1. Let $\phi : \mathbb{R}^n \to \mathbb{R}$ be such that $\phi(x) = 0 \Leftrightarrow x = 0$ and $\phi(\lambda x) = |\lambda|\phi(x), \forall x \in \mathbb{R}^n, \forall \lambda \in \mathbb{R}$ Show that if the set $B = \{x \in \mathbb{R}^n | \phi(x) \leq 1\}$ is convex, then ϕ defines a norm on $\mathbb{R}^n$.

   Solution: Non-degeneracy and scalar linearity are given from the definition of ϕ. So all that is left to prove is the triangle inequality and non-negativity.

   Triangle inequality: Let $x, y \in \mathbb{R}^n$, and take $r = \max\{\phi(x), \phi(y)\}$.

   Non-negativity: Suppose $x \in \mathbb{R}^n$. Then $\phi(-x) = |-1|\phi(x) = \phi(x)$, and:

$$\begin{aligned}\phi(x + (-x)) &\leq \phi(x) + \phi(-x) && \text{By Triangle Inequality}\\ \phi(0) &\leq 2\phi(x)\\ 0 &\leq \phi(x).\end{aligned}$$

2. Let E be a compact set in $\mathbb{R}^n$ and let F be a closed set in $\mathbb{R}^n$ such that $E \cap F = \emptyset$.

   (a) Show that there exists d > 0 such that $\|x - y\| > d$, $\forall x \in E$ and $\forall y \in F$.

   Solution: Take $d = \inf_{x \in E, y \in F} \|x - y\|$. Clearly this is less than any $\|x - y\|$ for $x \in E$, $y \in F$, and it cannot be negative since the norm is positive. So then $d \geq 0$.For contradiction suppose $d = 0$.

   (b) Does the result you proved in the previous question remain true if E and F are closed, but neither is compact? Justify your answer.

   Solution: This does not remain true. Take the sequence $\{e_n\}_{n\geq 2}$ given by $e_n = n$, and E as its image. Take $\{f_n\}_{n\geq 2} : f_n = e_n + \frac{1}{n}$ and F as its image (These sets contain only isolated points, and are closed). Then for any $d > 0$, we can pick $N \in \mathbb{N} : \frac{1}{N} < d$; and the points e_N and f_N will have $|e_N - f_N| = \frac{1}{N} < d$, meaning we can have arbitrarily close points between the closed sets E, F.

3. Let $E = \left\{(x, y) | y = \sin\left(\frac{1}{x}\right), x > 0\right\}$. Is E open? Is it closed? What are the accumulation points of E?

   Solution: This set is not open. Take an arbitrary ball of radius r about the point $p = \left(\frac{1}{\pi}, 0\right) \in E$. Then the point $q = \left(\frac{1}{\pi}, \frac{r}{2}\right) \in B_r(p)$, but $q \notin E$ since sin is well-defined. So any ball about p contains points not in E, and E is not open.

   By continuity of sin and $\frac{1}{x}$, all points of E are accumulation points.

   The accumulation points of E not contained in E are of the form $(0, a)$ for $a \in [-1, 1]$. Take one such point, and some $r > 0$, and consider the r-ball about $(0, a)$. Choose $k \in \mathbb{N}$ so that $\frac{1}{2\pi k} < r$, and let $x = \frac{1}{2\pi k + \arcsin a} \leq \frac{1}{2\pi k} < r$. Then:

$$\begin{aligned}\frac{1}{x} &= 2\pi k + \arcsin a\\ \frac{1}{x} - 2\pi k &= \arcsin a\\ \sin\left(\frac{1}{x} - 2\pi k\right) &= a\\ \sin\left(\frac{1}{x}\right) &= a.\end{aligned}$$

   Then the point (x, a) is in E, and $\|(x, a) - (0, a)\| = \|(x, 0)\| = \sqrt{x^2} = x < r$, so x is in the arbitrary open ball we chose around $(0, a)$, and so every open ball around p contains a distinct point in E, and as such p is an accumulation point of E.

   Clearly none of these accumulation points can be in E thanks to the condition $x > 0$, so E does not contain all its limit points and is not closed.

4. Let $f : \mathbb{R}^n \to \mathbb{R}$ be a function in $C^1(\mathbb{R}^n)$, i.e., $f, \partial_{x_1} f, \ldots, \partial_{x_n} f$ are continuous in $\mathbb{R}^n$. Suppose $f(tx) = tf(x), \forall x \in \mathbb{R}^n, \forall t \in \mathbb{R}$ Show that f is a linear function.

5. Given $u : \mathbb{R} \to \mathbb{R}$ a function in $C^2(\mathbb{R})$, define $f : \mathbb{R}^2 \to \mathbb{R}$ by $f(x,y) = \begin{cases} u(y) - u(x) & \text{if } y \neq x \\ u'(x) & \text{if } y = x \end{cases}$

   Show that f is differentiable at any point (a, a).

6. Let $f : \mathbb{R}^2 \to \mathbb{R}$ be a function that is defined in an open set Ω in $\mathbb{R}^2$. Show that if $\partial_x f(x,y), \partial_y f(x,y)$ and $\partial_{xy} f(x,y)$ are continuous in Ω, then $\partial_{yx} f(x,y)$ exists in Ω and we have $\partial_{yx} f(x,y) = \partial_{xy} f(x,y), \forall (x,y) \in \Omega$ Hint: Consider the expression $\Delta(s,t) = f(a+s, b+t) - f(a+s, b) - f(a, b+t) + f(a,b)$.

7. Compute the degree 3 Taylor polynomial $T_3(x, x_2)$ of the function $f : \mathbb{R}^2 \to \mathbb{R}$, defined by $f(x_1, x_2) = \frac{4x_1+6x_2-1}{2x_1+3x_2}$ at the point $(-1, 1)$.

   Solution: Begin by computing all necessary partials, and evaluating at $(-1, 1)$:

$$
\begin{aligned}
f(x_1, x_2) &= \frac{4x_1 + 6x_2 - 1}{2x_1 + 3x_2}, & f(-1,1) &= 1 \\
\frac{\partial f}{\partial x_1} &= \frac{2}{(2x_1 + 3x_2)^2}, & \frac{\partial f}{\partial x_1}(-1,1) &= 2 \\
\frac{\partial f}{\partial x_2} &= \frac{3}{(2x_1 + 3x_2)^2}, & \frac{\partial f}{\partial x_2}(-1,1) &= 3 \\
\frac{\partial^2 f}{\partial x_1 x_2} &= \frac{-12}{(2x_1 + 3x_2)^3}, & \frac{\partial^2 f}{\partial x_1 x_2}(-1,1) &= -12 \\
\frac{\partial^2 f}{\partial x_1 x_1} &= \frac{-8}{(2x_1 + 3x_2)^3}, & \frac{\partial^2 f}{\partial x_1 x_1}(-1,1) &= -8 \\
\frac{\partial^2 f}{\partial x_2 x_2} &= \frac{-18}{(2x_1 + 3x_2)^3}, & \frac{\partial^2 f}{\partial x_2 x_2}(-1,1) &= -18 \\
\frac{\partial^3 f}{\partial x_1 x_1 x_1} &= \frac{48}{(2x_1 + 3x_2)^4}, & \frac{\partial^3 f}{\partial x_1 x_1 x_1}(-1,1) &= 48 \\
\frac{\partial^3 f}{\partial x_2 x_2 x_2} &= \frac{162}{(2x_1 + 3x_2)^4}, & \frac{\partial^3 f}{\partial x_2 x_2 x_2}(-1,1) &= 162 \\
\frac{\partial^3 f}{\partial x_1 x_2 x_2} &= \frac{72}{(2x_1 + 3x_2)^4}, & \frac{\partial^3 f}{\partial x_1 x_2 x_2}(-1,1) &= 72 \\
\frac{\partial^3 f}{\partial x_1 x_1 x_2} &= \frac{108}{(2x_1 + 3x_2)^4}, & \frac{\partial^3 f}{\partial x_1 x_1 x_2}(-1,1) &= 108.
\end{aligned}
$$

Then begin expanding the first three terms of the Taylor expansion

$$
\begin{aligned}
f((-1,1)+x) &= f(-1,1) + \left(\sum_{k=1}^{3} \frac{1}{k!}\left((x_1+1)\frac{\partial}{\partial x_1} + (x_2-1)\frac{\partial}{\partial x_2}\right)^k f(-1,1)\right) \\
&= 1 + \frac{1}{1!}\left((x_1+1)\frac{\partial}{\partial x_1} + (x_2-1)\frac{\partial}{\partial x_2}\right)^1 f(-1,1) \\
&\quad + \frac{1}{2!}\left((x_1+1)\frac{\partial}{\partial x_1} + (x_2-1)\frac{\partial}{\partial x_2}\right)^2 f(-1,1) \\
&\quad + \frac{1}{3!}\left((x_1+1)\frac{\partial}{\partial x_1} + (x_2-1)\frac{\partial}{\partial x_2}\right)^3 f(-1,1) \\
&= 1 + (x_1+1)\frac{\partial f}{\partial x_1}(-1,1) + (x_2-1)\frac{\partial f}{\partial x_2}(-1,1) \\
&\quad + \frac{1}{2}\Big((x_1+1)^2\frac{\partial^2}{\partial x_1 x_1} + 2(x_1+1)(x_2-1)\frac{\partial}{\partial x_1 x_2} \\
&\quad + (x_2-1)^2\frac{\partial^2}{\partial x_2 x_2}\Big) f(-1,1) \\
&\quad + \frac{1}{6}\Big((x_1+1)^3\frac{\partial^3}{\partial x_1 x_1 x_1} + 3(x_1+1)^2(x_2-1)\frac{\partial^3}{\partial x_1 x_1 x_2} \\
&\quad + 3(x_1+1)(x_2-1)^2\frac{\partial^3}{\partial x_1 x_2 x_2} + (x_2-1)^3\frac{\partial^3}{\partial x_2 x_2 x_2}\Big) f(-1,1) \\
&= 1 + 2(x_1+1) + 3(x_2-1) \\
&\quad + \frac{1}{2}\left(-8(x_1+1)^2 - 24(x_1+1)(x_2-1) - 18(x_2-1)^2\right) \\
&\quad + \frac{1}{6}\Big(48(x_1+1)^3 + 3\cdot 108(x_1+1)^2(x_2-1) \\
&\quad + 3\cdot 72(x_1+1)(x_2-1)^2 + 162(x_2-1)^3\Big) \\
&= 2x_1 - 3x_2 - 4(x_1+1)^2 - 12(x_1+1)(x_2-1) - 9(x_2-1)^2 \\
&\quad + 8(x_1+1)^3 + 54(x_1+1)^2(x_2-1) \\
&\quad + 36(x_1+1)(x_2-1)^2 + 27(x_2-1)^3.
\end{aligned}
$$

8. Consider the function $f:\mathbb{R}^3 \to \mathbb{R}^3$, defined by $f(x,y,z) = (x^3-y-z, 2x+y+z, x+y-z)$
   (a) Compute $Jf(x,y,z)$ and show that $\partial f_{(x,y,z)}$ is invertible for any $(x,y,z)\in\mathbb{R}^3$.
   (b) Find the largest open $U\subset\mathbb{R}^3$ where f has a continuously differentiable inverse function g.

9. Consider the system of equations: $(\mathcal{S})$ $\begin{cases} x-y-u^2+v^2 &= 0 \\ x+y-2uv &= 0 \end{cases}$
   (a) Show that the system $(\mathcal{S})$ can be solved for u, v in term of (x,y) near the point $(x,y,u,v) = (1,1,1,1)$.
   (b) Compute $\partial_x u(1,1) + \partial_y v(1,1)$

10. Let $f:\mathbb{R}\to\mathbb{R}$ and $g:\mathbb{R}\to\mathbb{R}$ be such that $f(1) = g(1) = 0$, and consider the system

$$\begin{cases} f(xy)+g(yz) &= 0 \\ g(xy)+f(yz) &= 0 \end{cases}$$

Find conditions on f and g that guarantee the system (S) can be uniquely solved for y and z as functions of x near the point $(x,y,z) = (1,1,1)$.

11. Let A be a positive definite $n \times n$ matrix. Interpreting $x \in \mathbb{R}^n$ as a column matrix, show that $\|.\| : \mathbb{R}^n \to \mathbb{R}$ defined by $\|x\|^2 = x^t Ax$ is a norm on $\mathbb{R}^n$.

Solution: Non-negativity follows from the positive semi-definite condition; since $x^T Ax > 0$, we must have $\|x\| = \sqrt{x^T Ax} > 0$ whenever $x \neq 0$.

For non-degeneracy;

Scalar linearity is quick; $\|\alpha x\| = \sqrt{(\alpha x)^T A(\alpha x)} = \sqrt{\alpha^2 x^T Ax} = |\alpha|\sqrt{x^T Ax} = |\alpha|\|x\|$.

Finally, the triangle inequality.