}{\|v\|_V} \leq \|T\|$$
$$\implies \|Tv\|_W \leq \|T\|\,\|v\|_V$$

note that if $v = 0$ then $Tv = 0$ as well and thus the last inequality holds for all $v \in V$.

item 2 $\Rightarrow$ item 3:

$$\|Tv - Tu\|_W = \|T(u - v)\|_W \le C\,\|u - v\|_V$$

item 3 $\Rightarrow$ item 4: Trivial.

item 4 $\Rightarrow$ item 5: Let T be continuous at $u \in V$. Then there is a $\delta > 0$ such that

$$\|v - u\| < \delta \implies \|Tv - Tu\|_W = \|T(v - u)\|_W < 1$$

Now for an arbitrary non-zero v we have

$$\left\|\left(\frac{\delta v}{2\,\|v\|_V} + u\right) - u\right\|_V < \delta$$

Therefore

$$\left\|T\left(\frac{\delta v}{2\,\|v\|_V}\right)\right\|_W < 1$$
$$\left\|T\left(\frac{v}{\|v\|_V}\right)\right\|_W < \frac{2}{\delta}$$

item 5 $\Rightarrow$ item 1: Let $v \in V$ be an arbitrary vector. Then

$$\sup\left\|T\left(\frac{v}{\|v\|_V}\right)\right\|_W < \infty$$
$$\implies \sup\frac{\|Tv\|_W}{\|v\|_W} < \infty$$

Theorem 1.7. *If V is a finite dimensional normed vector space then any linear transformation $T : V \to W$ is continuous.*

Proof. Since V is finite dimensional, according to Theorem 1.2, any two norms are equivalent. Hence, take $\|\cdot\|_2$ to be Euclidean norm over a basis $\{e_1, \ldots, e_n\}$. Let x be such that $\|x\|_2 < \delta$ for some $\delta > 0$. Therefore, $|\xi_i| < \delta^2$

$$\|Tx\|_W = \left\|\sum \xi_i T(e_i)\right\|_W \le \sum |\xi_i|\,\|T(e_i)\|_W \le \delta^2 K$$

where $K = \max\|T(e_i)\|_W$. By letting $\delta = \sqrt{\frac{\epsilon}{K}}$ we proved continuity at 0 and hence the continuity by Theorem 1.6. ∎

Corollary 1.8. *Any finite dimensional normed vector space V over a normed complete field $\mathbb{F}$ is a Banach space.*

Proof. Let $\{e_1, \ldots, e_n\}$ be a basis for V and $\phi : V \to \mathbb{F}^n$ be the representation map for the basis. Since ϕ is a linear map and a bijection then ϕ is homeomorphism. Consider a Cauchy sequence $\{v_k\} \in V$ and let $x_k = \phi(v_k)$ then by continuity of ϕ and ϕ^{-1} we have

$$|x_i - x_j| = |\phi(v_i) - \phi(v_j)| \le \|\phi\|\,\|v_i - v_j\| \le \|\phi\|\,\left\|\phi^{-1}(x_i) - \phi^{-1}(x_j)\right\| \le \|\phi\|\,\left\|\phi^{-1}\right\|\,|x_i - x_j|$$

hence $\{x_k\}$ are Cauchy in $\mathbb{F}^n$ which by completeness of $\mathbb{F}$ implies that they are convergent, $x_k \to x$. Let $v = \phi^{-1}(x)$ then by the right side of the inequality $v_k \to v$. ∎

Remark 2. As seen in the last proof, for a bijective linear transformation T

$$1 \leq \|T\| \left\|T^{-1}\right\|$$

Theorem 1.9. *For two normed vector spaces V, W, $(\mathcal{B}(V,W), \|T\|)$ is a normed vector space. Moreover, it is a Banach space when W is a Banach space.*

Proof. Clearly $\mathcal{B}(V,W)$ is a vector space. For its norm $\|T\|$ we have

1. $\|T\| \geq 0$ by definition.
2. if $\alpha \in \mathbb{F}_W$ then
$$\|\alpha T\| = \sup\left\{\frac{\|(\alpha T)v\|_W}{\|v\|_V}\middle| v \neq 0\right\} = |\alpha| \sup\left\{\frac{\|Tv\|_W}{\|v\|_V}\middle| v \neq 0\right\} = |\alpha| \, \|T\|$$
3. for the triangle inequality
$$\begin{aligned}\|T_1 + T_2\| &= \sup\left\{\frac{\|(T_1+T_2)v\|_W}{\|v\|_V}\right\} \\ &\leq \sup\left\{\frac{\|T_1 v\|_W + \|T_2 v\|_W}{\|v\|_V}\right\} \\ &= \sup\left\{\frac{\|T_1 v\|_W}{\|v\|_V}\right\} + \sup\left\{\frac{\|T_2 v\|_W}{\|v\|_V}\right\} \\ &= \|T_1\| + \|T_2\|\end{aligned}$$

Suppose W is a Banach space and $\{T_i\} \in \mathcal{B}(V,W)$ is a Cauchy sequence. Then for all $v \in V$

$$\forall \epsilon \, \exists N \text{ s.t. } m, n > N \implies \|T_m v - T_n v\|_W \leq \|T_m - T_n\| \, \|v\|_V < \epsilon$$

$\{T_i v\}$ is a Cauchy sequence. Since W is complete then $T_i v \to Tv$ for some function T. We claim that T is a bounded linear map and is the limit of $T_i \to T$.

$$\begin{aligned}T(v + cu) &= \lim_{i\to\infty} T_i(v+cu) = \lim_{i\to\infty} T_i v + cT_i u \\ &= Tv + cTu\end{aligned}$$

Note that $|\|T_m\| - \|T_n\|| \leq \|T_m - T_n\|$ and hence $\|T_i\|$ is a Cauchy in sequence in $\mathbb{R}$ that has a limit t. There exists a N such that $|\|T_n\| - t| < 1$ for all $n \geq N$.

$$\frac{\|Tv\|_W}{\|v\|_V} = \lim_{i\to\infty} \frac{\|T_i v\|_W}{\|v\|_V} < t + 1$$

hence T is bounded and $T \in \mathcal{B}(V,W)$. Finally, we show that $T_i \to T$. For an arbitrary $v \neq 0$ and $\epsilon > 0$ there exist N such that

$$n \geq N \implies \|T_i v - Tv\|_W < \epsilon \|v\|_V$$

which means that

$$\|T_i - T\| = \sup \frac{\|T_i v - Tv\|_W}{\|v\|_V} < \epsilon$$

Therefore $T_i \to T$ as desired. ∎

Theorem 1.10. *Let $(V, \|\cdot\|)$ be a normed space. Then any linear transformation $T : \mathbb{R}^n \to V$ is continuous. Furthermore, if T is a bijection, it is a homeomorphism.*

Proof. Since $\mathbb{R}^n$ is finite then by Theorem 1.7, T is continuous. Assuming T is bijective, we must show that its inverse T^{-1} is continuous as well. Since T is a bijection then T is a linear isomorphism and $\dim V = \dim \mathbb{R}^n = n$ hence T^{-1} is a continuous map. ■

Definition (General linear group): The **general linear group** of a vector space, written $\mathrm{GL}(V)$ is the set of all bijective linear transformation.

Proposition 1.11. *If V is a finite (also works for infinite) vector space then $\mathrm{GL}(V)$ is open in $\mathcal{L}(V, V)$, in fact, if $f \in \mathrm{GL}(V)$ then the open ball centered at f with radius $\|f^{-1}\|^{-1}$ remains in $\mathrm{GL}(V)$. Furthermore, the inverse operator $i : \mathrm{GL}(V) \to \mathrm{GL}(V)$, $i(T) = T^{-1}$ is continuous.*

Proof. First assume $f = \mathbb{1}_V$ then we prove that any linear g that $\|\mathbb{1}_V - g\| < 1$ is invertible which then implies bijectivity (true for linear maps). Let $\|v\| = 1$ then

$$||\|v| - \|gv\||| \leq \|v - gv\| \leq \|\mathbb{1}_V - g\| \|v\| < 1$$

Therefore

$$0 < \|gv\| < 2$$

which means $\ker g = \{0\}$ and since V is finite then then g is invertible. For a general f, we have that

$$\left\|1 - f^{-1} \circ g\right\| \leq \left\|f^{-1}\right\| \|f - g\| < 1$$

therefore $f^{-1} \circ g$ is invertible and as a consequence $g = f \circ f^{-1} \circ g$ is invertible. To prove inverse operator is continuous, fix $\epsilon > 0$ then for a $\delta > 0$ if $\|T - S\| < \delta$ then

$$\begin{aligned} &\left\|\mathbb{1}_V - T^{-1} \circ S\right\| = \left\|T^{-1} \circ T - T^{-1} \circ S\right\| \leq \left\|T^{-1}\right\| \|T - S\| < \delta \left\|T^{-1}\right\| \\ \implies &\left\|T^{-1} - S^{-1}\right\| \leq \left\|T^{-1} \circ S - \mathbb{1}_V\right\| \left\|S^{-1}\right\| < \delta \left\|T^{-1}\right\| \left\|S^{-1}\right\| \end{aligned}$$

note that by letting $\delta = \|T^{-1}\|^{-1}/2$ then

$$\|S\| > -\frac{\|T^{-1}\|^{-1}}{2} + \|T\| > \frac{\|T^{-1}\|^{-1}}{2}$$

also if for any invertible linear map R

$$\|R\| > a \implies \|Rx\| > a\|x\| \implies \frac{\|y\|}{a} = \frac{\|R \circ R^{-1}(y)\|}{a} > \left\|R^{-1}y\right\|$$

which means that $\|S^{-1}\| < 2\|T^{-1}\|$, hence by letting

$$\delta = \min\left\{\frac{\epsilon\|T^{-1}\|^2}{2}, \frac{\|T^{-1}\|^{-1}}{2}\right\}$$

we proved the continuity. ■

Theorem 1.12. *$T : \mathbb{R}^n \to \mathbb{R}^n$ linear transformation is invertible if and only if there exists a c such that:*

$$c\|x\| \leq \|Tx\|$$

Proof. If T is invertible then $T^{-1} : \mathbb{R}^n \to \mathbb{R}^n$ is bounded and thus

$$\left\|T^{-1}x\right\| \leq c \left\|x\right\|$$

and since T is bijective then there exists y such that $x = Ty$ which implies

$$\left\|y\right\| \leq c \left\|Ty\right\|$$

If there exists such c then $\|Tx\| > 0$ for all non-zero x and hence $\ker T = 0$ which implies that T is a bijection and is invertible. ■

Definition: Let $V_1, V_2, \ldots, V_n$ be normed vector spaces. Then the function $\phi : V_1 \times \cdots \times V_n \to W$ is n**-linear** if by fixing any $n-1$ component, ϕ is linear relative to the remaining component.

Proposition 1.13. *If $V_1, V_2, \ldots, V_n$ are normed vector spaces and $\phi : V_1 \times \cdots \times V_n \to W$ is a n-linear then the followings are equivalent*

1. *ϕ is continuous.*
2. *ϕ is continuous at 0.*
3. *ϕ is bounded, that is there exists a constant $C > 0$ such that*

$$\left\|\phi(v_1, \ldots, v_n)\right\|_W \leq C \left\|v_1\right\|_{V_1} \ldots \left\|v_n\right\|_{V_n}$$

Remark 3. As oppose to linear transformation, n-linear function's continuity does not imply uniform continuity.

Proof. Item 1 $\implies$ Item 2: Trivial.

Item 2 $\implies$ Item 3: For the sake of contradiction, suppose Item 3 is false. That is, for every $k \in \natural$ there exists a point $v_k = (v_k^1, \ldots, v_k^n)$ such that

$$\left\|\phi\left(v_k^1, \ldots, v_k^n\right)\right\|_W > n^n \left\|v_k^1\right\|_{V_1} \ldots \left\|v_k^n\right\|_{V_k}$$

Note that v_k^m can not be zero for any k and m, otherwise $\phi(v_k) = 0$. Define

$$w_k^m = \frac{v_k^m}{n \left\|v_k^m\right\|_{V_k}} \to 0$$

which from the continuity at 0 implies that $w_k = (w_k^1, \ldots, w_k^n) \to 0$. However,

$$\left\|\phi(w_k) - \phi(0)\right\|_W > n^n \frac{1}{n} \ldots \frac{1}{n} = 1$$

which is a contradiction.

Item 3 $\implies$ Item 1. Let $v_n \to v$ and define the points

$$\bar{v}_k^m = (v^1, \ldots, v^m, v_k^{m+1}, \ldots, v_k^n), \qquad \bar{v}_k^0 = v_k$$

and $\bar{v}_k^n = v$. Note that v_k^m are bounded for sufficiently large $k \geq N_1$, therefore there exists M such that $\forall m,\ \|v_k^m\|_{V_m} \leq M$. Also, pick M such that $\forall m,\ \|v^m\|_{V_m} \leq M$ as well. Then

$$\begin{aligned}
\|\phi(v_k) - \phi(v)\|_W &\leq \sum_{i=1}^{n} \left\|\phi\left(\bar{v}_k^{i-1}\right) - \phi\left(\bar{v}_k^i\right)\right\|_W \\
&= \sum_{i=1}^{n} \left\|\phi\left(\bar{v}_k^{i-1} - \bar{v}_k^i\right)\right\|_W \\
&\leq \sum_{i=1}^{n} C \left\|v^1\right\|_{V_1} \cdots \left\|v^{i-1}\right\|_{V_{i-1}} \left\|v_k^i - v^i\right\|_{V_i} \left\|v_k^{i+1}\right\|_{V_{i+1}} \cdots \|v_k^n\|_{V_n} \\
&\leq CM^{n-1} \sum_{i=1}^{n} \left\|v_k^i - v^i\right\|_{V_i}
\end{aligned}$$

pick N_2 such that for all $k \geq N_2$, for each i, $\|v_k^i - v^i\|_{V_i} < \frac{\epsilon}{nCM^{n-1}}$ then

$$\|\phi(v_k) - \phi(v)\|_W < CM^{n-1} \sum_{i=1}^{n} \frac{\epsilon}{nCM^{n-1}} = \epsilon$$

Exercises

1. Show that for a linear transformation T, $\|T\| = \sup_{\|v\|_V \leq 1} \|Tv\|_W$.

1.2 Derivative

Let V, W be finite dimensional vector spaces and $f : U \subset V \to W$ where U is open. Then f is differentiable at x_0 when a linear transformation $T : V \to W$ such that

$$\lim_{\|h\|\to 0} \frac{\|f(x_0+h) - f(x_0) - T(h)\|}{\|h\|} = 0$$

Or equivalently there exists a sublinear function $R(h)$ such that

$$f(x_0+h) - f(x_0) - Th = R(h) \qquad \frac{R(h)}{\|h\|} \to 0$$

T if it exists is unique, represented by $f'(x_0)$, $\mathrm{D}f$, or $\mathrm{d}f(x)$ and called the **total derivative** or **Fréchet derivative**.

Example 1.2. Every linear function $f : V \to W$ with $f(v) = Tv + b$ where $b \in W$ is differentiable and $\mathrm{D}f(v) = T$. Since

$$\|h\|_V < \delta \implies \|f(v+h) - f(v) - (\mathrm{D}f(v))(h)\|_W = \|T(v+h) - Tv - Th\|_W = 0 < \epsilon \|h\|_V$$

Hence, the derivative of any linear function is constant. Consider $S : V \times V \to V$ with $S(v,u) = v + u$. S is differentiable because S is linear (why?). We claim that $\mathrm{D}S = S$ as

$$\|S((v+h),(u+k)) - S(v,u) - S(h,k)\| = 0$$

Example 1.3. Let $\mu : \mathbb{R} \times V \to V$ with $\mu(r,x) = rx$. Then μ is differentiable and $(\mathrm{D}\mu(r,x))(t,h) = rh + tx$ as

$$\begin{aligned}\|\mu((r+t),(x+h)) - \mu(r,x) - (\mathrm{D}\mu(r,x))(t,h)\| &= \|rx + rh + tx + th - rx - rh - tx\| \\ &= |t|\,\|h\| \le \epsilon\,\|(t,h)\|\end{aligned}$$

by letting $\|(t,h)\| = \sqrt{t^2 + \|h\|^2}$ and $\delta = \epsilon$.

Proposition 1.14. *Differentiability of f at x implies continuity at x.*

Proof.

$$\|f(x+h) - f(x)\| = \|(\mathrm{D}f(x))(h) + R(h)\| \le \|\mathrm{D}f(x)\|\,\|v\| + \|R(v)\| \to 0$$

as $v \to 0$. ∎

Proposition 1.15. *Assume $f : U \subset V \to W$ is differentiable at x_0 and let $u \in V$ be a non-zero vector then*

$$f'(x_0)\,(u) = \lim_{t\to 0} \frac{f(x_0+tu) - f(x_0)}{t}$$

Proof. Let $h = tu$ then

$$\begin{aligned} R(tu) &= f(x_0+tu) - f(x_0) - T(tu) \\ &= f(x_0+tu) - f(x_0) - tT(u) \\ \implies \frac{R(tu)}{t} &= \frac{f(x_0+tu) - f(x_0)}{t} - T(u) \\ \implies \lim_{t\to 0} \frac{f(x_0+tu) - f(x_0)}{t} &= T(u) \end{aligned}$$

Definition (Directional derivative): If we let $\|u\| = 1$ then the limit in Propostion 1.15 becomes the **directional derivative** of f in the direction of u and is denoted by $\mathrm{D}_u f$.

Remark 4. The existence of all directional derivatives of f doesnt imply its differentiability or even its continuity.

Remark 5. If $\mathrm{D}f : U \to \mathcal{L}(V, W)$ is continuous then each $\dfrac{\partial f_i}{\partial x_j}$ is continuous. Since

$$\mathrm{D}f(x) = \begin{bmatrix} \dfrac{\partial f_1}{\partial x_1}(x) & \dots & \dfrac{\partial f_1}{\partial x_n}(x) \\ \vdots & \ddots & \\ \dfrac{\partial f_m}{\partial x_1}(x) & \dots & \dfrac{\partial f_m}{\partial x_n}(x) \end{bmatrix}$$

and the reverse is true as well.

Theorem 1.16. *$f : V \to W$ has all of its partial derivative in a neighbourhood of $u \in U$ and they're continuous at u then f is differentiable at u. Especially, if $\dfrac{\partial f_i}{\partial x_j}$ exist and are continuous at every point of u then $f \in \mathcal{C}^1$.*

Proof. We prove that each f_i is differentiable. Let $\{e_1, \dots, e_n\}$ be a basis for V and take $\|x\| = \sum |\xi_j|$. Consider a convex neighbourhood E of a. Then, for a given $\epsilon > 0$ we will show there exists a $\delta > 0$ such that

$$\|h\| < \delta \implies \left\| f_i(a+h) - f_i(a) - \sum_{j=1}^{n} \big(\mathrm{D}_{e_j} f_i(a)\big)(h_j) \right\| \le \epsilon \|h\|$$

Cosider the point sequence $a^k = \sum_{j<k} a_j e_j + \sum_{j \ge k} (a_j + h_j) e_j$ where $a^1 = a + h$ and $a^{n+1} = a$ then

$$\left\| f_i(a+h) - f_i(a) - \sum_{j=1}^{n} \big(\mathrm{D}_{e_j} f_i(a)\big)(h_j) \right\| \le \sum_{k=1}^{n} \left\| f_i\big(a^k\big) - f_i\big(a^{k+1}\big) - (\mathrm{D}_{e_k} f_i(a))(h_k) \right\|$$

hence we are done if

$$\left\| f_i\big(a^k\big) - f_i\big(a^{k+1}\big) - (\mathrm{D}_{e_k} f_i(a))(h_k) \right\| \le \epsilon |h_k|$$

for $k = 1$ it is equivalent to the existence first partial derivative. and for the rest we use the continuity. ■

Proposition 1.17. *Let $f, g : V \to W$ be differentiable at x and $h : W \to U$ be differentiable at $y = f(x)$. Furthermore, let c be an scalar then*

1. $\mathrm{D}(f + cg) = \mathrm{D}f + c\,\mathrm{D}g$.

2. *$h \circ f$ is differentiable at x and*

$$\mathrm{D}(h \circ f) = (\mathrm{D}(h) \circ f) \circ \mathrm{D}(f)$$

3. For a bilinear function β

$$(\mathrm{D}\beta(f,g))(v) = \beta((\mathrm{D}f)(v)\,, g) + \beta(f, (\mathrm{D}g)(v))$$

Proof.

Proposition 1.18. *$f : U \subset V \to W_1 \times \cdots \times W_n$ is differentiable at x_0 if and only if all its component is differentiable at x_0. Furthermore, $\mathrm{D}f = (\mathrm{D}f_1, \ldots, \mathrm{D}f_n)$.*

Proof.

Theorem 1.19 (Leibnitz rule). *Let $V_1, V_2, \ldots, V_n$ be finite dimensional vector spaces and $f : V_1 \times \cdots \times V_n \to W$ is a n-linear function. f is differentiable at $a = (a_1, \ldots, a_n)$ and*

$$(\mathrm{D}f(a))(h_1, \ldots h_n) = f(h_1, a_2, \ldots, a_n) + f(a_1, h_2, \ldots, a_n) + \cdots + f(a_1, a_2, \ldots, h_n)$$

Proof. Consider the following points

$$\begin{aligned} \bar{a}^k &= (a_1, \ldots, a_k, a_{k+1} + h_{k+1}, \ldots, a_n + h_n), & \bar{a}^0 &= a + h, \bar{a}^n = a \\ \bar{b}^k &= (a_1, \ldots a_k, h_{k+1}, a_{k+2}, \ldots, a_n) & \bar{b}^0 &= (h_1, a_2, \ldots, a_n) \end{aligned}$$

for a fixed $\epsilon > 0$ we have ■

Example 1.4. Let $Z : \mathbb{R}^3 \times \mathbb{R}^3 \to \mathbb{R}$ with $Z(u, v) = u \times v$ be a bilinear function, $f, g : \mathbb{R} \to \mathbb{R}^3$ and $h(t) = f(t) \times g(t)$. $h = Z \circ \phi$ where $\phi(t) = (f(t)\,, g(t))$. Then we have:

$$\begin{aligned} \mathrm{D}h(t) &= (\mathrm{D}Z)(\phi(t)) \circ \mathrm{D}\phi(t) \\ &= (\mathrm{D}Z)(\phi(t)) \circ (\mathrm{D}f(t)\,, \mathrm{D}g(t)) \\ &= Z(\mathrm{D}f(t)\,, g(t)) + Z(f(t)\,, \mathrm{D}g(t)) \\ &= \mathrm{D}f(t) \times g(t) + f(t) \times \mathrm{D}g(t) \end{aligned}$$

Example 1.5. Consider $A = [f_{ij}(x_1, \ldots, x_n)]$ where each f_{ij} is differentiable. Then

$$\mathrm{D}\det(A)$$

can be calculated using the Leibnitz rule, since determinant is n-linear function.

1.2.1 Mean value theorem

in general doesnt work $f(t) = (t^2, t^3)$ however it works on a convex domain to reals.

Theorem 1.20. *Let V, W be normed finite dimensional vector spaces and $f : U \to W$ is differentiable and $A, B \in U$ are such that the line connecting in completely contained in U and for each p on that line*

$$\|\mathrm{D}f(p)\| \leq M$$

then

$$\|f(B) - f(A)\|_W \leq M \,\|B - A\|_V$$

First consider the following lemma: Assume the following lemma

Lemma 1.21. *If $\phi : [0,1] \to W$ is continuous, differentiable on $]0,1[$ and $\|\phi'(t)\| \leq M$ for all $t \in]0,1[$ then*

$$\|\phi(1) - \phi(0)\|_W \leq M$$

Proof. We provide three proofs for the lemma

1. Assuming the norm on W is induced by an inner product. Then, let $e = \frac{\phi(1)-\phi(0)}{\|\phi(1)-\phi(0)\|}$ be a unit vecor in W then $\psi : [0,1] \to \mathbb{R}$, $\psi(t) = e \cdot \phi(t)$ is continuous and differentiable on $]0,1[$. By the mean the value theorem

$$\begin{aligned} |\psi(1) - \psi(0)| &= |\psi'(t_0)| \\ |e \cdot (\phi(1) - \phi(0))| &= |e \cdot \phi'(t)| \\ \|\phi(1) - \phi(0)\| &\leq M \end{aligned}$$

2. Using the Hahn-Banach theorem, that is for a finite dimensional vector space V and $e \in V$ with $\|v\| = 1$ then there exists a linear function $\theta : V \to \mathbb{R}$ such that $\|\theta\| = 1$ and $\theta(e) = 1$. Now let $\psi(=)\,\theta(\phi(t))$ then

$$\begin{aligned} |\psi(1) - \psi(0)| &= |\psi'(t_0)| \\ |\theta(\phi(1) - \phi(0))| &= (\mathrm{D}\theta(\phi(t_0)))(\phi'(t_0)) \\ \|\phi(1) - \phi(0)\| &= \theta(\phi'(t_0)) \leq \|\theta\| \, \|\phi'(t_0)\| \leq M \end{aligned}$$

3. From Hoimander. For any ϵ consider the set T_ϵ.

$$T_\epsilon = \{t \in [0,1] \mid \forall s,\ 0 \leq s \leq t,\ \|\phi(s) - \phi(0)\| \leq (M+\epsilon)s + \epsilon\}$$

first note that $T_\epsilon = [0,c]$ and $c > 0$ because for $s = 0$ the inequality is strict and both sides are continuous with respect to s. We claim that $c = 1$ because otherwise $c < 1$ we have, by differentiability of ϕ, there exists a $\delta < 1 - c$ such that if

$$\begin{aligned} \|h\| < \delta \implies \|\phi(c+h) - \phi(c) - (\mathrm{D}\phi(c))(h)\| &\leq \epsilon \|h\| \\ \implies \|\phi(c+h) - \phi(c)\| &\leq \|h\| (\epsilon + \|\phi'(c)\|) \\ &\leq \|h\| (\epsilon + M) \end{aligned}$$

also since $c \in T_\epsilon$

$$\begin{aligned} \|\phi(c) - \phi(0)\| &< (M+\epsilon)c + \epsilon \\ \implies \|\phi(c+h) - \phi(0)\| &< (M+\epsilon)(c+h) + \epsilon \qquad 0 < h < \delta \end{aligned}$$

hence $c + h \in T_\epsilon$ which is a contradiction and thus $c = 1$. □

Proof. Let $\sigma : [0,1] \to U$ is the parameterization of the line connecting A to B, $\sigma(t) = (1-t)A + tB$. Let $\phi = f \circ \sigma$ then clearly ϕ is continuous on $[0,1]$ and differentiable on $]0,1[$ and we have

$$\begin{aligned} \phi'(t) &= (\mathrm{D}f(\sigma(t)))(\sigma'(t)) \\ &= (\mathrm{D}f(\sigma(t)))(B - A) \\ \implies \|\phi'(t)\| &\leq \|\mathrm{D}f(\sigma(t))\| \, \|B - A\|_V \leq M \|B - A\|_V \end{aligned}$$

therefore by the Lemma 1.21

$$\|f(B) - f(A)\|_W = \|\phi(1) - \phi(0)\|_W \leq M \|B - A\|_V$$

Corollary 1.22. *Let $U \subset V$ is connected and open and $f : U \to W$ is differentiable and $\mathrm{D}f(u) = 0$ for all $u \in U$ then f is constant.*

Proof. closedness easy, openness from the MVT. ■

Corollary 1.23. *Let V_1, V_2, W be finite dimensional normed vector space and $U \subset V_1 \times V_2$ is open such that for every $y \in V_2$ the intersection $(V_1 \times \{y\}) \cap U$ is connected. Assumne $f : U \to W$ is differentiable and $\mathrm{D}_{V_1} f(x, y) = 0$ for all $(x, y) \in U$ then for any two point $(x_1, y), (x_2, y) \in U$,$f(x_1, y) = f(x_2, y)$.*

1.2.2 Fundamental theorem of calculus

Theorem 1.24. *Let U be an open set of V such that for every $A, B \in U$ the line segment connecting A and B remains in U and let $\sigma : [0, 1] \to U$ be that line, $\sigma(t) = (1 - t)A + tB$, and lastly let $f : U \to W$ is continuously differentiable. Then*

$$f(B) - f(A) = T(B - A)$$

where T is

$$T = \int_0^1 \mathrm{D}f \circ \sigma(t) \, \mathrm{d}t$$

Proof. look at a matrix, integrate with respect to each element and apply ■

Theorem 1.25. *Consider the $T : U \times U \to \mathcal{L}(V, W)$ is continuous and such that*

$$f(B) - f(A) = (T(A, B))(B - A)$$

then $f \in \mathcal{C}^1$ and $\mathrm{D}f(A) = T(A, A)$

Proof. only need to proof f is differentiable and equals to that shit. ■

Corollary 1.26. *Let V be a normed finite dimensional vector space and U is open subset of V. If*

$$f : [a, b] \times U \to \mathbb{R}$$

is continuous then

$$F(y) \int_a^b f(x, y) \, \mathrm{d}x$$

is continuous. Furthermore, if $\dfrac{\partial f}{\partial y_i}$ exists and is continuous then $\dfrac{\partial F}{\partial y_i}$ exists and is continuous as well.

$$\frac{\partial F}{\partial y_i} = \int_a^b \frac{\partial f}{\partial y_i}(x, y) \, \mathrm{d}x$$

Proof. continuity implies there are balls, compactness implies there are finite balls, take minimum ■

1.2.3

Definition (Local convergence): A functional sequence f_n is **locally convergent** if for each $x \in U$ there exists a open set $x \in V \subset U$ such that $f_n|_V$ is uniformly convergent.

Theorem 1.27. *Let V, W be normed finite dimensional spaces, $U \subset V$ is open and connected, $x_0 \in U$ and $f_n : U \to W$ is a sequence of differentiable function that*

1. *$f_n(x_0)$ is convergent.*
2. *$\mathrm{D}f_n : U \to \mathcal{L}(V, W)$ is locally convergent to some function $g : U \to \mathcal{L}(V, W)$*

then the sequence f_n is locally convergent to $f : U \to W$ and $\mathrm{D}f = g$. Furthermore, because of connectedness of U for each $x \in U$, $f_n(x)$ is convergent.

Proof. take open ball W around x_0 such that $\mathrm{D}f_n|_W$ is uniformly convergent. then prove the first statement.

$$\|f_m(x) - f_n(x)\| \leq \|(f_m - f_n)(x) - (f_m - f_n)(x_0)\| + \|f_m(x_0) - f_n(x_0)\|$$

apply MVT here and make the bounds smaller using (2). Then prove the differentiability with e/3. To prove (3) use open/close argument. ∎

Corollary 1.28.