

# FUNDAMENTAL ALGEBRA & ANALYSIS

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# Contents

<b>1</b>	<b>Differential Calculus</b>	<b>1</b>
1.1	Landau symbol . . . . .	1
1.2	Differentiability . . . . .	4
1.3	Multilineal Mappings . . . . .	8
1.4	Convexity . . . . .	14
1.5	Mean Value Theorems . . . . .	17
1.6	Higher Differential . . . . .	22
1.7	Taylor's Formula . . . . .	27
1.8	Banach Space . . . . .	29
1.9	Local inversion . . . . .	33
1.10	Uniform Convergence . . . . .	42
1.11	Power Series . . . . .	48
1.12	Directional Differential . . . . .	53
<b>2</b>	<b>Integral Calculus</b>	<b>57</b>
2.1	Differential 1-form . . . . .	57
2.2	Primitive Functions . . . . .	59
2.3	Riesz Space . . . . .	60

# Chapter 1

# Differential Calculus

## 1.1 Landau symbol

In this section, we fix a complete valued field  $(K, |\cdot|)$  and a normed vector space  $(V, \|\cdot\|)$  over  $K$ .

**Definition 1.1.1** Let  $X$  be a set,  $f : X \rightarrow V$ ,  $g : X \rightarrow \mathbb{R}_{\geq 0}$  be mappings. Let  $Y \subseteq X$  be a subset. We use the expression

$$f(x) = \mathcal{O}(g(x))$$

to denote the statement:

$$\exists C > 0, \forall x \in Y, \|f(x)\| \leq C \cdot g(x).$$

Let  $\mathcal{F}$  be a filter on  $X$ , we use the expression

$$f(x) = \mathcal{O}(g(x)) \text{ along } \mathcal{F}$$

to denote the statement:

$$\exists C > 0, \exists A \in \mathcal{F}, \|f(x)\| \leq C \cdot g(x), \forall x \in A.$$

We use the expression

$$f(x) = o(g(x)) \text{ along } \mathcal{F}$$

to denote the statement:

$$\exists \varepsilon : X \rightarrow \mathbb{R}_{\geq 0}, \exists A \in \mathcal{F}, \lim_{\mathcal{F}} \varepsilon = 0 \text{ and } \forall x \in A, \|f(x)\| \leq \varepsilon(x)g(x).$$

**Proposition 1.1.2** Let  $X$  be a set and  $\mathcal{F}$  be a filter on  $X$ .

(1) Let  $f : X \rightarrow V, g : X \rightarrow \mathbb{R}_{\geq 0}$  be mappings. If  $f(x) = o(g(x))$  along  $\mathcal{F}$ , then  $f(x) = \mathcal{O}(g(x))$  along  $\mathcal{F}$ .

(2)

1. Let  $f_1 : X \rightarrow V, f_2 : X \rightarrow V$  and  $g : X \rightarrow \mathbb{R}_{\geq 0}$  be mappings. If  $f_1(x) = \mathcal{O}(g(x))$  and  $f_2(x) = \mathcal{O}(g(x))$  along  $\mathcal{F}$ , then  $f_1(x) + f_2(x) = \mathcal{O}(g(x))$  along  $\mathcal{F}$ .

2. Let  $f_1 : X \rightarrow V, f_2 : X \rightarrow V$  and  $g : X \rightarrow \mathbb{R}_{\geq 0}$  be mappings. If  $f_1(x) = o(g(x))$  and  $f_2(x) = o(g(x))$  along  $\mathcal{F}$ , then  $f_1(x) + f_2(x) = o(g(x))$  along  $\mathcal{F}$ .

(3) Let  $\lambda : X \rightarrow K, f : X \rightarrow V, g : X \rightarrow \mathbb{R}_{\geq 0}, h : X \rightarrow \mathbb{R}_{\geq 0}$  be mappings.

1. If  $\lambda(x) = \mathcal{O}(g(x))$  along  $\mathcal{F}, f(x) = \mathcal{O}(h(x))$  along  $\mathcal{F}$ , then

$$(\lambda f)(x) = \lambda(x)f(x) = \mathcal{O}(g(x)h(x)).$$

2. If  $\lambda(x) = \mathcal{O}(g(x))$  along  $\mathcal{F}, f(x) = o(h(x))$  along  $\mathcal{F}$ , or if  $\lambda(x) = o(g(x))$  along  $\mathcal{F}, f(x) = \mathcal{O}(h(x))$  along  $\mathcal{F}$ , then

$$\lambda(x)f(x) = o(g(x)h(x)).$$

### Proof

(1) We have  $\varepsilon : X \rightarrow \mathbb{R}_{\geq 0}, A \in \mathcal{F}$  such that  $\lim_{\mathcal{F}} \varepsilon = 0$  and  $\forall x \in A, \|f(x)\| \leq \varepsilon(x)g(x)$ . Since  $\lim_{\mathcal{F}} \varepsilon = 0$ , there exists  $B \in \mathcal{T}$  such that  $\forall x \in B, |\varepsilon(x)| < 1$ , hence  $\forall x \in A \cap B, \|f(x)\| \leq g(x)$ .

(2)

1.  $A_1, A_2 \in \mathcal{F}, C_1, C_2 > 0, \forall x \in A_1, \|f_1(x)\| \leq C_1g(x), \forall x \in A_2, \|f_2(x)\| \leq C_2g(x)$ . So  $f_1(x) + f_2(x) = \mathcal{O}(g(x))$

2. Let  $\varepsilon_1 : X \rightarrow \mathbb{R}_{\geq 0}, \varepsilon_2 : X \rightarrow \mathbb{R}_{\geq 0}, A \in \mathcal{F}, \lim_{\mathcal{F}} \varepsilon_1 = \lim_{\mathcal{F}} \varepsilon_2 = 0$ .  $\forall x \in A_1, \|f_1(x)\| \leq \varepsilon_1(x) \cdot g(x), \forall x \in A_2, \|f_2(x)\| \leq \varepsilon_2(x)g(x)$ . So  $\lim_{\mathcal{F}} \varepsilon_1 + \varepsilon_2 = 0$ .

$$\forall x \in A_1 \cap A_2, \|f_1(x) + f_2(x)\| \leq \|f_1(x)\| + \|f_2(x)\| \leq (\varepsilon_1(x) + \varepsilon_2(x))g(x).$$

(3)

1. There exists  $(C_1, C_2) \in \mathbb{R}_{>0}^2$  and  $(A_1, A_2) \in \mathcal{F}^2$  such that

$$\forall x \in A_1, |\lambda(x)| \leq C_1 g(x), \forall x \in A_2, \|f(x)\| \leq C_2 h(x).$$

Hence,

$$\forall x \in A_1 \cap A_2, \|(\lambda(x)f(x))\| \leq |\lambda(x)| \cdot \|f(x)\| \leq C_1 C_2 g(x) h(x).$$

2. We assume that

$$\lambda(x) = \mathcal{O}(g(x)) \text{ along } \mathcal{F}, f(x) = o(h(x)) \text{ along } \mathcal{F}.$$

There exists  $(A_1, A_2) \in \mathcal{F} \times \mathcal{F}, C \in \mathbb{R}_{\geq 0}$  and a mapping  $\varepsilon : X \rightarrow \mathbb{R}_{\geq 0}$  such that

$$\forall x \in A_1, |\lambda(x)| \leq C \cdot g(x), \forall x \in A_2, \|f(x)\| \leq \varepsilon(x) h(x).$$

Then one has

$$\lim_{\mathcal{F}} C\varepsilon(x) = 0$$

and

$$\forall x \in A_1 \cap A_2, \|(\lambda(x)f(x))\| \leq |\lambda(x)| \cdot \|f(x)\| \leq C \cdot g(x) \cdot \varepsilon(x) h(x)$$

As required. □

### Example 1.1.3

(1) Let  $I \subseteq \mathbb{N}$  infinite. Let  $(V, \|\cdot\|)$  be a normed vector space over complete valued field  $(K, |\cdot|)$ . Let  $\mathcal{F}$  be the filter on  $I$ . Let  $(x_n)_{n \in I} \in V^I, (b_n)_{n \in I} \in \mathbb{R}_{\geq 0}^I$ . We denote by

$$x_n = \mathcal{O}(b_n), n \in I, n \rightarrow +\infty$$

the statement  $x_n = \mathcal{O}(b_n)$  along  $\mathcal{F}$ . Namely,

$$\exists N \in \mathbb{N}, \exists C > 0, \forall n \in I_{\geq N}, \|x_n\| \leq C \cdot b_n.$$

$$x_n = o(b_n), n \in I, n \rightarrow +\infty$$

denotes the statement  $x_n = o(b_n)$  along  $\mathcal{F}$ . Namely,

$$\exists (\varepsilon_n)_{n \in I} \text{ such that } \lim_{n \rightarrow +\infty} \varepsilon_n = 0, \exists N \in \mathbb{N}, \forall n \in I_{\geq N}, \|x_n\| \leq \varepsilon_n \cdot b_n.$$

(2) Let  $(X, \mathcal{T})$  be a topological space,  $Y \subseteq X$ ,  $y_0 \in \bar{Y}$ . Let  $f : Y \rightarrow V$  and  $g : Y \rightarrow \mathbb{R}_{\geq 0}$  be mappings.

$$\mathcal{F} = \mathcal{V}_{y_0}(\mathcal{T})|_Y := \{U \cap Y \mid U \text{ is a neighborhood of } y_0\}$$

$f(y)\mathcal{O}(g(y))$ ,  $y \in Y$ ,  $y \rightarrow y_0$  denotes  $f(y) = \mathcal{O}(g(y))$  along  $\mathcal{F}$ . Namely,

$$\exists C > 0, \exists U \in \mathcal{V}_{y_0}(\mathcal{T}), \forall y \in U \cap Y, \|f(y)\| \leq C \cdot g(y).$$

$$f(y) = o(g(y)), y \in Y, y \rightarrow y_0$$

denotes  $f(y) = o(g(y))$  along  $\mathcal{F}$ . Namely,

$$\exists \varepsilon : Y \rightarrow \mathbb{R}_{\geq 0}, \lim_{y \in Y, y \rightarrow y_0} \varepsilon(y) = 0, \exists U \in \mathcal{V}_{y_0}(\mathcal{T}),$$

$$\forall y \in U \cap Y, \|f(y)\| \leq \varepsilon(y)g(y).$$

(3) Let  $\mathcal{F}$  be a filter on  $\mathbb{R}$  generated by subsets of the form  $[a, +\infty[$ . Let  $Y \subseteq \mathbb{R}$  not bounded from above. Let  $f : Y \rightarrow V$  and  $g : Y \rightarrow \mathbb{R}_{\geq 0}$  be mappings. Then

$$f(y) = \mathcal{O}(g(y)), y \in Y, y \rightarrow +\infty$$

denotes  $f(y) = \mathcal{O}(g(y))$  along  $\mathcal{F}|_Y$ . Namely,

$$\exists C > 0, \exists a \in \mathbb{R}, \forall y \in Y_{\geq a}, \|f(y)\| \leq C \cdot g(y).$$

$$f(y) = o(g(y)), y \in Y, y \rightarrow +\infty$$

denotes  $f(y) = o(g(y))$  along  $\mathcal{F}|_Y$ . Namely,

$$\exists \varepsilon : Y \rightarrow \mathbb{R}_{\geq 0}, \lim_{y \rightarrow +\infty} \varepsilon(y) = 0, \exists a \in \mathbb{R}, \forall y \in Y_{\geq a}, \|f(y)\| \leq \varepsilon(y)g(y).$$

## 1.2 Differentiability

We fix a complete valued field  $(K, |\cdot|)$ . We suppose that there exists  $a \in K^\times$ , such that  $|a| < 1$ . Let  $(E, \|\cdot\|_E)$  and  $(F, \|\cdot\|_F)$  be normed vector spaces over  $K$ .

$$\mathcal{L}(E, F) := \{\varphi \in \text{Hom}_K(E, F) \mid \|\varphi\| < +\infty\}.$$

$(\mathcal{L}(E, F), \|\cdot\|)$  is a normed vector space over  $K$ .

**Definition 1.2.1** Let  $U \subseteq E$  be subset and  $p \in U^\circ$ . We say that a mapping  $f : U \rightarrow F$  is **differentiable** at  $p$  if there exists  $\varphi \in \mathcal{L}(E, F)$  such that

$$f(p + h) - f(p) - \varphi(h) = o(\|h\|_E), \quad h \rightarrow 0_E.$$

If  $U = U^\circ$  and  $f$  is differentiable at every point of  $U$ , we say that  $f$  is **differentiable** on  $U$ .

**Proposition 1.2.2** Assume that  $f : U \rightarrow F$  is differentiable at  $p \in U^\circ$ . There exists a unique  $\varphi \in \mathcal{L}(E, F)$  such that

$$f(p + h) - f(p) - \varphi(h) = o(\|h\|_E), \quad h \rightarrow 0_E.$$

**Lemma 1.2.3**  $\forall \eta \in \mathcal{L}(E, F), \forall r > 0$ .

$$\|\eta\| = \sup_{x \in E, 0 < \|x\|_E \leq r} \frac{\|\eta(x)\|_F}{\|x\|_E} = \sup_{\substack{x \in E \\ 0 < \|x\|_E < r}} \frac{\|\eta(x)\|_F}{\|x\|_E}.$$

**Proof (of Lemma)**  $\|\eta\| \geq \sup_{x \in E, 0 < \|x\|_E < r} \frac{\|\eta(x)\|_F}{\|x\|_E}$ .  $\forall y \in E \setminus \{0\}, \|a^N y\|_E = |a|^N \|y\|_E < r$ .

$$\frac{\|\eta(a^N y)\|_F}{\|a^N y\|_E} = \frac{|a|^N \cdot \|\eta(y)\|_F}{|a|^N \cdot \|y\|_E} = \frac{\|\eta(y)\|_F}{\|y\|_E} \leq \sup_{\substack{x \in E \\ 0 < \|x\|_E < r}} \frac{\|\eta(x)\|_F}{\|x\|_E}.$$

□

**Proof (of Proposition)** Suppose  $\varphi, \psi \in \mathcal{L}(E, F)$  are such that

$$f(p + h) - f(p) - \varphi(h) = o(\|h\|_E), \quad h \rightarrow 0_E,$$

$$f(p + h) - f(p) - \psi(h) = o(\|h\|_E), \quad h \rightarrow 0_E.$$

Then

$$\varphi(h) - \psi(h) = o(\|h\|_E), \quad h \rightarrow 0_E.$$

$$\exists r > 0, \exists \varepsilon : \overline{B}(0_E, r) \rightarrow \mathbb{R}_{\geq 0} \text{ such that } \lim_{h \rightarrow 0_E} \varepsilon(h) = 0.$$

$$\forall h \in \overline{B}(0_E, r), \|(\varphi - \psi)(h)\|_F = \varepsilon(h)\|h\|_E.$$

$$\|\varphi - \psi\| = \sup_{\substack{x \in E \\ 0 < \|h\|_E < r'}} \frac{\|\varphi(h) - \psi(h)\|_F}{\|h\|_E} \leq \sup_{0 < \|h\|_E < r'} \varepsilon(h).$$

Taking the limit when  $r' \rightarrow 0$ , by  $\limsup_{h \rightarrow 0_E} \varepsilon(h) = 0$ . We get  $\|\varphi - \psi\| = 0$ , hence  $\varphi = \psi$ .  $\square$

**Definition 1.2.4** Let  $U \subseteq E$  and  $f : U \rightarrow F$  be a mapping that is differentiable at  $p \in U^\circ$ . The unique  $\varphi \in \mathcal{L}(E, F)$  such that

$$f(p + h) - f(p) - \varphi(h) = o(\|h\|_E), \quad h \rightarrow 0_E$$

is called the **differential** of  $f$  at  $p$  and is denoted as

$$D(f(p)).$$

### Example 1.2.5

(1)  $f : U \rightarrow F$ ,  $f(x) \equiv c$ ,  $c \in F$ .

$$f(x + h) - f(x) = 0_E = o(\|h\|_E).$$

So  $f$  is differentiable at every point of  $U$  and  $D(f(x)) = 0_F$ .

(2)  $\varphi \in \mathcal{L}(E, F)$ .

$$\varphi(p + h) - \varphi(p) - \varphi(h) = 0_F = o(\|h\|_E).$$

So  $\varphi$  is differentiable at every point of  $E$  and  $D(\varphi(p)) = \varphi$ .

(3) Let  $(F_i, \|\cdot\|_i)$  be normed vector spaces over  $K$ ,  $i \in \{1, \dots, n\}$ ,  $n \in \mathbb{N}$ . Suppose that  $F = F_1 \oplus \dots \oplus F_n$  and

$$\|(s_1, \dots, s_n)\|_F = \max\{\|s_1\|_1, \dots, \|s_n\|_n\}.$$

Let  $U \subseteq E$  be an open subset,  $f_i : U \rightarrow F_i$  be a mapping.

$$f : U \rightarrow F, \quad f(x) = (f_1(x), \dots, f_n(x)).$$

$$f(p + h) - f(p) = (f_1(p + h) - f_1(p), \dots, f_n(p + h) - f_n(p)).$$

Suppose that each  $f_i$  is differentiable

$$\begin{aligned} & f(p + h) - f(p) - (Df_1(p)(h), \dots, Df_n(p)(h))|_F \\ &= \max_{i \in \{1, \dots, n\}} \|f_i(p + h) - f_i(p) - Df_i(p)(h)\|_{F_i} \\ &= o(\|h\|_E). \end{aligned}$$

So  $f$  is differentiable at  $p$  and

$$Df(p)(h) = (Df_1(p)(h), \dots, Df_n(p)(h)).$$

(4) Suppose that  $E = K$ . If  $U \subseteq K$  is open and  $f : U \rightarrow F$  is differentiable at  $p \in U$ . We denote by  $f'(p)$  the element  $Df(p)(1) \in F$ .

$$f(p+h) - f(p) - Df(p)(h) = o(\|h\|_E).$$

So

$$\begin{aligned} f(p+h) - f(p) - hf'(p) &= o(\|h\|_E), \\ \frac{f(p+h) - f(p)}{h} - f'(p) &= o(1). \end{aligned}$$

That is,

$$\lim_{h \rightarrow 0} \frac{f(p+h) - f(p)}{h} = f'(p).$$

**Theorem 1.2.6** Let  $(E, \|\cdot\|_E)$ ,  $(F, \|\cdot\|_F)$ ,  $(G, \|\cdot\|_G)$  be normed vector spaces over a complete valued field  $(K, |\cdot|)$ . Let  $U \subseteq E$  and  $V \subseteq F$  be open subsets,  $f : U \rightarrow F$  and  $g : V \rightarrow G$  be mappings such that  $f(U) \subseteq V$ . Let  $p \in U$ . If  $f$  is differentiable at  $p$  and  $g$  is differentiable at  $f(p)$ , then  $g \circ f : U \rightarrow G$  is differentiable at  $p$  and

$$D(g \circ f)(p)(h) = Dg(f(p))(Df(p)(h)).$$

### Proof

$$f(p+h) - f(p) - Df(p)(h) = o(\|h\|_E),$$

so,

$$f(p+h) - f(p) = \mathcal{O}(\|h\|_E).$$

$$\begin{aligned} g(f(p+h)) - g(f(p)) - Dg(f(p))(f(p+h) - f(p)) \\ = o(\|f(p+h) - f(p)\|_F) = o(\mathcal{O}\|h\|_E) = o(\|h\|_E). \end{aligned}$$

$$\begin{aligned} & Dg(f(p))(f(p+h) - f(p)) - Dg(f(p))(Df(p)(h)) \\ &= Dg(f(p))(f(p+h) - f(p) - Df(p)(h)) \\ &= \mathcal{O}(o(\|h\|_E)) = o(\|h\|_E). \end{aligned}$$

So,

$$g(f(p+h)) - g(f(p)) - Dg(f(p))(Df(p)(h)) = o(\|h\|_E).$$

□

**Remark 1.2.7** If  $(E, \|\cdot\|_E) = (K, |\cdot|)$ ,

$$(g \circ f)'(p) = Dg(f(p))(f'(p)).$$

If  $E = F = K$ ,  $\|\cdot\|_E = \|\cdot\|_F = |\cdot|$ .

$$(g \circ f)'(p) = g'(f(p)) \cdot f'(p).$$

**Remark 1.2.8** Let  $U \subseteq E$  be open.  $f : U \rightarrow F_1 \times \cdots \times F_n$ . If  $f$  is differentiable at  $p \in U$ , for any  $i \in \{1, \dots, n\}$ , the mapping

$$f_i := \pi_i \circ f : U \rightarrow F_i$$

is differentiable at  $p$  and

$$D(f_i)(p)(h) = D\pi_i(f(p))(Df(p)(h)) = \pi_i(Df(p)(h)).$$

### 1.3 Multilineal Mappings

**Definition 1.3.1** Let  $K$  be a commutative unitary ring. Let  $E_1, \dots, E_n; F$  be  $K$ -modules. We say that

$$\varphi : E_1 \times \dots \times E_n \rightarrow F$$

is  $n$ -linear if for any  $i \in \{1, \dots, n\}$  and any  $(x_1, \dots, x_{i-1}, x_{i+1}, \dots, x_n) \in E_1 \times \dots \times E_{i-1} \times E_{i+1} \times \dots \times E_n$ , the mapping

$$E_i \rightarrow F, x_i \mapsto \varphi(x_1, \dots, x_{i-1}, x_i, x_{i+1}, \dots, x_n)$$

is a homomorphism of  $K$ -modules. ( $K$ -linear mapping)

If  $n = 1$ , 1-linear is also called linear.

If  $n = 2$ , 2-linear is also called bilinear.

#### Example 1.3.2

- (1)  $K \times K \rightarrow K$   $(a, b) \mapsto ab$  is bilinear.
- (2)  $K^n \times K^n \rightarrow K$   $(x, y) \mapsto x \cdot y = \sum_{i=1}^n x_i y_i$  is bilinear.
- (3)  $K \times \dots \times K \rightarrow K$   $(x_1, \dots, x_n) \mapsto x_1 \cdots x_n$  is  $n$ -linear.

**Definition 1.3.3** We denote by  $\text{Hom}_K^{(n)}(E_1 \times \dots \times E_n, F)$  the set of  $n$ -linear mappings from  $E_1 \times \dots \times E_n$  to  $F$ .

**Definition 1.3.4** Let  $(K, |\cdot|)$  be a complete valued field.

Let  $(E_1, \|\cdot\|_{E_1}), \dots, (E_n, \|\cdot\|_{E_n}), (F, \|\cdot\|_F)$  be normed vector spaces over  $K$ . For any  $\varphi \in \text{Hom}_K^{(n)}(E_1 \times \dots \times E_n, F)$ , we define

$$\|\varphi\| := \sup_{\substack{x_i \in E_i \setminus \{0\} \\ i \in \{1, \dots, n\}}} \frac{\|\varphi(x_1, \dots, x_n)\|_F}{\|x_1\|_{E_1} \cdots \|x_n\|_{E_n}}.$$

We denote by  $\mathcal{L}(E_1 \times \dots \times E_n, F)$  the set

$$\{\varphi \in \text{Hom}_K^{(n)}(E_1 \times \dots \times E_n, F) \mid \|\varphi\| < +\infty\}.$$

$\mathcal{L}^{(n)}(E_1 \times \dots \times E_n, F)$  is a normed vector space of  $\text{Hom}_K^{(n)}(E_1 \times \dots \times E_n, F)$ , and the norm is  $\|\cdot\|$ .

**Theorem 1.3.5** Let  $(E_1, \|\cdot\|_{E_1}), \dots, (E_n, \|\cdot\|_{E_n}), (F, \|\cdot\|_F)$  be normed vector spaces over  $K$ . Let  $\varphi \in \mathcal{L}^{(n)}(E_1 \times \dots \times E_n, F)$ . For any  $p = (p_1, \dots, p_n) \in E_1 \times \dots \times E_n$ ,  $\varphi$  is differentiable at  $p$  and

$$D\varphi(p)(h_1, \dots, h_n) = \sum_{i=1}^n \varphi(p_1, \dots, p_{i-1}, h_i, p_{i+1}, \dots, p_n).$$

### Proof

$$\begin{aligned} \varphi(p+h) - \varphi(p) &= \sum_{i=1}^n \varphi(p_1 + h_1, \dots, p_{i-1} + h_{i-1}, p_i + h_i, p_{i+1}, \dots, p_n) \\ &\quad - \varphi(p_1 + h_1, \dots, p_{i-1} + h_{i-1}, p_i, p_{i+1}, \dots, p_n) \end{aligned}$$

$$\begin{aligned} &\varphi(p_1 + h_1, \dots, p_{i-1} + h_{i-1}, h_i, p_{i+1}, \dots, p_n) \\ &\quad - \varphi(p_1, \dots, p_{i-1}, h_i, p_{i+1}, \dots, p_n) \\ &= \sum_{j=1}^{i-1} \varphi(p_1 + h_1, \dots, p_{j-1} + h_{j-1}, h_j, p_{j+1}, \dots, h_i, \dots, p_n). \end{aligned}$$

$$\begin{aligned}
& \|\varphi(p_1 + h_1, \dots, p_{j-1} + h_{j-1}, h_j, p_{j+1}, \dots, h_i, \dots, p_n)\|_F \\
& \leq \|\varphi\| \cdot \prod_{k=1}^{j-1} \|p_k + h_k\|_{E_k} \cdot \|h_j\|_{E_j} \cdot \prod_{k=j+1}^{i-1} \|p_k\|_{E_k} \cdot \|h_i\|_{E_i} \cdot \prod_{k=i+1}^n \|p_k\|_{E_k} \\
& = \mathcal{O}(\|h\|^2) = o(h), \quad h \rightarrow 0.
\end{aligned}$$

□

**Definition 1.3.6** Let  $K$  be a commutative unitary ring.  $n \in \mathbb{N}_{\geq 1}$ ,  $E$  and  $F$  be  $K$ -modules. We say that

$$\varphi \in \text{Hom}_K^{(n)}(E_1 \times \dots \times E_n, F)$$

is **symmetric** if

$$\forall \sigma \in \mathfrak{S}_{\{1, \dots, n\}}, \quad \forall (x_1, \dots, x_n) \in E^n, \quad \varphi(x_{\sigma(1)}, \dots, x_{\sigma(n)}) = \varphi(x_1, \dots, x_n).$$

Let  $P : E \rightarrow F$  be a mapping. If there exists a symmetric  $\varphi \in \text{Hom}_K^{(n)}(E \times \dots \times E, F)$  such that

$$\forall x \in E, \quad P(x) = \varphi(x, \dots, x),$$

we say that  $P$  is a **homogeneous polynomial mapping of degree  $n$** .

If  $F = K$ ,  $P$  is called a **homogeneous polynomial** on  $E$ . The symmetric polynomial mapping  $\varphi$  is called the **polarization** of  $P$ .

**Proposition 1.3.7** Let  $(K, |\cdot|)$  be a complete valued field that is non-trivial. Let  $(E, \|\cdot\|_E)$  and  $(F, \|\cdot\|_F)$  be normed vector spaces over  $K$ . Assume that  $P : E \rightarrow F$  is a homogeneous polynomial mapping of degree  $n$ . Which admits a bounded polarization  $\varphi$ . Then  $P$  is differentiable on  $E$  and,

$$\forall (x, h) \in E \times E, \quad DP(x)(h) = n\varphi(x, \dots, x, h).$$

**Proof** Let

$$\begin{aligned}
\Delta : E & \longrightarrow E^n, \\
x & \longmapsto (x, \dots, x).
\end{aligned}$$

Then  $P = \varphi \circ \Delta$ . Since  $\varphi$  and  $\Delta$  are differentiable, so it is  $P$ .

Moreover,

$$\begin{aligned}
 DP(x)(h) &= D\varphi(\Delta(x)) (D\Delta(x)(h)) \\
 &= D\varphi(x, \dots, x)(h, \dots, h) \\
 &= \sum_{i=1}^n \varphi(x, \dots, x, h, x, \dots, x) \\
 &= n\varphi(x, \dots, x, h).
 \end{aligned}$$

□

**Remark 1.3.8** Assume that  $E = K$ . Let  $P : K \rightarrow F$  be a homogeneous polynomial mapping of degree  $n$  of form  $P(x) = x^n s$ , where  $s \in F$ . Its polarization is of the form

$$\varphi(a_1, \dots, a_n) = a_1 \cdots a_n s.$$

$$P'(x) = DP(x)(1) = n\varphi(x, \dots, x, 1) = nx^{n-1}s.$$

**Proposition 1.3.9** Let  $n$  be a positive integer  $n \geq 2$ . Let  $(E_1, \|\cdot\|_1), \dots, (E_n, \|\cdot\|_n), (F, \|\cdot\|_F)$  be normed vector spaces. For any  $i \in \{1, \dots, n\}$ , the mapping

$$\mathcal{L}^{(n)}(E_1, \dots, E_n; F) \xrightarrow{f} \mathcal{L}^{(i)}(E_1, \dots, E_i, \mathcal{L}^{(n-i)}(E_{i+1}, \dots, E_n; F))$$

$$\varphi \longmapsto \left( \begin{array}{c} E_1 \times \dots \times E_n \xrightarrow{\mathcal{L}^{(i)}(E_{i+1}, \dots, E_n; F)} \\ (x_1, \dots, x_i) \longmapsto \left( \begin{array}{c} (x_{i+1}, \dots, x_n) \longmapsto \varphi(x_1, \dots, x_n) \\ E_{i+1} \times \dots \times E_n \in F \end{array} \right) \end{array} \right)$$

is an isomorphism of vector spaces over  $K$ , and in the same time an isometry, ( $\|f(\varphi)\| = \|\varphi\|$ ).

**Remark 1.3.10**

$$\forall (x_1, \dots, x_n) \in E_1 \times \dots \times E_n, f(\varphi)(x_1, \dots, x_i)(x_{i+1}, \dots, x_n) = \varphi(x_1, \dots, x_n)$$

**Proof**  $\forall (x_1, \dots, x_n) \in E_1 \times \dots \times E_n$ ,

$$\begin{aligned}
 \varphi(x_1, \dots, x_n) : E_{i+1} \times \dots \times E_n &\longrightarrow F \text{ is bounded} \\
 (x_{i+1}, \dots, x_n) &\longmapsto \varphi(x_1, \dots, x_n)
 \end{aligned}$$

Since

$$\|\varphi(x_1, \dots, x_n)\|_F \leq (\|\varphi\| \cdot \|x_1\| \dots \|x_i\|) \|x_{i+1}\| \dots \|x_n\|.$$

$$\begin{aligned}
\|f(\varphi)\| &= \sup_{x_j \in E_j \setminus \{0\}, j=1, \dots, i} \frac{\|\varphi(x_1, \dots, x_i, \cdot)\|}{\|x_1\|_{E_1} \cdots \|x_n\|_{E_i}} \\
&= \sup_{x_j \in E_j \setminus \{0\}, j=1, \dots, i} \sup_{x_k \in E_k \setminus \{0\}, k=i+1, \dots, n} \frac{\|\varphi(x_1, \dots, x_n)\|_F}{\|x_1\|_{E_1} \cdots \|x_n\|_{E_n}} \\
&= \|\varphi\|.
\end{aligned}$$

Hence  $f$  is injective. ( $\ker(f) = \{0\}$ )

For any  $\psi \in \mathcal{L}^{(i)}(E_1, \dots, E_i, \mathcal{L}^{(n-i)}(E_{i+1}, \dots, E_n))$ ,

$$\begin{aligned}
\varphi : E_1 \times \dots \times E_n &\longrightarrow F \\
(x_1, \dots, x_n) &\longmapsto \psi(x_1, \dots, x_i)(x_{i+1}, \dots, x_n)
\end{aligned}$$

belongs to  $\mathcal{L}^{(n)}(E_1, \dots, E_n; F)$  and  $f(\varphi) = \psi$ . So  $f$  is surjective.  $\square$

**Corollary 1.3.11** If  $E_1, \dots, E_n$  are all finite dimensional, then

$$\mathcal{L}^{(n)}(E_1, \dots, E_n; F) = \text{Hom}_K^{(n)}(E_1 \times \dots \times E_n, F).$$

**Proof** If  $n = 1$ ,  $\mathcal{L}(E_1, F) = \text{Hom}_K(E_1, F)$ .

$$\begin{aligned}
\mathcal{L}^{(n)}(E_1, \dots, E_n; F) &\cong \mathcal{L}(E_1, \mathcal{L}^{(n-1)}(E_2, \dots, E_n; F)) \\
&= \text{Hom}_K(E_1, \text{Hom}_K^{(n-1)}(E_2 \times \dots \times E_n, F)) \\
&\cong \text{Hom}_K^{(n)}(E_1 \times \dots \times E_n, F).
\end{aligned}$$

$\square$

Let  $(K, |\cdot|)$  be a complete nontrivial valued field. Let  $(E, \|\cdot\|_E)$  and  $(F, \|\cdot\|_F)$  be normed vector spaces over  $K$ .

**Definition 1.3.12** Let  $U \subseteq E$  be an open subset of  $E$ ,  $f : U \rightarrow F$  be a mapping.

If  $f$  is continuous on  $U$ , we say that  $f$  is **of class  $\mathcal{C}^0$**  and we denote by

$$\text{D}^0 f$$

the mapping  $f : U \rightarrow F$ . Denote by

$$\mathcal{C}^0(U, F)$$

the set of mappings from  $U$  to  $F$ .

$$U \xrightarrow{(f,g)} K \times K \xrightarrow{\times} K$$

$$p \longmapsto (f(p), g(p)) \longmapsto f(p) \times g(p)$$

Let  $p \in U$ . If  $f$  is differentiable on an open neighborhood  $V$  of  $p$  such that  $V \subseteq U$ . Then

$$\begin{aligned} Df : V &\longrightarrow \mathcal{L}(E, F) \\ x &\longmapsto Df(x) \end{aligned}$$

is a mapping. If  $Df$  is  $(n-1)$ -times differentiable at  $p$ , we say that  $f$  is **of class  $\mathcal{C}^n$**  at  $p$ . If  $f$  is of class  $\mathcal{C}^n$  at every point of  $U$ , we say that  $f$  is **n-times differentiable** at  $p$ . We denote by

$$D^n f(p) \in \mathcal{L}^{(n)}(E, \dots, E, F)$$

the  $n$ -linear mapping that sends  $(h_1, \dots, h_n) \in E^n$  to

$$D^{n-1}(Df)(p)(h_1, \dots, h_{n-1})(h_n) \in F.$$

### Remark 1.3.13

$$D^n f(p)(h_1, \dots, h_n) = D^i(D^{n-i} f)(p)(h_1, \dots, h_i)(h_{i+1}, \dots, h_n).$$

## 1.4 Convexity

**Definition 1.4.1** Let  $E$  be a vector space over a field  $K$ .  $S \subseteq E$  be a non-empty subset.

We call affine combination of elements of  $S$  any element of  $E$  of the form

$$a_1s_1 + a_2s_2 + \cdots + a_ns_n,$$

where  $n \in \mathbb{N}_{\geq 1}$ ,  $s_1, \dots, s_n \in S$ ,  $a_1, \dots, a_n \in K$  such that

$$a_1 + a_2 + \cdots + a_n = 1.$$

We denote by  $\text{Aff}(S)$  the set of all affine combinations of elements of  $S$ . One has  $S \subseteq \text{Aff}(S)$ .  $\text{Aff}(S)$  is called the affine hull of  $S$ .

If  $S = \text{Aff}(S)$ , we say that  $S$  is an affine subspace of  $E$ .

### Proposition 1.4.2

(1) If  $F$  is a vector subspace of  $E$ ,  $\forall p \in E$ ,

$$p + F = \{p + x \mid x \in F\}$$

is an affine subspace of  $E$ .

(2) If  $A \subseteq E$  is an affine subspace of  $E$ . For any  $p \in A$ ,

$$A - p := \{x - p \mid x \in A\}$$

is a vector subspace of  $E$ , which is not dependent on the choice of  $p$ . We call it the vector space **associated** with  $A$ .

### Proof

(1) Let  $(x_1, \dots, x_n) \in F^n$ ,  $(a_1, \dots, a_n) \in K^n$ , such that  $\sum_{i=1}^n a_i = 1$ . Then

$$\begin{aligned} \sum_{i=1}^n a_i(p + x_i) &= p \cdot \sum_{i=1}^n a_i + \sum_{i=1}^n a_i x_i \\ &= p + \sum_{i=1}^n a_i x_i \in p + F. \end{aligned}$$

(2) Let  $(x_1, \dots, x_n) \in A^n, (b_1, \dots, b_n) \in K^n$ .

$$\begin{aligned} \sum_{i=1}^n b_i(x_i - p) &= \sum_{i=1}^n b_i x_i - \left( \sum_{i=1}^n b_i \right) p \\ &= \left( \sum_{i=1}^n b_i x_i + \left( 1 - \sum_{i=1}^n b_i \right) p \right) - p \\ &\in A - p. \end{aligned}$$

Let  $q \in A$ ,  $\forall x \in A$ ,  $x - p = (x - q) + (q - p) \in A - q$ . So  $A - p \subseteq A - q$ . By symmetry,  $A - q \subseteq A - p$ . Hence  $A - p = A - q$ .  $\square$

**Example 1.4.3** Let  $A$  be an  $m$  by  $p$  matrix with coefficients in  $\mathbb{R}$ . Let  $(b_1, \dots, b_n) \in E^m$ . Consider the linear equation

$$A \begin{pmatrix} x_1 \\ \vdots \\ x_p \end{pmatrix} = \begin{pmatrix} b_1 \\ \vdots \\ b_m \end{pmatrix}.$$

The solution set is

$$S := \{(x_1, \dots, x_p) \in E^p \mid A \begin{pmatrix} x_1 \\ \vdots \\ x_p \end{pmatrix} = \begin{pmatrix} b_1 \\ \vdots \\ b_m \end{pmatrix}\}.$$

Claim:  $S$  is an affine subspace of  $E^p$ .

**Proof** Let  $\underline{x}^{(1)}, \dots, \underline{x}^{(n)}$  be elements of  $S$ , where  $\underline{x}^{(i)} = (x_1^{(i)}, \dots, x_p^{(i)})$ . Let  $(a_1, \dots, a_n) \in \mathbb{R}^n$ ,  $\underline{x} = a_1 \underline{x}^{(1)} + \dots + a_n \underline{x}^{(n)}$ .

$$A \begin{pmatrix} x_1 \\ \vdots \\ x_p \end{pmatrix} = A \left( a_1 \begin{pmatrix} x_1^{(1)} \\ \vdots \\ x_p^{(1)} \end{pmatrix} + \dots + a_n \begin{pmatrix} x_1^{(n)} \\ \vdots \\ x_p^{(n)} \end{pmatrix} \right).$$

$$a_1 A \begin{pmatrix} x_1^{(1)} \\ \vdots \\ x_p^{(1)} \end{pmatrix} + \dots + a_n A \begin{pmatrix} x_1^{(n)} \\ \vdots \\ x_p^{(n)} \end{pmatrix} = (a_1 + \dots + a_n) \begin{pmatrix} b_1 \\ \vdots \\ b_n \end{pmatrix} = \begin{pmatrix} b_1 \\ \vdots \\ b_n \end{pmatrix}.$$

$$x_j = a_1 x_j^{(1)} + \dots + a_n x_j^{(n)}.$$

$\square$

**Proposition 1.4.4** Let  $S \subseteq E$ . Then  $\text{Aff}(S)$  is the smallest affine subspace of  $E$  containing  $S$ .

### Proof

Let  $A \subseteq E$  be an affine subspace containing  $S$ .  $\forall n \in \mathbb{N}_{\geq 1}, \forall (x_1, \dots, x_n) \in S^n \subseteq A^n, (a_1, \dots, a_n) \in \mathbb{R}$ ,  $a_1 + \dots + a_n = 1$ , one has

$$\sum_{i=1}^n a_i x_i \in A.$$

So  $\text{Aff}(S) \subseteq A$ .

To show that  $\text{Aff}(S)$  is an affine subspace containing  $S$ , it is sufficient to check that  $\text{Aff}(S)$  is an affine subspace.

If  $S = \emptyset$ , then  $\text{Aff}(S) = \emptyset$ . It is an affine subspace.

Suppose that  $S \neq \emptyset, p \in S$ . We prove that  $\text{Aff}(S) - p$  is equal to  $\text{Span}_{\mathbb{R}}(S - p)$ . Let  $y = a_1 x_1 + \dots + a_n x_n \in \text{Aff}(S)$ .

$$y - p = a_1(x_1 - p) + \dots + a_n(x_n - p) \in \text{Span}_{\mathbb{R}}(S - p).$$

Let  $(x_1, \dots, x_n) \in S^n, (b_1, \dots, b_n) \in \mathbb{R}^n$ .

$$\sum_{i=1}^n b_i(x_i - p) = \left( \sum_{i=1}^n b_i x_i + \left( 1 - \sum_{i=1}^n b_i \right) p \right) - p \in \text{Aff}(S) - p.$$

□

**Definition 1.4.5** Let  $S \subseteq E$ . We call **convex combination** of elements of  $S$  any element of  $E$  of the form

$$a_1 s_1 + a_2 s_2 + \dots + a_n s_n,$$

where  $n \in \mathbb{N}_{\geq 1}, s_1, \dots, s_n \in S, a_1, \dots, a_n \in \mathbb{R}_{\geq 0}$  such that

$$a_1 + a_2 + \dots + a_n = 1.$$

We denote by  $\text{Conv}(S)$  the set of all convex combinations of elements of  $S$ .  $\text{Conv}(S)$  is called the **convex hull** of  $S$ . One has  $S \subseteq \text{Conv}(S) \subseteq \text{Aff}(S)$ .

**Proposition 1.4.6** Let  $E$  be a vector space over  $\mathbb{R}$  and  $C \subseteq E$ . Then  $C$  is convex

if and only if

$$\forall(x, y) \in C^2, \forall\lambda \in [0, 1], \lambda x + (1 - \lambda)y \in C.$$

**Proof** It is sufficient to check “ $\Leftarrow$ ”. We prove by induction on  $n$  that

$$\forall n \in \mathbb{N}_{\geq 1}, \forall(x_1, \dots, x_n) \in C^n, \forall(a_1, \dots, a_n) \in \mathbb{R}_{\geq 0}^n, \sum_{i=1}^n a_i = 1, \sum_{i=1}^n a_i x_i \in C.$$

The case where  $n = 1$  is trivial. The case where  $n = 2$  comes from the hypothesis. Suppose  $n \geq 3$  in assuming that the statement holds for any integer less than  $n$ . If  $a_n = 1$ , then  $a_1 = \dots = a_{n-1} = 0$ , so  $\sum_{i=1}^n a_i x_i = x_n \in C$ . If  $a_n < 1$ , we have  $a_1 + \dots + a_{n-1} = 1 - a_n > 0$ . By the induction hypothesis,

$$x := \sum_{i=0}^{n-1} \frac{a_i}{1 - a_n} x_i \in C.$$

Taking  $y = x_n, t = 1 - a_n$ ,

$$C \ni tx + (1 - t)y = \sum_{i=1}^n a_i x_i.$$

□

## 1.5 Mean Value Theorems

**Theorem 1.5.1** (Mean Value Inequality) Let  $(F, \|\cdot\|_F)$  be normed vector spaces over  $\mathbb{R}$ . Let  $(a, b) \in \mathbb{R}^2$  such that  $a < b$ . Let  $f : [a, b] \rightarrow F$  be a continuous mapping that is differentiable on  $]a, b[$ . Then

$$\|f(b) - f(a)\|_F \leq (b - a) \cdot \sup_{t \in ]a, b[} \|f'(t)\|_F.$$

**Proof** We may suppose that  $\sup_{t \in ]a, b[} \|f'(t)\|_F < +\infty$ . Take

$$M > \sup_{t \in ]a, b[} \|f'(t)\|_F.$$

Let  $m = \frac{a+b}{2}$ . Let

$$J = \{x \in [m, b] \mid \forall t \in [m, x], \|f(t) - f(m)\|_F \leq M(t - m)\}.$$

It is an interval containing  $m$ . So it is of the form

$$[m, c[ \text{ or } [m, c]$$

$$\forall t \in [m, c[, \|f(t) - f(m)\|_F \leq M(t - m).$$

Taking the limit  $t < c, t \rightarrow c$ , we get  $c \in J$ . So  $J = [m, c]$ . We then check  $c = b$ .

If  $c \neq b$ , then  $c \in ]a, b[$ , so  $f$  is differentiable at  $c$ . That is

$$\|f(c + h) - f(c)\|_F = \|f'(c)h + o(\|h\|)\|_F \leq \|f'(c)\|_F h + o(\|h\|), h \rightarrow 0.$$

Since  $M > \|f'(c)\|_F$ ,  $\exists h_0 > 0$  such that

$$\forall h \in ]0, h_0], \|f(c + h) - f(c)\|_F \leq Mh.$$

$$\begin{aligned} \|f(c + h) - f(m)\| &\leq \|f(c + h) - f(c)\| + \|f(c) - f(m)\| \\ &\leq Mh + M(c - m) = M(c + h - m). \end{aligned}$$

So  $[m, c + h_0] \subseteq J$ , contradiction. Thus  $b = c$ .  $\|f(b) - f(m)\|_F \leq M(b - m)$ .

By the same reason,  $\|f(m) - f(a)\|_F \leq M(m - a)$ . So

$$\|f(b) - f(a)\|_F \leq \|f(b) - f(m)\|_F + \|f(m) - f(a)\|_F \leq M(b - a).$$

Taking the limit when  $M \rightarrow \sup_{t \in ]a, b[} \|f'(t)\|_F$ , we get the announced result.  $\square$

**Corollary 1.5.2** Let  $(E, \|\cdot\|_E)$  and  $(F, \|\cdot\|_F)$  be normed vector spaces over  $\mathbb{R}$ .  $U \subseteq E$  be an open subset, and  $(x, y) \in U^2$  such that

$$[x, y] = \{tx + (1 - t)y \mid t \in [0, 1]\} \subseteq U.$$

Let  $f : U \rightarrow F$  be a differentiable mapping. Then

$$\|f(x) - f(y)\|_F \leq \left( \sup_{z \in ]x, y[} \|\mathrm{D}f(z)\| \right) \cdot \|x - y\|_E.$$

**Proof** Let

$$\begin{aligned} g : [0, 1] &\longrightarrow U \\ t &\longmapsto tx + (1 - t)y. \end{aligned}$$

$$g(0) = x, g(1) = y, g'(t) = x - y.$$

Then,

$$(f \circ g)'(t) = Df(g(t))(x - y),$$

$$D(f \circ g)(t)(1) = Df(g(t))(Dg(t)(1)).$$

By the theorem,

$$\begin{aligned} \|f(x) - f(y)\|_F &= \|f(g(1)) - f(g(0))\|_F \\ &\leq \sup_{t \in ]0,1[} \|Df(g(t))(x - y)\|_F \\ &\leq \sup_{t \in ]0,1[} |Df(g(t))| \cdot \|x - y\|_E \\ &= \sup_{z \in [x,y]} \|Df(z)\| \cdot \|x - y\|_E. \end{aligned}$$

□

**Definition 1.5.3** Let  $(X, \mathcal{T})$  be a topological space,  $p \in X$ . Let  $U$  be a neighborhood of  $p$  and  $f : U \rightarrow \mathbb{R}$  be a mapping. If there exists a neighborhood  $V$  of  $p$  such that  $p \in V \subseteq U$  and

$$\forall x \in V, f(p) \geq f(x),$$

we say that  $p$  is a **local maximum point** of  $f$  on  $U$ .

If  $p$  is a local maximum point or a local minimum point, we say that  $p$  is a **local extremum** of  $f$  on  $U$ .

If  $(E, \|\cdot\|_E)$  and  $(F, \|\cdot\|_F)$  are normed vector spaces.  $U \subseteq E$  open,  $f : U \rightarrow F$  is differentiable. If  $p \in U$  is such that

$$Df(p) = 0 \in \mathcal{L}(E, F),$$

we say that  $p$  is a **critical point** of  $f$ .

**Theorem 1.5.4** Let  $(E, \|\cdot\|)$  be a normed vector space over  $\mathbb{R}$ .  $U \subseteq E$  be an open subset,  $f : U \rightarrow \mathbb{R}$  be a differentiable mapping. If  $p \in U$  is a local extremum point of  $f$ , then it is a critical point ( $Df(p) = 0$ ).

**Proof** There exists  $r > 0$  such that  $p + B(0, r) \subseteq U$  and

$$(h \in B(0, r)) \mapsto f(p + h) - f(p) \in \mathbb{R}$$

does not change the sign.

$\forall h \in B(0, r), \forall \in [0, 1],$

$$(f(p + th) - f(p))(f(p - th) - f(p)) \geq 0.$$

Taking the limit when  $t \rightarrow 0, -Df(p)(h)^2 \geq 0$ . So  $Df(p)(h) = 0$ .  $\square$

**Theorem 1.5.5** (Rolle) Let  $(a, b) \in \mathbb{R}^2, a < b$ . Let  $f : [a, b] \rightarrow \mathbb{R}$  be a continuous mapping that is differentiable on  $]a, b[$ . If  $f(a) = f(b)$ , then

$$\exists t \in ]a, b[, f'(t) = 0.$$

**Proof** If there exists  $t$  which is in  $]a, b[$  and is an extremum point of  $f$ , then  $f'(t) = 0$ . Since  $[a, b]$  is compact and  $f$  is continuous, so  $f$  attains its maximum and minimum.

If the extremum points of  $f$  are in  $\{a, b\}$ . Since  $f(a) = f(b)$ ,  $f$  is compact, so  $f'(t) = 0$  on  $]a, b[$ .  $\square$

**Theorem 1.5.6** (Gronwall inequality) Let  $(F, \|\cdot\|)$  be a normed vector space over  $\mathbb{R}$ ,  $(a, b) \in \mathbb{R}^2, a < b$ . Let  $f : [a, b] \rightarrow F$  and  $g : [a, b] \rightarrow \mathbb{R}$  be differentiable mappings on  $]a, b[$ . If  $\forall t \in ]a, b[, \|f'(t)\| \leq g'(t)$ , then

$$\|f(b) - f(a)\|_F \leq g(b) - g(a).$$

**Proof** Let  $m \in ]a, b[$ . Let  $\varepsilon > 0$ ,

$$J := \{t \in [m, b] \mid \forall s \in [m, t], \|f(s) - f(m)\|_F \leq g(s) - g(m) + \varepsilon(s - m)\}.$$

Since  $f$  and  $g$  are continuous,  $J$  is a closed interval of the form  $[m, c]$ .

If  $c < b$ ,

$$\begin{aligned} f(c + h) &= f(c) + hf'(c) + o(h), \\ g(c + h) &= g(c) + hg'(c) + o(h), \quad h > 0, h \rightarrow 0. \end{aligned}$$

$\exists \delta > 0$ , such that  $[c, c + \delta] \subseteq [c, b]$  and  $\forall h \in [0, \delta]$ ,

$$\|f(c + h) - f(c)\| \leq h\|f'(c)\| + \frac{\varepsilon}{2}h.$$

$$g(c + h) - g(c) \geq hg'(c) - \frac{\varepsilon}{2}h.$$

So,

$$\|f(c + h) - f(c)\| \leq g(c + h) - g(c) + \varepsilon h.$$

By the triangle inequality,

$$\|f(c+h) - f(m)\| \leq g(c+h) - g(m) + \varepsilon(c+h-m).$$

So  $J \supseteq [m, c+\delta]$ , contradiction.

Therefore  $c = b$ .

$$\|f(b) - f(m)\| \leq g(b) - g(m) + \varepsilon(b-m).$$

A similar argument shows that

$$\|f(m) - f(a)\| \leq g(m) - g(a) + \varepsilon(m-a).$$

Hence,

$$\|f(b) - f(a)\| \leq g(b) - g(a) + \varepsilon(b-a).$$

$$\|f(c+h) - f(c) + hf'(c)\| \leq \varphi(h)h, \lim_{h \rightarrow 0} \varphi(h) = 0.$$

$$\exists \delta > 0, \forall h > 0, 0 \leq h < \delta \Rightarrow |\varphi(h)| \leq \frac{\varepsilon}{2}.$$

□

**Theorem 1.5.7** (Mean value theorem of Lagrange) Let  $(a, b) \in \mathbb{R}^2$ ,  $a < b$ . Let  $f : [a, b] \rightarrow \mathbb{R}$  be a continuous mapping that is differentiable on  $]a, b[$ . Then

$$\exists \xi \in ]a, b[, f(b) - f(a) = f'(\xi)(b-a).$$

**Proof** Let  $g : [a, b] \rightarrow \mathbb{R}$ .

$$g(t) := f(b) - f(t) + C(b-t), \text{ where } C = -\frac{f(b) - f(a)}{b-a}.$$

Then  $g(a) = g(b) = 0$ ,  $g'(t) = -f'(t) - C$ .

$$\exists \xi \in ]a, b[, g'(\xi) = 0, f'(\xi) = -C = \frac{f(b) - f(a)}{b-a}.$$

□

**Theorem 1.5.8** (Darboux) Let  $I$  be an open interval in  $\mathbb{R}$  and  $f : I \rightarrow \mathbb{R}$  be a differentiable mapping. Then  $f'(I)$  is an interval.

**Proof** Let  $a, b$  be two elements in  $I$  such that  $a < b$ . Let

$$\begin{aligned} g : [a, b] &\longrightarrow \mathbb{R} \\ t &\longmapsto \begin{cases} \frac{f(t) - f(a)}{t - a}, & t \neq a \\ f'(a), & t = a \end{cases} \end{aligned}$$

$g$  is continuous, and  $g([a, b])$  is an interval. By the mean value theorem of Lagrange,  $g([a, b]) \subseteq f'(I)$ .

Let

$$\begin{aligned} h : [a, b] &\longrightarrow \mathbb{R} \\ t &\longmapsto \begin{cases} \frac{f(t) - f(b)}{t - b}, & t \neq b \\ f'(b), & t = b \end{cases} \end{aligned}$$

$h([a, b])$  is an interval contained in  $f'(I)$ .

$h([a, b]) \cup g([a, b])$  is an interval since

$$\frac{f(b) - f(a)}{b - a} \in h([a, b]) \cap g([a, b]),$$

$$\{f'(a), f'(b)\} \subseteq h([a, b]) \cup g([a, b]).$$

So the interval linking  $f'(a), f'(b)$  is contained in  $f'(I)$ . Hence,  $f'(I)$  is an interval.

□

## 1.6 Higher Differential

We fix a complete non-trivially valued field  $(K, |\cdot|)$ . Let  $(E, \|\cdot\|_E)$  and  $(F, \|\cdot\|_F)$  be normed vector spaces over  $K$ .

**Definition 1.6.1** Let  $U \subseteq E$  be an open subset,  $f : U \rightarrow F$  be a mapping,  $p \in U$ .

(1) If  $f$  is continuous at  $p$ , we say that  $f$  is 0-time differentiable at  $p$ , and we let

$$D^0 f(p) := f(p).$$

(2) If  $f$  is differentiable at  $p$ , we say that  $f$  is 1-time differentiable at  $p$ , and we let

$$D^1 f(p) := Df(p).$$

(3) Let  $n \geq 2$ . If exists open neighborhood  $V$  of  $p$  such that  $V \subseteq U$  and  $f$  is differentiable on  $V$  and  $Df$  is  $n - 1$ -time differentiable on  $V$ , we say that  $f$  is

$n$ -time differentiable at  $p$ , and we let

$$\mathrm{D}^n f(p) \in \mathcal{L}(E, \dots, E, F)$$

be the multilinear mapping sending  $(h_1, \dots, h_n) \in E^n$  to

$$\mathrm{D}^{n-1}(\mathrm{D}f)(p)(h_1, \dots, h_{n-1})(h_n).$$

If  $E = K$ ,  $\mathrm{D}^n f(p)(1, \dots, 1)$  is denoted as  $f^{(n)}(p) \in F$ .  $f^{(0)}(p)$  is often denoted as  $f(p)$ .

**Remark 1.6.2**  $\forall i \in \{1, \dots, n\}$ ,

$$\mathrm{D}^n f(p)(h_1, \dots, h_n) = \mathrm{D}^i(\mathrm{D}^{n-i} f)(p)(h_1, \dots, h_i)(h_{i+1}, \dots, h_n).$$

If  $E = K$ ,

$$f^{(n)}(p)(h_1, \dots, h_n) = \mathrm{D}^{n-1}(\mathrm{D}f)(p)(h_1, \dots, h_{n-1})(h_n).$$

**Definition 1.6.3** Let  $X$  be a set, we denote by  $\mathfrak{S}_X$  the element of all bijection from  $X$  to  $X$ .  $(\mathfrak{S}_X, \circ)$  forms a group. The identity mapping  $\mathrm{Id}_X$  is the neutral element of  $(\mathfrak{S}_X, \circ)$ .  $(\mathfrak{S}_X, \circ)$  is called the symmetric group of  $X$ . The elements of  $(\mathfrak{S}_X, \circ)$  are called permutations of  $X$ .

Let  $n \in \mathbb{N}_{\geq 2}$ ,  $x_1, \dots, x_n$  be distinct elements of  $X$ . We denote by  $(x_1 x_2 \cdots x_n)$  the element of  $\mathfrak{S}_X$  that sends  $x_i$  to  $x_{i+1}$ ,  $(i \in \{1, \dots, n-1\})$ ,  $x_n$  to  $x_1$ ,  $y \in X \setminus \{x_1, \dots, x_n\}$  to  $y$  itself. This element is called an  $n$ -cycle. A 2-cycle is also called a transposition.

**Remark 1.6.4**  $\mathfrak{S}_X$  acts on  $X$ .

$$\begin{aligned} \mathfrak{S}_X \times X &\longrightarrow X \\ (\sigma, x) &\longmapsto \sigma(x). \end{aligned}$$

If  $\sigma \in \mathfrak{S}_X$ ,  $x \in X$ , we denote by  $\mathrm{orb}_\sigma(x)$  the set  $\{\sigma^n(x) \mid n \in \mathbb{Z}\}$ .

$$\langle \sigma \rangle := \{\sigma^n \mid n \in \mathbb{Z}\} \subseteq \mathfrak{S}_X$$

is a group.  $\mathrm{orb}_\sigma(x)$  is the orbit of  $x$  under the action of  $\langle \sigma \rangle$ .

**Proposition 1.6.5** If  $\text{orb}_\sigma(x)$  is finite of  $d$  elements, then  $\sigma^d(x) = x$ , and  $\text{orb}_\sigma(x) = \{x, \sigma(x), \dots, \sigma^{d-1}(x)\}$ . Moreover, the restriction of  $\sigma$  to  $\text{orb}_\sigma(x)$  identifies to the restriction of the cycle  $(x, \sigma(x), \dots, \sigma^{d-1}(x))$ .

**Proof** Since  $\text{orb}_\sigma(x)$  is finite,

$$\{(n, m) \in \mathbb{Z}^2 \mid n < m, \sigma^n(x) = \sigma^m(x)\}$$

Let

$$l = \min\{m - n \mid (n, m) \in \mathbb{Z}^2, n < m, \sigma^n(x) = \sigma^m(x)\}.$$

Then  $x, \sigma(x), \dots, \sigma^{l-1}(x)$  are distinct, and  $\sigma^l(x) = x$ .  $\forall n \in \mathbb{Z}$ , then  $n$  can be written as  $n = lp + r$ , where  $p \in \mathbb{Z}, r \in \{0, \dots, l-1\}$ .

$$\sigma^n(x) = \sigma^r(\sigma^{lp}(x)) = \sigma^r((\sigma^l \circ \dots \circ \sigma^l)(x)) = \sigma^r(x).$$

So,  $\text{orb}_\sigma(x) = \{x, \sigma(x), \dots, \sigma^{l-1}(x)\}$ , ( $l = d$ ). □

**Remark 1.6.6** If  $X$  is finite, then  $X$  can be written as a distinct union of orbits (under the action of  $\langle \sigma \rangle$ ). Let  $d_i = \#(\text{orb}_\sigma(x_i)), i = 1, \dots, n$ , then

$$\sigma|_{\text{orb}_\sigma(x^{(i)})} = (x^{(i)}, \sigma(x^{(i)}), \dots, \sigma^{d_i-1}(x^{(i)}))|_{\text{orb}_\sigma(x^{(i)})}.$$

So  $\sigma = \tau_1 \circ \dots \circ \tau_n$ , where  $\tau_i := (x^{(i)}, \sigma(x^{(i)}), \dots, \sigma^{d_i-1}(x^{(i)}))$ .

**Corollary 1.6.7** Suppose that  $X$  is finite. Any  $\sigma \in \mathfrak{S}_X$  can be written as a composition of transpositions.

**Proof**

$$(x_1 \dots x_n) = (x_1 x_2) \circ (x_2 \dots x_n),$$

So,

$$(x_1 \dots x_n) = (x_1 x_2) \circ (x_2 x_3) \circ \dots \circ (x_{n-1} x_n). □$$

**Definition 1.6.8** Denote by  $\mathfrak{S}_n$  the symmetric group  $\mathfrak{S}_{\{1, \dots, n\}}$ . A composition of the form  $(i \ i+1)$ ,  $i \in \{1, \dots, n-1\}$  is called an adjacent transposition.

**Corollary 1.6.9** Any  $\sigma \in \mathfrak{S}_n$  can be written as a composition of adjacent transpositions.

**Proof** Let  $(j, k) \in \{1, \dots, n\}^2$ ,  $j < k$ ,

$$(j-1 \ j) \circ (j \ k) \circ (j-1 \ j) = (j-1 \ k).$$

$$(j \ k) = (j \ j+1) \circ (j+1 \ j+2) \circ \dots \circ (k-1 \ k) \circ \dots (j \ j+1).$$

□

**Theorem 1.6.10** (Schwarz) Let  $U \subseteq E$  be an open subset,  $f : U \rightarrow F$  be a mapping.  $n \in \mathbb{N}_{\geq 1}$ ,  $p \in U$ . Assume that  $f$  is  $n$ -times differentiable at  $p$ . Then  $\forall \sigma \in \mathfrak{S}_n, \forall (h_1, \dots, h_n) \in E^n$ ,

$$D^n f(p)(h_1, \dots, h_n) = D^n f(p)(h_{\sigma(1)}, \dots, h_{\sigma(n)}).$$

**Proof (By induction)** The case where  $n = 1$  is trivial. Case  $n = 2$ : Exists  $V$  open,  $p \in V \subseteq U$ .  $f$  is differentiable on  $V$  and  $Df$  is differentiable at  $p$ .

$$Df(p+h)(\cdot) - Df(p)(\cdot) - D^2 f(p)(h, \cdot) = o(\|h\|_E).$$

Let  $\varepsilon > 0, \exists \delta > 0, \forall h \in E, \|h\|_E \leq 2\delta \Rightarrow p+h \in V$  and

$$\|Df(p+h)(\cdot) - Df(p)(\cdot) - D^2 f(p)(h, \cdot)\| \leq \varepsilon \|h\|_E.$$

Let  $h \in E$  such that  $\|h\|_E \leq \delta$ . Define  $g_h : B(0, \delta) \rightarrow F$  as

$$g_h(k) = f(p+h+k) - f(p+h) - f(p+k) + f(p) - D^2 f(p)(h, k).$$

Then,

$$\begin{aligned} Dg_h(k)(\cdot) &= Df(p+h+k)(\cdot) - Df(p+k)(\cdot) - D^2 f(p)(h, \cdot) \\ &= Df(p+h+k)(\cdot) - Df(p)(\cdot) - D^2 f(p)(h+k, \cdot) \\ &\quad - (Df(p+k)(\cdot) - Df(p)(\cdot) - D^2 f(p)(k, \cdot)) \end{aligned}$$

$$\|Dg_h(k)(\cdot)\| \leq \varepsilon \|h+k\|_E + \varepsilon \|k\|_E \leq 3\varepsilon \max\{\|k\|_E, \|h\|_E\}.$$

$g_h(0) = 0$ . Therefore,  $\|g_h(k)\| \leq 3\varepsilon \max\{\|k\|_E, \|h\|_E\}^2$  (mean value inequality).

$$\|g_h(k) - g_h(0)\| \leq \left( \sup_{t \in ]0,1[} \|Dg_h(tk)\| \right) \cdot \|k\|.$$

Therefore,

$$f(p+h+k) - f(p+h) - f(p+k) + f(p) - D^2 f(p)(h, k) = o(\max\{\|k\|_E, \|h\|_E\}^2).$$

By symmetry,

$$f(p+h+k) - f(p+h) - f(p+k) + f(p) - D^2 f(p)(k, h) = o(\max\{\|k\|_E, \|h\|_E\}^2).$$

$$D^2 f(p)(h, k) - D^2 f(p)(k, h) = o(\max\{\|h\|_E, \|k\|_h\}^2).$$

$$D^2 f(p)(th, tk) - D^2 f(p)(tk, th) = o(|t|^2), \quad t \rightarrow 0.$$

$$D^2 f(p)(h, k) - D^2 f(p)(k, h) = o(1), \quad t \rightarrow 0.$$

Suppose  $n \geq 3$ .

$$D^n f(p)(h_1, \dots, h_n) = D^{n-1}(Df)(p)(h_1, \dots, h_{n-1})(h_n).$$

If  $\sigma = (j \ j+1)$ ,  $j \leq 2$ ,

$$D^{n-1}(Df)(p)(h_1, \dots, h_{n-1})(h_n) = D^{n-1}(Df)(p)(h_{\sigma(1)}, \dots, h_{\sigma(n-1)})(h_n)$$

by the induction hypothesis, if  $\sigma = (n-1 \ n)$ ,

$$D^n f(p)(h_1, \dots, h_n) = D^2((D^{n-2} f)(h_1, \dots, h_{n-2})(h_{n-1}, h_n))$$

$$\begin{aligned} D^n f(p)(h_{\sigma(1)}, \dots, h_{\sigma(n)}) &= D^n f(p)(h_1, \dots, h_{n-1}) \\ &= D^2((D^{n-2} f)(h_1, \dots, h_{n-2})(h_n, h_{n-1})) \\ &= D^n f(p)(h_1, \dots, h_n). \end{aligned}$$

□

## 1.7 Taylor's Formula

**Theorem 1.7.1** (Toylor-Young) Let  $(E, \|\cdot\|_E)$  and  $(F, \|\cdot\|_F)$  be normed vector spaces over  $\mathbb{R}$ ,  $U \subseteq E$  open,  $n \in \mathbb{N}$ ,  $f : U \rightarrow F$  be a mapping,  $p \in U$ . Suppose that  $f$  is  $n$ -times differentiable at  $p$ . Then

$$f(x) = f(p) + \sum_{k=1}^n \frac{1}{k!} D^k f(p)(x - p, \dots, x - p) + o(\|x - p\|^n), \quad x \rightarrow p.$$

**Proof (By induction on  $n$ )**

$n = 0$ ,  $f(x) = f(p) + o(1)$  follows by continuity of  $f$ ;  $n = 1$  follows by the differentiability of  $f$ .

From  $n - 1$  to  $n$ . Let  $g : U \rightarrow F$

$$g(x) = f(x) - f(p) - \sum_{k=1}^n \frac{1}{k!} D^k f(p)(x - p, \dots, x - p).$$

$g$  is differentiable on an open neighborhood of  $p$ ,

$$Dg(x)(h) = Df(x)(h) - \sum_{k=1}^n \frac{1}{k!} k D^k f(p)(x - p, \dots, x - p, h)$$

$$Dg(x) = Df(x) - \sum_{l=0}^{n-1} \frac{1}{l!} D^l(Df)(x - p, \dots, x - p) \stackrel{\text{hyp.}}{=} o(\|x - p\|^{n-1}), \quad x \rightarrow p.$$

So  $g(x) = o(\|x - p\|^n)$ .

$$\forall \varepsilon > 0, \exists \delta > 0, \forall x \in B(p, \delta), \|Dg(x)\| \leq \varepsilon \|x - p\|^{n-1}.$$

$g(p) = 0$ , so

$$\|g(x) - g(p)\| \leq \varepsilon \|x - p\|^{n-1} \cdot \|x - p\| = \varepsilon \|x - p\|^n.$$

□

**Theorem 1.7.2** (Taylor-Lagrange) Let  $(a, b) \in \mathbb{R}^2$ ,  $a < b$ .  $f : [a, b] \rightarrow \mathbb{R}$  be a continuous mapping. Suppose that  $f$  is  $(n + 1)$ -times differentiable on  $]a, b[$  and  $\forall k \in \{3, \dots, n\}, f^{(k)} : ]a, b[ \rightarrow \mathbb{R}$  tends to a continuous mapping  $[a, b] \rightarrow \mathbb{R}$ .

Then

$$\exists \xi \in ]a, b[, f(b) - \sum_{k=0}^n \frac{(b-a)^k}{k!} f^{(k)}(a) = \frac{f^{(n+1)}(\xi)(b-a)^{n+1}}{(n+1)!}.$$

**Proof** Let  $g : [a, b] \rightarrow \mathbb{R}$ .

$$g(t) := \sum_{k=0}^n \frac{(b-t)^k}{k!} f^{(k)}(t) - C \frac{(b-t)^{n+1}}{(n+1)!}.$$

$$\text{Then } g(b) = f(b), g(a) = \sum_{k=0}^n \frac{(b-a)^k}{k!} f^{(k)}(a) - C \frac{(b-a)^{n+1}}{(n+1)!}.$$

$$\begin{aligned} g'(t) &= \sum_{k=0}^n \frac{(b-t)^k}{k!} f^{(k+1)}(t) - \sum_{k=1}^n \frac{(b-t)^{k-1}}{(k-1)!} f^{(k)}(t) + C \frac{(b-t)^n}{n!} \\ &= \frac{(b-t)^n}{n!} f^{(n+1)}(t) + C \frac{(b-t)^n}{n!}. \end{aligned}$$

Take  $C$  such that  $g(a) = g(b)$ . Then by Rolle's theorem,  $\exists \xi \in ]a, b[, g'(\xi) = 0$ ,  $C = -f^{(n+1)}(\xi)$ . Then,

$$g(a) = \sum_{k=0}^n \frac{(b-a)^k}{k!} f^{(k)}(a) + \frac{f^{(n+1)}(\xi)}{(n+1)!} + \frac{f^{(n+1)}(\xi)}{(n+1)!} (b-a)^{n+1} = f(b) = g(b).$$

□

**Theorem 1.7.3** Let  $(E, \|\cdot\|_E)$  and  $(F, \|\cdot\|_F)$  be two normed vector spaces over  $\mathbb{R}$ ,  $U \subseteq E$  be an open subset, and  $f : U \rightarrow F$  be a mapping that is  $(n+1)$ -times differentiable, where  $n \in \mathbb{N}$ . Let  $p \in U$ ,  $h \in E$  such that  $\forall t \in [0, 1], p + th \in U$ . Let

$$M = \sup_{t \in [0, 1]} \|D^{n+1}f(p + th)\|.$$

Then,

$$\|f(p+h) - \sum_{k=0}^n \frac{1}{k!} D^k f(p)(h, \dots, h)\|_F \leq \frac{M}{(n+1)!} \|h\|_E^{n+1}.$$

**Proof** We define  $\phi : [0, 1] \rightarrow F$

$$\phi(t) = f(p + th) + \sum_{k=1}^n \frac{(1-t)^k}{k!} D^k f(p + th)(h, \dots, h).$$

$$\phi(0) = \sum_{k=0}^n \frac{1}{k!} D^k f(p)(h, \dots, h), \quad \phi(1) = f(p + h).$$

$$\begin{aligned} \phi'(t) &= Df(p + h)(h) + \sum_{k=1}^n \frac{(1-t)^k}{k!} D^{k+1} f(p + th)(h, \dots, h) \\ &\quad - \sum_{k=1}^n \frac{(1-t)^{k-1}}{(k-1)!} D^k f(p + th)(h, \dots, h) \\ &= \sum_{k=0}^n \frac{(1-t)^k}{k!} D^{k+1} f(p + th)(h, \dots, h) \\ &\quad - \sum_{l=0}^{n-1} \frac{(1-t)^l}{(l)!} D^{l+1} f(p + th)(h, \dots, h) \\ &= \frac{(1-t)^n}{n!} D^{n+1} f(p + th)(h, \dots, h). \end{aligned}$$

So,

$$\|\phi'(t)\| \leq M \|h\|_E^{n+1} \frac{(1-t)^n}{n!}, \quad t \in [0, 1].$$

By Gronwall's inequality,

$$\|\phi(1) - \phi(0)\|_F \leq M \cdot \|h\|_E^{n+1} \frac{1}{(n+1)!}.$$

□

## 1.8 Banach Space

**Proposition 1.8.1** Let  $(X, d)$  be a metric space and  $(x_n)_{n \in \mathbb{N}}$  be a sequence in  $X$ . If

$$\sum_{n \in \mathbb{N}} d(x_n, x_{n+1}) < +\infty,$$

then  $(x_n)_{n \in \mathbb{N}}$  is a Cauchy sequence.

**Proof** Let  $N \in \mathbb{N}$ . If  $(n, m) \in \mathbb{N}_{\geq N}^2$ ,  $n > m$ , by the triangle inequality,

$$d(x_m, x_n) \leq \sum_{k=m}^{n-1} d(x_k, x_{k+1}) \leq \sum_{k \geq N} d(x_k, x_{k+1}).$$

So,

$$0 \leq \sup_{(n,m) \in \mathbb{N}_{\geq N}^2} d(x_n, x_m) \leq \sum_{k \geq N} d(x_k, x_{k+1}).$$

Taking the limit when  $N \rightarrow +\infty$ , we get

$$\lim_{N \rightarrow +\infty} \sup_{(n,m) \in \mathbb{N}_{\geq N}^2} d(x_n, x_m) = 0.$$

Let  $(a_n)_{n \in \mathbb{N}} \in \mathbb{R}^{\mathbb{N}}$ . If  $(\sum_{k=0}^n a_k)_{n \in \mathbb{N}}$  converges to some  $l$  in  $\mathbb{R}$ . Then,  $l - \sum_{k=0}^{N-1} a_k$  converges to 0. If  $a_k \leq 0$  for any  $k \in \mathbb{N}$ ,  $l - \sum_{k=0}^{N-1} a_k = \sum_{k=N}^{+\infty} a_k$ .

$$l - \sum_{k=0}^{N-1} a_k = \lim_{n \rightarrow +\infty} \left( \sum_{k=0}^n a_k - \sum_{k=0}^{N-1} a_k \right) = \lim_{n \rightarrow +\infty} \sum_{k=N}^n a_k.$$

□

**Definition 1.8.2** Let  $(K, |\cdot|)$  be a complete valued field and  $(E, \|\cdot\|)$  be a normed vector space over  $K$ . If  $E$  equipped with the metric

$$\begin{aligned} E \times E &\longrightarrow \mathbb{R}_{\geq 0} \\ (x, y) &\longmapsto \|x - y\|_E. \end{aligned}$$

is complete, we say that  $(E, \|\cdot\|)$  is a **Banach space**.

Let  $(E, \|\cdot\|)$  be a Banach space. If  $(x_n)_{n \in \mathbb{N}}$  is a sequence in  $E$  such that  $\sum_{n \in \mathbb{N}} \|x_n\| < +\infty$ , we say that  $\sum_{n \in \mathbb{N}} x_n$  **converges absolutely**.

**Remark 1.8.3** Suppose that  $\sum_{n \in \mathbb{N}} x_n$  converges absolutely. Then  $\left( \sum_{k=0}^n x_k \right)_{n \in \mathbb{N}}$  is a Cauchy sequence, since

$$\|x_n\| = \left\| \sum_{k=0}^n x_k - \sum_{k=0}^{n-1} x_k \right\|.$$

So,  $\sum_{n \in \mathbb{N}} x_n$  converges.

**Theorem 1.8.4** (Root test of Cauchy) Let  $(E, \|\cdot\|)$  be a Banach space and  $(x_n)_{n \in \mathbb{N}} \in E^{\mathbb{N}}$ . Let

$$r = \limsup_{n \rightarrow +\infty} \|x_n\|^{\frac{1}{n}} \in [0, +\infty]$$

If  $r < 1$ , then  $\sum_{n \in \mathbb{N}} x_n$  converges absolutely.

If  $r > 1$ , then  $\sum_{n \in \mathbb{N}} x_n$  diverges.

**Lemma 1.8.5** If a series  $\sum_{n \in \mathbb{N}} x_n$  converges, then  $\lim_{n \rightarrow +\infty} \|x_n\| = 0$ .

### Proof (of lemma)

$$\|x_n\| = \left\| \sum_{k=0}^n x_k - \sum_{k=0}^{n-1} x_k \right\|.$$

Since  $\sum_k x_k$  converges to some  $l \in E$ .

$$\lim_{n \rightarrow +\infty} \|x_n\| = \lim_{n \rightarrow +\infty} \left\| \sum_{k=0}^n x_k - \sum_{k=0}^{n-1} x_k \right\| = \|l - l\| = 0.$$

□

**Proof (of theorem)** If  $r > 1$ ,  $\exists \beta > 1$  such that  $r > \beta$ . Since  $r = \limsup_{n \rightarrow +\infty} \|x_n\|^{\frac{1}{n}}$ ,  $\exists I \subseteq \mathbb{N}$  infinite such that  $\lim_{n \in I, n \rightarrow +\infty} \|x_n\|^{\frac{1}{n}} = r$  (Bolzano-Weierstrass).

$$\exists N \in \mathbb{N}, \forall n \in I_{\geq N}, \|x_n\|^{\frac{1}{n}} \geq \beta.$$

So,  $\|x_n\| \geq \beta^n \geq 1$ . So  $\sum_{n \in \mathbb{N}} x_n$  diverges.

If  $r < 1$ ,  $\exists \alpha \in ]0, 1[$ ,  $r < \alpha$ . Since  $r = \limsup_{n \rightarrow +\infty} \|x_n\|^{\frac{1}{n}}$ ,

$$\exists N \in \mathbb{N}, \forall n \geq N, \|x_n\|^{\frac{1}{n}} \leq \alpha, \|x_n\| \leq \alpha^n.$$

So,

$$\sum_{n \geq N} \|x_n\| \leq \sum_{n \geq N} \alpha^n = \frac{\alpha^N}{1 - \alpha} < +\infty.$$

Therefore,  $\sum_{n \in \mathbb{N}} x_n$  converges absolutely. □

**Theorem 1.8.6** (Ratio test of D'Alembert) Let  $(E, \|\cdot\|)$  be a Banach space and  $(x_n)_{n \in \mathbb{N}} \in E^{\mathbb{N}}$ .

(1) If

$$\limsup_{n \rightarrow +\infty} \frac{\|x_{n+1}\|}{\|x_n\|} < 1,$$

then  $\sum_{n \in \mathbb{N}} x_n$  converges absolutely.

(2) If

$$\limsup_{n \rightarrow +\infty} \frac{\|x_{n+1}\|}{\|x_n\|} > 1,$$

then  $\sum_{n \in \mathbb{N}} x_n$  diverges.

### Proof

(1) Let  $0 < \alpha < 1$  such that

$$\limsup_{n \rightarrow +\infty} \frac{\|x_{n+1}\|}{\|x_n\|} < \alpha.$$

$$\exists N \in \mathbb{N}, \forall n \in \mathbb{N}_{\geq N}, \|x_{n+1}\| \leq \alpha \|x_n\| \leq \alpha^{n+1-N} \|x_N\|.$$

Thus,

$$\sum_{n \geq N} \|x_n\| \leq \sum_{n \geq N} \|x_N\| \alpha^{n-N} = \|x_N\| \frac{1}{1-\alpha} < +\infty.$$

(2) Let  $\beta > 1$  such that

$$\liminf_{n \rightarrow +\infty} \frac{\|x_{n+1}\|}{\|x_n\|} > \beta.$$

$$\exists N \in \mathbb{N}, x_N \neq 0, \text{ and } \forall n \in \mathbb{N}_{\geq N}, \|x_{n+1}\| \geq \beta \|x_n\|$$

$$\forall n \geq N, \|x_n\| \geq \beta^{n-N} \|x_N\| \rightarrow +\infty (n \rightarrow +\infty)$$

So  $\sum_{n \in \mathbb{N}} x_n$  diverges. □

Let  $z \in \mathbb{C}$ . The series  $\sum_{n \in \mathbb{N}} \frac{z^n}{n!}$  converges absolutely since

$$\left| \frac{z^{n+1}/(n+1)!}{z^n/n!} \right| = \frac{|z|}{n+1} \rightarrow 0 (n \rightarrow +\infty).$$

We denote by  $e^z$  this limit.

## 1.9 Local inversion

**Definition 1.9.1** Let  $X$  be a topological space and  $Y \subseteq X$ . If  $\overline{Y} = X$ , we say that  $Y$  is dense.

**Theorem 1.9.2** (Baire) Let  $(X, d)$  be a complete metric space. Let  $(\Omega_n)_{n \in \mathbb{N}}$  be a sequence of dense open subset of  $X$ . Let  $\Omega = \bigcap_{n \in \mathbb{N}} \Omega_n$ , then  $\Omega$  is dense in  $X$ .

**Proof** Suppose that  $\Omega$  is not dense. Let  $x_0 \in X \setminus \overline{\Omega}$ , exists  $\varepsilon > 0$  such that  $B(x_0, \varepsilon) \subseteq X \setminus \overline{\Omega}$ .

Let  $r_0 = \varepsilon$ . We construct in a recursive way sequence  $(x_n)_{n \in \mathbb{N}} \in X^{\mathbb{N}}$  and  $(r_n)_{n \in \mathbb{N}} \in \mathbb{R}_{\geq 0}^n$  as follows.

Suppose that  $(x_n, r_n)$  is chosen.  $B(x_n, r_n) \cap \Omega_n \neq \emptyset$ . We pick  $x_{n+1} \in X$  and  $r_{n+1} \leq \frac{x_n}{2}$  such that  $B(x_{n+1}, r_{n+1}) \subseteq B(x_n, r_n) \cap \Omega_n$ ,  $d(x_{n+1}, x_n) < r_n$ .  $\sum_{n \in \mathbb{N}} r_n < +\infty$  (ratio test).

Then the sequence converges to some  $l$ . For any  $n \in \mathbb{N}$ ,  $x_n \in B(x_0, \varepsilon)$ . So  $l \in \overline{B}(x_0, \varepsilon)$ .

Moreover,  $\forall n \in \mathbb{N}$ ,  $l \in \overline{B}(x_{n+1}, r_{n+1}) \subseteq B_{x_n, r_n} \cap \Omega_n$ . Thus  $l \in \bigcap_{n \in \mathbb{N}} \Omega_n = \Omega$ . Contradiction.  $\square$

**Corollary 1.9.3** Let  $(X, d)$  be a non-empty complete metric space and  $(Y_n)_{n \in \mathbb{N}}$  be a family of closed subsets of  $X$  such that  $X = \bigcup_{n \in \mathbb{N}} Y_n$ . Then exists  $n \in \mathbb{N}$  such that  $Y_n^\circ \neq \emptyset$ .

**Proof** Let  $\Omega_n = X \setminus Y_n$ . Suppose that  $\forall n \in \mathbb{N}$ ,  $Y_n^\circ = \emptyset$ . Then  $\overline{\Omega}_n = X \setminus Y_n^\circ = X$ . Thus  $\Omega := \bigcap_{n \in \mathbb{N}} \Omega_n$  is dense in  $X$ . Namely,  $X = \Omega$ . So

$$\emptyset = X \setminus \overline{\Omega} = (X \setminus \Omega)^\circ = \left( X \setminus \bigcap_{n \in \mathbb{N}} \Omega_n \right)^\circ = \left( \bigcup_{n \in \mathbb{N}} Y_n \right)^\circ = X^\circ = X.$$

Contradiction.  $\square$

**Theorem 1.9.4** (Banach) Let  $(K, |\cdot|)$  be a complete non-trivially valued field, and  $E$  be a vector space over  $K$ . Let  $\|\cdot\|_1, \|\cdot\|_2$  be two norms on  $E$  such that  $(E, \|\cdot\|_1)$  and  $(E, \|\cdot\|_2)$  are both Banach spaces.

If  $\exists C > 0$  such that  $\|\cdot\|_2 \leq C\|\cdot\|_1$ . Then  $\|\cdot\|_1$  and  $\|\cdot\|_2$  are equivalent. ( $\exists C' > 0$ ,  $\|\cdot\|_1 \leq C'\|\cdot\|_2$ )

**Proof** For  $x \in E$  and  $r > 0$ . Let

$$B_i(x, r) := \{y \in E \mid \|y - x\|_i < r\}, \quad i = 1, 2$$

$\forall y \subseteq E$ , let  $\overline{Y}^{\|\cdot\|_2}$  be the closure of  $Y$  in  $(E, \|\cdot\|_2)$ .

$$E = \bigcup_{n \geq 1} B_1(0, n) = \bigcup_{n \geq 1} \overline{B_1(0, n)}^{\|\cdot\|_2}.$$

Hence,  $\exists n_0 \geq 1, p \in E, r_0 > 0$  such that

$$B_2(p, r_0) \subseteq \overline{B_1(0, n_0)}^{\|\cdot\|_2}$$

or equivalently,

$$B_2(0, r_0) \subseteq \overline{B_1(-p, n_0)}^{\|\cdot\|_2} \subseteq \overline{B_1(0, n_0 + \|p\|_1)}^{\|\cdot\|_2}$$

since  $\forall x \in B_1(-p, n_0)$

$$\|x\|_1 = \|x - p + p\|_1 \leq \|x - p\| + \|p\|_1 < n_0 + \|p\|_1.$$

Let  $r_1 = n_0 + \|p\|_1$ ,

$$B_2(0, r_0) \subseteq \overline{B_1(0, r_1)}^{\|\cdot\|_2} \subseteq B_1(0, r_1) + B_2(0, r_0|a|)$$

where  $a \in K, 0 < |a| < \frac{1}{2}$ .

In fact,  $\forall x \in \overline{B_1(0, r_0)}^{\|\cdot\|_2}$ , exists sequence  $(x_n)_{n \in \mathbb{N}} \in B_1(0, r_1)^{\mathbb{N}}$ , such that  $x_n \rightarrow x$  in  $(E, \|\cdot\|_2)$ ,  $\exists n \in \mathbb{N}, \|x_n - x\|_2 < r_0|a|$

$$B_2(0, r_0|a|^n) \subseteq B_1(0, r_1|a|^n) + B_2(0, r_0|a|^{n+1})$$

Let  $y \in B_2(0, r_0)$ , we choose  $(x_0, y_0) \in B_1(0, r_1) \times B_2(0, r_0|a|)$  such that  $y = x_0 + y_0$ . When  $(x_n, y_n)$  si chosen, let  $(x_{n+1}, y_{[n+1]}) \in B_1(0, r_0|a|^{n+1}) \times B_2(0, r_0|a|^{n+2})$ ,  $y_n = x_{n+1} + y_{n+1}$ ,  $y = y_n + \sum_{k=0}^n x_k$ . So  $\sum_{n \in \mathbb{N}} x_n$  converges to  $y$ .

Moreover,  $\sum_{n \in \mathbb{N}} \|x_n\| < +\infty$ , so it converges in  $(E, \|\cdot\|_1)$  to some  $x$ . Therefore,  $x = y$  since  $\|\cdot\|_2 \leq C\|\cdot\|_1$ . So  $\|y\|_1\|x\|_1 \leq \sum_{n \in \mathbb{N}} \|x_n\|_1 \leq \frac{r_1}{1-|a|}$ .

Therefore  $B_2(0, r_0) \subseteq B_1(0, \frac{r_1}{1-|a|})$ . So  $\|\cdot\|_1$  is bounded by a constant times  $\|\cdot\|_2$ .  $\square$

**Proposition 1.9.5** Let  $(E, \|\cdot\|_E)$  and  $(F, \|\cdot\|_F)$  be Banach spaces over a complete non-trivially valued field  $(K, |\cdot|)$ , and  $f : E \rightarrow F$  be a bounded mapping.

- (1) If  $f$  is invertible, then  $f^{-1}$  is bounded.
- (2) If  $f$  is surjective, for any  $U \subseteq E$  open,  $f(U)$  is open in  $F$ .

### Proof

- (1) We define a mapping

$$\begin{aligned} \|\cdot\|'_E : E &\longrightarrow \mathbb{R}_{\geq 0} \\ x &\longmapsto \|f(x)\|_F. \end{aligned}$$

This is a norm on  $E$ . In fact, if  $\|x\|'_E = \|f(x)\|_F = 0$ , then  $f(x) = 0_F$ . So  $x = 0_E$ . Moreover,

$$\forall x \in E, \|x\|'_E = \|f(x)\|_F \leq \|f\| \|x\|_E.$$

So there exists  $C > 0$  such that  $\|\cdot\|_E \leq C \|\cdot\|'_E$ . That is,

$$\forall y \in F, \|y\|_F = \|f(f^{-1}(y))\|_F = \|f^{-1}(y)\|'_E \geq C^{-1} \|f^{-1}(y)\|_E.$$

So,  $\|f^{-1}\| \leq C$ .

- (2) Let

$$E_0 = \ker(f) = \{x \in E \mid f(x) = 0_F\}.$$

This is a closed vector subspace of  $E$ .  $\|\cdot\|_E$  induces by passing to quotient a norm  $\|\cdot\|_Q$  on  $Q := E/E_0$ . Let

$$\begin{aligned} g : Q &\longrightarrow F \\ [x] &\longmapsto f(x). \end{aligned}$$

This is a  $K$ -linear bijection.

If  $\alpha \in Q$ ,

$$\forall x \in \alpha, \|g(\alpha)\|_F = \|f(x)\|_F \leq \|f\| \|\alpha\|_E.$$

Since  $\|\alpha\|_Q := \inf_{x \in \alpha} \|x\|_E$ ,  $\|g(\alpha)\|_F \leq \|f\| \|\alpha\|_Q$ . So  $\|g\| \leq \|f\|$ . By (1),  $g^{-1}$  is bounded (hence is continuous).

If  $V \subseteq Q$  is open, then  $g(V) \subseteq F$  is open. Let  $U \subseteq E$  be an open subset. Let

$$\begin{aligned} \pi : E &\longrightarrow Q \\ x &\longmapsto [x]. \end{aligned}$$

Let  $x \in U, r > 0$  such that  $B(x, r) \subseteq U$ . For any  $\alpha \in Q$ , if

$$\|\alpha - [x]\|_Q = \inf_{y \in \alpha} \|y - x\|_E < r,$$

then, exists  $y \in \alpha$  such that  $\|y - x\|_E < r$ .

Therefore,

$$B([x], r) \subseteq \pi(B(x, r)) \subseteq \pi(U).$$

This means that  $\pi(U)$  is open. So  $f(U) = g(\pi(U))$  is open.  $\square$

**Definition 1.9.6** Let  $(E, \|\cdot\|_E)$  and  $(F, \|\cdot\|_F)$  be normed vector space over a complete non-trivially valued field  $(K, |\cdot|)$ ,  $U \subseteq E$  open,  $f : U \rightarrow F$ . If  $\forall p \in U$ ,  $f$  is  $n$ -times differentiable at  $p$ , and  $D^n f : U \rightarrow \mathcal{L}^{(n)}(E, \dots, E, F)$  is continuous, we say that  $f$  is of class  $\mathcal{C}^n$ .

If  $\forall n \in \mathbb{N}$ ,  $f$  is  $n$ -times differentiable on  $U$ , we say that  $f$  is smooth, or of class  $\mathcal{C}^\infty$ . ( $\forall n \in \mathbb{N}$ ,  $f$  is of class  $\mathcal{C}^n$ .)

**Proposition 1.9.7** Let  $(E, \|\cdot\|_E)$ ,  $(F, \|\cdot\|_F)$  and  $(G, \|\cdot\|_G)$  be normed vector space over a complete non-trivially valued field  $(K, |\cdot|)$ .  $U \subseteq E$ ,  $V \subseteq F$  be open subsets,  $f : U \rightarrow V$ ,  $g : V \rightarrow G$  be mappings.  $n \in \mathbb{N}$ .

(1) Let  $p \in U$ . If  $f$  is  $n$ -times differentiable at  $p$  and  $g$  is  $n$ -times differentiable at  $f(p)$ , then  $g \circ f$  is  $n$ -times differentiable at  $p$ .

(2) If  $f$  is of class  $\mathcal{C}^n$  on  $U$  and  $g$  is of class  $\mathcal{C}^n$  on  $V$ , then  $g \circ f$  is of class  $\mathcal{C}^n$  on  $U$ .

### Proof (induction on $n$ )

$n = 0$ , continuity composition.

$n = 1$ , differentiability of composition.

$n \geq 2$ ,

$$D(g \circ f)(p)(\cdot) = Dg(f(p))(Df(p)(\cdot))$$

Let

$$\begin{aligned} \Phi : \mathcal{L}(F, G) \times \mathcal{L}(E, F) &\longrightarrow \mathcal{L}(E, G) \\ (\alpha, \beta) &\longmapsto \alpha \circ \beta. \end{aligned}$$

This is a bounded bilinear mapping.  $\|\alpha \circ \beta\| \leq \|\alpha\| \cdot \|\beta\|$ .

$$(\|\alpha \circ \beta(h)\|_G = \|\alpha(\beta(h))\|_G \leq \|\alpha\| \cdot \|\beta(h)\|_F \leq \|\alpha\| \|\beta\| \|h\|_E)$$

$\Phi$  is of class  $\mathcal{C}^\infty$ .

$$D(g \circ f) = \Phi(Dg \circ f, Df).$$

(2) Since  $Dg$  and  $Df$  is of class  $\mathcal{C}^{n-1}$ , we obtain that  $D(g \circ f)$  is of class  $\mathcal{C}^{n-1}$ , so  $g \circ f$  is of class  $\mathcal{C}^n$ .

(1) If  $g$  is  $n$ -times differentiable at  $f(p)$ ,  $Dg$  is  $(n-1)$ -times differentiable at  $f(p)$ .

So  $Dg \circ f$  is  $(n - 1)$ -times differentiable at  $p$ .  $Df$  is  $(n - 1)$ -times differentiable at  $p$ . So  $D(g \circ f)$  is  $(n - 1)$ -times differentiable at  $p$ .  $\square$

**Theorem 1.9.8** Let  $(E, \|\cdot\|)$  be a Banach space over a complete non-trivially valued field  $(K, |\cdot|)$ . Let

$$\mathrm{GL}(E) := \{\varphi \in \mathcal{L}(E, E) \mid \varphi \text{ is invertible}\}.$$

This set forms a group under  $\circ$ .

(1)  $\forall \varphi \in \mathcal{L}(E, E)$ , if  $\|\varphi\| < 1$ , then  $\mathrm{Id}_E + \varphi \in \mathrm{GL}(E)$ .

(2)  $\mathrm{GL}(E) \subseteq \mathcal{L}(E, E)$  is open.

(3)

$$\begin{aligned} \iota : \quad \mathrm{GL}(E) &\longrightarrow \mathrm{GL}(E) \\ \varphi &\longmapsto \varphi^{-1} \end{aligned}$$

is of class  $\mathcal{C}^\infty$ .

### Proof

(1) The series  $\sum_{n \in \mathbb{N}} (-1)^n \varphi^n$  converges absolutely since  $\|\varphi^n\| \leq \|\varphi\|^n$ .

Let  $\eta$  be the limit of  $\sum_{n \in \mathbb{N}} (-1)^n \varphi^n$ .

$$(\mathrm{Id} + \varphi) \circ \sum_{k=0}^n (-1)^k \varphi^k = \mathrm{Id} + (-1)^n \varphi^{n+1}.$$

Taking the limit when  $n \rightarrow +\infty$ , we get  $(\mathrm{Id}_E + \varphi) \circ \eta = \mathrm{Id}_E$ . For the same reason,  $\eta \circ (\mathrm{Id}_E + \varphi) = \mathrm{Id}_E$ .

(2) If  $f \in \mathrm{GL}(E)$ ,  $\forall \varphi \in \mathcal{L}(E, E)$  such that

$$\|\varphi\| < \frac{1}{\|f^{-1}\|}, \quad f + \varphi = f \circ (\mathrm{Id}_E + f^{-1} \circ \varphi), \quad \|f^{-1} \circ \varphi\| \leq \|f^{-1}\| \cdot \|\varphi\| < 1.$$

So  $\mathrm{Id}_E + f^{-1} \circ \varphi \in \mathrm{GL}(E)$ . Hence  $f + \varphi \in \mathrm{GL}(E)$ .

(3) Let  $f \in \mathrm{GL}(E)$ ,  $\varphi \in \mathcal{L}(E, E)$ .  $\|\varphi\| \leq \frac{1}{\|f^{-1}\|}$ .

$$\begin{aligned} \iota(f + \varphi) - \iota(f) &= (f + \varphi)^{-1} - f^{-1} \\ &= (f \circ (\mathrm{Id}_E + f^{-1} \circ \varphi))^{-1} - f^{-1} \\ &= (\mathrm{Id}_E + f^{-1} \circ \varphi)^{-1} \circ f^{-1} - f^{-1} \\ &= \sum_{n \in \mathbb{N}} (-1)^n (f^{-1} \circ \varphi)^n \circ f^{-1} - f^{-1} \\ &= -f^{-1} \circ \varphi \circ f^{-1} + o(\|\varphi\|) \end{aligned}$$

since

$$\begin{aligned}
 & \sum_{n \geq 2} \|(-1)^n (f^{-1} \circ \varphi)^n \circ f^{-1}\| \\
 & \leq \sum_{n \geq 2} \|f^{-1}\| \cdot (\|f^{-1}\| \cdot \|\varphi\|)^n \\
 & = \|\varphi\|^2 \left( \|f\|^3 \cdot \sum_{n \geq 2} (\|f^{-1}\| \cdot \|\varphi\|)^{n-2} \right) \\
 & = o(\|\varphi\|).
 \end{aligned}$$

Let

$$\begin{aligned}
 \Phi : \mathcal{L}(E, E)^3 & \longrightarrow \mathcal{L}(E, E) \\
 (\alpha, \beta, \gamma) & \longmapsto \alpha \circ \beta \circ \gamma.
 \end{aligned}$$

bounded 3-linear mapping.

$$D\iota(f)(\cdot) = -\Phi(\iota(f), \cdot, \iota(f)).$$

By induction, we obtain that  $\iota$  is of class  $C^n$  for any  $n \in \mathbb{N}$ . □

**Definition 1.9.9** Let  $(X, d)$  be a metric space,  $f : X \rightarrow X$  be a mapping. If exists  $\alpha \in ]0, 1[$ , such that  $f$  is  $\alpha$ -Lipschitzian, we say that  $f$  is a **contraction**.

**Definition 1.9.10** Let  $f : X \rightarrow X$  be a mapping. If  $x \in X$  is such that  $f(x) = x$ , we say that  $x$  is a **fixed point** of  $f$ .

**Theorem 1.9.11** (Banach fixed point theorem) Let  $(X, d)$  be a non-empty complete metric space and  $f : X \rightarrow X$  be a contraction. Then  $f$  admits a unique fixed point.

### Proof

“Uniqueness”: Let  $\alpha \in ]0, 1[$ , such that  $f$  is  $\alpha$ -Lipschitzian. If  $a$  and  $b$  are fixed point of  $f$ , then  $d(a, b) = d(f(a), f(b)) \leq \alpha d(a, b)$ . So  $d(a, b) = 0$ ,  $a = b$ .

“Existence”: Let  $x_0 \in X$ . For any  $n \in \mathbb{N}$ , let  $x_n = f^n(x_0)$ . Then

$$d(x_n, x_{n+1}) = d(f(x_{n-1}), f(x_n)) \leq \alpha d(x_{n-1}, x_n) \leq \dots \leq \alpha^n d(x_0, x_1).$$

So

$$\sum_{n \in \mathbb{N}} d(x_n, x_{n+1}) \leq \sum_{n \in \mathbb{N}} \alpha^n d(x_0, x_1) = \frac{1}{1-\alpha} d(x_0, x_1) < +\infty.$$

Hence  $(x_n)_{n \in \mathbb{N}}$  converges to some  $a \in X$ .

$$d(a, f(a)) = \lim_{n \rightarrow +\infty} d(x_n, f(x_n)) = \lim_{n \rightarrow +\infty} d(x_n, x_{n+1}) = 0.$$

So  $a = f(a)$ . □

**Definition 1.9.12** Let  $(E, \|\cdot\|_E)$  and  $(F, \|\cdot\|_F)$  be normed vector spaces over a complete value filed  $(K, |\cdot|)$ ,  $U \subseteq E, V \subseteq F$  be open subsets,  $f : U \rightarrow V$  be a bijection,  $n \in \mathbb{N} \cup \{\infty\}$ . If  $f$  and  $f^{-1}$  are both of class  $\mathcal{C}^n$ , we say that  $f$  is a  $\mathcal{C}^n$ -diffeomorphism.

**Theorem 1.9.13** Let  $(E, \|\cdot\|_E)$  and  $(F, \|\cdot\|_F)$  be Banach spaces over  $\mathbb{R}$ ,  $U \subseteq E$  open and  $f : U \rightarrow F$  be a mapping of class  $\mathcal{C}^n$  ( $n \in \mathbb{N} \cup \{\infty\}$ ). Let  $p \in U$ . Suppose that  $Df(p) \in \mathcal{L}(E, F)$  is invertible. Then there exists a open neighborhood  $V$  of  $p$  contained in  $U$ , such that  $f|_V : V \rightarrow f(V)$  is a  $\mathcal{C}^n$ -homeomorphism. Moreover

$$Df^{-1}(y) = Df(f^{-1}(y))^{-1}.$$

**Proof** By replacing  $f$  by

$$\tilde{f} : x \mapsto Df(p)^{-1}(f(p+x) - f(p)).$$

We may assume that  $E = F, p = f(p) = 0, Df(p) = \text{Id}_E$ .

$$D\tilde{f}(0)(h) = Df(p)^{-1}(Df(p)(h)) = h, D\tilde{f}(0) = \text{Id}_E.$$

Let  $\mu : U \rightarrow E, \mu(x) = f(x) - x, D\mu(0) = 0$ . Since  $Df$  is continuous, so is  $D\mu$ .

$$\exists r > 0, \forall x \in \overline{B}(0_E, r), \|D\mu(x)\| \leq \frac{1}{2}.$$

So  $\mu$  is  $\frac{1}{2}$ -Lipschitzian on  $\overline{B}(0_E, r)$  (mean value inequality).

$$\forall (x, y) \in \overline{B}(0_E, r)^2, \|f(x) - f(y)\| \geq \|x - y\| \|\mu(x) - \mu(y)\| \geq \frac{1}{2} \|x - y\|.$$

So  $f$  is injective on  $\overline{B}(0_E, r)$ . Let  $a \in \overline{B}(0_E, \frac{r}{2})$ .

$$\forall x \in \overline{B}(0_E, r), \|a - \mu(x)\| \leq \|a\| + \|\mu(x)\| \leq \frac{1}{2}r + \frac{1}{2}r = r.$$

Let

$$\begin{aligned}\nu : \overline{B}(0, r) &\longrightarrow \overline{B}(0, r) \\ x &\longmapsto a - \mu(x)\end{aligned}$$

$\nu$  is a contraction. By Banach's fixed point theorem,

$$\exists! g(a) \in \overline{B}(0, r), \nu(g(a)) = a - \mu(g(a)) = a - f(g(a)).$$

That is  $f(g(a)) = a$ . Let  $W = B(0, \frac{r}{2})$ ,  $V = f^{-1}(W) \cap B(0, r)$ ,  $f|_V : V \rightarrow W$  is a bijection.

$$\forall z \in B(0, r), Df(z) = \text{Id}_E + D\mu(z) \in \text{GL}(E).$$

$$\forall (x, x_0) \in V \times V, y = f(x), y_0 = f(x_0), y - y_0 = Df(x_0)(x - x_0) + o(\|x - x_0\|).$$

$$\begin{aligned}\|x - x_0\| &= \|y - y_0 - (\mu(x) - \mu(x_0))\| \leq \|y - y_0\| + \frac{1}{2}\|x - x_0\|, \\ \frac{1}{2}\|f^{-1}(y) - f^{-1}(y_0)\| &= \frac{1}{2}\|x - x_0\| \leq \|y - y_0\|.\end{aligned}$$

So,

$$Df(x_0)(x - x_0) = y - y_0 + o(\|y - y_0\|),$$

$$\begin{aligned}f^{-1}(y) - f^{-1}(y_0) &= x - x_0 = Df(x_0)^{-1}(y - y_0) + o(\|y - y_0\|) \\ &= Df(f^{-1}(y_0))^{-1}(y - y_0) + o(\|y - y_0\|)\end{aligned}$$

Thus,

$$Df^{-1} = \iota \circ Df \circ f^{-1}.$$

□

**Proposition 1.9.14** Let  $n \in \mathbb{N}_{\geq 1}$ . Let  $(K, |\cdot|)$  be a complete valued field,  $(E_i, \|\cdot\|_i)$ ,  $i \in \{1, \dots, n\}$  be normed vector spaces over  $K$ ,  $(F, \|\cdot\|_F)$  be a Banach space over  $K$ . Then,  $(\mathcal{L}^{(n)}(E_1, \dots, E_n, F), \|\cdot\|)$  is a Banach space.

**Proof** Let  $(\varphi_i)_{i \in \mathbb{N}}$  be a Cauchy sequence in  $\mathcal{L}^{(n)}(E_1, \dots, E_n, F)$ . For  $N \in \mathbb{N}$ , let

$$\varepsilon_N := \sup_{(i,j) \in \mathbb{N}_{\geq N}} \|\varphi_i - \varphi_j\|, \lim_{N \rightarrow +\infty} \varepsilon_N = 0.$$

For any  $(x_1, \dots, x_n) \in E_1 \times \dots \times E_n$ , and any  $(i, j) \in \mathbb{N}_{\geq N}^2$ ,

$$\|\varphi_i(x_1, \dots, x_n) - \varphi_j(x_1, \dots, x_n)\| \leq \|\varphi_i - \varphi_j\| \cdot \prod_{l=1}^n \|x_l\|_l \leq \varepsilon_N \prod_{l=1}^n \|x_l\|_l.$$

So  $(\varphi_i(x_1, \dots, x_n))_{i \in \mathbb{N}}$  is a Cauchy sequence in  $F$ , hence it converges to some element of  $F$ , denoted as  $\varphi(x_1, \dots, x_n)$ .

Note that  $\varphi$  is a point-wise limit of an  $n$ -linear mapping, so it is also  $n$ -linear.

$$\begin{aligned} \|\varphi(x_1, \dots, x_n)\|_F &= \lim_{i \rightarrow +\infty} \|\varphi_i(x_1, \dots, x_n)\|_F \\ &\leq \limsup_{i \rightarrow +\infty} \|\varphi_i\| \cdot \|x_1\|_{E_1} \cdots \|x_n\|_{E_n} \\ &\leq \left( \sup_{i \in \mathbb{N}} \|\varphi_i\| \right) \cdot \|x_1\|_{E_1} \cdots \|x_n\|_{E_n} \end{aligned}$$

So  $\varphi \in \mathcal{L}(E_1, \dots, E_n, F)$ .

For fixed  $N \in \mathbb{N}$ ,  $\forall (x_1, \dots, x_n) \in E_1 \times \dots \times E_n$ ,

$$\begin{aligned} &\|\varphi(x_1, \dots, x_n) - \varphi_N(x_1, \dots, x_n)\|_F \\ &= \lim_{n \rightarrow +\infty} \|\varphi_n(x_1, \dots, x_n) - \varphi_N(x_1, \dots, x_n)\|_F \\ &\leq \varepsilon_N \|x_1\| \cdots \|x_n\|. \end{aligned}$$

So  $0 \leq \|\varphi - \varphi_N\| \leq \varepsilon_N$ . By squeeze theorem

$$\lim_{N \rightarrow +\infty} \|\varphi - \varphi_N\| = 0.$$

□

## 1.10 Uniform Convergence

**Definition 1.10.1** Let  $X$  be a set,  $(Y, \mathcal{T})$  be a topological space,  $(f_n)_{n \in \mathbb{N}}$  be a sequence of mappings from  $X$  to  $Y$ . We say that the sequence  $(f_n)_{n \in \mathbb{N}}$  converges **point-wise** to a mapping  $f : X \rightarrow Y$  if for every  $x \in X$  the sequence  $(f_n(x))_{n \in \mathbb{N}}$  converges to  $f(x)$ .

Suppose that  $(Y, d)$  is a metric space. We say that the sequence  $(f_n)_{n \in \mathbb{N}}$  converges **uniformly** to a mapping  $f : X \rightarrow Y$  if

$$\lim_{n \rightarrow +\infty} \sup_{x \in X} d(f_n(x), f(x)) = 0.$$

**Remark 1.10.2** Let  $f, g : X \rightarrow Y$  be mappings.

$$d(f, g) = \sup_{x \in X} d(f(x), g(x))$$

is a metric. Uniform convergence can be seen as convergence of  $(f_n)_{n \in \mathbb{N}}$  with respect to this metric.

**Theorem 1.10.3** Let  $(X, \mathcal{T}_X)$  be a topological space,  $(Y, d_Y)$  be a metric space,  $(f_n)_{n \in \mathbb{N}}$  be a sequence of mappings from  $X$  to  $Y$  that converges uniformly to a mapping  $f : X \rightarrow Y$ . If  $\forall n \in \mathbb{N}$ ,  $f_n$  is continuous at  $p \in X$ , then  $f$  is continuous at  $p$ .

**Proof** We will prove that for any  $\varepsilon > 0$ ,  $f^{-1}(B(f(p), \varepsilon))$  is a neighborhood of  $p$ .

Let  $n \in \mathbb{N}$  such that

$$\sup_{x \in X} d(f_n(x), f(x)) < \frac{\varepsilon}{3}.$$

We claim that

$$f_n^{-1}\left(B\left(f_n(x), \frac{\varepsilon}{3}\right)\right) \subseteq f^{-1}(B(f(x), \varepsilon)).$$

Let  $x$  be an element of  $X$  such that

$$d(f_n(x), f_n(p)) < \frac{\varepsilon}{3}.$$

One has

$$d(f(x), f(p)) \leq d(f(x), f_n(x)) + d(f_n(x), f_n(p)) + d(f_n(p), f(p)) < \varepsilon.$$

□

**Theorem 1.10.4** Let  $(X, d_X)$  and  $(Y, d_Y)$  be two metric spaces,  $(f_n)_{n \in \mathbb{N}}$  be sequence of uniformly continuous mappings from  $X$  to  $Y$ . Suppose that  $(f_n)_{n \in \mathbb{N}}$  converges uniformly to  $f : X \rightarrow Y$ . Then  $f$  is uniformly continuous.

**Proof** Let  $\varepsilon > 0$ . There exists  $n \in \mathbb{N}$  such that

$$\sup_{x \in X} d(f_n(x), f(x)) < \frac{\varepsilon}{3}.$$

$f_n$  is uniformly continuous, so the exists  $\delta > 0$

$$\forall (x, y) \in X \times X, d(x, y) < \delta \Rightarrow d(f_n(x), f_n(y)) < \frac{\varepsilon}{3}.$$

Therefore, for any  $(x, y) \in X \times X$  such that  $d(x, y) < \delta$ ,

$$d(f(x), f(y)) \leq d(f(x), f_n(x)) + d(f_n(x), f_n(y)) + d(f_n(y), f(y)) < \varepsilon.$$

So  $f$  is uniformly continuous.  $\square$

**Theorem 1.10.5** Let  $(E, \|\cdot\|_E)$ ,  $(F, \|\cdot\|_F)$  be normed vector spaces over a complete non-trivially valued field  $(K, |\cdot|)$ . Let  $U \subseteq E$  open,  $(f_n)_{n \in \mathbb{N}}$  a sequence of differentiable mappings from  $U$  to  $F$ . Let  $f : U \rightarrow F$ ,  $g : U \rightarrow \mathcal{L}(E, F)$  be mappings,  $p \in U$ . Suppose that

- (1) The sequence  $(Df_n)_{n \in \mathbb{N}}$  converges uniformly to  $g$ .
- (2)  $(f_n)_{n \in \mathbb{N}}$  converges uniformly to  $f$ .
- (3) There exists  $N \in \mathbb{N}$  and mapping  $\delta : U \rightarrow \mathbb{R}_{\geq 0}$  such that  $\lim_{x \rightarrow p} \delta(x) = 0$  and for any  $n \in \mathbb{N}_{\geq N}$ , any  $x \in U$ ,

$$\|f_n(x) - f_n(p) - Df_n(p)(x - p)\|_F \leq \delta(x) \|x - p\|_E.$$

Then  $f$  is differentiable and  $Df = g$ .

**Proof** For any  $n \in \mathbb{N}$ , define

$$\varepsilon_n := \sup_{x \in U} \|Df_n(x) - g(x)\|, \quad d_n := \sup_{x \in U} \|f_n(x) - f(x)\|.$$

One has

$$\begin{aligned}\|f(x) - f(p) - g(p)(x - p)\| &\leq \|(f(x) - f_n(x)) - (f(p) - f_n(p))\| \\ &\quad + \|f_n(x) - f_n(p) - Df_n(p)(x - p)\| \\ &\quad + \|Df_n(p)(x - p) - g(p)(x - p)\| \\ &\leq 2d_n + \delta(x)\|x - p\|_E + \varepsilon_n\|x - p\|_E.\end{aligned}$$

for sufficiently large  $n$ .

Therefore,

$$\limsup_{x \rightarrow p} \frac{\|f(x) - f(p) - g(p)(x - p)\|_F}{\|x - p\|_E} \leq 2\varepsilon_n.$$

Taking the limit when  $n \rightarrow \infty$ , we obtain

$$\limsup_{x \rightarrow p} \frac{\|f(x) - f(p) - g(p)(x - p)\|_F}{\|x - p\|_E} = 0.$$

Namely,

$$f(x) - f(p) - g(p)(x - p) = o(\|x - p\|_E), \quad x \rightarrow p.$$

□

**Theorem 1.10.6** Let  $(E, \|\cdot\|_E)$  and  $(F, \|\cdot\|_F)$  be normed vector spaces over  $\mathbb{R}$ ,  $U \subseteq E$  open,  $(f_n)_{n \in \mathbb{N}}$  be sequence of differentiable mappings from  $U$  to  $F$ ,  $g : U \rightarrow \mathcal{L}(E, F)$ . We suppose that

- (1)  $(Df_n)_{n \in \mathbb{N}}$  converges uniformly to  $g$ .
- (2)  $(f_n)_{n \in \mathbb{N}}$  converges point-wise to  $f : U \rightarrow F$ .

Then  $f$  is differentiable and  $Df = g$ .

**Proof** Let  $p \in U$ , for any  $(n, m) \in \mathbb{N} \times \mathbb{N}$ , for any  $n \in \mathbb{N}$ ,

$$c_{m,n} := \sup_{x \in U} \|Df_m(x) - Df_n(x)\|, \quad \varepsilon_n := \sup_{x \in U} \|Df_n(x) - g(x)\|.$$

For  $r > 0$ ,  $B(p, r) \subseteq U$  by the mean value inequality,

$$\|(f_n(x) - f_m(x)) - (f_n(p) - f_m(p))\| \leq c_{m,n}\|x - p\|, \quad x \in B(p, r).$$

Passing to the limit when  $m \rightarrow +\infty$ , we obtain

$$\|(f_n(x) - f(x)) - (f_n(p) - f(p))\| \leq \varepsilon_n\|x - p\|.$$

we have

$$\begin{aligned} \|f(x) - f(p) - g(p)(x - p)\| &\leq \|(f(x) - f_n(x)) - (f(p) - f_n(p))\| \\ &\quad + \|f_n(x) - f_n(p) - Df_n(p)(x - p)\| \\ &\quad + \|Df_n(p)(x - p) - g(p)(x - p)\|. \\ \limsup_{x \rightarrow p} \frac{\|f(x) - f(p) - g(p)(x - p)\|_F}{\|x - p\|_E} &\leq 3\varepsilon_n. \end{aligned}$$

Taking the limit  $n \rightarrow +\infty$

$$\lim_{x \rightarrow p} \frac{\|f(x) - f(p) - g(p)(x - p)\|_F}{\|x - p\|_E} = 0.$$

Namely,

$$f(x) - f(p) - g(p)(x - p) = o(\|x - p\|_E), \quad x \rightarrow p.$$

□

**Proposition 1.10.7** Let  $(E, \|\cdot\|_E)$ ,  $(F, \|\cdot\|_F)$  be normed vector spaces over  $\mathbb{R}$ . Assume that  $(F, \|\cdot\|_F)$  is a Banach space,  $U \subseteq E$  be a path connected open,  $(f_n)_{n \in \mathbb{N}}$  be a sequence of differentiable mappings from  $U$  to  $F$ . Suppose that (1)  $(Df_n)_{n \in \mathbb{N}}$  converges uniformly to  $g : U \rightarrow \mathcal{L}(E, F)$ .

(2) There exists  $p \in U$  such that  $(f_n(p))_{n \in \mathbb{N}}$  converges.

Then the sequence  $(f_n)_{n \in \mathbb{N}}$  converges point-wise on  $U$  to a differentiable mapping  $f : U \rightarrow F$  such that  $Df = g$ .

**Proof** We first treat the case where  $U$  is convex.

For any  $(n, m) \in \mathbb{N} \times \mathbb{N}$ , let

$$c_{m,n} := \sup_{x \in U} \|Df_m(x) - Df_n(x)\|.$$

Let  $x \in U$ . By the mean value inequality,

$$\|(f_n(x) - f_m(x)) - (f_n(p) - f_m(p))\| \leq c_{m,n} \|x - p\|,$$

which leads to

$$\|f_n(x) - f_m(x)\|_F \leq \|f_n(p) - f_m(p)\|_F + c_{m,n} \|x - p\|_E.$$

Therefore  $(f_n(x))_{n \in \mathbb{N}}$  is a Cauchy sequence in  $F$  (Banach space), so  $f_n(x)$  converges in  $F$  to some  $f(x)$ . Now it suffices to use the theorem 1.10.6.

We will now treat the general case. Let  $x \in U$ . There exists  $\gamma : [0, 1] \rightarrow U$  continuous such that  $\gamma(0) = p, \gamma(1) = x$ . Let  $I$  be the set of  $t \in [0, 1]$  such that  $f_n(\gamma(s))$  converges for all  $s \in [0, t]$ . By definition,  $I$  is an interval in  $[0, 1]$  and  $0 \in I$ . Therefore, it is of the form  $[0, c]$  or  $[0, c[$ .

Let  $B(\gamma(c), r) \subseteq U$ . Since  $\gamma$  is continuous,  $\gamma^{-1}(B(\gamma(c), r))$  is open in  $[0, 1]$  and  $c \in \gamma^{-1}(B(\gamma(c), r))$ . Assume by contradiction that  $I = [0, c[$ , then  $I \cap \gamma^{-1}(B(\gamma(c), r)) \neq \emptyset$ . There exists  $q \in \gamma^{-1}(B(\gamma(c), r)) \cap I$  such that  $f_n(q)$  converges. So from the “convex  $U$  version”  $f$  converges point-wise on  $B(\gamma(c), r)$ . So  $f_n(\gamma(c))$  converges. Contradiction. We deduce that  $I = [0, c]$ .

If  $c \neq 1$ , then  $c$  is an adherent point of  $]c, 1]$ .  $\gamma^{-1}(B(\gamma(c), r))$  open, so there exists  $r' > 0$  such that  $B(c, r') \subseteq \gamma^{-1}(B(\gamma(c), r))$ . In particular,  $B(c, r') \cap ]c, 1]$  is an open interval in  $[0, 1]$  that continuous. So  $I \supseteq ]0, c + r']$ . Contradiction. Therefore  $c = 1$ .  $\square$

**Definition 1.10.8** Let  $U$  be a set and  $(F, \|\cdot\|)$  be a Banach space over complete valued field  $(K, |\cdot|)$ .  $(f_n)_{n \in \mathbb{N}} \in (F^U)^{\mathbb{N}}$  be a sequence of mappings from  $U$  to  $F$ . If

$$\sum_{n \in \mathbb{N}} \sup_{p \in U} \|f_n(p)\|_F < +\infty,$$

then we say that  $\sum_{n \in \mathbb{N}} f_n$  **converges normally**.

**Proposition 1.10.9** If  $\sum f_n$  converges normally, then it converges uniformly.

**Proof** For any  $n \in \mathbb{N}$ , let  $g_n = \sum_{k=0}^n f_k$ . We need to check that the sequence  $(g_n)_{n \in \mathbb{N}}$  converges uniformly. For any  $x \in U$ ,  $\sum_{n \in \mathbb{N}} \|f_n(x)\| < +\infty$ . So  $\sum_{n \in \mathbb{N}} f_n(x)$  converges absolutely. In particular,  $(g_n(x))_{n \in \mathbb{N}}$  converges to some  $g(x)$ .

$$\begin{aligned} \|g_n(x) - g(x)\|_F &= \lim_{m \rightarrow +\infty} \|g_n(x) - g_m(x)\|_F \\ &\leq \lim_{m \rightarrow +\infty} \|f_{n+1}(x) + \cdots + f_m(x)\|_F \\ &\leq \limsup_{m \rightarrow +\infty} \sum_{k \geq n+1} \|f_k(x)\|_F \\ &\leq \varepsilon_n. \end{aligned}$$

Let

$$\varepsilon_n = \sum_{k \geq n+1} \sup_{p \in U} \|f_k(p)\|_F, \quad \lim_{n \rightarrow +\infty} \varepsilon_n = 0.$$

So,

$$\limsup_{n \rightarrow +\infty} \left( \sup_{x \in U} \|g_n(x) - g(x)\|_F \right) = 0,$$

namely,  $(g_n)_{n \in \mathbb{N}}$  converges to  $g$ . □

**Proposition 1.10.10** Let  $(K, |\cdot|)$  be a complete valued field which is non-trivially valued,  $(E, \|\cdot\|)$  be a normed vector space and  $(F, \|\cdot\|_F)$  be a Banach space over  $K$ .  $U \subseteq E$  be an open subset,  $(f_n)_{n \in \mathbb{N}}$  be a sequence of differentiable mappings  $U \rightarrow F$  and  $p \in U$ . Assume that

- (1)  $\sum_{n \in \mathbb{N}} f_n$  converges normally (uniformly suffices).
- (2)  $\sum_{n \in \mathbb{N}} Df_n$  converges normally (uniformly suffices).
- (3)  $\exists N \in \mathbb{N}$  and mappings  $(\delta_n : U \rightarrow \mathbb{R}_{\geq 0})_{n \in \mathbb{N}_{\geq N}}$  such that

- 1.  $\forall n \in \mathbb{N}_{\geq N}, \lim_{x \rightarrow p} \delta_n(x) = \delta_n(p) = 0$ .
- 2.  $\sum_{n \in \mathbb{N}} \delta_n$  converges normally (uniformly suffices).
- 3.  $\forall n \in \mathbb{N}_{\geq N}, \forall x \in U,$

$$\|f_n(x) - f_n(p) - Df_n(p)(x - p)\|_F \leq \delta_n(x) \|x - p\|_E.$$

Let  $f$  and  $g$  be limits of  $\sum_{n \in \mathbb{N}} f_n$  and  $\sum_{n \in \mathbb{N}} Df_n$  respectively. Then  $f$  is differentiable at  $p$  and  $Df = g$ .

**Proposition 1.10.11** Let  $(E, \|\cdot\|_E)$  be a normed vector space and  $(F, \|\cdot\|_F)$  be a Banach space over  $\mathbb{R}$ . Let  $U \subseteq E$  open, and  $(f_n : U \rightarrow F)_{n \in \mathbb{N}}$  be a sequence of mappings  $U \rightarrow F$ . Suppose that

- (1)  $\sum_{n \in \mathbb{N}} Df_n$  converges normally (uniformly suffices) to some  $g : U \rightarrow \mathcal{L}(E, F)$ .
  - (2)  $\sum_{n \in \mathbb{N}} f_n$  converges point-wise to some  $f : U \rightarrow F$ .
- Then  $f$  is differentiable on  $U$  and  $Df = g$ .

**Remark 1.10.12** If  $U$  is path connected, one can replace (2) by (2'):  $\exists p \in U, \sum_{n \in \mathbb{N}} f_n(p)$  converges.

## 1.11 Power Series

We fix a complete non-trivially valued field  $(K, |\cdot|)$ , and let  $(E, \|\cdot\|_E)$  be a Banach space over  $K$ .

**Definition 1.11.1** Let  $(S_n)_{n \in \mathbb{N}} \in E^{\mathbb{N}}$  and  $b \in K$ . We call power series **centered at  $b$**  with coefficients  $(s_n)_{n \in \mathbb{N}}$  the sequence of polynomial mappings.

$$\left( (z \in K) \longmapsto \sum_{l=0}^n (z - b)^l s_l \right)_{n \in \mathbb{N}}$$

denoted as

$$\sum_{l=0}^n (z - b)^l s_l.$$

If  $S = \sum_{n \in \mathbb{N}} (z - b)^n s_n$ , we denote by  $R(S)$  the element

$$\left( \limsup_{n \rightarrow +\infty} \|s_n\|^{\frac{1}{n}} \right)^{-1} \in [0, +\infty]$$

called the **convergence radius** of  $S$ . ( $0^+ := +\infty$ ,  $(+\infty)^{-1} := 0$ )

**Proposition 1.11.2** Let  $S = \sum_{n \in \mathbb{N}} (z - b)^n s_n$ .

- (1)  $\forall a \in K$ , if  $|a - b| < R(S)$ , then  $S(a) := \sum_{n \in \mathbb{N}} (a - b)^n s_n$  converges absolutely.
- (2) If  $r > 0$  such that  $(r^n \|s_n\|)_{n \in \mathbb{N}}$  is bounded, then  $R(S) \geq r$ .
- (3) If  $a \in K$  is such that  $|a - b| > R(S)$ , then  $\sum_{n \in \mathbb{N}} (a - b)^n s_n$  diverges.

### Proof

(1)

$$\begin{aligned} \|(a - b)^n s\|^{\frac{1}{n}} &= ((|a - b|^n) \cdot \|s_n\|)^{\frac{1}{n}} = |a - b| \cdot \|s_n\|^{\frac{1}{n}}. \\ \limsup_{n \rightarrow +\infty} \|(a - b)^n s_n\|^{\frac{1}{n}} &= |a - b| \cdot \limsup_{n \rightarrow +\infty} \|s_n\|^{\frac{1}{n}}. \end{aligned}$$

If  $|a - b| < R(S)$ , then  $|a - b| \cdot \limsup_{n \rightarrow +\infty} \|s_n\|^{\frac{1}{n}} < 1$ . By the root test of Cauchy,  $\sum_{n \in \mathbb{N}} (a - b)^n s_n$  converges absolutely.

(2)

$$\|s_n\|^{\frac{1}{n}} = \frac{1}{r} (r^n \|s_n\|)^{\frac{1}{n}}.$$

Since  $(r^n \|s_n\|)_{n \in \mathbb{N}}$  is bounded,

$$\limsup_{n \rightarrow +\infty} (r^n \|s_n\|)^{\frac{1}{n}} \leq 1.$$

So  $\limsup_{n \rightarrow +\infty} \|s_n\|^{\frac{1}{n}} \leq \frac{1}{r}$ . So  $R(S) \geq r$ .

(3) If  $|a - b| > R(S)$ , then

$$\limsup_{n \rightarrow +\infty} \|(a - b)^n s_n\|^{\frac{1}{n}} = |a - b| \cdot \limsup_{n \rightarrow +\infty} \|s_n\|^{\frac{1}{n}} > 1.$$

So  $\sum_{n \in \mathbb{N}} (a - b)^n s_n$  diverges.  $\square$

**Proposition 1.11.3** Let  $S = \sum_{n \in \mathbb{N}} (z - b)^n s_n$  be a power series.

- (1)  $\forall r \in \mathbb{R}_{\geq 0}$  such that  $r < R(S)$ . the series  $S$  converges normally on  $\overline{B}(b, r)$ .
- (2)  $(a \in B(b, R(S))) \mapsto S(a) := \sum_{n \in \mathbb{N}} (a - b)^n s_n$  is continuous.

### Proof

(1)  $\forall a \in \overline{B}(b, r)$ ,

$$\sum_{n \in \mathbb{N}} \|(a - b)^n s_n\| \leq \sum_{n \in \mathbb{N}} r^n \|s_n\| < +\infty$$

since  $\limsup_{n \rightarrow +\infty} r \cdot \|s_n\|^{\frac{1}{n}} < 1$ .

(2)  $a \mapsto S(a)$  is continuous on any  $B(b, r)$ ,  $r < R(S)$ . Since

$$B(b, R(S)) = \bigcup_{r < R(S)} B(b, r),$$

$S$  is continuous on  $B(b, R(S))$ .  $\square$

**Definition 1.11.4** Let  $S = \sum_{n \in \mathbb{N}} (z - b)^n s_n$ . We define the formal derivative of  $S$  as

$$\sum_{n \in \mathbb{N}_{\geq 1}} (z - b)^{n-1} (ns_n).$$

**Proposition 1.11.5** Let  $S = \sum_{n \in \mathbb{N}} (z - b)^n s_n$  be a formal power series. Let  $P \in K[T]$ . For any  $n \in \mathbb{N}$ , let  $P(n) := P(n1_K) \in K$ . Let

$$S_p := \sum_{n \in \mathbb{N}} (z - b)^n (P(n)s_n).$$

Then  $R(S_p) \geq R(S)$ .

**Proof** We assume that  $P \neq 0$ ,  $P(T)$  is of the form

$$C_d T^d + C_{d-1} T^{d-1} + \cdots + C_1 T + C_0, \quad C_d \neq 0.$$

$$|P(n)| = \mathcal{O}(n^d) = o(r^n), \text{ for any } r > 1.$$

Hence,  $\exists N \in \mathbb{N}$  such that  $|P(n)| \leq r^n, \forall n \in \mathbb{N}_{\geq N}$ .

$$\limsup_{n \rightarrow +\infty} \|P(n)s_n\|^{\frac{1}{n}} \leq r \cdot \limsup_{n \rightarrow +\infty} \|s_n\|^{\frac{1}{n}}.$$

Taking the limit when  $r \rightarrow 1$ , get

$$\limsup_{n \rightarrow +\infty} \|P(n)s_n\|^{\frac{1}{n}} \leq \limsup_{n \rightarrow +\infty} \|s_n\|^{\frac{1}{n}}.$$

$$R(S_p) \geq R(S).$$

□

**Lemma 1.11.6** Let  $(z_0, z) \in K^2, n \in \mathbb{N}_{\geq 1}$ .

$$z^n - z_0^n - nz_0^{n-1}(z - z_0) = (z - z_0)^2 \sum_{j=0}^{n-2} (n-j-1) z^j z_0^{n-2-j}.$$

**Proof**

$$\begin{aligned} z^n - z_0^n - nz_0^{n-1}(z - z_0) &= (z - z_0) \sum_{i=0}^{n-1} z^i z^{n-1-i}. \\ z^n - z_0^n - nz_0^{n-1}(z - z_0) &= (z - z_0) \sum_{i=0}^{n-1} (z^i z_0^{n-1-i} - z_0^{n-1}) \\ &= (z - z_0) \sum_{i=0}^{n-1} z_0^{n-i-1} (z^i - z_0^i) \\ &= (z - z_0)^2 \sum_{i=1}^{n-1} z_0^{n-1-i} \sum_{j=0}^{i-1} z^j z_0^{i-j-1} \\ &= (z - z_0)^2 \sum_{j=0}^{n-2} \sum_{i=j+1}^{n-1} z^j z_0^{n-2-j} \\ &= (z - z_0)^2 \sum_{j=0}^{n-2} (n-j-1) z^j z_0^{n-2-j}. \end{aligned}$$

□

**Theorem 1.11.7** Let  $\sum_{n \in \mathbb{N}} (z - b)^n s_n$  be a power series and  $R$  be its convergence radius. For any  $z \in B(b, R)$ , let  $S(z)$  be the limit of the series. Then the mapping  $S : B(b, R) \rightarrow E$  is differentiable, and its derivative is given by the limit of the power series

$$\sum_{n \in \mathbb{N}_{\geq 1}} (z - b)^{n-1} (ns_n).$$

**Proof** Let  $r < R$ ,  $(z, z_0) \in B(b, r)^2$ .

$$\begin{aligned} & \| (z - b)^n s_n - (z_0 - b)^n s_n - (z - z_0)(z_0 - b)^{n-1} n s_n \| \\ &= |z - z_0|^2 \cdot \| \sum_{j=0}^{n-2} (n-1-j)(z-b)^j (z_0-b)^{n-2-j} s_n \| \\ &\quad \| \sum_{j=0}^{n-2} (n-1-j)(z-b)^j (z_0-b)^{n-2-j} s_n \| \\ &\leq \sum_{j=0}^{n-2} (n-1-j)r^{n-2} \|s_n\| = \frac{n(n-1)}{2} r^{n-2} \|s_n\|. \end{aligned}$$

We know that

$$\sum_{n \in \mathbb{N}} \frac{n(n-1)}{2} r^{n-2} \|s_n\| < +\infty.$$

Therefore, the result follows from the proposition 1.10.10.  $\square$

**Definition 1.11.8** Let  $(a_n)_{n \in \mathbb{N}} \in K^{\mathbb{N}}$  and  $(s_n)_{n \in \mathbb{N}} \in E^{\mathbb{N}}$ . We call **Cauchy product** of the series  $\sum_{n \in \mathbb{N}} a_n$  and  $\sum_{n \in \mathbb{N}} s_n$  as the series:

$$\sum_{n \in \mathbb{N}} \left( \sum_{k=0}^n a_k s_{n-k} \right).$$

**Theorem 1.11.9 (Merterns)** Let  $(a_n)_{n \in \mathbb{N}} \in K^{\mathbb{N}}$  and  $(s_n)_{n \in \mathbb{N}} \in E^{\mathbb{N}}$ . Suppose that  $\sum_{n \in \mathbb{N}} a_n$  and  $\sum_{n \in \mathbb{N}} s_n$  converges to  $b \in K$  and  $t \in E$  respectively.

- (1) If at least one of  $\sum_{n \in \mathbb{N}} a_n$ ,  $\sum_{n \in \mathbb{N}} s_n$  converges absolutely, then their Cauchy product converges to  $bt$ .
- (2) If both  $\sum_{n \in \mathbb{N}} a_n$  and  $\sum_{n \in \mathbb{N}} s_n$  converge absolutely, then the Cauchy product also converges absolutely.

**Proof**

(1) Suppose that  $\sum_{n \in \mathbb{N}} a_n$  converges absolutely. For any  $n \in \mathbb{N}$ , let

$$A_n := \sum_{k=0}^n a_k, \quad S_n := \sum_{k=0}^n s_k.$$

For any  $N \in \mathbb{N}$ , let

$$t_N = \sum_{n=0}^N \left( \sum_{k=0}^n a_k s_{n-k} \right) = \sum_{\substack{(k,l) \in \mathbb{N}^2 \\ k+l \leq N}} a_k s_l = \sum_{k=0}^N a_k S_{N-k} = A_n t + \sum_{k=0}^N a_k (S_{N-k} - t).$$

Then,

$$t_N - bt = (A_N - b)t + \sum_{k=0}^N a_k (S_{N-k} - t).$$

Let  $\alpha := \sum_{n \in \mathbb{N}} |a_n|$  and for any  $n \in \mathbb{N}$  let

$$\varepsilon_n := \sup_{m \in \mathbb{N}, m \leq n} \|S_m - t\|.$$

For any  $l \in \{0, \dots, N\}$ , one has

$$\begin{aligned} \left\| \sum_{k=0}^N a_k (S_{N-k} - t) \right\| &\leq \sum_{k=0}^{N-l} |a_k| \cdot \|S_{N-k} - t\| + \sum_{k=N-l+1}^N |a_k| \cdot \|S_{N-k} - t\| \\ &\leq \varepsilon_l \cdot \alpha + \max_{i \in \{0, \dots, l-1\}} \|S_i - t\| \cdot \sum_{k=N-l+1}^N |a_k|. \end{aligned}$$

We get

$$\forall l \in \mathbb{N}, \limsup_{N \rightarrow +\infty} \left\| \sum_{k=0}^N a_k (S_{N-k} - t) \right\| \leq \varepsilon_l \alpha.$$

Taking the infimum with respect to  $l$ , we get

$$\limsup_{N \rightarrow +\infty} \left\| \sum_{k=0}^N a_k (S_{N-k} - t) \right\| = 0.$$

We deduce therefore that

$$\lim_{N \rightarrow +\infty} t_N = bt.$$

(2) Let

$$\alpha = \sum_{n \in \mathbb{N}} |a_n|, \quad \beta = \sum_{n \in \mathbb{N}} \|s_n\|.$$

For any  $N \in \mathbb{N}$ , one has

$$\sum_{n=0}^N \left\| \sum_{k=0}^n a_k s_{n-k} \right\| \leq \sum_{n=0}^N \sum_{k=0}^n |a_k| \cdot \|s_n\| \leq \sum_{\substack{(k,l) \in \mathbb{N}^2 \\ k \leq N, l \leq N}} |a_k| \|s_l\| \leq \alpha \cdot \beta.$$

So the Cauchy product of  $\sum_{n \in \mathbb{N}} a_n$  and  $\sum_{n \in \mathbb{N}} s_n$  converges absolutely.  $\square$

**Example 1.11.10** Consider

$$e^z = \exp(z) := \sum_{n \in \mathbb{N}} \frac{z^n}{n!}, \quad z \in \mathbb{C}.$$

By the ratio test of D'Alembert, for any  $r > 0$ ,  $\sum_{n \in \mathbb{N}} \frac{r^n}{n!} < +\infty$ .  $e^z$  is well defined.

Let  $\alpha \in \mathbb{C}$ ,

$$\exp'(\alpha z) = \alpha \exp(\alpha z).$$

We define

$$\begin{aligned} \cos(z) &:= \frac{e^{iz} + e^{-iz}}{2}, \quad \sin(z) := \frac{e^{iz} - e^{-iz}}{2i}, \\ \cosh(z) &:= \frac{e^z + e^{-z}}{2}, \quad \sinh(z) := \frac{e^z - e^{-z}}{2}. \end{aligned}$$

**Proposition 1.11.11** Let  $(a, b, z) \in \mathbb{C}^3$ , then

$$\exp((a+b)z) = \exp(az) \exp(bz).$$

**Proof** The Cauchy product of  $\sum_{n \in \mathbb{N}} \frac{(az)^n}{n!}$  and  $\sum_{n \in \mathbb{N}} \frac{(bz)^n}{n!}$  is  $\sum_{n \in \mathbb{N}} \frac{(a+b)^n z^n}{n!}$ . Use the theorem of Mertens.  $\square$

## 1.12 Directional Differential

**Definition 1.12.1** Let  $(K, |\cdot|)$  be a complete non-trivially valued field, and  $(E, \|\cdot\|_E)$  and  $(F, \|\cdot\|_F)$  be normed vector spaces over  $K$ . Let  $U \subseteq K$  open,

$f : U \rightarrow F$  be a mapping,  $p \in U$ ,  $h \in E$ . If the limit

$$\lim_{t \rightarrow 0} \frac{f(p + th) - f(p)}{t}$$

exists, we say that  $f$  admits the **directional derivative** at  $p$  along  $h$ .

### Notation 1.12.2

$$\partial_h f(p) = \lim_{t \rightarrow 0} \frac{f(p + th) - f(p)}{t}.$$

**Definition 1.12.3** Let  $(E_1, \|\cdot\|_1), \dots, (E_n, \|\cdot\|_n)$  be normed vector spaces,  $E := E_1 \times \dots \times E_n$ ,

$$\|(s_1, \dots, s_n)\| = \max_{i \in \{1, \dots, n\}} \|s_i\|.$$

If  $f : U \rightarrow F$ . We say that  $f$  has the **i-th partial differential** at  $p = (p_1, \dots, p_n) \in U$ , if the mapping

$$x_i \mapsto f(p_1, \dots, p_{i-1}, x_i, p_{i+1}, \dots, p_n)$$

is differentiable at  $p_i$ . We denote the existing differential at  $p_i$  by

$$D_i f(p) \in \mathcal{L}(E_i, F).$$

In the case when  $E_i = K$ ,

$$D_i f(p)(1) := \partial_i f(p) \text{ or } \frac{\partial f}{\partial x_i}(p).$$

Note that

$$\partial_i f(p) = \underset{i\text{-th}}{\partial}_{(0, \dots, 1, \dots, 0)} f(p).$$

**Remark 1.12.4** Let  $(K, |\cdot|)$  be a complete non-trivially valued field,  $(E_i, \|\cdot\|_i)$ ,  $i \in \{1, \dots, n\}$ ,  $(F, \|\cdot\|_F)$  be normed vector spaces.  $E = E_1 \times \dots \times E_n$ , equipped with the norm  $\|\cdot\|$  defined as

$$\|(x_1, \dots, x_n)\| = \max_{i \in \{1, \dots, n\}} \|x_i\|_i.$$

Let  $U \subseteq E$  be an open subset,  $p \in U$ ,  $f : U \rightarrow F$  be a mapping. If  $f$  is differentiable at  $p$ , then  $f$  has the  $i$ -th partial differential at  $p$  for  $i \in \{1, \dots, n\}$ .

In fact,

$$f(p_1, \dots, p_i + h_i, \dots, p_n) = f(p) + Df(p)(0, \dots, h_i, \dots, 0) + o(\|h_i\|_i).$$

$$D_i f(p)(h_i) = Df(p)(0, \dots, h_i, \dots, 0).$$

$$Df(p)(h) = \sum_{i=1}^n Df(p)(0, \dots, h_i, \dots, 0) = \sum_{i=1}^n D_i f(p)(h_i).$$

**Proposition 1.12.5** Let  $(E_i, \|\cdot\|_i)$ ,  $i \in \{1, \dots, n\}$ ,  $(F, \|\cdot\|_F)$  be normed vector spaces over  $\mathbb{R}$ , with  $\dim_{\mathbb{R}}(F) < +\infty$ . Let  $E = E_1 \times \dots \times E_n$ , equipped with the norm  $\|\cdot\|$  defined as

$$\|(x_1, \dots, x_n)\| = \max_{i \in \{1, \dots, n\}} \|x_i\|_i.$$

Let  $U \subseteq E$  be an open subset,  $f : U \rightarrow F$  be a mapping. Suppose that, for any  $i \in \{1, \dots, n\}$ ,  $f$  has  $i^{\text{th}}$  partial differential on  $U$ , and  $D_i f : U \rightarrow \mathcal{L}(E_i, F)$  is continuous. Then  $f$  is differentiable on  $U$ , and

$$\forall p \in U, Df(p)(h_1, \dots, h_n) = \sum_{i=1}^n D_i f(p)(h_i).$$

**Proof** We first treat the case where  $F = \mathbb{R}$ . Let  $p \in U$ , and  $r > 0$  such that  $B(p, r) \subseteq U$ . Let  $h = (h_1, \dots, h_n) \in B(0, r)$ .

$$\begin{aligned} f(p + h) - f(p) &= \sum_{i=1}^n (f(p_1 + h_1, \dots, p_i + h_i + \dots, p_{i+1}, \dots, p_n) \\ &\quad - f(p_1 + h_1, \dots, p_i, \dots, p_{i+1}, \dots, p_n)). \end{aligned}$$

By the mean value theorem of Lagrange,

$$\exists(t_1(h), \dots, t_n(h)) \in ]0, 1[^n$$

such that

$$f(p + h) - f(p) = \sum_{i=1}^n D_i f(p_1 + h_1, \dots, p_i + t_i(h)h_i, \dots, p_{i+1}, \dots, p_n)(h_i).$$

$$\begin{aligned} & f(p+h) - f(p) - \sum_{i=1}^n D_i f(p)(h) \\ &= \sum_{i=1}^n D_i f(p_1 + h_1, \dots, p_i + t_i(h)h_i, \dots, p_{i+1}, \dots, p_n)(h_i) \\ &\quad - \sum_{i=1}^n D_i f(p_1, \dots, p_i, \dots, p_{i+1}, \dots, p_n)(h_i) \\ &= o(\|h\|). \end{aligned}$$

□

# Chapter 2

# Integral Calculus

## 2.1 Differential 1-form

**Definition 2.1.1** Let  $(K, |\cdot|)$  be a complete non-trivially valued field. Let  $(E, \|\cdot\|_E)$  and  $(F, \|\cdot\|_F)$  be normed vector spaces over  $K$ . Let  $U \subseteq E$  be an open subset. We call **1-form** on  $U$  with coefficients in  $F$  any mapping

$$\alpha : U \longrightarrow \mathcal{L}(E, F).$$

If there exists  $f : U \longrightarrow F$  differentiable such that  $Df = \alpha$ , we say that  $\alpha$  is an **exact** 1-form. (Sometimes  $Df$  is also written as  $df$ .)

**Definition 2.1.2** We call a complete valued field **extension** of  $(K, |\cdot|)$  any complete valued field  $(K', |\cdot|')$  such that  $K \subseteq K'$  and  $|\cdot| = |\cdot|'|_K$ .

Let  $(F, \|\cdot\|)$  be a normed vector space over  $K$ . If  $\alpha : U \longrightarrow \mathcal{L}(E, K')$  and  $s : U \longrightarrow F$  be mappings, we denote by

$$\alpha \otimes s : U \longrightarrow \mathcal{L}(E, F)$$

be the mapping sending  $p \in U$  to

$$(h \in E) \longmapsto \alpha(p)(h)s(p).$$

Note that

$$\|\alpha(p)(h)s(p)\|_F \leq |\alpha(p)(h)|_{K'} \cdot \|s(p)\|_F \leq \|\alpha(p)\| \cdot \|s(p)\|_F \cdot \|h\|_E.$$

If  $(F, \|\cdot\|_F) = (K', |\cdot|')$ ,  $\alpha \otimes s$  is also written as  $\alpha s$ .

**Example 2.1.3**  $(K, |\cdot|) = (\mathbb{R}, |\cdot|)$ ,  $K' = \mathbb{C}$ ,  $|x + iy|' := \sqrt{x^2 + y^2}$ .

**Example 2.1.4** Let  $\varphi \in \mathcal{L}(E, F)$ ,

$$\begin{aligned} D\varphi : E &\longrightarrow \mathcal{L}(E, F) \\ p &\longmapsto \varphi. \end{aligned}$$

is a constant mapping.

As a 1-form, it is often written as  $d\varphi$ .

**Example 2.1.5**  $E = K^n$ ,  $x_i : K^n \longrightarrow K$ ,  $(p_1, \dots, p_n) \longmapsto p_i$ .  $U \subseteq E$  open,  $f : U \longrightarrow K$  differentiable.

$$df(p) = \sum_{i=1}^n \frac{\partial f}{\partial x_i}(p) dx_i.$$

**Example 2.1.6** Let  $w \in \mathbb{C}$ ,  $f : \mathbb{R} \longrightarrow \mathbb{C}$ ,  $t \longmapsto \exp(wt)$ .

$$df(t) = f'(t)dt = w \exp(wt)dt.$$

**Proposition 2.1.7** Let  $(K', |\cdot|)$  be a complete valued extension of  $(K, |\cdot|)$ , and  $(F, \|\cdot\|_F)$  be a normed vector space over  $K'$ . Let  $(E, \|\cdot\|_E)$  be a normed vector space over  $K$ ,  $U \subseteq E$  be an open subset. Let  $f : U \longrightarrow K'$  and  $g : U \longrightarrow F$  be two mappings that are differentiable, then

$$d(fg) = f dg + df \otimes g.$$

**Proposition 2.1.8** Let  $(K', |\cdot|')$  be a complete valued extension of  $(K, |\cdot|)$ .  $(E, \|\cdot\|_E)$  be a normed vector space over  $K$ ,  $(F, \|\cdot\|_F)$  be a normed vector space over  $K'$ . Let  $U \subseteq E$  be an open subset, and  $V \subseteq K'$  be an open subset.  $f : U \longrightarrow V$ ,  $g : V \longrightarrow F$  be differentiable mappings, then

$$d(g \circ f) = df \otimes (g' \circ f).$$

**Proof** For  $p \in U$  and  $h \in E$ ,

$$\begin{aligned} D(g \circ f)(p)(h) &= Dg(f(p))(Df(p)(h)) \\ &= Df(p)(h) \cdot Dg(f(p))(1) \\ &= Df(p)(h) \cdot g'(f(p)) \end{aligned}$$

□

## 2.2 Primitive Functions

**Proposition 2.2.1** Let  $(E, \|\cdot\|)$  and  $(F, \|\cdot\|)$  be normed vector spaces over  $\mathbb{R}$  and  $U \subseteq E$  be a path connected open subset. If  $f : U \rightarrow F$  is a mapping such that  $Df = 0$ , then  $f$  is a constant mapping.

**Proof** Let  $p$  and  $q$  be elements of  $U$ . There exists  $\gamma : [0, 1] \rightarrow U$  continuous and differentiable on  $]0, 1[$ , such that  $\gamma(0) = p, \gamma(1) = q$ .

$$\|f(p) - f(q)\|_F = \|f(\gamma(0)) - f(\gamma(1))\|_F \leq \sup_{t \in ]0, 1[} \|Df(\gamma(t))(\gamma'(t))\|_F = 0.$$

So  $f(p) = f(q)$ . □

**Definition 2.2.2** Let  $I \subseteq \mathbb{R}$  be an open interval and  $\varphi : I \rightarrow F$  be a mapping. If there exists  $\Phi : I \rightarrow F$  such that  $\Phi' = \varphi$ , we say that  $\Phi$  is a primitive function of  $\varphi$ . We denote by

$$\int \varphi(t) dt$$

an arbitrary primitive function of  $\varphi$ . By the previous proposition,

$$\int \varphi(t) dt = \Phi(t) + C.$$

where  $C$  is a constant mapping.

**Example 2.2.3** Let  $w \in \mathbb{C}$ ,

$$\int \exp(wt) dt = \begin{cases} \frac{\exp(wt)}{w} + C & , w \neq 0 \\ t + C & , w = 0. \end{cases}$$

**Proposition 2.2.4** Let  $I \subseteq \mathbb{R}$  be an open interval. Let  $g : I \rightarrow \mathbb{R}$  and  $\varphi : I \rightarrow F$  be mappings having  $G : I \rightarrow \mathbb{R}$  and  $\Phi : I \rightarrow F$  as primitive functions. Then

$$\int G(t)d\Phi(t) + \int dG(t) \otimes \Phi(t) = G(t)\Phi(t) + C.$$

or equivalently,

$$\int G(t)dt \otimes \varphi(t) + \int g(t)dt \otimes \Phi(t) = G(t)\Phi(t) + C.$$

If  $F = \mathbb{R}$  or  $F = \mathbb{C}$ , the formula can be written as

$$\int G(t)d\Phi(t) + \int \Phi(t)dG(t) = G(t)\Phi(t) + C.$$

or

$$\int G(t)\varphi(t)dt + \int \Phi(t)g(t)dt = G(t)\Phi(t) + C.$$

### Example 2.2.5

$$\int te^t dt = \int t d(e^t) = te^t - \int e^t dt = te^t - e^t + C.$$

**Proposition 2.2.6** Let  $U \subseteq \mathbb{R}$  be an open subset,  $V \subseteq \mathbb{R}$  be an open subset,  $f : U \rightarrow V$  and  $g : V \rightarrow F$  differentiable mappings. One has

$$\int df(t) \otimes g'(f(t)) = g(f(t)) + C.$$

### Example 2.2.7

$$\int \sin(t) \cos(t) dt = \int \sin(t) d(\sin(t)) = \frac{1}{2} \sin(t)^2 + C.$$

## 2.3 Riesz Space

We fix a set  $\Omega$ . We equipped  $\mathbb{R}^\Omega$  with the partial order  $\leq$  as follows:

$$\forall (f, g) \in \mathbb{R}^\Omega \times \mathbb{R}^\Omega, f \leq g \Leftrightarrow \forall \omega \in \Omega, f(\omega) \leq g(\omega).$$

If  $(f_1, \dots, f_n) \in (\mathbb{R}^\Omega)^n$ ,  $\inf\{f_1, \dots, f_n\}$  and  $\sup\{f_1, \dots, f_n\}$  exists.

$$\forall \omega \in \Omega, \inf\{f_1, \dots, f_n\}(\omega) = \min\{f_1(\omega), \dots, f_n(\omega)\}$$

$$\forall \omega \in \Omega, \sup\{f_1, \dots, f_n\}(\omega) = \max\{f_1(\omega), \dots, f_n(\omega)\}$$

**Definition 2.3.1** We call Riesz space on  $\Omega$  any vector space  $S$  of  $\mathbb{R}^\Omega$ , such that

$$\forall (f, g) \in S \times S, \inf\{f, g\} \in S.$$

**Remark 2.3.2**  $\forall (f, g) \in S \times S,$

$$\sup\{f, g\} = f + g - \inf\{f, g\} \in S.$$

By induction,  $\forall n \in \mathbb{N}_{\geq 1}, \forall (f_1, \dots, f_n) \in S^n,$

$$\inf\{f_1, \dots, f_n\}, \sup\{f_1, \dots, f_n\} \subseteq S.$$

$$\forall \omega \in \Omega, \sup\{f, g\}(\omega) = \max\{f(\omega), g(\omega)\} = f(\omega) + g(\omega) - \min\{f(\omega), g(\omega)\}.$$

**Definition 2.3.3** Let  $S$  be a Riesz space on  $\Omega$ . We call **integral operator** on  $S$  any  $\mathbb{R}$ -linear mapping  $I : S \rightarrow \mathbb{R}$  such that

- (1)  $\forall (f, g) \in S \times S$ , if  $f \leq g$ , then  $I(f) \leq I(g)$ .
- (2) If  $(f_n)_{n \in \mathbb{N}}$  is a decreasing sequence in  $S$ , that converges point-wise to constant zero mapping 0, one has

$$\lim_{n \rightarrow +\infty} I(f_n) = 0.$$

**Example 2.3.4** Let  $\Omega = \mathbb{R}, \forall A \subseteq \mathbb{R}$ , let

$$\begin{aligned} \mathbb{1}_A : \mathbb{R} &\longrightarrow \{0, 1\} \\ x &\longmapsto \begin{cases} 1, & x \in A \\ 0, & x \notin A \end{cases} \end{aligned}$$

Let  $S$  be the vector space of  $\mathbb{R}^\mathbb{R}$  generated by mappings of the form  $\mathbb{1}_{]a,b]}$ , ( $a \leq b$ )  
Let  $\varphi : \mathbb{R} \rightarrow \mathbb{R}$  be a right continuous mapping,

$$\forall t \in \mathbb{R}, \varphi(t) = \lim_{\varepsilon > 0, \varepsilon \rightarrow 0} \varphi(t + \varepsilon).$$

which is increasing. Then  $I_\varphi : S \rightarrow \mathbb{R}$ ,

$$I_\varphi \left( \sum_{i=1}^n \lambda_i \mathbb{1}_{]a_i, b_i]} \right) := \sum_{i=1}^n \lambda_i (\varphi(b_i) - \varphi(a_i))$$

is an integral operator.

**Proposition 2.3.5** Let  $\Omega$  be a set and  $S$  be a Riesz space on  $\Omega$ . An  $\mathbb{R}$ -linear mapping  $I : S \rightarrow \mathbb{R}$  that satisfies  $(f \leq g \Rightarrow I(f) \leq I(g))$  is an integral operator if and only if, for any increasing sequence  $(f_n)_{n \in \mathbb{N}}$  in  $S$  that converges point-wise to some  $f \in S$ , one has

$$\lim_{n \rightarrow +\infty} I(f_n) = I(f).$$

### Proof

“ $\Rightarrow$ ”:  $(f - f_n)_{n \in \mathbb{N}}$  is decreasing and converges to 0. So

$$\lim_{n \rightarrow +\infty} I(f - f_n) = 0.$$

So  $\lim_{n \rightarrow +\infty} I(f_n) = I(f)$ .

“ $\Leftarrow$ ”: Let  $(f_n)_{n \in \mathbb{N}}$  be a decreasing sequence in  $S$  that converges point-wise to 0. Then  $(f_n)_{n \in \mathbb{N}}$  is increasing and converges point-wise to 0. So

$$\lim_{n \rightarrow +\infty} I(-f_n) = 0.$$

So,  $\lim_{n \rightarrow +\infty} I(f_n) = 0$ . □

**Proposition 2.3.6** Let  $\Omega$  be a set and  $S$  be a Riesz space on  $\Omega$  and  $I : S \rightarrow \mathbb{R}$  be an integral operator. Let  $g \in S$  and  $(f_n)_{n \in \mathbb{N}}$  be an increasing sequence in  $S$ . If

$$\forall \omega \in \Omega, g(\omega) \leq \lim_{n \rightarrow +\infty} f_n(\omega),$$

then

$$I(g) \leq \lim_{n \rightarrow +\infty} I(f_n).$$

**Proof**  $(\inf\{g, f_n\})_{n \in \mathbb{N}}$  is an increasing sequence in  $S$ . It converges to  $g$ . Hence,

$$I(g) = \lim_{n \rightarrow +\infty} I(\inf\{g, f_n\}) \leq \lim_{n \rightarrow +\infty} I(f_n).$$

□

**Corollary 2.3.7** Let  $(f_n)_{n \in \mathbb{N}}$  and  $(g_n)_{n \in \mathbb{N}}$  be increasing sequences in  $S$ . Suppose that

$$\forall \omega \in \Omega, \lim_{n \rightarrow +\infty} f_n(\omega) \leq \lim_{n \rightarrow +\infty} g_n(\omega).$$

Then,

$$\lim_{n \rightarrow +\infty} I(f_n) \leq \lim_{n \rightarrow +\infty} I(g_n).$$

**Proof**  $\forall k \in \mathbb{N}, \forall \omega \in \Omega,$

$$f_k(\omega) \leq \lim_{n \rightarrow +\infty} f_n(\omega) \leq \lim_{n \rightarrow +\infty} g_n(\omega).$$

So  $I(f_k) \leq \lim_{n \rightarrow +\infty} I(g_n)$ . Taking the limit when  $k \rightarrow +\infty$ , we get

$$\lim_{k \rightarrow +\infty} I(f_k) \leq \lim_{n \rightarrow +\infty} I(g_n).$$

□