Exercise For Convexity and Optimization in $\mathbb{R}^n$

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Contents

Dedicated to the knee scrapes, playdates, and heartaches.

1 Topics in Real Analysis

1.1 Introduction

Exercise 1.1. For any vectors $\mathbf{x}$ and $\mathbf{y}$ in $\mathbb{R}^n$, show that $\|\mathbf{x}+\mathbf{y}\|^2+\|\mathbf{x}-\mathbf{y}\|^2 = 2\|\mathbf{x}\|^2+2\|\mathbf{y}\|^2$. Interpret this relation as a statement about parallelograms in $\mathbb{R}^2$ and $\mathbb{R}^3$.

Solution. To prove that $\|\mathbf{x}+\mathbf{y}\|^2+\|\mathbf{x}-\mathbf{y}\|^2 = 2\|\mathbf{x}\|^2+2\|\mathbf{y}\|^2$ for any vectors $\mathbf{x},\mathbf{y}\in\mathbb{R}^n$, we use the definition of the Euclidean norm and properties of the dot product. Recall that $\|\mathbf{x}\|^2 = \mathbf{x}\cdot\mathbf{x}$.
First, expand $\|\mathbf{x}+\mathbf{y}\|^2$:

$$\|\mathbf{x}+\mathbf{y}\|^2 = (\mathbf{x}+\mathbf{y})\cdot(\mathbf{x}+\mathbf{y}) = \mathbf{x}\cdot\mathbf{x}+2\mathbf{x}\cdot\mathbf{y}+\mathbf{y}\cdot\mathbf{y} = \|\mathbf{x}\|^2+2(\mathbf{x}\cdot\mathbf{y})+\|\mathbf{y}\|^2.$$

Next, expand $\|\mathbf{x}-\mathbf{y}\|^2$:

$$\|\mathbf{x}-\mathbf{y}\|^2 = (\mathbf{x}-\mathbf{y})\cdot(\mathbf{x}-\mathbf{y}) = \mathbf{x}\cdot\mathbf{x}-2\mathbf{x}\cdot\mathbf{y}+\mathbf{y}\cdot\mathbf{y} = \|\mathbf{x}\|^2-2(\mathbf{x}\cdot\mathbf{y})+\|\mathbf{y}\|^2.$$

Add these two expressions:
$$\|\mathbf{x}+\mathbf{y}\|^2+\|\mathbf{x}-\mathbf{y}\|^2 = \left(\|\mathbf{x}\|^2+2(\mathbf{x}\cdot\mathbf{y})+\|\mathbf{y}\|^2\right)+\left(\|\mathbf{x}\|^2-2(\mathbf{x}\cdot\mathbf{y})+\|\mathbf{y}\|^2\right) = \|\mathbf{x}\|^2+\|\mathbf{x}\|^2+\|\mathbf{y}\|^2+\|\mathbf{y}\|^2+2(\mathbf{x}\cdot\mathbf{y})-2(\mathbf{x}\cdot\mathbf{y}).$$
The cross terms $2(\mathbf{x}\cdot\mathbf{y})$ and $-2(\mathbf{x}\cdot\mathbf{y})$ cancel, yielding:

$$\|\mathbf{x}+\mathbf{y}\|^2+\|\mathbf{x}-\mathbf{y}\|^2 = 2\|\mathbf{x}\|^2+2\|\mathbf{y}\|^2.$$

Thus, the equality holds for all $\mathbf{x},\mathbf{y}\in\mathbb{R}^n$.

In $\mathbb{R}^2$ and $\mathbb{R}^3$, this equality has a geometric interpretation related to parallelograms. Consider vectors $\mathbf{x}$ and $\mathbf{y}$ emanating from the same initial point. These vectors form two adjacent sides of a parallelogram. The vector $\mathbf{x}+\mathbf{y}$ represents one diagonal of the parallelogram, and $\mathbf{x}-\mathbf{y}$ represents the other diagonal (assuming the parallelogram is completed appropriately).
The left side of the equality, $\|\mathbf{x}+\mathbf{y}\|^2+\|\mathbf{x}-\mathbf{y}\|^2$, is the sum of the squares of the lengths of the two diagonals. The right side, $2\|\mathbf{x}\|^2+2\|\mathbf{y}\|^2$, is twice the sum of the squares of the lengths of the two adjacent sides. Since a parallelogram has two pairs of equal sides, the sum of the squares of the lengths of all four sides is $2\|\mathbf{x}\|^2+2\|\mathbf{y}\|^2$ (two sides of length $\|\mathbf{x}\|$ and two of length $\|\mathbf{y}\|$).
Therefore, the equality states that for any parallelogram in $\mathbb{R}^2$ or $\mathbb{R}^3$, the sum of the squares of the lengths of the diagonals equals the sum of the squares of the lengths of all four sides. This is a fundamental property of parallelograms in Euclidean geometry, often called the parallelogram law.

1.3 Algebra of Sets

Lemma 3.1. Let $\{S_\alpha\}_{\alpha\in A}$ be a collection of subsets of a set X. Then

$$\bigcup_{\alpha\in A} S_\alpha = c\left[\bigcap_{\alpha\in A}(cS_\alpha)\right],$$
$$\bigcap_{\alpha\in A} S_\alpha = c\left[\bigcup_{\alpha\in A}(cS_\alpha)\right].$$

Proof. We establish both identities by showing mutual inclusion of the corresponding sets.

1. $\bigcup\limits_{\alpha\in A} S_\alpha = c\Big[\bigcap\limits_{\alpha\in A}(cS_\alpha)\Big]$**.**
(i) Subset relation $\subseteq$. Let $x\in\bigcup_{\alpha\in A}S_\alpha$. Then there exists an index $\alpha_0\in A$ such that $x\in S_{\alpha_0}$. If x were also contained in $\bigcap_{\alpha\in A}(cS_\alpha)$, it would belong to cS_{α_0}, i.e. $x\notin S_{\alpha_0}$, a contradiction. Therefore $x\notin\bigcap_{\alpha\in A}(cS_\alpha)$, which means $x\in c\big[\bigcap_{\alpha\in A}(cS_\alpha)\big]$.
(ii) Subset relation $\supseteq$. Conversely, take $x\in c\big[\bigcap_{\alpha\in A}(cS_\alpha)\big]$. Then $x\notin\bigcap_{\alpha\in A}(cS_\alpha)$, so there exists an index $\alpha_1\in A$ with $x\notin cS_{\alpha_1}$. Equivalently, $x\in S_{\alpha_1}$, hence $x\in\bigcup_{\alpha\in A}S_\alpha$. Combining (i) and (ii) yields the desired equality.

2. $\bigcap\limits_{\alpha\in A} S_\alpha = c\Big[\bigcup\limits_{\alpha\in A}(cS_\alpha)\Big]$**.**
The argument is analogous.
(i) Subset relation $\subseteq$. Let $x\in\bigcap_{\alpha\in A}S_\alpha$. Then $x\in S_\alpha$ for every α. Consequently, $x\notin cS_\alpha$ for any α, which implies $x\notin\bigcup_{\alpha\in A}(cS_\alpha)$. Hence $x\in c\big[\bigcup_{\alpha\in A}(cS_\alpha)\big]$.
(ii) Subset relation $\supseteq$. Let $x\in c\big[\bigcup_{\alpha\in A}(cS_\alpha)\big]$. Then $x\notin\bigcup_{\alpha\in A}(cS_\alpha)$, so for every $\alpha\in A$ we have $x\notin cS_\alpha$; equivalently $x\in S_\alpha$. Therefore $x\in\bigcap_{\alpha\in A}S_\alpha$.
Since both inclusions hold, the second identity follows. $\square$

1.4 Metric Topology of $\mathbb{R}^n$

Exercise 4.1. Use the properties of the norm to show that the function d defined by

$$d(\mathbf{x}, \mathbf{y}) = \|\mathbf{x} - \mathbf{y}\| = \left(\sum_{i=1}^{n} (x_i - y_i)^2 \right)^{1/2}$$

is a metric, or distance function, on $\mathbb{R}^n$.

Proof. To verify that $d(\mathbf{x}, \mathbf{y}) = \|\mathbf{x} - \mathbf{y}\|$ is a metric on $\mathbb{R}^n$, we must show that it satisfies the following three properties for all $\mathbf{x}, \mathbf{y}, \mathbf{z} \in \mathbb{R}^n$: *(i)* non–negativity with the identity of indiscernibles, *(ii)* symmetry, and *(iii)* the triangle inequality.

1. Non–negativity and identity of indiscernibles. The Euclidean norm is always non–negative, so

$$d(\mathbf{x}, \mathbf{y}) = \|\mathbf{x} - \mathbf{y}\| \geq 0.$$

Moreover, $d(\mathbf{x}, \mathbf{y}) = 0$ if and only if $\|\mathbf{x} - \mathbf{y}\| = 0$, which occurs precisely when $\mathbf{x} - \mathbf{y} = \mathbf{0}$, i.e. when $\mathbf{x} = \mathbf{y}$.

2. Symmetry. Because $\|\mathbf{v}\| = \|-\mathbf{v}\|$ for any vector $\mathbf{v}$,

$$d(\mathbf{x}, \mathbf{y}) = \|\mathbf{x} - \mathbf{y}\| = \|-(\mathbf{x} - \mathbf{y})\| = \|\mathbf{y} - \mathbf{x}\| = d(\mathbf{y}, \mathbf{x}).$$

3. Triangle inequality. The Euclidean norm satisfies the triangle inequality $\|\mathbf{u} + \mathbf{v}\| \leq \|\mathbf{u}\| + \|\mathbf{v}\|$. Choosing $\mathbf{u} = \mathbf{x} - \mathbf{y}$ and $\mathbf{v} = \mathbf{y} - \mathbf{z}$ gives

$$d(\mathbf{x}, \mathbf{z}) = \|\mathbf{x} - \mathbf{z}\| = \|(\mathbf{x} - \mathbf{y}) + (\mathbf{y} - \mathbf{z})\| \leq \|\mathbf{x} - \mathbf{y}\| + \|\mathbf{y} - \mathbf{z}\| = d(\mathbf{x}, \mathbf{y}) + d(\mathbf{y}, \mathbf{z}).$$

Since all three axioms hold, the function d is indeed a metric on $\mathbb{R}^n$. $\square$

Exercise 4.2. (a) Sketch the graph of $y = \sin(1/x)$ for $x > 0$.
(b) Consider the graph as a set in $\mathbb{R}^2$ and find the limit points of this set.

Solution. **(a) Sketch of the curve.** Set $t = 1/x$ for $x > 0$. Then the graph of $y = \sin(1/x)$ for $x > 0$ corresponds to the standard sine curve $y = \sin t$ for $t > 0$, but viewed through the change of variables $x = 1/t$. As $x \to 0^+$ we have $t \to +\infty$, so the curve oscillates infinitely often between -1 and 1 while its x–coordinate approaches 0. For moderate values of x the graph resembles the usual sine curve stretched horizontally, whereas near the y–axis the oscillations become increasingly rapid, creating a "comb-like" fringe that accumulates on the interval $\{0\} \times [-1, 1]$.

(b) Limit points of the graph. Let

$$S := \left\{ (x, \sin(1/x)) : x > 0 \right\} \subset \mathbb{R}^2.$$

We claim that the set of limit points of S is

$$S' = S \cup \left\{ (0, y) : -1 \leq y \leq 1 \right\}.$$

The verification proceeds in two steps.

Step 1: Every point of S is a limit point. Fix $(x_0, \sin(1/x_0)) \in S$ with $x_0 > 0$ and let $\varepsilon > 0$ be given. Recall the elementary inequality $|\sin u - \sin v| \leq |u - v|$ valid for all real numbers u, v. Set

$$\delta := \min\left\{ \frac{\varepsilon}{2}, \frac{\varepsilon x_0^2}{4}, \frac{x_0}{2} \right\}.$$

Pick any $x_\varepsilon \in (x_0 - \delta, x_0 + \delta) \setminus \{x_0\}$ and define $P_\varepsilon := (x_\varepsilon, \sin(1/x_\varepsilon))$. Then $P_\varepsilon \in S$ and

$$|x_\varepsilon - x_0| < \frac{\varepsilon}{2}, \qquad |\sin(1/x_\varepsilon) - \sin(1/x_0)| \leq |1/x_\varepsilon - 1/x_0| = \frac{|x_\varepsilon - x_0|}{|x_\varepsilon| x_0} \leq \frac{2\delta}{x_0^2} \leq \frac{\varepsilon}{2}.$$

Consequently

$$\left\| P_\varepsilon - (x_0, \sin(1/x_0)) \right\| \leq \sqrt{\left(|x_\varepsilon - x_0| \right)^2 + \left(|\sin(1/x_\varepsilon) - \sin(1/x_0)| \right)^2} < \varepsilon,$$

proving that $(x_0, \sin(1/x_0))$ is indeed a limit point of S.

Step 2: Points of the form $(0, y)$ with $|y| \leq 1$ are limit points. Fix $y \in [-1, 1]$ and $\varepsilon > 0$. Because the sine function attains every value in $[-1, 1]$ infinitely often, we can pick $t_\varepsilon > \max\{1/\varepsilon, 0\}$ such that $|\sin t_\varepsilon - y| < \varepsilon$. Setting $x_\varepsilon = 1/t_\varepsilon$ we obtain $0 < x_\varepsilon < \varepsilon$ and

$$\left\| (x_\varepsilon, \sin(1/x_\varepsilon)) - (0, y) \right\| < \sqrt{\varepsilon^2 + \varepsilon^2} < \sqrt{2}\, \varepsilon.$$

Thus $(0, y)$ is approached by points of S distinct from itself, so it is a limit point.

Step 3: No other points are limit points. If $x < 0$, every open ball centred at (x, y) contains points whose first coordinate is negative, whereas S lies entirely in $x > 0$; thus such points cannot be limit points. If $x = 0$ but $|y| > 1$, the vertical separation $|y| - 1$ already exceeds the range of sin, so no sequence in S can approach $(0, y)$.
Finally, consider a point (x, y) with $x > 0$ that does
emphnot belong to S. Write $y_0 := \sin(1/x)$ and set $d := |y - y_0| > 0$. Choose

$$r := \min\left\{ \frac{d}{2}, \frac{x}{2} \right\}.$$

For any $(x', \sin(1/x')) \in S$ satisfying $|x'-x| < r$ we have $x' \geq x/2$ and hence, using $|\sin u - \sin v| \leq |u-v|$ again,

$$|\sin(1/x') - y_0| \leq \frac{|x'-x|}{x'x} \leq \frac{2r}{x^2} \leq \frac{d}{2}.$$

Therefore

$$|\sin(1/x') - y| \geq |y-y_0| - |\sin(1/x') - y_0| > \frac{d}{2},$$

so the Euclidean distance between $(x', \sin(1/x'))$ and (x,y) exceeds $d/2$. Hence the ball $B\big((x,y), d/2\big)$ contains no point of S, proving that (x,y) is not a limit point. Collecting the cases established in Steps 1–3 completes the description of S'.

Consequently, the set of all limit points of the graph is precisely $S \cup \big(\{0\} \times [-1,1]\big)$, as asserted.

Exercise 4.3. Show that for $x \in \mathbb{R}^n$ and $r > 0$ the set $B(x,r)$ is open; that is, show that an open ball is open.

Proof. Let $y \in B(x,r)$, so by definition $\|y-x\| < r$. Define

$$\varepsilon \;:=\; r - \|y-x\| \;>\; 0.$$

We claim that the entire ball $B(y,\varepsilon)$ is contained in $B(x,r)$. Indeed, if $z \in B(y,\varepsilon)$ then $\|z-y\| < \varepsilon$, and by the triangle inequality,

$$\|z-x\| \;\leq\; \|z-y\| + \|y-x\| \;<\; \varepsilon + \|y-x\| \;=\; r.$$

Hence $z \in B(x,r)$. Since every point y of $B(x,r)$ is an interior point, the set $B(x,r)$ is open. □

Remark. *Idea of the proof.* To show that the open ball $B(x,r)$ is an open set we verify that every point it contains is an interior point. Fix $y \in B(x,r)$ and measure how much "room" is left before reaching the boundary: the gap is $\varepsilon := r - \|y-x\| > 0$. Any point z that sits within this gap around y (that is, $\|z-y\| < \varepsilon$) cannot escape the larger ball, because the triangle inequality guarantees $\|z-x\| < \|z-y\| + \|y-x\| < \varepsilon + \big(r-\varepsilon\big) = r$. Thus the smaller ball $B(y,\varepsilon)$ lies completely inside $B(x,r)$, making y an interior point. Since y was arbitrary, $B(x,r)$ is open.

Exercise 4.4. Show that for $x \in \mathbb{R}^n$ and $r > 0$ the closed ball $\overline{B(x,r)}$ is closed.

Proof. Set $C := \overline{B(x,r)} = \{y \in \mathbb{R}^n : \|y-x\| \leq r\}$. We show that its complement C^c is open. Let $y \in C^c$, so $\|y-x\| > r$. Define

$$\varepsilon \;:=\; \frac{\|y-x\| - r}{2} \;>\; 0.$$

If $z \in B(y,\varepsilon)$ then $\|z-y\| < \varepsilon$, and by the triangle inequality,

$$\|z-x\| \;\geq\; \|y-x\| - \|z-y\| \;>\; \big(r+2\varepsilon\big) - \varepsilon \;=\; r+\varepsilon \;>\; r.$$

Hence $z \notin C$. Therefore $B(y,\varepsilon) \subset C^c$, proving that every point of C^c is interior. The complement of C is open, so C is closed. □

Remark. *Idea of the proof.* For a point y lying *outside* the closed ball we measure how far it is from the boundary: the surplus distance is $\delta := \|y-x\| - r > 0$. Choosing half of this surplus as a radius, $\varepsilon = \delta/2$, guarantees that the entire ball $B(y,\varepsilon)$ stays outside, because any point inside that small ball remains at least $r+\varepsilon > r$ away from x. Since such a neighbourhood exists around each exterior point, the complement of the closed ball is open, which is exactly the definition of the original set being closed.

Exercise 4.5. Show that any finite set of points $x_1, \ldots, x_k$ in $\mathbb{R}^n$ is closed.

Proof. Denote the finite set by $F := \{x_1, \ldots, x_k\}$. We show that its complement F^c is open. Let $y \in F^c$; then $y \neq x_i$ for every i. Define the positive distances

$$d_i := \|y-x_i\| > 0, \qquad i = 1, \ldots, k, \quad \text{and set} \quad \varepsilon := \tfrac{1}{2} \min_{1 \leq i \leq k} d_i > 0.$$

For any $z \in B(y,\varepsilon)$ we have $\|z-y\| < \varepsilon \leq d_i/2$, hence by the triangle inequality

$$\|z-x_i\| \;\geq\; \|y-x_i\| - \|z-y\| \;>\; d_i - \varepsilon \;\geq\; \tfrac{1}{2} d_i > 0 \quad (1 \leq i \leq k).$$

Consequently $z \neq x_i$ for every i, i.e. $z \in F^c$. Thus $B(y,\varepsilon) \subset F^c$, so every exterior point is interior to the complement; F^c is open and F is closed.
An alternative argument is to note that each singleton $\{x_i\}$ is closed (apply the previous step with $k=1$) and that a finite union of closed sets remains closed:

$$F \;=\; \bigcup_{i=1}^{k} \{x_i\}.$$ □

Remark. *Idea of the proof.* For a point y not in the finite set we compute its distances to each listed point. The smallest of these distances is still positive; taking half of it as the radius gives a neighbourhood around y that misses the entire finite set, showing the complement is open. Equivalently, observe that singletons are closed and a finite union of closed sets is closed.

Exercise 4.6. Show that in $\mathbb{R}^n$ no point x with $\|x\| = 1$ is an interior point of the closed unit ball $\overline{B(0,1)}$.

Proof. Let $x \in \mathbb{R}^n$ satisfy $\|x\| = 1$. To show that x is *not* an interior point of $\overline{B(0,1)}$ we must prove that every open ball centred at x contains points that lie *outside* $\overline{B(0,1)}$.
Fix an arbitrary radius $r > 0$ and define

$$y \;:=\; \left(1 + \tfrac{r}{2}\right) x.$$

Then

$$\|y - x\| = \left|1 + \tfrac{r}{2} - 1\right| \|x\| = \frac{r}{2} < r, \qquad \text{but} \qquad \|y\| = 1 + \tfrac{r}{2} > 1.$$

Hence y lies within the ball $B(x, r)$ yet satisfies $\|y\| > 1$, so $y \notin \overline{B(0,1)}$. Consequently $B(x, r)$ is *not* contained in $\overline{B(0,1)}$. Because $r > 0$ was arbitrary, no open neighbourhood of x sits inside the closed unit ball, and thus x is not an interior point. □

Remark. *Idea of the proof.* Any boundary point x with $\|x\| = 1$ can be pushed slightly outward along its own direction: scaling by $1 + \varepsilon$ moves the point a distance roughly ε while immediately leaving the unit ball. No matter how small a radius we choose, such an outward perturbation fits inside the radius yet escapes the ball, so the original point cannot be interior.