Chapter 9: Functions of Several Variables

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Exercise 9.1. *If S is a nonempty subset of a vector space X, prove (as asserted in Section 9.1) that the span of S is a vector space.*

Denote the span of S by $\text{span}(S)$.

Proof.

(1) Since $S \neq \varnothing$, there is $\mathbf{z} \in S$. So $1\mathbf{z} = \mathbf{z} \in \text{span}(S) \neq \varnothing$. (In fact, $\text{span}(S) \supseteq S$.)

(2) If $\mathbf{x}, \mathbf{y} \in \text{span}(S)$, then there exist elements $\mathbf{x}_1, \ldots, \mathbf{x}_m$, $\mathbf{y}_1, \ldots, \mathbf{y}_n \in S$ and scalars $a_1, \ldots, a_m$, $b_1, \ldots, b_n$ such that

$$\mathbf{x} = a_1\mathbf{x}_1 + \cdots + a_m\mathbf{x}_m,$$
$$\mathbf{y} = b_1\mathbf{y}_1 + \cdots + b_n\mathbf{y}_n.$$

Then
$$\mathbf{x} + \mathbf{y} = a_1\mathbf{x}_1 + \cdots + a_m\mathbf{x}_m + b_1\mathbf{y}_1 + \cdots + b_n\mathbf{y}_n$$
is a linear combination of the elements of S. For any scalar c,

$$c\mathbf{x} = (ca_1)\mathbf{x}_1 + \cdots + (ca_m)\mathbf{x}_m$$

is again linear combination of the elements of S.

(3) By (1)(2), $\text{span}(S)$ is a vector space.

□

Note. Any subspace of X that contains S must also contain $\text{span}(S)$.

Exercise 9.2. *Prove (as asserted in Section 9.6) that BA is linear if A and B are linear transformations. Prove also that A^{-1} is linear and invertible if A is invertible.*

Proof. Use the notation in Definitions 9.6.

(1) *Show that BA is linear if A and B are linear transformations.* Let X, Y, Z be vector spaces, $A \in L(X, Y)$ and $B \in L(Y, Z)$.

(a) Given any $\mathbf{x}_1, \mathbf{x}_2 \in X$.

$$\begin{aligned}
(BA)(\mathbf{x}_1 + \mathbf{x}_2) &= B(A(\mathbf{x}_1 + \mathbf{x}_2)) \\
&= B(A\mathbf{x}_1 + A\mathbf{x}_2) && (A \text{ is a linear transformation}) \\
&= B(A\mathbf{x}_1) + B(A\mathbf{x}_2) && (B \text{ is a linear transformation}) \\
&= (BA)\mathbf{x}_1 + (BA)\mathbf{x}_2.
\end{aligned}$$

(b) For any $\mathbf{x} \in X$ and scalar c,

$$\begin{aligned}
(BA)(c\mathbf{x}) &= B(A(c\mathbf{x})) \\
&= B(cA\mathbf{x}) && (A \text{ is a linear transformation}) \\
&= cB(A\mathbf{x}) && (B \text{ is a linear transformation}) \\
&= c(BA)\mathbf{x}.
\end{aligned}$$

By (a)(b), $BA \in L(X, Z)$.

(2) *Show that A^{-1} is linear if A is invertible.*

(a) Given any $\mathbf{y}_1, \mathbf{y}_2 \in X$. Since A is surjective, there exist $\mathbf{x}_1, \mathbf{x}_2 \in X$ such that

$$\begin{aligned}
\mathbf{y}_1 &= A\mathbf{x}_1 \\
\mathbf{y}_2 &= A\mathbf{x}_2.
\end{aligned}$$

So

$$\begin{aligned}
A^{-1}\mathbf{y}_1 &= A^{-1}(A\mathbf{x}_1) = \mathbf{x}_1 \\
A^{-1}\mathbf{y}_2 &= A^{-1}(A\mathbf{x}_2) = \mathbf{x}_2
\end{aligned}$$

(by Definitions 9.4). Hence

$$\begin{aligned}
A^{-1}(\mathbf{y}_1 + \mathbf{y}_2) &= A^{-1}(A\mathbf{x}_1 + A\mathbf{x}_2) \\
&= A^{-1}(A(\mathbf{x}_1 + \mathbf{x}_2)) && (A \text{ is a linear transformation}) \\
&= \mathbf{x}_1 + \mathbf{x}_2 && (\text{Definitions 9.4}) \\
&= A^{-1}\mathbf{y}_1 + A^{-1}\mathbf{y}_2.
\end{aligned}$$

(b) For any $\mathbf{y} \in X$ and scalar c, there is a corresponding $\mathbf{x} \in X$ such that $\mathbf{y} = A\mathbf{x}$ since A is surjective. So $A^{-1}\mathbf{y} = \mathbf{x}$ by Definition 9.4. Hence

$$\begin{aligned}
A^{-1}(c\mathbf{y}) &= A^{-1}(cA\mathbf{x}) \\
&= A^{-1}(A(c\mathbf{x})) && (A \text{ is a linear transformation}) \\
&= c\mathbf{x} && (\text{Definitions 9.4}) \\
&= cA^{-1}\mathbf{y}.
\end{aligned}$$

By (a)(b), $A^{-1} \in L(X)$.

(3) *Show that A^{-1} is invertible if A is invertible.* It suffices to show that A^{-1} is injective and surjective.

   (a) *Show that A^{-1} is injective.* Given any $\mathbf{y}_1, \mathbf{y}_2 \in X$. Since A is surjective, there exist $\mathbf{x}_1, \mathbf{x}_2 \in X$ such that

$$\begin{aligned}\mathbf{y}_1 &= A\mathbf{x}_1 \\ \mathbf{y}_2 &= A\mathbf{x}_2.\end{aligned}$$

   Suppose $A^{-1}\mathbf{y}_1 = A^{-1}\mathbf{y}_2$. So $A^{-1}(A\mathbf{x}_1) = A^{-1}(A\mathbf{x}_2)$, or $\mathbf{x}_1 = \mathbf{x}_2$, or $\mathbf{y}_1 = A\mathbf{x}_1 = A\mathbf{x}_2 = \mathbf{y}_2$.

   (b) *Show that A^{-1} is surjective.* For any $\mathbf{x} \in X$, there exists $A\mathbf{x} \in X$ such that $A^{-1}(A\mathbf{x}) = \mathbf{x}$ by Definitions 9.4.

□

Exercise 9.3. *Assume $A \in L(X, Y)$ and $A\mathbf{x} = \mathbf{0}$ only when $\mathbf{x} = \mathbf{0}$. Prove that A is then* 1-1.

Proof. Suppose $A\mathbf{x} = A\mathbf{y}$. Since A is a linear transformation, $A(\mathbf{x} - \mathbf{y}) = A\mathbf{x} - A\mathbf{y} = \mathbf{0}$. By assumption, $\mathbf{x} - \mathbf{y} = \mathbf{0}$ or $\mathbf{x} = \mathbf{y}$. □

Exercise 9.4. *Prove (as asserted in Section 9.30) that null spaces and ranges of linear transformations are vector spaces.*

Proof. Use the notation in Definitions 9.30. Suppose X, Y are vector spaces, and $A \in L(X, Y)$, as in Definition 9.6.

(1) *Show that $\mathscr{N}(A)$ is a vector space in X.*

   (a) Note that $\mathbf{0} \in X$. Since $A\mathbf{0} = \mathbf{0}$, $\mathbf{0} \in \mathscr{N}(A) \neq \varnothing$.

   (b) Suppose $\mathbf{x}_1, \mathbf{x}_2 \in \mathscr{N}(A)$. Then

$$\begin{aligned}A(\mathbf{x}_1 + \mathbf{x}_2) &= A\mathbf{x}_1 + A\mathbf{x}_2 && (A \text{ is a linear transformation}) \\ &= \mathbf{0} + \mathbf{0} && (\mathbf{x}_1, \mathbf{x}_2 \in \mathscr{N}(A)) \\ &= \mathbf{0}.\end{aligned}$$

   So $\mathbf{x}_1 + \mathbf{x}_2 \in \mathscr{N}(A)$.

   (c) Suppose $\mathbf{x} \in \mathscr{N}(A)$ and c is a scalar. Then

$$\begin{aligned}A(c\mathbf{x}) &= cA\mathbf{x} && (A \text{ is a linear transformation}) \\ &= c\mathbf{0} && (\mathbf{x} \in \mathscr{N}(A)) \\ &= \mathbf{0}.\end{aligned}$$

   So $c\mathbf{x} \in \mathscr{N}(A)$.

By (a)(b)(c), $\mathscr{N}(A)$ is a vector space.

(2) *Show that $\mathscr{R}(A)$ is a vector space in Y.*

(a) Note that $\mathbf{0} \in X$. So $A\mathbf{0} = \mathbf{0} \in \mathscr{R}(A) \neq \varnothing$.

(b) Suppose $\mathbf{y}_1, \mathbf{y}_2 \in \mathscr{R}(A)$. Then there exist $\mathbf{x}_1, \mathbf{x}_2 \in X$ such that $A\mathbf{x}_1 = \mathbf{y}_1$ and $A\mathbf{x}_2 = \mathbf{y}_2$. Hence

$$\begin{aligned} \mathbf{y}_1 + \mathbf{y}_2 &= A\mathbf{x}_1 + A\mathbf{x}_2 \\ &= A(\mathbf{x}_1 + \mathbf{x}_2) \qquad (A \text{ is a linear transformation}). \end{aligned}$$

So $\mathbf{y}_1 + \mathbf{y}_2 \in \mathscr{R}(A)$.

(c) Suppose $\mathbf{y} \in \mathscr{R}(A)$ and c is a scalar. Then there exists $\mathbf{x} \in X$ such that $A\mathbf{x} = \mathbf{y}$. Hence

$$\begin{aligned} c\mathbf{y} &= cA\mathbf{x} \\ &= A(c\mathbf{x}) \qquad (A \text{ is a linear transformation}). \end{aligned}$$

So $c\mathbf{y} \in \mathscr{R}(A)$.

By (a)(b)(c), $\mathscr{R}(A)$ is a vector space.

□

Exercise 9.5. *Prove that to every $A \in L(\mathbb{R}^n, \mathbb{R}^1)$ corresponds a unique $\mathbf{y} \in \mathbb{R}^n$ such that $A\mathbf{x} = \mathbf{x} \cdot \mathbf{y}$. Prove also that $\|A\| = |\mathbf{y}|$. (Hint: Under certain conditions, equality holds in the Schwarz inequality.)*

Proof.

(1) Recall that $\{\mathbf{e}_1, \ldots, \mathbf{e}_n\}$ is the standard basis of $\mathbb{R}^n$ (Definitions 9.1). Given any $\mathbf{x} \in \mathbb{R}^n$, write $\mathbf{x} = (x_1, \ldots, x_n)$ as $\mathbf{x} = \sum x_j \mathbf{e}_j$.

(2) *Show that $\mathbf{y}$ exists.* Since A is a linear transformation,

$$\begin{aligned} A\mathbf{x} &= A\left(\sum x_j \mathbf{e}_j\right) \\ &= \sum x_j A\mathbf{e}_j \\ &= (x_1, \ldots, x_n) \cdot (A\mathbf{e}_1, \ldots, A\mathbf{e}_n) \\ &= \mathbf{x} \cdot \sum (A\mathbf{e}_j)\mathbf{e}_j. \end{aligned}$$

Define $\mathbf{y} = \sum (A\mathbf{e}_j)\mathbf{e}_j \in \mathbb{R}^n$ so that $A\mathbf{x} = \mathbf{x} \cdot \mathbf{y}$.

(3) *Show that $\mathbf{y}$ is unique.* Suppose there exists some $\mathbf{z} \in \mathbb{R}^n$ such that $A\mathbf{x} = \mathbf{x} \cdot \mathbf{z}$. So

$$\begin{aligned} 0 &= A\mathbf{x} - A\mathbf{x} \\ &= \mathbf{x} \cdot \mathbf{y} - \mathbf{x} \cdot \mathbf{z} \\ &= \mathbf{x} \cdot (\mathbf{y} - \mathbf{z}) \end{aligned}$$

for any $\mathbf{x} \in \mathbb{R}^n$. In particular, take $\mathbf{x} = \mathbf{y} - \mathbf{z} \in \mathbb{R}^n$ to get

$$0 = (\mathbf{y} - \mathbf{z}) \cdot (\mathbf{y} - \mathbf{z}) = |\mathbf{y} - \mathbf{z}|^2$$

or $\mathbf{y} - \mathbf{z} = \mathbf{0}$ or $\mathbf{y} = \mathbf{z}$.

(4) *Show that* $\|A\| = |\mathbf{y}|$. By the Schwarz inequality (Theorem 1.37(d)),

$$|A\mathbf{x}| = |\mathbf{x} \cdot \mathbf{y}| \leq |\mathbf{x}||\mathbf{y}| \leq |\mathbf{y}|$$

as $|\mathbf{x}| \leq 1$. Take the sup over all $|\mathbf{x}| \leq 1$ to get

$$\|A\| \leq |\mathbf{y}|.$$

If $\mathbf{y} = \mathbf{0}$, then $\|A\| = |\mathbf{y}| = 0$. If $\mathbf{y} \neq \mathbf{0}$, then the equality holds when $\mathbf{x} = \frac{\mathbf{y}}{|\mathbf{y}|} \in \mathbb{R}^n$. (Here $|\mathbf{x}| = 1$.)

$\square$

Exercise 9.6. *If* $f(0,0) = 0$ *and*

$$f(x,y) = \frac{xy}{x^2 + y^2} \qquad \text{if } (x,y) \neq (0,0),$$

prove that $(D_1 f)(x,y)$ *and* $(D_2 f)(x,y)$ *exist at every point of* $\mathbb{R}^2$*, although* f *is not continuous at* $(0,0)$.

Proof.

(1) *Show that*

$$(D_1 f)(x,y) = \begin{cases} 0 & \text{if } (x,y) = (0,0), \\ \frac{y(y^2 - x^2)}{(x^2+y^2)^2} & \text{if } (x,y) \neq (0,0). \end{cases}$$

Write

$$\begin{aligned} (D_1 f)(x,y) &= \lim_{t \to 0} \frac{f((x,y) + t(1,0)) - f(x,y)}{t} \\ &= \lim_{t \to 0} \frac{f(x+t,y) - f(x,y)}{t}. \end{aligned}$$

If $(x,y) = (0,0)$,

$$(D_1 f)(0,0) = \lim_{t \to 0} \frac{f(t,0) - f(0,0)}{t} = \lim_{t \to 0} \frac{0 - 0}{t} = 0.$$

If $(x, y) \neq (0, 0)$,

$$\begin{aligned}
(D_1 f)(x, y) &= \lim_{t \to 0} \frac{f(x+t, y) - f(x, y)}{t} \\
&= \lim_{t \to 0} \frac{\frac{(x+t)y}{(x+t)^2+y^2} - \frac{xy}{x^2+y^2}}{t} \\
&= \lim_{t \to 0} \frac{y(y^2 - x^2) - txy}{((x+t)^2 + y^2)(x^2 + y^2)} \\
&= \frac{y(y^2 - x^2)}{(x^2 + y^2)^2}.
\end{aligned}$$

(2) *Show that*

$$(D_2 f)(x, y) = \begin{cases} 0 & \text{if } (x, y) = (0, 0), \\ \frac{x(x^2-y^2)}{(x^2+y^2)^2} & \text{if } (x, y) \neq (0, 0). \end{cases}$$

Similar to (1).

(3) *Show that f is not continuous at $(0, 0)$.* Note that

$$\lim_{n \to \infty} f\left(\frac{1}{n}, \frac{1}{n}\right) = \lim_{n \to \infty} \frac{\frac{1}{n} \cdot \frac{1}{n}}{\frac{1}{n^2} + \frac{1}{n^2}} = \lim_{n \to \infty} \frac{1}{2} = \frac{1}{2}$$

and

$$\lim_{n \to \infty} f\left(\frac{1}{n}, 0\right) = \lim_{n \to \infty} \frac{0}{\frac{1}{n^2} + 0} = \lim_{n \to \infty} 0 = 0.$$

Hence the limit $\lim_{(x,y) \to (0,0)} f(x, y)$ does not exist.

□

Exercise 9.7. *Suppose that f is a real-valued function defined in an open set $E \subseteq \mathbb{R}^n$, and that the partial derivatives $D_1 f, \ldots, D_n f$ are bounded in E. Prove that f is continuous in E. (Hint: Proceed as in the proof of Theorem 9.21.)*

Proof.

(1) Since $D_j f$ is bounded in E, there is a real number M_j such that $|D_j f| \leq M_j$ in E. Take $M = \max_{1 \leq j \leq n} M_j$ so that $|D_j f| \leq M$ in E for all $1 \leq j \leq n$.

(2) Fix $\mathbf{x} \in E$ and $\varepsilon > 0$. Since E is open, there is an open neighborhood

$$B(\mathbf{x}; r) = \{\mathbf{x} + \mathbf{h} \in E : |\mathbf{h}| < r\} \subseteq E$$

with

$$0 < r < \frac{\varepsilon}{n(M + 1)}.$$

(3) Write $\mathbf{h} = \sum h_j \mathbf{e}_j$, $|\mathbf{h}| < r$, put $\mathbf{v}_0 = \mathbf{0}$, and $\mathbf{v}_k = h_1\mathbf{e}_1 + \cdots + h_k\mathbf{e}_k$ for $1 \leq k \leq n$. Then

$$f(\mathbf{x}+\mathbf{h}) - f(\mathbf{x}) = \sum_{j=1}^{n} [f(\mathbf{x}+\mathbf{v}_j) - f(\mathbf{x}+\mathbf{v}_{j-1})].$$

Since $|\mathbf{v}_k| < r$ for $1 \leq k \leq n$ and since $B(\mathbf{x}; r)$ is convex, the open interval with end points $\mathbf{x}+\mathbf{v}_{j-1}$ and $\mathbf{x}+\mathbf{v}_j$ lie in $B(\mathbf{x}; r)$. Since $\mathbf{v}_j = \mathbf{v}_{j-1} - h_j\mathbf{e}_j$, the mean value theorem (Theorem 5.10) show that

$$f(\mathbf{x}+\mathbf{v}_j) - f(\mathbf{x}+\mathbf{v}_{j-1}) = h_j (D_j f)(\mathbf{x}+\mathbf{v}_{j-1} + \theta_j h_j \mathbf{e}_j)$$

for some $\theta_j \in (0, 1)$.

(4) Note that $|h_j| \leq |\mathbf{h}| < r < \frac{\varepsilon}{n(M+1)}$. Hence

$$\begin{aligned}
|f(\mathbf{x}+\mathbf{h}) - f(\mathbf{x})| &\leq \sum_{j=1}^{n} |f(\mathbf{x}+\mathbf{v}_j) - f(\mathbf{x}+\mathbf{v}_{j-1})| \\
&= \sum_{j=1}^{n} |h_j||(D_j f)(\mathbf{x}+\mathbf{v}_{j-1} + \theta_j h_j \mathbf{e}_j)| \\
&\leq \sum_{j=1}^{n} \frac{\varepsilon}{n(M+1)} \cdot M \\
&< \varepsilon
\end{aligned}$$

as $|\mathbf{h}| < r < \frac{\varepsilon}{n(M+1)}$. Hence f is continuous at all $\mathbf{x} \in E$.

□

Exercise 9.8. *Suppose that f is a differentiable real function in an open set $E \subseteq \mathbb{R}^n$, and that f has a local maximum at a point $\mathbf{x} \in E$. Prove that $f'(\mathbf{x}) = 0$.*

Proof (Theorem 5.8).

(1) Apply Theorem 5.8 to each $D_j f$ for $1 \leq j \leq n$. Since f has a local maximum at a point $\mathbf{x} \in E$, there is an open neighborhood $B(\mathbf{x}; r)$ of $\mathbf{x}$ in E such that

$$f(\mathbf{y}) \leq f(\mathbf{x})$$

for all $\mathbf{y} \in B(\mathbf{x}; r)$. Therefore,

$$f(\mathbf{x} + t\mathbf{e}_j) \leq f(\mathbf{x})$$

for all $|t| < r$ and $1 \leq j \leq n$, or $t \mapsto f(\mathbf{x} + t\mathbf{e}_j)$ has a local maximum at a point $t = 0 \in (-r, r)$.

(2) Since f is a differentiable in E, each partial derivatives $D_j f$ exist (Theorem 9.21). Hence Theorem 5.8 implies that $(D_j f)(\mathbf{x}) = 0$ for all $1 \leq j \leq n$. So

$$f'(\mathbf{x}) = [(D_1 f)(\mathbf{x}) \cdots (D_k f)(\mathbf{x})] = [0 \cdots 0] = 0$$

(as the zero matrix).

□

Exercise 9.9. *If* $\mathbf{f}$ *is a differentiable mapping of a connected open set* $E \subseteq \mathbb{R}^n$*, and if* $\mathbf{f}'(\mathbf{x}) = 0$ *for every* $\mathbf{x} \in E$*, prove that* $\mathbf{f}$ *is a constant in* E*.*

Proof.

(1) *Show that* $\mathbf{f}$ *is* ***locally constant****.* Given any $\mathbf{x} \in E$. Since E is open, there exists an open neighborhood $B(\mathbf{x}; r)$ of $\mathbf{x}$ such that $B(\mathbf{x}; r) \subseteq E$ and $r > 0$. Corollary to Theorem 9.19 implies that $\mathbf{f}$ is a constant on $B(\mathbf{x}; r)$, that is, $\mathbf{f}$ is locally constant.

(2) *Show that* $\mathbf{f}$ *is constant if* $\mathbf{f}$ *is locally constant in a connected set* $E \subseteq \mathbb{R}^n$*.* Might assume that $E \neq \varnothing$. (Otherwise there is nothing to do.) Take some $\mathbf{x}_0 \in E$.

   (a) Let
   $$U = \{\mathbf{y} \in E : \mathbf{f}(\mathbf{y}) = \mathbf{f}(\mathbf{x}_0)\}.$$

   (b) U is open since $\mathbf{f}$ is locally constant (by (1)). (Take any $\mathbf{y} \in U$. Since $\mathbf{f}$ is locally constant, there is an open neighborhood $B(\mathbf{y}) \subseteq E$ of $\mathbf{y}$ such that $f(\mathbf{z}) = f(\mathbf{y}) = f(\mathbf{x}_0)$ whenever $\mathbf{z} \in B(\mathbf{y})$. So that $B(\mathbf{y}) \subseteq U$, or U is open.)

   (c) Besides, since $\mathbf{f}$ is continuous (Remarks 9.13(c)), the set U is closed. (The proof is the same as Proof (Definition 2.18(d)) in Exercise 4.3.)

   (d) So U is open and closed. Write $E = U \cup (E - U)$. Here U and $E - U$ are both open and closed. Hence $U \cap \overline{E - U} = U \cap (E - U) = \varnothing$ and $\overline{U} \cap (E - U) = U \cap (E - U) = \varnothing$. Note that $\mathbf{x}_0 \in U \neq \varnothing$. By the connectedness of E, $E - U = \varnothing$, or $E = U$, or $\mathbf{f}$ is constant on E.

   Note. The only subsets of a connected set E *which are both open and closed are* E *and* $\varnothing$*.*

□

Exercise 9.10. *If* f *is a real function defined in a convex open set* $E \subseteq \mathbb{R}^n$*, such that* $(D_1 f)(\mathbf{x}) = 0$ *for every* $\mathbf{x} \in E$*, prove that* $f(\mathbf{x})$ *depends only on* $x_2, \ldots, x_n$*. Show that the convexity of* E *can be replaced by a weaker condition, but that some condition is required. For example, if* $n = 2$ *and* E *is shaped like* *a horseshoe, the statement may be false.*

Proof.

(1) It suffices to show that

$$f(a, x_2, \dots, x_n) = f(b, x_2, \dots, x_n)$$

whenever $\mathbf{x} = (a, x_2, \dots, x_n) \in E$ and $\mathbf{y} = (b, x_2, \dots, x_n) \in E$ if $(D_1 f)(\mathbf{x}) = 0$ in the convex open set E.

(2) Might assume that $a < b$. Since $g : t \mapsto f(t, x_2, \dots, x_n)$ is a real continuous function on $[a, b]$ (by the openness of E) and differentiable in (a, b) (by the existence of $D_1 f$),

$$g(b) - g(a) = (b - a)g'(\xi)$$

for some $\xi \in (a, b)$. Note that

$$g'(\xi) = (D_1 f)(\xi, x_2, \dots, x_n) = 0$$

by assumption. $g(b) = g(a)$ or $f(a, x_2, \dots, x_n) = f(b, x_2, \dots, x_n)$.

(3) (2) shows that the convexity of E can be replaced by a weaker condition that $E \subseteq \mathbb{R}^n$ is convex in the first coordinate, say E is open and

$$\lambda\mathbf{x} + (1 - \lambda)\mathbf{y} = (\lambda a + (1 - \lambda)b, x_2, \dots, x_n) \in E$$

whenever $\mathbf{x} = (a, x_2, \dots, x_n) \in E$, $\mathbf{y} = (b, x_2, \dots, x_n) \in E$, and $0 < \lambda < 1$.

(4) *Show that the convexity of E or some weaker condition is required.* Define $f(x, y) = \operatorname{sgn}(x)$ on $E = \{(x, y) \in \mathbb{R}^2 : x \neq 0\}$. E is open and $(D_1 f)(x, y) = 0$ in E. Note that $f(1989, 0) = 1$ and $f(-64, 0) = -1$, and thus $f(x, y)$ does not depend only on $y = 0$.

□

Exercise 9.11. *If f and g are differentiable real functions in $\mathbb{R}^n$, prove that*

$$\nabla(fg) = f\nabla g + g\nabla f$$

and that

$$\nabla\left(\frac{1}{f}\right) = -\frac{1}{f^2}\nabla f$$

whenever $f \neq 0$.

Proof. Recall Example 9.18:

$$(\nabla(f))(\mathbf{x}) = \sum_{i=1}^{n}(D_i f)(\mathbf{x})\mathbf{e}_i.$$

(1) *Show that* $\nabla(fg) = f\nabla g + g\nabla f$. For any $\mathbf{x} \in \mathbb{R}^n$,

$$\begin{aligned}
(\nabla(fg))(\mathbf{x}) &= \sum_{i=1}^{n}(D_i(fg))(\mathbf{x})\mathbf{e}_i \\
&= \sum_{i=1}^{n}(g(D_if) + f(D_ig))(\mathbf{x})\mathbf{e}_i && \text{(Theorem 5.3(b))} \\
&= \sum_{i=1}^{n}\left[g(\mathbf{x})(D_if)(\mathbf{x}) + f(\mathbf{x})(D_ig)(\mathbf{x})\right]\mathbf{e}_i \\
&= g(\mathbf{x})\sum_{i=1}^{n}(D_if)(\mathbf{x})\mathbf{e}_i + f(\mathbf{x})\sum_{i=1}^{n}(D_ig)(\mathbf{x})\mathbf{e}_i \\
&= g(\mathbf{x})(\nabla f)(\mathbf{x}) + f(\mathbf{x})(\nabla g)(\mathbf{x}) \\
&= (f\nabla g + g\nabla f)(\mathbf{x}).
\end{aligned}$$

(2) *Show that*

$$\nabla\left(\frac{1}{f}\right) = -\frac{1}{f^2}\nabla f$$

whenever $f \neq 0$. Note that $\nabla(1) = 0$ since

$$\nabla(1)(\mathbf{x}) = \sum(D_i1)(\mathbf{x})\mathbf{e}_i = \sum(0)(\mathbf{x})\mathbf{e}_i = \sum 0\mathbf{e}_i = 0.$$

Hence as $f \neq 0$, we have

$$\begin{aligned}
0 &= \nabla(1) \\
&= \nabla\left(f\frac{1}{f}\right) && (f \neq 0) \\
&= f\nabla\left(\frac{1}{f}\right) + \frac{1}{f}\nabla f && ((1)),
\end{aligned}$$

or $\nabla\left(\frac{1}{f}\right) = -\frac{1}{f^2}\nabla f$.

□

Exercise 9.12. *Fix two real numbers a and b, $0 < a < b$. Define a mapping $\mathbf{f} = (f_1, f_2, f_3)$ of $\mathbb{R}^2$ into $\mathbb{R}^3$ by*

$$\begin{aligned}
f_1(s,t) &= (b + a\cos s)\cos t \\
f_2(s,t) &= (b + a\cos s)\sin t \\
f_3(s,t) &= a\sin s.
\end{aligned}$$

Describe the range K if $\mathbf{f}$. (It is a certain compact subset of $\mathbb{R}^3$.)

(a) *Show that there are exactly 4 points* $\mathbf{p} \in K$ *such that*

$$(\nabla f_1)(\mathbf{f}^{-1}(\mathbf{p})) = \mathbf{0}.$$

Find these points.

(b) *Determine the set of all* $\mathbf{q} \in K$ *such that*

$$(\nabla f_3)(\mathbf{f}^{-1}(\mathbf{q})) = \mathbf{0}.$$

(c) *Show that one of the point* $\mathbf{p}$ *found in part (a) corresponds to a local maximum of* f_1*, one corresponds to a local minimum, and that the other two are neither (they are so-called "saddle points"). Which of the points* $\mathbf{q}$ *found in part (b) corresponds to maxima or minima?*

(d) *Let* λ *be an irrational real number, and define* $\mathbf{g}(t) = \mathbf{f}(t, \lambda t)$*. Prove that* $\mathbf{g}$ *is a one-to-one mapping of* $\mathbb{R}^1$ *onto a dense subset of* K*. Prove that*

$$|\mathbf{g}'(t)|^2 = a^2 + \lambda^2 (b + a\cos t)^2.$$

Proof.

(1) K is a torus, where

(a) s, t are angles which make a full circle (so that their values start and end at the same point).

(b) b is the distance from the center of the tube to the center of the torus.

(c) a is the radius of the tube.

(2) *Show that* K *is compact.* Since sin and cos are periodic (with period 2π), $K = \mathbf{f}\left([0, 2\pi]^2\right)$ is compact by the compactness of $[0, 2\pi]^2$ and the continuity of $\mathbf{f}$ (Theorem 4.14).

□

Proof of (a).

(1)

$$\begin{aligned}
(\nabla f_1)(\mathbf{x}) &= (D_1 f_1)(\mathbf{x})\mathbf{e}_1 + (D_2 f_1)(\mathbf{x})\mathbf{e}_2 \\
&= ((D_1 f_1)(s, t), (D_2 f_1)(s, t)) \\
&= (-a \sin s \cos t, -(b + a\cos t)\sin t)
\end{aligned}$$

So $(\nabla f_1)(\mathbf{x}) = \mathbf{0}$ if and only if

$$\begin{aligned}
0 &= -a \sin s \cos t, \\
0 &= -(b + a\cos t)\sin t.
\end{aligned}$$

(2) Note that $b + a\cos t > 0$ for any $b > a > 0$ and $t \in \mathbb{R}^1$. Hence $(\nabla f_1)(\mathbf{x}) = \mathbf{0}$ if and only if $\sin t = \sin s = 0$. Therefore, $\mathbf{p} = (\pm(b \pm a), 0, 0)$, or there are exactly 4 points $\mathbf{p} = (b + a, 0, 0)$, $(b - a, 0, 0)$, $(-b - a, 0, 0)$, or $(-b + a, 0, 0) \in K$.

$\square$

Proof of (b).

(1)

$$\begin{aligned}(\nabla f_3)(\mathbf{x}) &= (D_1 f_3)(\mathbf{x})\mathbf{e}_1 + (D_2 f_3)(\mathbf{x})\mathbf{e}_2 \\ &= ((D_1 f_3)(s,t), (D_2 f_3)(s,t)) \\ &= (a\cos s, 0)\end{aligned}$$

So $(\nabla f_1)(\mathbf{x}) = \mathbf{0}$ if and only if $\cos s = 0$ (since $a > 0$).

(2) Therefore, $\mathbf{q} = (b\cos t, b\sin t, \pm a)$.

$\square$

Proof of (c).

(1) Since $-1 \leq \cos s \leq 1$ and $-1 \leq \cos t \leq 1$, $-b - a \leq f_1(s,t) \leq b + a$.

   (a) $(b + a, 0, 0)$ corresponds to a local maximum of f_1.

   (b) $(-b - a, 0, 0)$ corresponds to a local minimum of f_1.

   (c) $(b - a, 0, 0)$ and $(-b + a, 0, 0)$ are saddle points by considering any open neighborhood of (s,t) at which $\cos s = \pm 1$ and $\cos t = \mp 1$.

(2) Since $-1 \leq \sin s \leq 1$, $-a \leq f_3(s,t) \leq a$.

   (a) $(b\cos t, b\sin t, a)$ corresponds to a local maximum of f_3.

   (b) $(b\cos t, b\sin t, -a)$ corresponds to a local minimum of f_3.

$\square$

Proof of (d).

(1)

$$\mathbf{g}(t) = \mathbf{f}(t, \lambda t) = ((b + a\cos t)\cos(\lambda t), (b + a\cos t)\sin(\lambda t), a\sin t).$$

(2) *Show that* $\mathbf{g}$ *is a one-to-one mapping of* $\mathbb{R}^1$. It suffices to show that $\mathbf{g}(t) = \mathbf{g}(s)$ implies $t = s$.

(a) By $\mathbf{g}(t) = \mathbf{g}(s)$,

$$(b + a\cos t)\cos(\lambda t) = (b + a\cos s)\cos(\lambda s), \tag{I}$$
$$(b + a\cos t)\sin(\lambda t) = (b + a\cos s)\sin(\lambda s), \tag{II}$$
$$a\sin t = a\sin s. \tag{III}$$

(I) and (II) imply that $\cos t = \cos s$ (since $b > a > 0$). (III) implies that $\sin t = \sin s$. Hence

$$t = s + 2n\pi$$

for some integer n.

(b) Again, (I) and (II) imply that

$$\cos(\lambda t) = \cos(\lambda s) \qquad \text{and} \qquad \sin(\lambda t) = \sin(\lambda s).$$

Hence

$$\lambda t = \lambda s + 2m\pi$$

for some integer m. By assumption that $t = s + 2n\pi$, we have $m = n\lambda$. Since λ is irrational, $m = n = 0$. Therefore $t = s$ holds.

(3) *Show that $\mathbf{g}(\mathbb{R}^1)$ is dense in K.* Note that $\mathbf{f}\left([0, 2\pi]^2\right) = K$. Use the notations $\{x\}$ in Exercise 4.16. It suffices to show that the set

$$\left\{ \left(2\pi \left\{ \frac{t}{2\pi} \right\}, 2\pi \left\{ \frac{\lambda t}{2\pi} \right\} \right) : t \in \mathbb{R}^1 \right\}$$

is dense in $[0, 2\pi]^2$ (Exercise 4.4), or to show that

$$\left\{ (\{t\}, \{\lambda t\}) : t \in \mathbb{R}^1 \right\}$$

is dense in $[0, 1]^2$, which is the conclusion of Exercise 4.25(b).

(4) *Show that $|\mathbf{g}'(t)|^2 = a^2 + \lambda^2(b + a\cos t)^2$.* By

$$\begin{aligned}\mathbf{g}'(t) = (\ & -a\sin t\cos(\lambda t) - \lambda(b + a\cos t)\sin(\lambda t), \\ & -a\sin t\sin(\lambda t) + \lambda(b + a\cos t)\cos(\lambda t), \\ & a\cos t\ ),\end{aligned}$$

$$
\begin{aligned}
|\mathbf{g}'(t)|^2 =&\mathbf{g}'(t)\cdot\mathbf{g}'(t)\\
=&(-a\sin t\cos(\lambda t)-\lambda(b+a\cos t)\sin(\lambda t))^2\\
&+(-a\sin t\sin(\lambda t)+\lambda(b+a\cos t)\cos(\lambda t))^2+(a\cos t)^2\\
=&\underbrace{a^2\sin^2 t\cos^2(\lambda t)+a^2\cos^2 t}_{=a^2}\\
&+\underbrace{\lambda^2(b+a\cos t)^2\sin^2(\lambda t)+\lambda^2(b+a\cos t)^2\cos^2(\lambda t)}_{=\lambda^2(b+a\cos t)^2}\\
&+2a\lambda\sin t\cos(\lambda t)\lambda(b+a\cos t)\sin(\lambda t)\\
&-2a\lambda\sin t\sin(\lambda t)\lambda(b+a\cos t)\cos(\lambda t)\\
=&a^2+\lambda^2(b+a\cos t)^2.
\end{aligned}
$$

□

Exercise 9.13. *Suppose* $\mathbf{f}$ *is a differentiable mapping of* $\mathbb{R}^1$ *into* $\mathbb{R}^3$ *such that* $|\mathbf{f}(t)|=1$ *for every* t*. Prove that* $\mathbf{f}'(t)\cdot\mathbf{f}(t)=0$*. Interpret this result geometrically.*

Proof.

(1) Write $\mathbf{f}=(f_1,f_2,f_3)$ as a vector-valued function. By Remarks 5.16, $\mathbf{f}$ is differentiable if and only if each f_1,f_2,f_3 is differentiable. So $\mathbf{f}'=(f_1',f_2',f_3)'$. Hence

$$
\begin{aligned}
&|\mathbf{f}(t)|=1 \text{ for every } t\\
\Longleftrightarrow&\mathbf{f}(t)\cdot\mathbf{f}(t)=1\\
\Longleftrightarrow&f_1(t)^2+f_2(t)^2+f_3(t)^2=1\\
\Longrightarrow&2f_1(t)f_1'(t)+2f_2(t)f_2'(t)+2f_3(t)f_3'(t)=0\\
\Longleftrightarrow&f_1(t)f_1'(t)+f_2(t)f_2'(t)+f_3(t)f_3'(t)=0\\
\Longleftrightarrow&(f_1(t),f_2(t),f_3(t))\cdot(f_1'(t),f_2'(t),f_3'(t))=0\\
\Longleftrightarrow&\mathbf{f}(t)\cdot\mathbf{f}'(t)=\mathbf{f}'(t)\cdot\mathbf{f}(t)=0.
\end{aligned}
$$

(2) The vector $\mathbf{f}'(t)$ is called the ***tangent vector*** (or ***velocity vector***) of $\mathbf{f}$ at t. Geometrically, given any mapping $\mathbf{f}$ lying on the sphere S^2, its tangent vector at t is lying on the tangent plane of S^2 at t.

□

Exercise 9.14. *Define* $f(0,0)=0$ *and*

$$f(x,y)=\frac{x^3}{x^2+y^2} \qquad \text{if } (x,y)\neq(0,0).$$

(a) *Prove that $D_1 f$ and $D_2 f$ are bounded functions in $\mathbb{R}^2$. (Hence f is continuous.)*

(b) *Let $\mathbf{u}$ be any unit vector in $\mathbb{R}^2$. Show that the directional derivative $(D_{\mathbf{u}} f)(0,0)$ exists, and that its absolute value is at most 1.*

(c) *Let γ be a differentiable mapping of $\mathbb{R}^1$ into $\mathbb{R}^2$ (in other words, γ is a differentiable curve in $\mathbb{R}^2$), with $\gamma(t) = (0,0)$ and $\gamma'(t) \neq (0,0)$ for any $t \in \mathbb{R}^1$. Put $g(t) = f(\gamma(t))$ and prove that g is differentiable for every $t \in \mathbb{R}^1$. If $\gamma \in \mathscr{C}'$, prove that $g \in \mathscr{C}'$.*

(d) *In spite of this, prove that f is not differentiable at $(0,0)$.*

Proof of (a).

(1) *Show that*

$$(D_1 f)(x,y) = \begin{cases} 1 & \text{if } (x,y) = (0,0), \\ \frac{x^2(x^2+3y^2)}{(x^2+y^2)^2} & \text{if } (x,y) \neq (0,0). \end{cases}$$

If $(x,y) = (0,0)$,

$$(D_1 f)(0,0) = \lim_{t \to 0} \frac{f(t,0) - f(0,0)}{t} = \lim_{t \to 0} \frac{t - 0}{t} = 1.$$

If $(x,y) \neq (0,0)$,

$$\begin{aligned} (D_1 f)(x,y) &= \lim_{t \to 0} \frac{f(x+t,y) - f(x,y)}{t} \\ &= \lim_{t \to 0} \frac{\frac{(x+t)^3}{(x+t)^2+y^2} - \frac{x^3}{x^2+y^2}}{t} \\ &= \lim_{t \to 0} \frac{x^2(x^2+3y^2) + tx(2x^2+3y^2) + t^2(x^2+y^2)}{((x+t)^2+y^2)(x^2+y^2)} \\ &= \frac{x^2(x^2+3y^2)}{(x^2+y^2)^2}. \end{aligned}$$

(Or differentiate directly.)

(2) *Show that $(D_1 f)(x,y)$ is bounded.* It suffices to show that $(D_1 f)(x,y)$ is bounded if $(x,y) \neq (0,0)$. Write $x = r\cos\theta$ and $y = r\sin\theta$ in the polar coordinates. (Here $r > 0$.) Hence

$$(D_1 f)(x,y) = \frac{x^2(x^2+3y^2)}{(x^2+y^2)^2} = \cos^2\theta(\cos^2\theta + 3\sin^2\theta)$$

is bounded by $1 \cdot (1+3) = 4$.

(3) *Show that*

$$(D_2 f)(x,y) = \begin{cases} 0 & \text{if } (x,y) = (0,0), \\ \frac{-2x^3 y}{(x^2+y^2)^2} & \text{if } (x,y) \neq (0,0). \end{cases}$$

If $(x,y) = (0,0)$,

$$(D_2 f)(0,0) = \lim_{t \to 0} \frac{f(0,t) - f(0,0)}{t} = \lim_{t \to 0} \frac{0-0}{t} = 0.$$

If $(x,y) \neq (0,0)$,

$$\begin{aligned} (D_2 f)(x,y) &= \lim_{t \to 0} \frac{f(x,y+t) - f(x,y)}{t} \\ &= \lim_{t \to 0} \frac{\frac{x^3}{x^2+(y+t)^2} - \frac{x^3}{x^2+y^2}}{t} \\ &= \lim_{t \to 0} \frac{-2x^3 y - tx^3}{(x^2+(y+t)^2)(x^2+y^2)} \\ &= \frac{-2x^3 y}{(x^2+y^2)^2}. \end{aligned}$$

(Or differentiate directly.)

(4) *Show that $(D_2 f)(x,y)$ is bounded.* Similar to (2).

(5) *Show that f is continuous.* Apply Exercise 9.7 to (2)(4).

□

Proof of (b).

(1) Write $\mathbf{u} = (u_1, u_2)$. The formula

$$(D_{\mathbf{u}} f)(0,0) = (D_1 f)(0,0) u_1 + (D_2 f)(0,0) u_2 = u_1$$

might be false since we don't know if f is differentiable or not. Actually, we will show that $(D_{\mathbf{u}} f)(0,0) = u_1^3 \neq u_1$.

(2)

$$\begin{aligned} (D_{\mathbf{u}} f)(0,0) &= \lim_{t \to 0} \frac{f(tu_1, tu_2) - f(0,0)}{t} \\ &= \lim_{t \to 0} \frac{\frac{t^3 u_1^3}{t^2 u_1^2 + t^2 u_2^2} - 0}{t} \\ &= \lim_{t \to 0} u_1^3 & (|\mathbf{u}| = 1) \\ &= u_1^3. \end{aligned}$$

Also $|(D_{\mathbf{u}} f)(0,0)| = |u_1|^3 \leq 1$ since $|\mathbf{u}| = 1$.

□

Proof of (c).

(1) Given any $t \in \mathbb{R}^1$.

$$g'(t) = \lim_{x \to t} \frac{g(x) - g(t)}{x - t} = \lim_{x \to t} \frac{f(\gamma(x)) - f(\gamma(t))}{x - t}.$$

Write $\gamma(t) = (\gamma_1(t), \gamma_2(t))$.

(2) Suppose that $\gamma(t) \neq (0,0)$. Since γ is differentiable, γ is continuous. So there exists an open neighborhood $B(t) \subseteq \mathbb{R}^1$ of t such that $\gamma(x) \neq (0,0)$ whenever $x \in B(t)$. Hence

$$\begin{aligned} g'(t) &= \lim_{x \to t} \frac{\frac{\gamma_1(x)^3}{\gamma_1(x)^2+\gamma_2(x)^2} - \frac{\gamma_1(t)^3}{\gamma_1(t)^2+\gamma_2(t)^2}}{x - t} \\ &= \frac{d}{dt}\left(\frac{\gamma_1(t)^3}{\gamma_1(t)^2 + \gamma_2(t)^2}\right) \\ &= \frac{3\gamma_1(t)^2\gamma_1'(t)}{\gamma_1(t)^2 + \gamma_2(t)^2} - \frac{\gamma_1(t)^3(2\gamma_1(t)\gamma_1'(t) + 2\gamma_2(t)\gamma_2'(t))}{(\gamma_1(t)^2 + \gamma_2(t)^2)^2}. \end{aligned}$$

exists since γ_1 and γ_2 are differentiable.

(3) Suppose that $\gamma(t) = (0,0)$ and thus $\gamma'(t) \neq (0,0)$. So

$$g'(t) = \lim_{x \to t} \frac{f(\gamma(x))}{x - t}$$

Note that $\gamma(x) \neq (0,0)$ in some open neighborhood of t since

$$\lim_{\substack{x \to t \\ \gamma(x) = (0,0)}} \frac{\gamma(x) - \gamma(t)}{x - t} = (0,0),$$

contrary to the assumption that $\gamma'(t) \neq (0,0)$. Note that $\gamma_1(t) = \gamma_2(t) = 0$. So

$$\begin{aligned} g'(t) &= \lim_{x \to t} \frac{f(\gamma(x))}{x - t} \\ &= \lim_{x \to t} \frac{\gamma_1(x)^3}{\gamma_1(x)^2 + \gamma_2(x)^2} \cdot \frac{1}{x - t} \\ &= \lim_{x \to t} \frac{(\gamma_1(x) - \gamma_1(t))^3}{(\gamma_1(x) - \gamma_1(t))^2 + (\gamma_2(x) - \gamma_2(t))^2} \cdot \frac{1}{x - t} \\ &= \lim_{x \to t} \frac{\left(\frac{\gamma_1(x) - \gamma_1(t)}{x - t}\right)^3}{\left(\frac{\gamma_1(x) - \gamma_1(t)}{x - t}\right)^2 + \left(\frac{\gamma_2(x) - \gamma_2(t)}{x - t}\right)^2} \\ &= \frac{\gamma_1'(t)^3}{\gamma_1'(t)^2 + \gamma_2'(t)^2} \end{aligned}$$

since $\gamma'(t) \neq (0,0)$.

(4) By (2)(3), $g'(t)$ exists and

$$g'(t) = \begin{cases} \frac{3\gamma_1(t)^2\gamma_1'(t)}{\gamma_1(t)^2+\gamma_2(t)^2} - \frac{\gamma_1(t)^3(2\gamma_1(t)\gamma_1'(t)+2\gamma_2(t)\gamma_2'(t))}{(\gamma_1(t)^2+\gamma_2(t)^2)^2} & \text{if } \gamma(t) \neq (0,0), \\ \frac{\gamma_1'(t)^3}{\gamma_1'(t)^2+\gamma_2'(t)^2} & \text{if } \gamma(t) = (0,0). \end{cases}$$

(5) Now suppose $\gamma \in \mathscr{C}'$. To show $g' \in \mathscr{C}'$, it suffices to show that

$$\lim_{x\to t} g'(x) = g'(t)$$

if $\gamma(t) = (0,0)$ since $g'(t)$ is always continuous if $\gamma(t) \neq (0,0)$. Here all $\gamma_1, \gamma_2, \gamma_1', \gamma_2'$ are continuous and $\gamma_1(t)^2 + \gamma_2(t)^2 \neq 0$ by assumption. So

$$\begin{aligned} &\lim_{x\to t} \frac{3\gamma_1(x)^2\gamma_1'(x)}{\gamma_1(x)^2+\gamma_2(x)^2} \\ =&\lim_{x\to t} \frac{3\left(\frac{\gamma_1(x)-\gamma_1(t)}{x-t}\right)^2\gamma_1'(x)}{\left(\frac{\gamma_1(x)-\gamma_1(t)}{x-t}\right)^2+\left(\frac{\gamma_2(x)-\gamma_2(t)}{x-t}\right)^2} \\ =&\frac{3\gamma_1'(t)^2\cdot\gamma_1'(t)}{\gamma_1'(t)^2+\gamma_2'(t)^2} \\ =&\frac{3\gamma_1'(t)^3}{\gamma_1'(t)^2+\gamma_2'(t)^2} \end{aligned}$$

and similarly

$$\begin{aligned} &\lim_{x\to t} \frac{\gamma_1(t)^3(2\gamma_1(t)\gamma_1'(t)+2\gamma_2(t)\gamma_2'(t))}{(\gamma_1(t)^2+\gamma_2(t)^2)^2} \\ =&\lim_{x\to t} \frac{\left(\frac{\gamma_1(x)-\gamma_1(t)}{x-t}\right)^3\left(2\frac{\gamma_1(x)-\gamma_1(t)}{x-t}\gamma_1'(t)+2\frac{\gamma_2(x)-\gamma_2(t)}{x-t}\gamma_2'(t)\right)}{\left(\left(\frac{\gamma_1(x)-\gamma_1(t)}{x-t}\right)^2+\left(\frac{\gamma_2(x)-\gamma_2(t)}{x-t}\right)^2\right)^2} \\ =&\frac{\gamma_1'(t)^3\cdot(2\gamma_1'(t)\gamma_1'(t)+2\gamma_2'(t)\gamma_2'(t))}{(\gamma_1'(t)^2+\gamma_2'(t)^2)^2} \\ =&\frac{2\gamma_1'(t)^3}{\gamma_1'(t)^2+\gamma_2'(t)^2}. \end{aligned}$$

Hence

$$\lim_{x\to t} g'(x) = \frac{3\gamma_1'(t)^3}{\gamma_1'(t)^2+\gamma_2'(t)^2} - \frac{2\gamma_1'(t)^3}{\gamma_1'(t)^2+\gamma_2'(t)^2} = g'(t).$$

□

Proof of (d). (Reductio ad absurdum) If f were differentiable, then

$$(D_{\mathbf{u}}f)(0,0) = (D_1f)(0,0)u_1 + (D_2f)(0,0)u_2 = u_1$$

(Formula (40) in Chapter 9), contrary to (b) if we take $\mathbf{u} = \left(\frac{1}{64}, \frac{\sqrt{4095}}{64}\right)$. $\square$

Exercise 9.15. *Define $f(0,0) = 0$, and put*

$$f(x,y) = x^2 + y^2 - 2x^2y - \frac{4x^6y^2}{(x^4+y^2)^2}$$

if $(x,y) \neq (0,0)$.

(a) *Prove, for all $(x,y) \in \mathbb{R}^2$, that*

$$4x^4y^2 \leq (x^4+y^2)^2.$$

Conclude that f is continuous.

(b) *For $0 \leq \theta \leq 2\pi$, $-\infty < t < \infty$, define*

$$g_\theta(t) = f(t\cos\theta, t\sin\theta).$$

Show that $g_\theta(0) = 0$, $g_\theta'(0) = 0$, $g_\theta''(0) = 2$. Each g_θ has therefore a strict local minimum at $t = 0$. In other words, the restriction of f to each line through $(0,0)$ has a strict local minimum at $(0,0)$.

(c) *Show that $(0,0)$ is nevertheless not a local minimum for f, since $f(x,x^2) = -x^4$.*

Proof of (a).

(1) Since $t^2 \geq 0$ for all $t \in \mathbb{R}^1$,

$$(x^4+y^2)^2 - 4x^4y^2 = (x^4-y^2)^2 \geq 0.$$

Hence $4x^4y^2 \leq (x^4+y^2)^2$.

(2) $f(x,y)$ is continuous at $(x,y) \neq (0,0)$. Besides,

$$\begin{aligned}
|f(x,y)| &= \left| x^2 + y^2 - 2x^2y - \frac{4x^6y^2}{(x^4+y^2)^2} \right| \\
&\leq \left|x^2\right| + \left|y^2\right| + \left|2x^2y\right| + \left|x^2\right| \left| \frac{4x^4y^2}{(x^4+y^2)^2} \right| \\
&\leq \left|x^2\right| + \left|y^2\right| + \left|2x^2y\right| + \left|x^2\right|.
\end{aligned}$$

Hence $\left|x^2\right| + \left|y^2\right| + \left|2x^2y\right| + \left|x^2\right| \to 0$ as $(x,y) \to (0,0)$, or

$$\lim_{(x,y)\to(0,0)} |f(x,y)| = 0 = f(0,0),$$

or $\lim_{(x,y)\to(0,0)} f(x,y) = f(0,0)$, or $f(x,y)$ is continuous at $(0,0)$.

□

Proof of (b).

(1)
$$g_\theta(t) = \begin{cases} t^2 - 2t^3\cos^2\theta\sin\theta - \frac{4t^4\cos^6\theta\sin^2\theta}{(t^2\cos^4\theta+\sin^2\theta)^2} & \text{if } t \neq 0, \\ 0 & \text{if } t = 0. \end{cases}$$

(Note that $\frac{4t^4\cos^6\theta\sin^2\theta}{(t^2\cos^4\theta+\sin^2\theta)^2}$ is undefined as $t = 0$ and $\sin\theta = 0$.)

(2) $g_\theta(0) = 0$ by definition.

(3) *Show that $g'_\theta(0) = 0$ for any $\theta \in [0, 2\pi]$.* If $\sin\theta \neq 0$ ($\theta \neq 0, \pi, 2\pi$), then

$$\begin{aligned} g'_\theta(0) &= \lim_{t\to 0} \frac{t^2 - 2t^3\cos^2\theta\sin\theta - \frac{4t^4\cos^6\theta\sin^2\theta}{(t^2\cos^4\theta+\sin^2\theta)^2} - 0}{t} \\ &= \lim_{t\to 0}\left(t - 2t^2\cos^2\theta\sin\theta - \frac{4t^3\cos^6\theta\sin^2\theta}{(t^2\cos^4\theta+\sin^2\theta)^2}\right) \\ &= 0. \end{aligned}$$

If $\sin\theta = 0$, then

$$g'_\theta(0) = \lim_{t\to 0}\frac{t^2 - 0}{t} = \lim_{t\to 0} t = 0.$$

(4) Combine (3) and a direct calculation for the case $t \neq 0$, we have

$$g'_\theta(t) = \begin{cases} 2t - 6t^2\cos^2\theta\sin\theta - \frac{16t^3\cos^6\theta\sin^4\theta}{(t^2\cos^4\theta+\sin^2\theta)^3} & \text{if } t \neq 0, \\ 0 & \text{if } t = 0. \end{cases}$$

(5) *Show that $g''_\theta(0) = 2$ for any $\theta \in [0, 2\pi]$.* If $\sin\theta \neq 0$ ($\theta \neq 0, \pi, 2\pi$), then

$$\begin{aligned} g''_\theta(0) &= \lim_{t\to 0} \frac{2t - 6t^2\cos^2\theta\sin\theta - \frac{16t^3\cos^6\theta\sin^4\theta}{(t^2\cos^4\theta+\sin^2\theta)^3} - 0}{t} \\ &= \lim_{t\to 0}\left(t - 6t\cos^2\theta\sin\theta - \frac{16t^2\cos^6\theta\sin^4\theta}{(t^2\cos^4\theta+\sin^2\theta)^3}\right) \\ &= 2. \end{aligned}$$

If $\sin\theta = 0$, then

$$g''_\theta(0) = \lim_{t\to 0}\frac{2t - 0}{t} = \lim_{t\to 0} 2 = 2.$$

(6) Since $g''_\theta(0) > 0$ and $g'_\theta(0) = 0$, g_θ has a strict local minimum at $t = 0$. As θ is fixed, f is restricted to some line through $(0, 0)$. Hence, such restriction of f has a strict local minimum at $t = 0$.

□

Proof of (c). Since $f(x, x^2) = -x^4 \leq 0 = f(0,0)$ in any open neighborhood of $(0,0)$, $f(0,0) = 0$ cannot be a local minimum for f. □

Exercise 9.16. *Show that the continuity of* $\mathbf{f}'$ *at the point* $\mathbf{a}$ *is needed in the inverse function theorem, even in the case* $n = 1$*: If*

$$f(t) = t + 2t^2 \sin \frac{1}{t}$$

for $t \neq 0$*, and* $f(0) = 0$*, then* $f'(0) = 1$*,* f' *is bouneded in* $(-1, 1)$*, but* f *is not one-to-one in any neighborhood of* 0.

Proof.

(1) *Show that*

$$f'(t) = \begin{cases} 1 + 4t \sin \frac{1}{t} - 2 \cos \frac{1}{t} & \text{if } t \neq 0, \\ 1 & \text{if } t = 0. \end{cases}$$

It suffices to show that $f'(0) = 1$. In fact,

$$f'(0) = \lim_{t \to 0} \frac{t + 2t^2 \sin \frac{1}{t} - 0}{t - 0} = \lim_{t \to 0} \left(1 + 2t \sin \frac{1}{t} \right) = 1$$

(since $\sin \frac{1}{t}$ is bounded and $2t \to 0$ as $t \to 0$).

Note. $f'(t)$ is not continuous at $t = 0$.

(2) *Show that* f' *is bouneded in* $(-1, 1)$.

$$|f'(t)| \leq 1 + 4|t| \left| \sin \frac{1}{t} \right| + 2 \left| \cos \frac{1}{t} \right| \leq 1 + 4 + 2 = 7$$

if $t \neq 0$. Hence f' is bounded by 7 in $(-1, 1)$.

(3) *Show that* f *is not one-to-one in any neighborhood of* 0. Take

$$x_n = \frac{1}{2n\pi} \qquad \text{and} \qquad y_n = \frac{1}{2n\pi + \pi}$$

for $n = 1, 2, 3, \ldots$. So that

$$f'(x_n) = -1 < 0 \qquad \text{and} \qquad f'(y_n) = 3 > 0.$$

Since $f'(t)$ is continuous if $t \neq 0$, there exists $\xi_n \in (y_n, x_n)$ such that $f'(\xi_n) = 0$ (Theorem 4.23). Then Theorem 5.11 implies that f has a local maximum at ξ_n, that is, f is not one-to-one in the interval $[y_n, x_n]$ (by applying Theorem 4.23 again). Since $x_n \to 0$ and $y_n \to 0$ as $n \to \infty$, f is not one-to-one in any neighborhood of 0.

□

Exercise 9.17. *Let* $\mathbf{f} = (f_1, f_2)$ *be the mapping of* $\mathbb{R}^2$ *into* $\mathbb{R}^2$ *given by*

$$f_1(x, y) = e^x \cos y, \qquad f_2(x, y) = e^x \sin y.$$

(a) *What is the range of* $\mathbf{f}$*?*

(b) *Show that the Jacobian of* $\mathbf{f}$ *is not zero at any point of* $\mathbb{R}^2$*. Thus every point of* $\mathbb{R}^2$ *has a neighborhood in which* $\mathbf{f}$ *is one-to-one. Nevertheless,* $\mathbf{f}$ *is not one-to-one on* $\mathbb{R}^2$*.*

(c) *Put* $\mathbf{a} = \left(0, \frac{\pi}{3}\right)$*,* $\mathbf{b} = \mathbf{f}(\mathbf{a})$*, let* $\mathbf{g}$ *be the continuous inverse of* $\mathbf{f}$*, defined in a neighborhood of* $\mathbf{b}$ *such that* $\mathbf{g}(\mathbf{b}) = \mathbf{a}$*. Find an explicit formula for* $\mathbf{g}$*, compute* $\mathbf{f}'(\mathbf{a})$ *and* $\mathbf{g}'(\mathbf{b})$*, and verify the formula*

$$\mathbf{g}'(\mathbf{y}) = \{\mathbf{f}'(\mathbf{g}(\mathbf{y}))\}^{-1}.$$

(d) *What are the images under* $\mathbf{f}$ *of lines parallel to the coordinate axes?*

Proof of (a).

(1) The range of $\mathbf{f}$ is $\mathbb{R}^2 - \{(0, 0)\}$.

(2) If $(a, b) \neq (0, 0)$, then $\mathbf{f} : \left(\log \sqrt{a^2 + b^2}, \operatorname{atan2}(b, a)\right) \mapsto (a, b)$ where

$$\operatorname{atan2}(b, a) = \begin{cases} \arctan\left(\frac{b}{a}\right) & \text{if } a > 0, \\ \arctan\left(\frac{b}{a}\right) + \pi & \text{if } a < 0 \text{ and } b \geq 0, \\ \arctan\left(\frac{b}{a}\right) - \pi & \text{if } a < 0 \text{ and } b < 0, \\ \frac{\pi}{2} & \text{if } a = 0 \text{ and } b > 0, \\ -\frac{\pi}{2} & \text{if } a = 0 \text{ and } b < 0. \end{cases}$$

(Or apply Theorem 8.7(d).)

(3) If $(a, b) = (0, 0)$, then for any $(x, y) \in \mathbb{R}^2$ we have $f_1(x, y)^2 + f_2(x, y)^2 = e^{2x} \neq 0$. So that there is no (x, y) such that $\mathbf{f} : (x, y) \mapsto (0, 0)$.

□

Proof of (b).

(1)

$$[\mathbf{f}'(x, y)] = \begin{bmatrix} e^x \cos y & -e^x \sin y \\ e^x \sin y & e^x \cos y \end{bmatrix}.$$

So $\mathbf{f}'$ is continuous and

$$J_{\mathbf{f}}(x, y) = \det \mathbf{f}'(x, y) = e^{2x} \neq 0.$$

(2) Since $J_{\mathbf{f}}(x,y) \neq 0$, $\mathbf{f}'(x,y)$ is invertible (Theorem 9.36). So the inverse function theorem (Theorem 9.24) implies that there exists an open neighborhood $B(x,y)$ of (x,y) such that $\mathbf{f}$ is injective on $B(x,y)$.

(3) Note that

$$\mathbf{f}(0,0) = \mathbf{f}(0,2\pi) = (1,0).$$

So that $\mathbf{f}$ is not injective on the whole $\mathbb{R}^2$. (Injectivity of $\mathbf{f}$ is a local property.)

□

Proof of (c).

(1) If $\mathbf{a} = \left(0, \frac{\pi}{3}\right)$, then $\mathbf{b} = \mathbf{f}(\mathbf{a}) = \left(\frac{1}{2}, \frac{\sqrt{3}}{2}\right)$.

(2) Similar to (2) in the proof of (a), define $\mathbf{g} : U \to \mathbb{R}^2$ by

$$\mathbf{g}(x,y) = \left(\log\sqrt{x^2+y^2}, \arctan\left(\frac{y}{x}\right)\right).$$

where U is some open neighborhood of the point $\mathbf{b} \in \mathbb{R}^2$ described in (b). So $\mathbf{g}$ is a continuous inverse of $\mathbf{f}$.

(3) Since

$$[\mathbf{f}'(x,y)] = \begin{bmatrix} e^x \cos y & -e^x \sin y \\ e^x \sin y & e^x \cos y \end{bmatrix},$$

$$[\mathbf{f}'(\mathbf{a})] = \left[\mathbf{f}'\left(0, \tfrac{\pi}{3}\right)\right] = \begin{bmatrix} e^0 \cos \frac{\pi}{3} & -e^0 \sin \frac{\pi}{3} \\ e^0 \sin \frac{\pi}{3} & e^0 \cos \frac{\pi}{3} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & -\frac{\sqrt{3}}{2} \\ \frac{\sqrt{3}}{2} & \frac{1}{2} \end{bmatrix}.$$

(4) Since

$$[\mathbf{g}'(x,y)] = \begin{bmatrix} \frac{x}{x^2+y^2} & \frac{y}{x^2+y^2} \\ \frac{-y}{x^2+y^2} & \frac{x}{x^2+y^2} \end{bmatrix},$$

$$[\mathbf{g}'(\mathbf{b})] = \left[\mathbf{g}'\left(\tfrac{1}{2}, \tfrac{\sqrt{3}}{2}\right)\right] = \begin{bmatrix} \frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{\sqrt{3}}{2} & \frac{1}{2} \end{bmatrix}.$$

Here we can see $[\mathbf{f}'(\mathbf{a})][\mathbf{g}'(\mathbf{b})] = [\mathbf{g}'(\mathbf{b})][\mathbf{f}'(\mathbf{a})] = 1$.

(5)

$$\begin{aligned}
[\mathbf{g}'(\mathbf{y})] &= [\mathbf{g}'(\mathbf{f}(\mathbf{x}))] \\
&= [\mathbf{g}'(e^x \cos y, e^x \sin y)] \\
&= \begin{bmatrix} \frac{e^x \cos y}{e^{2x}} & \frac{e^x \sin y}{e^{2x}} \\ \frac{-e^x \sin y}{e^{2x}} & \frac{e^x \cos y}{e^{2x}} \end{bmatrix} \\
&= \begin{bmatrix} e^{-x} \cos y & e^{-x} \sin y \\ -e^{-x} \sin y & e^{-x} \cos y \end{bmatrix},
\end{aligned}$$

and

$$[\mathbf{f}'(\mathbf{g}(\mathbf{y}))] = [\mathbf{f}'(\mathbf{x})] = \begin{bmatrix} e^x \cos y & -e^x \sin y \\ e^x \sin y & e^x \cos y \end{bmatrix}.$$

Note that

$$\begin{bmatrix} e^{-x} \cos y & e^{-x} \sin y \\ -e^{-x} \sin y & e^{-x} \cos y \end{bmatrix} \begin{bmatrix} e^x \cos y & -e^x \sin y \\ e^x \sin y & e^x \cos y \end{bmatrix} = 1.$$

Therefore

$$\mathbf{g}'(\mathbf{y}) = \{\mathbf{f}'(\mathbf{g}(\mathbf{y}))\}^{-1}$$

on $\mathbf{g}(U)$.

□

Proof of (d).

(1) The case $L_r = \{(x, y) \in \mathbb{R}^2 : x = r\}$ parallel to y-axis where $r \in \mathbb{R}^1$ is constant. The image under $\mathbf{f}$ is

$$\begin{aligned} \mathbf{f}(L_r) &= \{(e^r \cos y, e^r \sin y) \in \mathbb{R}^2 : y \in \mathbb{R}^1\} \\ &= \{(s, t) \in \mathbb{R}^2 : s^2 + t^2 = (e^r)^2\}, \end{aligned}$$

a circle which is centered at the origin $(0, 0) \in \mathbb{R}^2$ with radius $e^r > 0$.

(2) The case $L_\theta = \{(x, y) \in \mathbb{R}^2 : y = \theta\}$ parallel to x-axis where $\theta \in \mathbb{R}^1$ is constant. The image under $\mathbf{f}$ is

$$\begin{aligned} \mathbf{f}(L_\theta) &= \{(e^x \cos\theta, e^x \sin\theta) \in \mathbb{R}^2 : x \in \mathbb{R}^1\} \\ &= \{(y \cos\theta, y \sin\theta) \in \mathbb{R}^2 : y > 0\}, \end{aligned}$$

which is a ray from the origin $(0, 0)$ (not included) to the infinity passing through a point $(\cos\theta, \sin\theta)$ in the unit circle.

□

Exercise 9.18. *Answer analogous questions for the mapping defined by*

$$u = x^2 - y^2, \qquad v = 2xy.$$

Outline. Let $\mathbf{f}(x, y) = (u, v) = (x^2 - y^2, 2xy)$.

(a) *What is the range of* $\mathbf{f}$*?*

(b) *Show that the Jacobian of* $\mathbf{f}$ *is not zero at any point of* $\mathbb{R}^2 - \{(0, 0)\}$*. Thus every point of* $\mathbb{R}^2 - \{(0, 0)\}$ *has a neighborhood in which* $\mathbf{f}$ *is one-to-one. Nevertheless,* $\mathbf{f}$ *is not one-to-one on* $\mathbb{R}^2 - \{(0, 0)\}$*.*

(c) *Put* $\mathbf{a} = (1,1)$, $\mathbf{b} = \mathbf{f}(\mathbf{a})$, *let* $\mathbf{g}$ *be the continuous inverse of* $\mathbf{f}$, *defined in a neighborhood of* $\mathbf{b}$ *such that* $\mathbf{g}(\mathbf{b}) = \mathbf{a}$. *Find an explicit formula for* $\mathbf{g}$, *compute* $\mathbf{f}'(\mathbf{a})$ *and* $\mathbf{g}'(\mathbf{b})$, *and verify the formula*

$$\mathbf{g}'(\mathbf{y}) = \{\mathbf{f}'(\mathbf{g}(\mathbf{y}))\}^{-1}.$$

(d) *What are the images under* $\mathbf{f}$ *of lines parallel to the coordinate axes?*

Proof of (a). Show that the range of f is $\mathbb{R}^2$. Clearly, $f(0,0) = (0,0)$. If $(a,b) \neq (0,0)$, then

$$\mathbf{f} : \left(\sqrt{\frac{\sqrt{a^2+b^2}+a}{2}}, \mathrm{sgn}(b)\sqrt{\frac{\sqrt{a^2+b^2}-a}{2}}, \right) \mapsto (a,b).$$

□

Proof of (b).

(1)
$$[\mathbf{f}'(x,y)] = \begin{bmatrix} 2x & -2y \\ 2y & 2x \end{bmatrix}.$$

So $\mathbf{f}'$ is continuous and

$$J_{\mathbf{f}}(x,y) = \det \mathbf{f}'(x,y) = 4(x^2+y^2) \neq 0$$

if $(x,y) \neq (0,0)$.

(2) Since $J_{\mathbf{f}}(x,y) \neq 0$ if $(x,y) \neq (0,0)$, $\mathbf{f}'(x,y)$ is invertible if $(x,y) \neq (0,0)$ (Theorem 9.36). So the inverse function theorem (Theorem 9.24) implies that there exists an open neighborhood $B(x,y)$ of $(x,y) \neq (0,0)$ such that $\mathbf{f}$ is injective on $B(x,y)$.

(3) Note that
$$\mathbf{f}(1,0) = \mathbf{f}(-1,0) = (1,0).$$
So that $\mathbf{f}$ is not injective on the whole $\mathbb{R}^2 - \{(0,0)\}$. (Injectivity of $\mathbf{f}$ is a local property.)

□

Proof of (c).

(1) If $\mathbf{a} = (1,1)$, then $\mathbf{b} = \mathbf{f}(\mathbf{a}) = (0,2)$.

(2) Similar to (2) in the proof of (a), define $\mathbf{g} : U \to \mathbb{R}^2$ by

$$\mathbf{g}(x,y) = \left(\sqrt{\frac{\sqrt{x^2+y^2}+x}{2}}, \sqrt{\frac{\sqrt{x^2+y^2}-x}{2}}, \right),$$

where U is some open neighborhood of the point $\mathbf{b} \in \mathbb{R}^2 - \{(0,0)\}$ described in (b). So $\mathbf{g}$ is a continuous inverse of $\mathbf{f}$.

(3) Since

$$[\mathbf{f}'(x,y)] = \begin{bmatrix} 2x & -2y \\ 2y & 2x \end{bmatrix},$$

$$[\mathbf{f}'(\mathbf{a})] = \big[\mathbf{f}'(1,1)\big] = \begin{bmatrix} 2 & -2 \\ 2 & 2 \end{bmatrix}.$$

(4) Since

$$[\mathbf{g}'(x,y)] = \frac{1}{2\sqrt{x^2+y^2}} \begin{bmatrix} \sqrt{\frac{\sqrt{x^2+y^2}+x}{2}} & \sqrt{\frac{\sqrt{x^2+y^2}-x}{2}} \\ -\sqrt{\frac{\sqrt{x^2+y^2}-x}{2}} & \sqrt{\frac{\sqrt{x^2+y^2}+x}{2}} \end{bmatrix},$$

$$[\mathbf{g}'(\mathbf{b})] = \big[\mathbf{g}'(0,2)\big] = \begin{bmatrix} \frac{1}{4} & \frac{1}{4} \\ -\frac{1}{4} & \frac{1}{4} \end{bmatrix}.$$

Here we can see $[\mathbf{f}'(\mathbf{a})][\mathbf{g}'(\mathbf{b})] = [\mathbf{g}'(\mathbf{b})][\mathbf{f}'(\mathbf{a})] = 1$.

(5)

$$\begin{aligned} [\mathbf{g}'(\mathbf{y})] &= [\mathbf{g}'(\mathbf{f}(\mathbf{x}))] \\ &= [\mathbf{g}'(x^2-y^2, 2xy)] \\ &= \begin{bmatrix} \frac{x}{2(x^2+y^2)} & \frac{y}{2(x^2+y^2)} \\ -\frac{y}{2(x^2+y^2)} & \frac{x}{2(x^2+y^2)} \end{bmatrix}, \end{aligned}$$

and

$$[\mathbf{f}'(\mathbf{g}(\mathbf{y}))] = [\mathbf{f}'(\mathbf{x})] = \begin{bmatrix} 2x & -2y \\ 2y & 2x \end{bmatrix}.$$

Note that

$$\begin{bmatrix} \frac{x}{2(x^2+y^2)} & \frac{y}{2(x^2+y^2)} \\ -\frac{y}{2(x^2+y^2)} & \frac{x}{2(x^2+y^2)} \end{bmatrix} \begin{bmatrix} 2x & -2y \\ 2y & 2x \end{bmatrix} = 1.$$

Therefore

$$\mathbf{g}'(\mathbf{y}) = \{\mathbf{f}'(\mathbf{g}(\mathbf{y}))\}^{-1}$$

on $\mathbf{g}(U)$.

□

Proof of (d).

(1) The case $L_\alpha = \{(x,y) \in \mathbb{R}^2 : x = \alpha\}$ parallel to y-axis where $\alpha \in \mathbb{R}^1$ is constant. If $\alpha = 0$, then

$$\mathbf{f}(L_0) = \{(-y^2, 0) \in \mathbb{R}^2 : y \in \mathbb{R}^1\} = \{(-t, 0) \in \mathbb{R}^2 : t \in \mathbb{R}^1, t \geq 0\}$$

is a ray from the origin $(0,0)$ (included) to the infinity $(-\infty, 0)$. If $\alpha \neq 0$, then

$$\begin{aligned} \mathbf{f}(L_\alpha) &= \{(\alpha^2 - y^2, 2\alpha y) \in \mathbb{R}^2 : y \in \mathbb{R}^1\} \\ &= \left\{(s,t) \in \mathbb{R}^2 : s = \alpha^2 - \frac{t^2}{4\alpha^2}\right\}, \end{aligned}$$

which is a parabola.

(2) The case $L_\beta = \{(x,y) \in \mathbb{R}^2 : y = \beta\}$ parallel to x-axis where $\beta \in \mathbb{R}^1$ is constant. If $\beta = 0$, then

$$\mathbf{f}(L_0) = \{(x^2, 0) \in \mathbb{R}^2 : x \in \mathbb{R}^1\} = \{(t,0) \in \mathbb{R}^2 : t \in \mathbb{R}^1, t \geq 0\}$$

is a ray from the origin $(0,0)$ (included) to the infinity $(\infty, 0)$. If $\beta \neq 0$, then

$$\begin{aligned} \mathbf{f}(L_\beta) &= \{(x^2 - \beta^2, 2\beta x) \in \mathbb{R}^2 : x \in \mathbb{R}^1\} \\ &= \left\{(s,t) \in \mathbb{R}^2 : s = \frac{t^2}{4\beta^2} - \beta^2\right\}, \end{aligned}$$

which is a parabola.

□

Exercise 9.19. *Show that the system of equations*

$$\begin{aligned} 3x + y - z + u^2 &= 0 \\ x - y + 2z + u &= 0 \\ 2x + 2y - 3z + 2u &= 0 \end{aligned}$$

can solved for x, y, u in terms of z; for x, z, u in terms of y; for y, z, u in terms of x; but not for x, y, z in terms of u.

Proof (Brute-force).

(1) Denote

$$\begin{aligned} 3x + y - z + u^2 &= 0 \qquad \text{(I)} \\ x - y + 2z + u &= 0 \qquad \text{(II)} \\ 2x + 2y - 3z + 2u &= 0 \qquad \text{(III)} \end{aligned}$$

So (I) - 3(II) implies that

$$4y + u(u-3) = 7z, \tag{IV}$$

and (III) - 2(II) implies that

$$4y = 7z. \tag{V}$$

By (IV)(V), we have $u(u-3) = 0$. Hence $u = 0$ or $u = 3$ in any case.

(2) *Show that (I)(II)(III) can be solve for x, y, u in terms of z.* (V) implies that $y = \frac{7z}{4}$. Hence

$$(x, y, u) = \left(-\frac{z}{4}, \frac{7z}{4}, 0\right), \left(-\frac{z}{4} - 3, \frac{7z}{4}, 3\right).$$

(3) *Show that (I)(II)(III) can be solve for x, z, u in terms of y.*

$$(x, z, u) = \left(-\frac{y}{7}, \frac{4y}{7}, 0\right), \left(-\frac{y}{7} - 3, \frac{4y}{7}, 3\right).$$

(4) *Show that (I)(II)(III) can be solve for y, z, u in terms of x.*

$$(y, z, u) = (-7x, -4x, 0), (-7x - 21, -4x - 12, 3).$$

(5) *Show that (I)(II)(III) can not be solve for x, y, z in terms of u.* Actually,

$$(x, y, z) = (-t - u, 7t, 4t)$$

for all $t \in \mathbb{R}^1$.

$\square$

Proof (The implicit function theorem).

(1) Define $\mathbf{f}$ be a $\mathscr{C}'$-mapping of $\mathbb{R}^{3+1}$ into $\mathbb{R}^3$ by

$$\mathbf{f}(x, y, z, u) = (3x + y - z + u^2, x - y + 2z + u, 2x + 2y - 3z + 2u).$$

Note that $\mathbf{f}(0, 0, 0, 0) = \mathbf{0}$ and $\mathbf{f}(-3, 0, 0, 3) = \mathbf{0}$.

(2) Since

$$[\mathbf{f}'(x, y, z, u)] = \begin{bmatrix} 3 & 1 & -1 & 2u \\ 1 & -1 & 2 & 1 \\ 2 & 2 & -3 & 2 \end{bmatrix},$$

$\mathbf{f}'$ is continuous,

$$[\mathbf{f}'(0, 0, 0, 0)] = \begin{bmatrix} 3 & 1 & -1 & 0 \\ 1 & -1 & 2 & 1 \\ 2 & 2 & -3 & 2 \end{bmatrix},$$

and

$$[\mathbf{f}'(-3, 0, 0, 3)] = \begin{bmatrix} 3 & 1 & -1 & 6 \\ 1 & -1 & 2 & 1 \\ 2 & 2 & -3 & 2 \end{bmatrix}.$$

(3) The submatrix

$$[\mathbf{f}'(0,0,0,0)]_x = \begin{bmatrix} 1 & -1 & 0 \\ -1 & 2 & 1 \\ 2 & -3 & 2 \end{bmatrix}$$

is invertiable since its determinant is $3 \neq 0$. By the implicit function theorem (Theorem 9.28), the system can be solved for y, z, u in terms of x. Similar arguments to $[\mathbf{f}'(0,0,0,0)]_y$, $[\mathbf{f}'(0,0,0,0)]_z$, $[\mathbf{f}'(-3,0,0,3)]_x$, $[\mathbf{f}'(-3,0,0,3)]_y$, and $[\mathbf{f}'(-3,0,0,3)]_z$.

(4) Note that $[\mathbf{f}'(0,0,0,0)]_u$ and $[\mathbf{f}'(-3,0,0,3)]_u$ are not invertible, we cannot apply the implicit function theorem (Theorem 9.28). We need to show by brute-force in this case.

□

Exercise 9.20. *Take $n = m = 1$ in the implicit function theorem, and interpret the theorem (as well as its proof) graphically.*

Implicit function theorem (for $n = m = 1$). Let $f(x, y)$ be a $\mathscr{C}'$-mapping of an open set $E \subseteq \mathbb{R}^2$ into $\mathbb{R}$, such that $f(a, b) = 0$ for some point $(a, b) \in E$. Assume that

$$D_1 f(a, b) \neq 0.$$

Then there exist open sets $U \subseteq E$ and $W \subseteq \mathbb{R}^1$, with $(a, b) \in U$ and $b \in W$, having the following property:

To every $y \in W$ corresponds a unique x such that

$$(x, y) \in U \qquad \text{and} \qquad f(x, y) = 0.$$

If this x is defined to be $g(y)$, then g is a $\mathscr{C}'$-mapping of W into $\mathbb{R}^1$, $g(b) = a$,

$$f(g(y), y) = 0 \qquad (y \in W),$$

and

$$g'(b) = -\frac{D_2 f(a, b)}{D_1 f(a, b)}.$$

Proof.

(1) In the notations of Exercise 4.6, define the graph of f by the set

$$S = \{(x, y) \in E : f(x, y) = 0\}.$$

(2) Consider the graph S. As $D_1 f(a, b) \neq 0$ and $f(x, y) \in \mathscr{C}'$, there are an open neighborhood $U \subseteq E$ of (a, b) and an open neighborhood W of b such that $x \mapsto f(x, y)$ is strictly monotonic whenever $y \in W$. "Graphically" by the monotony of $f(x, y)$, for any fixed y there is a unique x such that $f(x, y) = 0$.

(3) "Graphically" the tangent line passing through (a, b) is

$$D_1 f(a,b)(x-a) + D_2 f(a,b)(y-b) = 0.$$

Thus $g'(b) = -\frac{D_2 f(a,b)}{D_1 f(a,b)}$ if $D_1 f(a,b) \neq 0$.

□

Exercise 9.21. *Define f in $\mathbb{R}^2$ by*

$$f(x,y) = 2x^3 - 3x^2 + 2y^3 + 3y^2.$$

(a) *Find the four points in $\mathbb{R}^2$ at which the gradient of f is zero. Show that f has exactly one local maximum and one local minimum in $\mathbb{R}^1$.*

(b) *Let S be the set of all $(x,y) \in \mathbb{R}^2$ at which $f(x,y) = 0$. Find those points of S that have no neighborhoods in which the equation $f(x,y) = 0$ can be solved for y in terms of x (or for x in terms of y). Describe S as precisely as you can.*

Proof of (a).

(1)

$$(\nabla f)(x,y) = ((D_1 f)(x,y), (D_2 f)(x,y)) = (6x(x-1), 6y(y+1)).$$

So $(\nabla f)(x,y) = 0$ if and only if $(x,y) = (0,0)$, $(0,-1)$, $(1,0)$, $(1,-1)$.

(2) $x \mapsto 2x^3 - 3x^2$ have one local maximum at $x = 0$ and one local minimum at $x = 1$. $y \mapsto 2y^3 + 3y^2$ have one local maximum at $y = -1$ and one local minimum at $y = 0$.

(3) Hence $f : (x,y) \mapsto to(2x^3 - 3x^2) + (2y^3 + 3y^2)$ have one local maximum at $(x,y) = (0,-1)$ and one local minimum at $(x,y) = (1,0)$. Other two points $(0,0)$ and $(1,-1)$ are saddle points.

□

Proof of (b).

(1) By definition,

$$\begin{aligned} S &= \{f(x,y) = 0\} \\ &= \{(x+y)(2x^2 - 2xy - 3x + 2y^2 + 3y) = 0\} \\ &= \{x + y = 0\} \cup \{2x^2 - 2xy - 3x + 2y^2 + 3y = 0\}, \end{aligned}$$

which is a union of a line $L = \{x + y = 0\}$ and an ellipse $E = \{2x^2 - 2xy - 3x + 2y^2 + 3y = 0\}$. The intersection of $L \cap E$ is $\{(0,0), (1,-1)\}$, and it suggested that $f(x,y) = 0$ cannot be solved for y in terms of x (or for x in terms of y) on $L \cap E = \{(0,0), (1,-1)\}$.

(2) By (1) in the proof of (a) and the implicit function theorem (Theorem 9.28), $f(x,y) = 0$ can be solved for y in terms of x (or for x in terms of y) whenever $(D_2 f)(x,y) \neq 0$ (or $(D_1 f)(x,y) \neq 0$).

(3) *Show that $f(x,y) = 0$ cannot be solved for y in terms of x if $(D_2 f)(x,y) = 0$.* $(D_2 f)(x,y) = 0$ if and only if

$$(x,y) \in T = \left\{ (0,0), \left(\frac{3}{2}, 0\right), (1,-1), \left(-\frac{1}{2}, -1\right) \right\}.$$

Solve y to get

$$\begin{aligned} y &= -x \\ y &= \frac{1}{4}\left(2x - 3 + \sqrt{-3(2x+1)(2x-3)}\right) \\ y &= \frac{1}{4}\left(2x - 3 - \sqrt{-3(2x+1)(2x-3)}\right) \end{aligned}$$

In any case, y can not be uniquely determined by x for any $(x,y) \in T$. ("Graphically" we can see the set S to get the conclusion. Explicitly, we can take the limit to each expression (as $(s,t) \to (x,y) \in T$), and observe that not all limits are equal.)

(4) *Show that $f(x,y) = 0$ cannot be solved for x in terms of y if $(D_1 f)(x,y) = 0$.* $(D_1 f)(x,y) = 0$ if and only if

$$(x,y) \in T = \left\{ (0,0), \left(0, -\frac{3}{2}\right), (1,-1), \left(1, \frac{1}{2}\right) \right\}.$$

Similar to (3), x can not be uniquely determined by y for any $(x,y) \in T$.

$\square$

Supplement (Second-derivative test for extrema).

(1) *(Theorem 13.11 in Tom M. Apostol, Mathematical Analysis, 2nd edition). Let f be a real-valued function with continuous second-order partial derivatives at a stationary point $\mathbf{a} \in \mathbb{R}^2$. Let*

$$A = (D_{11} f)(\mathbf{a}), \qquad B = (D_{12} f)(\mathbf{a}), \qquad C = (D_{22} f)(\mathbf{a}),$$

and let

$$\Delta = \det \begin{bmatrix} A & B \\ B & C \end{bmatrix} = AC - B^2.$$

Then we have:

(a) *If $\Delta > 0$ and $A > 0$, f has a local minimum at $\mathbf{a}$.*

(b) *If $\Delta > 0$ and $A < 0$, f has a local maximum at $\mathbf{a}$.*

(c) *If* $\Delta < 0$, f *has a saddle point at* $\mathbf{a}$.

(2) We can give another proof of (a) by the second-derivative test for extrema.

Exercise 9.22. *Given a similar discussion for*

$$f(x, y) = 2x^3 + 6xy^2 - 3x^2 + 3y^2.$$

Outline.

(a) *Find the two points in* $\mathbb{R}^2$ *at which the gradient of* f *is zero. Show that* f *has one saddle point and one local minimum in* $\mathbb{R}^1$.

(b) *Let* S *be the set of all* $(x, y) \in \mathbb{R}^2$ *at which* $f(x, y) = 0$. *Find those points of* S *that have no neighborhoods in which the equation* $f(x, y) = 0$ *can be solved for* y *in terms of* x *(or for* x *in terms of* y*). Describe* S *as precisely as you can.*

Proof of (a).

(1)

$$(\nabla f)(x, y) = ((D_1 f)(x, y), (D_2 f)(x, y)) = (6(x^2 + y^2 - x), 6y(2x + 1)).$$

So $(\nabla f)(x, y) = 0$ if and only if $(x, y) = (0, 0)$ or $(1, 0)$.

(2) *Show that* f *has one saddle point at* $(x, y) = (0, 0)$. Since $f(x, x) = 8x^3$, $f(x, x) \leq 0 = f(0, 0)$ if $x < 0$ and $f(x, x) \geq 0 = f(0, 0)$ if $x > 0$. Hence (x, y) is not a local maximum or a local minimum for f.

(3) *Show that* f *has one local minimum at* $(x, y) = (1, 0)$. Write

$$f(x, y) = 2x^3 - 3x^2 + (6x + 3)y^2.$$

Note that $2x^3 - 3x^2 \geq -1$ and $(6x + 3)y^2 \geq 0$ in some open neighborhood $B\left((1, 0); \frac{1}{64}\right)$ of $(1, 0)$. Therefore f has one local minimum at $(x, y) = (1, 0)$.

□

Proof of (b).

(1) S is a folium of Descartes with a double point at the origin and asymptote $x + \frac{1}{2} = 0$.

whenever $(D_2 f)(x, y) \neq 0$ (or $(D_1 f)(x, y) \neq 0$).

(3) *Show that $f(x,y)=0$ cannot be solved for y in terms of x if $(D_2 f)(x,y)=0$.* $(D_2 f)(x,y)=0$ if and only if

$$(x,y)\in T=\left\{(0,0),\left(\frac{3}{2},0\right)\right\}.$$

Solve y to get

$$y=\sqrt{\frac{-x^2(2x-3)}{3(2x+1)}}$$
$$y=-\sqrt{\frac{-x^2(2x-3)}{3(2x+1)}}$$

In any case, y can not be uniquely determined by x for any $(x,y)\in T$. ("Graphically" we can see the set S to get the conclusion. Explicitly, we can take the limit to each expression (as $(s,t)\to(x,y)\in T$), and observe that two limits are different.)

(4) *Show that $f(x,y)=0$ cannot be solved for x in terms of y if $(D_1 f)(x,y)=0$.* $(D_1 f)(x,y)=0$ if and only if

$$(x,y)\in T=\left\{(0,0),\pm\sqrt{-\frac{3}{4}+\sqrt{\frac{3}{4}}}\right\}.$$

Similar to (3), x can not be uniquely determined by y for any $(x,y)\in T$. That is,

$$\begin{aligned}x=&g(y)\\=&\frac{1-4y^2}{2}\left\{2\sqrt{16y^6+24y^4-3y^2}-12y^2+1\right\}^{-\frac{1}{3}}\\&+\left\{2\sqrt{16y^6+24y^4-3y^2}-12y^2+1\right\}^{\frac{1}{3}}+1.\end{aligned}$$

So as $y\neq 0$, $x=g(y)=g(-y)$. The expression $x=g(y)$ is not unique.

□

Exercise 9.23. *Define f in $\mathbb{R}^3$ by*

$$f(x,y_1,y_2)=x^2y_1+e^x+y_2.$$

Show that $f(0,1,-1)=0$, $(D_1 f)(0,1,-1)\neq 0$, and that there exists therefore a differentiable function g in some neighborhood of $(1,-1)$ in $\mathbb{R}^2$, such that $g(1,-1)=0$ and

$$f(g(y_1,y_2),y_1,y_2)=0.$$

Find $(D_1 g)(1,-1)$ and $(D_2 g)(1,-1)$.

Proof.

(1) Note that $f(0,1,-1)=0$. Since

$$\begin{aligned}[\nabla f((x,y_1,y_2)]_{(x,y_1,y_2)=(0,1,-1)} &= \left[(2xy_1+e^x,x^2,1)\right]_{(x,y_1,y_2)=(0,1,-1)} \\ &= (1,0,1),\end{aligned}$$

$A_x=(1)$ and $A_y=(0,1)$. By the implicit function theorem (Theorem 9.28), there exists a $\mathscr{C}'$ function in some open neighborhood of $(1,-1)$ such that $g(1,-1)=0$ and $f(g(y_1,y_2),y_1,y_2)=0$.

(2) Besides, $g'(1,-1)=-(A_x)^{-1}A_y=(0,-1)$ implies that $(D_1g)(1,-1)=0$ and $(D_2g)(1,-1)=-1$.

□

Exercise 9.24. *For $(x,y)\neq(0,0)$, define $\mathbf{f}=(f_1,f_2)$ by*

$$f_1(x,y)=\frac{x^2-y^2}{x^2+y^2},\qquad f_2(x,y)=\frac{xy}{x^2+y^2}.$$

Compute the rank of $\mathbf{f}'(x,y)$, and find the range of $\mathbf{f}$.

Proof.

(1)

$$[\mathbf{f}'(x,y)]=\begin{bmatrix}\frac{4xy^2}{(x^2+y^2)^2} & \frac{4x^2y}{(x^2+y^2)^2}\\ \frac{-y(x^2-y^2)}{(x^2+y^2)^2} & \frac{x(x^2-y^2)}{(x^2+y^2)^2}\end{bmatrix}.$$

(2) *Show that* $\operatorname{rank}([\mathbf{f}'(x,y)])\neq 2$. It is equivalent to show that $\det[\mathbf{f}'(x,y)]=0$. Actually,

$$\det[\mathbf{f}'(x,y)]=\frac{4xy^2}{(x^2+y^2)^2}\cdot\frac{x(x^2-y^2)}{(x^2+y^2)^2}-\frac{4x^2y}{(x^2+y^2)^2}\cdot\frac{-y(x^2-y^2)}{(x^2+y^2)^2}=0.$$

(3) *Show that* $\operatorname{rank}([\mathbf{f}'(x,y)])\neq 0$.

$$\begin{aligned}[\mathbf{f}'(x,y)]\begin{bmatrix}1\\0\end{bmatrix} &= \begin{bmatrix}\frac{4xy^2}{(x^2+y^2)^2} & \frac{4x^2y}{(x^2+y^2)^2}\\ \frac{-y(x^2-y^2)}{(x^2+y^2)^2} & \frac{x(x^2-y^2)}{(x^2+y^2)^2}\end{bmatrix}\begin{bmatrix}1\\0\end{bmatrix}\\ &= \begin{bmatrix}\frac{4xy^2}{(x^2+y^2)^2}\\ \frac{-y(x^2-y^2)}{(x^2+y^2)^2}\end{bmatrix}\\ &\neq \begin{bmatrix}0\\0\end{bmatrix}\end{aligned}$$

for all $(x,y)\in\mathbb{R}^2-\{(0,0)\}$.

(4) Since the rank of $\mathbf{f}'$ is the dimension of the subspace $\mathscr{R}(\mathbf{f}')$ in $\mathbb{R}^2$, $\mathrm{rank}([\mathbf{f}'(x,y)]) = 0, 1, 2$. By (2)(3), $\mathrm{rank}([\mathbf{f}'(x,y)]) = 1$.

(5) *Show that the range of* $\mathbf{f}$ *is an ellipse*

$$E = \{(s,t) \in \mathbb{R}^2 : s^2 + 4t^2 = 1\}.$$

(a) Clearly, $(f_1(x,y), f_2(x,y)) \in E$.

(b) Conversely, for any $(s,t) \in E$ write

$$s = \cos\theta \qquad \text{and} \qquad t = \frac{1}{2}\sin\theta$$

for some unique $\theta \in [0, 2\pi)$ (Theorem 8.7(d)). By the tangent half-angle formula,

$$s = \cos\theta = \frac{1 - \tan^2\frac{\theta}{2}}{1 + \tan^2\frac{\theta}{2}} \qquad \text{and} \qquad t = \frac{1}{2}\sin\theta = \frac{\tan\frac{\theta}{2}}{1 + \tan^2\frac{\theta}{2}}.$$

Thus, there exists a point $\left(1, \tan\frac{\theta}{2}\right) \in \mathbb{R}^2$ such that

$$f : \left(1, \tan\frac{\theta}{2}\right) \mapsto (s,t) \in E.$$

(c) Or we can do a linear projection from a given point $P = (1,0)$, say for any $\lambda \in \mathbb{R}^1$ we define a line through P with slope $-\lambda$ meeting E in a further point

$$Q_\lambda = \left(\frac{\lambda^2 - 1}{\lambda^2 + 1}, \frac{\lambda}{\lambda^2 + 1}\right).$$

Might define $Q_\infty = P$. Graphically and informally,

$$\{Q_\lambda : \lambda \in \mathbb{P}^1(\mathbb{R}) = \mathbb{R} \cup \{\infty\}\} = E.$$

Therefore, $f(1,0) = P$ and $f(\lambda, 1) \in E - \{P\}$.

By (a)(b), the range of $\mathbf{f}$ is exactly the same as an ellipse E.

$\square$

Exercise 9.25. *Suppose $A \in L(\mathbb{R}^n, \mathbb{R}^m)$, let r be the rank of A.*

(a) *Define S as the proof of Theorem 9.32. Show that SA is a projection in $\mathbb{R}^n$ whose null space is $\mathscr{N}(A)$ and whose range is $\mathscr{R}(S)$. (Hint: By (68), $SASA = SA$.)*

(b) *Use (a) to show that*

$$\dim \mathscr{N}(A) + \dim \mathscr{R}(A) = n.$$

Proof of (a). Might assume $r > 0$.

(1) Since $\dim \mathscr{R}(A) = r$ (Definition 9.30), $\mathscr{R}(A)$ has a basis $\{\mathbf{y}_1, \dots, \mathbf{y}_r\}$. Choose $\mathbf{z}_i \in \mathbb{R}^n$ so that $A\mathbf{z}_i = \mathbf{y}_i$ ($1 \leq i \leq r$), and define a linear mapping S of $\mathscr{R}(A)$ into $\mathbb{R}^n$ by setting

$$S(c_1\mathbf{y}_1 + \cdots + c_r\mathbf{y}_r) = c_1\mathbf{z}_1 + \cdots + c_r\mathbf{z}_r$$

for all scalars $c_1, \dots, c_r$.

(2) *Show that SA is a projection.* Given any $\mathbf{x} \in \mathbb{R}^n$. Since $A\mathbf{x} \in \mathscr{R}(A)$, there exist scalars $c_1, \dots, c_r$ such that

$$A\mathbf{x} = c_1\mathbf{y}_1 + \cdots + c_r\mathbf{y}_r.$$

Note that $AS\mathbf{y}_i = A\mathbf{z}_i = \mathbf{y}_i$ for $1 \leq i \leq r$. Hence

$$\begin{aligned} SASA\mathbf{x} &= SAS(c_1\mathbf{y}_1 + \cdots + c_r\mathbf{y}_r) \\ &= SA(c_1\mathbf{z}_1 + \cdots + c_r\mathbf{z}_r) \\ &= S(c_1\mathbf{y}_1 + \cdots + c_r\mathbf{y}_r) \\ &= SA\mathbf{x}, \end{aligned}$$

(3) *Show that $\mathscr{N}(SA) = \mathscr{N}(A)$.* It is clear that $\mathscr{N}(SA) \supseteq \mathscr{N}(A)$. Conversely, given any $\mathbf{x} \in \mathscr{N}(SA)$. Write $\mathbf{0} = SA\mathbf{x} = S(A\mathbf{x})$. Since S is injective, $A\mathbf{x} = 0$, or $\mathbf{x} \in \mathscr{N}(A)$.

(4) *Show that $\mathscr{R}(SA) = \mathscr{R}(S)$.* It is clear that $\mathscr{R}(SA) \subseteq \mathscr{R}(S)$. Conversely, given any $\mathbf{z} \in \mathscr{R}(S)$. There exists $\mathbf{y} \in \mathscr{R}(A)$ such that $\mathbf{z} = S\mathbf{y}$. Since $\mathbf{y} \in \mathscr{R}(A)$, there exists $\mathbf{x} \in \mathbb{R}^n$ such that $\mathbf{y} = A\mathbf{x}$. So $\mathbf{z} = S\mathbf{y} = SA\mathbf{x}$, or $\mathbf{z} \in \mathscr{R}(SA)$.

□

Proof of (b).

(1) By Projections 9.31(a),

$$\dim \mathscr{N}(P) + \dim \mathscr{R}(P) = n$$

for any projection P.

(2) Since SA is a projection,

$$\dim \mathscr{N}(SA) + \dim \mathscr{R}(SA) = n.$$

Since $\mathscr{N}(SA) = \mathscr{N}(A)$ and $\mathscr{R}(SA) = \mathscr{R}(S)$, it suffices to show that $\dim \mathscr{R}(S) = \dim \mathscr{R}(A)$. Since S is injective, $\mathscr{R}(A) \cong S(\mathscr{R}(A)) = \mathscr{S}(A)$. Thus $\dim \mathscr{R}(S) = \dim \mathscr{R}(A)$.

□

Exercise 9.26. *Show that the existence (and even the continuity) of $D_{12}f$ does not imply the existence of $D_1 f$. For example, let $f(x,y) = g(x)$, where g is nowhere differentiable.*

Proof.

(1) Consider the function g defined on $\mathbb{R}^1$ by

$$g(x) = \begin{cases} 0 & (x \text{ irrational}), \\ \frac{1}{n} & (x = \frac{m}{n}). \end{cases}$$

$g(x)$ is nowhere differentiable by (1) in the note of Exercise 4.18. Define $f(x,y) = g(x)$ on $\mathbb{R}^2$.

(2) $(D_1 f)(x,y) = g'(x)$ does not exist on $\mathbb{R}^2$. However, $(D_{12}f)(x,y) = (D_1 0)(x,y) = 0$ is continuous on $\mathbb{R}^2$.

□

Note. Some nowhere differentiable functions.

(1) Exercise 4.18.

(2) Theorem 7.18.

(3) (Weierstrass functions.)

$$f(x) = \sum_{n=0}^{\infty} a^n \cos(b^n \pi x)$$

where $0 < a < 1$, b is a positive odd integer, and $ab > 1 + \frac{3}{2}\pi$.

(4)

$$f(x) = \sum_{n=1}^{\infty} \frac{1}{n^2} \sin\big(n^2 \pi x\big).$$

(And so on.)

Exercise 9.27. *Put $f(0,0) = 0$, and*

$$f(x,y) = \frac{xy(x^2 - y^2)}{x^2 + y^2}$$

if $(x,y) \neq (0,0)$. Prove that

(a) *f, $D_1 f$, $D_2 f$ are continuous in $\mathbb{R}^2$.*

(b) *$D_{12} f$ and $D_{21} f$ exist at every point of $\mathbb{R}^2$, and are continuous except at $(0,0)$.*

(c) *$(D_{12} f)(0,0) = 1$, and $(D_{21} f)(0,0) = -1$.*

Proof of (a).

(1) *Show that f is continuous in $\mathbb{R}^2$.*

   (a) Clearly, $f(x,y)$ is continuous if $(x,y) \neq (0,0)$. So it suffices to show that
   $$\lim_{(x,y)\to(0,0)} f(x,y) = f(0,0) = 0.$$

   (b) Write $x = r\cos\theta$ and $y = r\sin\theta$ in the polar coordinates. (Here $r > 0$.) Hence
   $$\begin{aligned}\lim_{(x,y)\to(0,0)} f(x,y) &= \lim_{(x,y)\to(0,0)} \frac{xy(x^2-y^2)}{x^2+y^2} \\ &= \lim_{r\to 0} r^2 \cos\theta\sin\theta(\cos^2\theta - \sin^2\theta) \\ &= 0\end{aligned}$$
   since $\cos\theta\sin\theta(\cos^2\theta - \sin^2\theta)$ is bounded by 2.

(2) *Show that $D_1 f$ is continuous in $\mathbb{R}^2$.*

   (a) $(x,y) \neq (0,0)$ implies that
   $$(D_1 f)(x,y) = \frac{x^4 y + 4x^2y^3 - y^5}{(x^2+y^2)^2}.$$
   Besides,
   $$\begin{aligned}(D_1 f)(0,0) &= \lim_{x\to 0} \frac{f(x,0) - f(0,0)}{x - 0} \\ &= \lim_{x\to 0} \frac{0}{x} \\ &= 0.\end{aligned}$$
   In summary,
   $$(D_1 f)(x,y) = \begin{cases} 0 & \text{if } (x,y) = (0,0) \\ \frac{x^4y+4x^2y^3-y^5}{(x^2+y^2)^2} & \text{if } (x,y) \neq (0,0). \end{cases}$$

   (b) Clearly, $(D_1 f)(x,y)$ is continuous if $(x,y) \neq (0,0)$. So it suffices to show that
   $$\lim_{(x,y)\to(0,0)} (D_1 f)(x,y) = (D_1 f)(0,0) = 0.$$

(c) Similar to (1)(b). Write $x = r\cos\theta$ and $y = r\sin\theta$ in the polar coordinates. (Here $r > 0$.) Hence

$$\begin{aligned}\lim_{(x,y)\to(0,0)}(D_1 f)(x,y) &= \lim_{(x,y)\to(0,0)} \frac{x^4 y + 4x^2y^3 - y^5}{(x^2+y^2)^2}\\ &= \lim_{r\to 0} r(\cos^4\theta\sin\theta + 4\cos^2\theta\sin^3\theta - \sin^5\theta)\\ &= 0\end{aligned}$$

since $\cos^4\theta\sin\theta + 4\cos^2\theta\sin^3\theta - \sin^5\theta$ is bounded by 6.

(3) Similar to (2). *Show that $D_2 f$ is continuous in $\mathbb{R}^2$.*

(a) $(x,y) \neq (0,0)$ implies that

$$(D_2 f)(x,y) = \frac{x^5 - 4x^3y^2 - xy^4}{(x^2+y^2)^2}.$$

Besides,

$$\begin{aligned}(D_2 f)(0,0) &= \lim_{y\to 0} \frac{f(0,y) - f(0,0)}{y - 0}\\ &= \lim_{y\to 0} \frac{0}{y}\\ &= 0.\end{aligned}$$

In summary,

$$(D_2 f)(x,y) = \begin{cases} 0 & \text{if } (x,y) = (0,0) \\ \frac{x^5-4x^3y^2-xy^4}{(x^2+y^2)^2} & \text{if } (x,y) \neq (0,0). \end{cases}$$

(b) Clearly, $(D_2 f)(x,y)$ is continuous if $(x,y) \neq (0,0)$. So it suffices to show that

$$\lim_{(x,y)\to(0,0)}(D_2 f)(x,y) = (D_2 f)(0,0) = 0.$$

(c) Similar to (1)(b). Write $x = r\cos\theta$ and $y = r\sin\theta$ in the polar coordinates. (Here $r > 0$.) Hence

$$\begin{aligned}\lim_{(x,y)\to(0,0)}(D_2 f)(x,y) &= \lim_{(x,y)\to(0,0)} \frac{x^5 - 4x^3y^2 - xy^4}{(x^2+y^2)^2}\\ &= \lim_{r\to 0} r(\cos^5\theta - 4\cos^3\theta\sin^2\theta - \cos\theta\sin^4\theta)\\ &= 0\end{aligned}$$

since $\cos^5\theta - 4\cos^3\theta\sin^2\theta - \cos\theta\sin^4\theta$ is bounded by 6.

$\square$

Proof of (b).

(1) *Show that $D_{12}f$ exists at every point of $\mathbb{R}^2$.*

(a) $(x, y) \neq (0, 0)$ implies that

$$(D_{12}f)(x, y) = (D_1 D_2 f)(x, y) = \frac{x^6 + 9x^4y^2 - 9x^2y^4 - y^6}{(x^2 + y^2)^3}.$$

(b) Besides,

$$\begin{aligned}(D_{12}f)(0, 0) &= \lim_{x \to 0} \frac{(D_2 f)(x, 0) - (D_2 f)(0, 0)}{x - 0} \\ &= \lim_{x \to 0} \frac{x}{x} \\ &= 1.\end{aligned}$$

In summary,

$$(D_{12}f)(x, y) = \begin{cases} 1 & \text{if } (x, y) = (0, 0) \\ \frac{x^6 + 9x^4y^2 - 9x^2y^4 - y^6}{(x^2 + y^2)^3} & \text{if } (x, y) \neq (0, 0). \end{cases}$$

(2) *Show that $D_{12}f$ is continuous except at $(0, 0)$.*

(a) Clearly, $(D_{12}f)(x, y)$ is continuous if $(x, y) \neq (0, 0)$. So it suffices to show that

$$\lim_{(x,y) \to (0,0)} (D_{12}f)(x, y)$$

does not exist.

(b) Take

$$\mathbf{p}_n = \left(\frac{1}{n}, 0 \right) \qquad \text{and} \qquad \mathbf{q}_n = \left(0, \frac{1}{n} \right)$$

for $n = 1, 2, 3, \ldots$. So $\lim \mathbf{p}_n = \lim \mathbf{q}_n = \mathbf{0}$,

$$\lim (D_{12}f)(\mathbf{p}_n) = 1 \qquad \text{and} \qquad \lim (D_{12}f)(\mathbf{q}_n) = -1.$$

Hence $\lim_{(x,y) \to (0,0)} (D_{12}f)(x, y)$ does not exist.

(3) *Show that $D_{21}f$ exists at every point of $\mathbb{R}^2$.* Similar to (1).

(a) $(x, y) \neq (0, 0)$ implies that

$$(D_{21}f)(x, y) = (D_2 D_1 f)(x, y) = \frac{x^6 + 9x^4y^2 - 9x^2y^4 - y^6}{(x^2 + y^2)^3},$$

which is the same as $(D_{12}f)(x, y)$.

(b) Besides,

$$\begin{aligned}(D_{21}f)(0,0) &= \lim_{y\to 0}\frac{(D_1f)(0,y)-(D_1f)(0,0)}{y-0}\\ &= \lim_{y\to 0}\frac{-y}{y}\\ &= -1.\end{aligned}$$

In summary,

$$(D_{21}f)(x,y) = \begin{cases} -1 & \text{if } (x,y)=(0,0)\\ \frac{x^6+9x^4y^2-9x^2y^4-y^6}{(x^2+y^2)^3} & \text{if } (x,y)\neq(0,0).\end{cases}$$

(4) *Show that $D_{21}f$ is continuous except at $(0,0)$.* Exactly the same as (2) since $(D_{21}f)(x,y)=(D_{12}f)(x,y)$ if $(x,y)\neq(0,0)$.

□

Proof of (c). See (2)(4) in the proof of (b). □

Exercise 9.28. *For $t \geq 0$, put*

$$\varphi(x,t) = \begin{cases} x & (0 \leq x \leq \sqrt{t}),\\ -x+2\sqrt{t} & (\sqrt{t}\leq x\leq 2\sqrt{t}),\\ 0 & (\textit{otherwise}).\end{cases}$$

and put $\varphi(x,t) = -\varphi(x,|t|)$ if $t<0$. Show that φ is continuous on $\mathbb{R}^2$, and

$$(D_2\varphi)(x,0) = 0$$

for all x. Define

$$f(t) = \int_{-1}^{1}\varphi(x,t)dx.$$

Show that $f(t)=t$ if $|t|<\frac{1}{4}$. Hence

$$f'(0) \neq \int_{-1}^{1}(D_2\varphi)(x,0)dx.$$

Proof.

(1) *Show that φ is continuous on $\mathbb{R}^2$.*

(2) *Show that $(D_2\varphi)(x,0)=0$ for all $x\in\mathbb{R}^1$.*

(3) *Show that* $f(t) = \int_{-1}^{1} \varphi(x,t)dx = t$ *if* $|t| < \frac{1}{4}$. As $0 \leq t < \frac{1}{4}$,

$$\begin{aligned}
f(t) &= \int_{-1}^{1} \varphi(x,t)dx \\
&= \int_{-1}^{0} \varphi(x,t)dx + \int_{0}^{\sqrt{t}} \varphi(x,t)dx + \int_{\sqrt{t}}^{2\sqrt{t}} \varphi(x,t)dx + \int_{2\sqrt{t}}^{1} \varphi(x,t)dx \\
&= 0 + \int_{0}^{\sqrt{t}} xdx + \int_{\sqrt{t}}^{2\sqrt{t}} (-x + 2\sqrt{t})dx + 0 \\
&= \left[\frac{x^2}{2}\right]_{x=0}^{x=\sqrt{t}} + \left[-\frac{x^2}{2} + 2\sqrt{t}x\right]_{x=\sqrt{t}}^{x=2\sqrt{t}} \\
&= t.
\end{aligned}$$

As $-\frac{1}{4} < t \leq 0$,

$$f(t) = \int_{-1}^{1} \varphi(x,t)dx = -\int_{-1}^{1} \varphi(x,-t)dx = -(-t) = t.$$

Hence $f(t) = t$ if $-\frac{1}{4} < t < \frac{1}{4}$.

(4) *Show that* $f'(0) \neq \int_{-1}^{1} (D_2\varphi)(x,0)dx$. By (3),

$$f'(0) = \lim_{t \to 0} \frac{f(t) - f(0)}{t - 0} = \lim_{t \to 0} \frac{t - 0}{t - 0} = 1.$$

By (2),

$$\int_{-1}^{1} (D_2\varphi)(x,0)dx = \int_{-1}^{1} 0dx = 0.$$

Hence $f'(0) \neq \int_{-1}^{1} (D_2\varphi)(x,0)dx$.

□

Exercise 9.29 (Symmetry of second derivatives). *Let E be an open set in $\mathbb{R}^n$. The classes $\mathscr{C}'(E)$ and $\mathscr{C}''(E)$ are defined in the text. By induction, $\mathscr{C}^{(k)}(E)$ can be defined as follows, for all positive integer k: To say that $f \in \mathscr{C}^{(k)}(E)$ means that the partial derivatives $D_1 f, \ldots D_n f$ belongs to $\mathscr{C}^{(k-1)}(E)$. Assume $f \in \mathscr{C}^{(k)}(E)$, and show (by repeated application of Theorem 9.41) that the kth-order derivative*

$$D_{i_1 i_2 \cdots i_k} f = D_{i_1} D_{i_2} \cdots D_{i_k} f$$

is unchanged if the subscripts $i_1, \ldots, i_k$ are permuted. For instance, if $n \geq 3$, then

$$D_{1213} f = D_{3112} f$$

for every $f \in \mathscr{C}^{(4)}(E)$.

Proof.

(1) *Show that the kth-order derivative is unchanged if any two adjacent subscripts* i_h *and* i_{h+1} *are exchanged.* Since $D_{i_{h+2}} \cdots D_{i_k} f \in \mathscr{C}^{(k-h-1)}(E) \subseteq \mathscr{C}^2(E)$,

$$D_{i_{h+1} i_h i_{h+2} \cdots i_k} f = D_{i_h i_{h+1} i_{h+2} \cdots i_k} f.$$

Hence

$$D_{i_1 \cdots i_{h-1} i_{h+1} i_h i_{h+2} \cdots i_k} f = D_{i_1 \cdots i_{h-1} i_h i_{h+1} i_{h+2} \cdots i_k} f = D_{i_1 \cdots i_k} f.$$

(2) *Show that every permutation can be written as a product of adjacent transpositions.* It is well known that every permutation can be written as a product of transpositions. Notice that

$$(i\ \ j) = (i\ \ i+1)(i+1\ \ i+2) \cdots (j-1\ \ j)(j-2\ \ j-1) \cdots (i\ \ i+1)$$

By (1)(2), the result is established. □

Exercise 9.30. *Let* $f \in \mathscr{C}^{(m)}(E)$*, where* E *is an open subset of* $\mathbb{R}^n$*. Fix* $\mathbf{a} \in E$*, and suppose* $\mathbf{x} \in \mathbb{R}^n$ *is so close to* $\mathbf{0}$ *that the points*

$$\mathbf{p}(t) = \mathbf{a} + t\mathbf{x}$$

lie in E *whenever* $0 \leq t \leq 1$*. Define*

$$h(t) = f(\mathbf{p}(t))$$

for all $t \in \mathbb{R}^1$ *for which* $\mathbf{p}(t) \in E$.

(a) *For* $1 \leq k \leq m$*, show (by repeated application of the chain rule) that*

$$h^{(k)}(t) = \sum (D_{i_1 \cdots i_k} f)(\mathbf{p}(t)) x_{i_1} \cdots x_{i_k}.$$

The sum extends over all ordered k*-tuples* $(i_1, \ldots, i_k)$ *in which each* i_j *is one of the integers* $1, \ldots, n$.

(b) *By Taylor's theorem (Theorem 5.15),*

$$h(1) = \sum_{k=0}^{m-1} \frac{h^{(k)}(0)}{k!} + \frac{h^{(m)}(t)}{m!}$$

for some $t \in (0, 1)$*. Use this to prove Taylor's theorem in* n *variables by show that the formula*

$$f(\mathbf{a} + \mathbf{x}) = \sum_{k=0}^{m-1} \frac{1}{k!} (D_{i_1 \cdots i_k} f)(\mathbf{a}) x_{i_1} \cdots x_{i_k} + r(\mathbf{x})$$

represents $f(\mathbf{a}+\mathbf{x})$ as the sum of its so-called "Taylor polynomial of degree $m-1$," plus a remainder that satisfies

$$\lim_{\mathbf{x}\to\mathbf{0}} \frac{r(\mathbf{x})}{|\mathbf{x}|^{m-1}} = 0.$$

Each of the inner sums extends over all ordered k-tuples $(i_1, \ldots, i_k)$, as in part (a); as usual, the zero-order derivative of f is simply f, so that the constant term of the Taylor polynomial of f at $\mathbf{a}$ is $f(\mathbf{a})$.

(c) *Exercise 9.29 shows that repetition occurs in the Taylor polynomial as written in part (b). For instance, D_{113} occurs three times, as $D_{113}, D_{131}, D_{311}$. The sum of the corresponding three terms can be written in the form*

$$3(D_1^2 D_3 f)(\mathbf{a})x_1^2 x_3.$$

Prove (by calculating how often each derivative occurs) that the Taylor polynomial in be can be written in the form

$$\sum \frac{(D_1^{s_1}\cdots D_n^{s_n} f)(\mathbf{a})}{s_1!\cdots s_n!} x_1^{s_1}\cdots x_n^{s_n}.$$

Here the summation extends over all ordered n-tuples $(s_1, \ldots, s_n)$ such that each s_i is a nonnegative integer, and $s_1 + \cdots + s_n \leq m-1$.

Proof of (a). Induction on k.

(1) The base case $k = 1$. Note that

$$f'(\mathbf{p}(t)) = \begin{bmatrix} (D_1 f)(\mathbf{p}(t)) & \cdots & (D_n f)(\mathbf{p}(t)) \end{bmatrix}$$

and

$$\mathbf{p}'(t) = \mathbf{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}.$$

Hence by the chain rule (Theorem 9.15),

$$\begin{aligned} h'(t) &= f'(\mathbf{p}(t))\mathbf{p}'(t) \\ &= \begin{bmatrix} (D_1 f)(\mathbf{p}(t)) & \cdots & (D_n f)(\mathbf{p}(t)) \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} \\ &= \sum_{i=1}^{n} (D_i f)(\mathbf{p}(t)) x_i. \end{aligned}$$

(2) The inductive step. *Show that for any $s \geq 1$, if $h^{(s)}(t) = \sum (D_{i_1 \cdots i_s} f)(\mathbf{p}(t)) x_{i_1} \cdots x_{i_s}$ holds, then $h^{(s+1)}(t) = \sum (D_{i_1 \cdots i_{s+1}} f)(\mathbf{p}(t)) x_{i_1} \cdots x_{i_{s+1}}$ also holds.*

$$\begin{aligned}
h^{(s+1)}(t) &= \frac{d}{dt} h^{(s)}(t) \\
&= \frac{d}{dt} \sum (D_{i_1 \cdots i_s} f)(\mathbf{p}(t)) x_{i_1} \cdots x_{i_s} \\
&= \sum \frac{d}{dt} (D_{i_1 \cdots i_s} f)(\mathbf{p}(t)) x_{i_1} \cdots x_{i_s} \\
&= \sum \left(\sum D_{i_{s+1}} (D_{i_1 \cdots i_s} f)(\mathbf{p}(t)) x_{i_{s+1}} \right) x_{i_1} \cdots x_{i_s} && \text{(The chain rule)} \\
&= \sum (D_{i_{s+1} i_1 \cdots i_s} f)(\mathbf{p}(t)) x_{i_{s+1}} x_{i_1} \cdots x_{i_s} \\
&= \sum (D_{i_1 \cdots i_{s+1}} f)(\mathbf{p}(t)) x_{i_1} \cdots x_{i_{s+1}} && \text{(Rearrange index).}
\end{aligned}$$

Here

$$\begin{aligned}
\frac{d}{dt} (D_{i_1 \cdots i_s} f)(\mathbf{p}(t)) &= \begin{bmatrix} (D_1 D_{i_1 \cdots i_s} f)(\mathbf{p}(t)) & \cdots & (D_n D_{i_1 \cdots i_s} f)(\mathbf{p}(t)) \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} \\
&= \sum_{i_{s+1}=1}^{n} D_{i_{s+1}} (D_{i_1 \cdots i_s} f)(\mathbf{p}(t)) x_{i_{s+1}}.
\end{aligned}$$

(3) Since both the base case ((1)) and the inductive step ((2)) have been proved as true, by mathematical induction the conclusion holds for every positive integer k.

□

Proof of (b).

(1)

$$\begin{aligned}
f(\mathbf{a} + \mathbf{x}) =& h(1) \\
=& \sum_{k=0}^{m-1} \frac{h^{(k)}(0)}{k!} + \frac{h^{(m)}(t)}{m!} && \text{(Theorem 5.15)} \\
=& \sum_{k=0}^{m-1} \frac{1}{k!} \sum (D_{i_1 \cdots i_k} f)(\mathbf{p}(0)) x_{i_1} \cdots x_{i_k} \\
&+ \sum \frac{1}{m!} (D_{i_1 \cdots i_m} f)(\mathbf{p}(t)) x_{i_1} \cdots x_{i_m} && \text{((a))} \\
=& \sum_{k=0}^{m-1} \frac{1}{k!} \sum (D_{i_1 \cdots i_k} f)(\mathbf{a}) x_{i_1} \cdots x_{i_k} + r(\mathbf{x})
\end{aligned}$$

where

$$\begin{aligned} r(\mathbf{x}) &= \frac{1}{m!} \sum (D_{i_1 \cdots i_m} f)(\mathbf{p}(t)) x_{i_1} \cdots x_{i_m} \\ &= \frac{1}{m!} \sum (D_{i_1 \cdots i_m} f)(\mathbf{a} + t\mathbf{x}) x_{i_1} \cdots x_{i_m} \end{aligned}$$

for some $t \in (0, 1)$.

(2) Since $f \in \mathscr{C}^{(m)}(E)$, f is continuous on a compact subset

$$K = \{\mathbf{y} : |\mathbf{a} - \mathbf{y}| \leq |\mathbf{x}|\}$$

of E (by the construction of $\mathbf{x}$). Note that all $\mathbf{p}(t) = \mathbf{a} + t\mathbf{x} \in K$ for all $0 \leq t \leq 1$. Hence $(D_{i_1 \cdots i_m} f)(\mathbf{a} + t\mathbf{x})$ is bounded by some $M \in \mathbb{R}^1$ (Theorem 4.15). Hence

$$\begin{aligned} |r(\mathbf{x})| &= \left| \frac{h^{(m)}(t)}{m!} \right| \\ &= \left| \frac{1}{m!} \sum (D_{i_1 \cdots i_m} f)(\mathbf{a} + t\mathbf{x}) x_{i_1} \cdots x_{i_m} \right| \\ &\leq \frac{1}{m!} \sum |(D_{i_1 \cdots i_m} f)(\mathbf{a} + t\mathbf{x})| |x_{i_1}| \cdots |x_{i_m}| \\ &\leq \frac{1}{m!} \sum M |\mathbf{x}|^m \\ &= \frac{1}{m!} \cdot m! M |\mathbf{x}|^m \\ &= M |\mathbf{x}|^m. \end{aligned}$$

So

$$0 \leq \left| \frac{r(\mathbf{x})}{|\mathbf{x}|^{m-1}} \right| \leq |\mathbf{x}|.$$

Therefore,

$$\lim_{\mathbf{x} \to \mathbf{0}} \frac{r(\mathbf{x})}{|\mathbf{x}|^{m-1}} = 0.$$

□

Proof of (c).

(1) As $s_1 + \cdots + s_n = k$, the number of terms of the form

$$(D_1^{s_1} \cdots D_n^{s_n} f)(\mathbf{a}) x_1^{s_1} \cdots x_n^{s_n}$$

is

$$\binom{k}{s_1 \ \cdots \ s_n} = \frac{k!}{s_1! \cdots s_n!}.$$

(2) Hence we can write

$$\begin{aligned}
f(\mathbf{a}+\mathbf{x}) &= \sum_{k=0}^{m-1} \frac{1}{k!}(D_{i_1\cdots i_k} f)(\mathbf{a}) x_{i_1}\cdots x_{i_k} + r(\mathbf{x}) \\
&= \sum_{s_1+\cdots+s_n \leq m-1} \frac{1}{k!}\frac{k!}{s_1!\cdots s_n!}(D_1^{s_1}\cdots D_n^{s_n} f)(\mathbf{a}) x_1^{s_1} x_n^{s_n} + r(\mathbf{x}) \\
&= \sum_{s_1+\cdots+s_n \leq m-1} \frac{(D_1^{s_1}\cdots D_n^{s_n} f)(\mathbf{a})}{s_1!\cdots s_n!} x_1^{s_1}\cdots x_n^{s_n} + r(\mathbf{x}).
\end{aligned}$$

□

Exercise 9.31. *Suppose $f \in \mathscr{C}^{(3)}$ in some neighborhood of a point $\mathbf{a} \in \mathbb{R}^2$, the gradient of f is $\mathbf{0}$ at $\mathbf{a}$, but not all second-order derivatives of f are 0 at $\mathbf{a}$. Show how one can then determine from the Taylor polynomial of f at $\mathbf{a}$ (of degree 2) whether f has a local maximum, or a local minimum, or neither, at the point $\mathbf{a}$. Extend this to $\mathbb{R}^n$ in place of $\mathbb{R}^2$.*

Proof.

(1) Since the gradient of f is $\mathbf{0}$ at $\mathbf{a}$,

$$(D_1 f)(\mathbf{a}) = (D_2 f)(\mathbf{a}) = 0.$$

So that the Taylor polynomial of f at $\mathbf{a}$ is

$$\begin{aligned}
f(\mathbf{a}+\mathbf{x}) - f(\mathbf{a}) =& (D_1 f)(\mathbf{a})x_1 + (D_2 f)(\mathbf{a})x_2 \\
&+ \frac{1}{2}\left[(D_1^2 f)(\mathbf{a})x_1^2 + 2(D_1 D_2 f)(\mathbf{a})x_1 x_2 + (D_2^2 f)(\mathbf{a})x_2^2\right] \\
&+ r(\mathbf{x}) \\
=& \frac{1}{2}\left[(D_1^2 f)(\mathbf{a})x_1^2 + 2(D_1 D_2 f)(\mathbf{a})x_1 x_2 + (D_2^2 f)(\mathbf{a})x_2^2\right] \\
&+ r(\mathbf{x}) \\
=& \frac{1}{2}\begin{bmatrix} x_1 & x_2 \end{bmatrix} \begin{bmatrix} (D_{11} f)(\mathbf{a}) & (D_{12} f)(\mathbf{a}) \\ (D_{21} f)(\mathbf{a}) & (D_{22} f)(\mathbf{a}) \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + r(\mathbf{x}).
\end{aligned}$$

Here $\mathbf{x} \in \mathbb{R}^2$ is so close to $\mathbf{0}$, and the remainder satisfies

$$\lim_{\mathbf{x}\to\mathbf{0}} \frac{r(\mathbf{x})}{|\mathbf{x}|^2} = 0.$$

(2) Define the **Hessian matrix** of f of $\mathbf{a}$ be

$$H(\mathbf{a}) = \begin{bmatrix} (D_{11} f)(\mathbf{a}) & (D_{12} f)(\mathbf{a}) \\ (D_{21} f)(\mathbf{a}) & (D_{22} f)(\mathbf{a}) \end{bmatrix}.$$

Let $H(\mathbf{a})_k$ be the submatrix of $H(\mathbf{a})$ obtained by taking the upper left-hand corner $k \times k$ submatrix of $H(\mathbf{a})$. Furthermore, let $\Delta_k = \det H(\mathbf{a})_k$, the kth principal minor of $H(\mathbf{a})$.

(a) f has a local minimum if $H(\mathbf{a})$ is positive definite. Since $H(\mathbf{a})$ is positive definite if and only if $\Delta_k > 0$, f has a local minimum if $\Delta_k > 0$ $(k = 1, 2)$.

(b) f has a local maximum if $H(\mathbf{a})$ is negative definite. Since $H(\mathbf{a})$ is negative definite if and only if $(-1)^k \Delta_k > 0$, f has a local maximum if $(-1)^k \Delta_k > 0$ $(k = 1, 2)$.

(c) f has no local minimum or local maximum at the point $\mathbf{a}$ if $H(\mathbf{a})$ is indefinite.

(See Supplement (Second-derivative test for extrema) in Exercise 9.21.)

(3) Now we extend this to $\mathbb{R}^n$ in place of $\mathbb{R}^2$. Similar to (1)-(5), Define the **Hessian matrix** of f of $\mathbf{a}$ be

$$H(\mathbf{a}) = \begin{bmatrix} (D_{11}f)(\mathbf{a}) & \cdots & (D_{1n}f)(\mathbf{a}) \\ \vdots & \ddots & \vdots \\ (D_{n1}f)(\mathbf{a}) & \cdots & (D_{nn}f)(\mathbf{a}) \end{bmatrix}.$$

So

(a) f has a local minimum if $\Delta_k > 0$ $(k = 1, \cdots, n)$.

(b) f has a local maximum if $(-1)^k \Delta_k > 0$ $(k = 1, \cdots, n)$.

(c) f has no local minimum or local maximum at the point $\mathbf{a}$ if $H(\mathbf{a})$ is indefinite.

□