

Script 18

The Euclidean Space \mathbb{R}^n

7/7: For the next three sheets, we will be studying multivariable calculus, that is “calculus on \mathbb{R}^n .” First, we need to understand the space \mathbb{R}^n .

Definition 18.1. The **Euclidean n -space** \mathbb{R}^n is the n -fold Cartesian product of \mathbb{R} . Symbolically,

$$\mathbb{R}^n = \{(x_1, \dots, x_n) \mid x_1, \dots, x_n \in \mathbb{R}\}$$

is the set of n -tuples of real numbers. We often write

$$\mathbf{x} = (x_1, \dots, x_n)$$

to denote an element, which is also referred to as a **vector**, in \mathbb{R}^n and

$$\mathbf{0} = (0, \dots, 0)$$

Definition 18.2. Let $\mathbf{x} = (x_1, \dots, x_n), \mathbf{y} = (y_1, \dots, y_n) \in \mathbb{R}^n$ and $\lambda \in \mathbb{R}$. We define the following operations.

- (a) (Addition) $\mathbf{x} + \mathbf{y} = (x_1 + y_1, \dots, x_n + y_n)$.
- (b) (Scalar Multiplication) $\lambda \mathbf{x} = (\lambda x_1, \dots, \lambda x_n)$.

Exercise 18.3. Prove that the addition on \mathbb{R}^n satisfies FA1-FA4 (see Definition 7.8). Moreover, prove that

VS1. (Associativity of Scalar Multiplication) If $\lambda, \mu \in \mathbb{R}$ and $\mathbf{x} \in \mathbb{R}^n$, then $(\lambda\mu)\mathbf{x} = \lambda(\mu\mathbf{x})$.

VS2. (Distributivity of Scalars) If $\lambda, \mu \in \mathbb{R}$ and $\mathbf{x} \in \mathbb{R}^n$, then $(\lambda + \mu)\mathbf{x} = \lambda\mathbf{x} + \mu\mathbf{x}$.

VS3. (Distributivity of Vectors) If $\lambda \in \mathbb{R}$ and $\mathbf{x}, \mathbf{y} \in \mathbb{R}^n$, then $\lambda(\mathbf{x} + \mathbf{y}) = \lambda\mathbf{x} + \lambda\mathbf{y}$.

VS4. (Scalar Multiplicative Identity) If $\mathbf{x} \in \mathbb{R}^n$, then $1\mathbf{x} = \mathbf{x}$.

These eight properties together are called the **vector space axioms**.

Proof. To prove that \mathbb{R}^n obeys FA1 from Definition 7.8, it will suffice to show that for all $\mathbf{x}, \mathbf{y} \in \mathbb{R}^n$, $\mathbf{x} + \mathbf{y} = \mathbf{y} + \mathbf{x}$. Let \mathbf{x}, \mathbf{y} be arbitrary elements of \mathbb{R}^n . Then by Definition 18.2,

$$\begin{aligned}\mathbf{x} + \mathbf{y} &= (x_1 + y_1, \dots, x_n + y_n) \\ &= (y_1 + x_1, \dots, y_n + x_n) \\ &= \mathbf{y} + \mathbf{x}\end{aligned}$$

as desired.

To prove that \mathbb{R}^n obeys FA2 from Definition 7.8, it will suffice to show that for all $\mathbf{x}, \mathbf{y}, \mathbf{z} \in \mathbb{R}^n$, $(\mathbf{x} + \mathbf{y}) + \mathbf{z} = \mathbf{x} + (\mathbf{y} + \mathbf{z})$. Let $\mathbf{x}, \mathbf{y}, \mathbf{z}$ be arbitrary elements of \mathbb{R}^n . Then by Definition 18.2,

$$\begin{aligned} (\mathbf{x} + \mathbf{y}) + \mathbf{z} &= (x_1 + y_1, \dots, x_n + y_n) + \mathbf{z} \\ &= ((x_1 + y_1) + z_1, \dots, (x_n + y_n) + z_n) \\ &= (x_1 + (y_1 + z_1), \dots, x_n + (y_n + z_n)) \\ &= \mathbf{x} + (y_1 + z_1, \dots, y_n + z_n) \\ &= \mathbf{x} + (\mathbf{y} + \mathbf{z}) \end{aligned}$$

as desired.

To prove that \mathbb{R}^n obeys FA3 from Definition 7.8, it will suffice to find an element $\mathbf{0} \in \mathbb{R}^n$ such that $\mathbf{x} + \mathbf{0} = \mathbf{0} + \mathbf{x} = \mathbf{x}$ for all $\mathbf{x} \in \mathbb{R}^n$. Choose $\mathbf{0}$ to be our $\mathbf{0}$. Let \mathbf{x} be an arbitrary element of \mathbb{R}^n . Then by Definition 18.2,

$$\begin{aligned} \mathbf{x} + \mathbf{0} &= (x_1 + 0, \dots, x_n + 0) \\ &= (x_1, \dots, x_n) \\ &= \mathbf{x} \\ &= (0 + x_1, \dots, 0 + x_n) \\ &= \mathbf{0} + \mathbf{x} \end{aligned}$$

as desired.

To prove that \mathbb{R}^n obeys FA4 from Definition 7.8, it will suffice to show that for all $\mathbf{x} \in \mathbb{R}^n$, there exists $\mathbf{y} \in \mathbb{R}^n$ such that $\mathbf{x} + \mathbf{y} = \mathbf{y} + \mathbf{x} = \mathbf{0}$. Let \mathbf{x} be an arbitrary element of \mathbb{R}^n . Choose $\mathbf{y} = (-x_1, \dots, -x_n)$. Then by Definition 18.2,

$$\begin{aligned} \mathbf{x} + \mathbf{y} &= (x_1 + (-x_1), \dots, x_n + (-x_n)) \\ &= (0, \dots, 0) \\ &= \mathbf{0} \\ &= ((-x_1) + x_1, \dots, (-x_n) + x_n) \\ &= \mathbf{y} + \mathbf{x} \end{aligned}$$

as desired.

To prove that \mathbb{R}^n obeys VS1, it will suffice to show that for all $\lambda, \mu \in \mathbb{R}$ and $\mathbf{x} \in \mathbb{R}^n$, we have $(\lambda\mu)\mathbf{x} = \lambda(\mu\mathbf{x})$. Let λ, μ be arbitrary elements of \mathbb{R} , and let \mathbf{x} be an arbitrary element of \mathbb{R}^n . Then by Definition 18.2,

$$\begin{aligned} (\lambda\mu)\mathbf{x} &= ((\lambda\mu)x_1, \dots, (\lambda\mu)x_n) \\ &= (\lambda(\mu x_1), \dots, \lambda(\mu x_n)) \\ &= \lambda(\mu\mathbf{x}) \end{aligned}$$

as desired.

To prove that \mathbb{R}^n obeys VS2, it will suffice to show that for all $\lambda, \mu \in \mathbb{R}$ and $\mathbf{x} \in \mathbb{R}^n$, we have $(\lambda + \mu)\mathbf{x} = \lambda\mathbf{x} + \mu\mathbf{x}$. Let λ, μ be arbitrary elements of \mathbb{R} , and let \mathbf{x} be an arbitrary element of \mathbb{R}^n . Then by Definition 18.2,

$$\begin{aligned} (\lambda + \mu)\mathbf{x} &= ((\lambda + \mu)x_1, \dots, (\lambda + \mu)x_n) \\ &= (\lambda x_1 + \mu x_1, \dots, \lambda x_n + \mu x_n) \\ &= (\lambda x_1, \dots, \lambda x_n) + (\mu x_1, \dots, \mu x_n) \\ &= \lambda\mathbf{x} + \mu\mathbf{x} \end{aligned}$$

as desired.

To prove that \mathbb{R}^n obeys VS3, it will suffice to show that for all $\lambda \in \mathbb{R}$ and $\mathbf{x}, \mathbf{y} \in \mathbb{R}^n$, we have $\lambda(\mathbf{x} + \mathbf{y}) = \lambda\mathbf{x} + \lambda\mathbf{y}$. Let λ be an arbitrary element of \mathbb{R} , and let \mathbf{x}, \mathbf{y} be arbitrary elements of \mathbb{R}^n . Then by Definition 18.2,

$$\begin{aligned}\lambda(\mathbf{x} + \mathbf{y}) &= \lambda(x_1 + y_1, \dots, x_n + y_n) \\ &= (\lambda(x_1 + y_1), \dots, \lambda(x_n + y_n)) \\ &= (\lambda x_1 + \lambda y_1, \dots, \lambda x_n + \lambda y_n) \\ &= (\lambda x_1, \dots, \lambda x_n) + (\lambda y_1, \dots, \lambda y_n) \\ &= \lambda\mathbf{x} + \lambda\mathbf{y}\end{aligned}$$

as desired.

To prove that \mathbb{R}^n obeys VS4, it will suffice to show that for all $\mathbf{x} \in \mathbb{R}^n$, we have $1\mathbf{x} = \mathbf{x}$. Let \mathbf{x} be an arbitrary element of \mathbb{R}^n . Then by Definition 18.2,

$$\begin{aligned}1\mathbf{x} &= (1x_1, \dots, 1x_n) \\ &= (x_1, \dots, x_n) \\ &= \mathbf{x}\end{aligned}$$

as desired. □

Remark 18.4. Since \mathbb{R}^n with the two operations defined as above satisfies these eight axioms, we call \mathbb{R}^n a **vector space**.

Exercise 18.5. Prove that if $\mathbf{x} \in \mathbb{R}^n$, then $0\mathbf{x} = \mathbf{0}$.

Proof. By Definition 18.2, we have that

$$\begin{aligned}0\mathbf{x} &= (0x_1, \dots, 0x_n) \\ &= (0, \dots, 0) \\ &= \mathbf{0}\end{aligned}$$

as desired. □

Definition 18.6. Let $\mathbf{x} \in \mathbb{R}^n$. The **norm** of \mathbf{x} is defined as

$$\|\mathbf{x}\| = \sqrt{x_1^2 + \dots + x_n^2}$$

Definition 18.7. We call $\|\mathbf{y} - \mathbf{x}\|$ the **distance** between \mathbf{x} and \mathbf{y} .

Remark 18.8. If $n = 1$, the norm coincides with the definition of the absolute value in \mathbb{R} .

Lemma 18.9.

(a) If $x, y \in \mathbb{R}$, then $xy \leq \frac{x^2 + y^2}{2}$.

Proof. Let x, y be arbitrary elements of \mathbb{R} . Then by Lemma 7.26, $0 \leq (x - y)^2$. Therefore, we have that

$$\begin{aligned}xy &= \frac{2xy + 0}{2} \\ &\leq \frac{2xy + (x - y)^2}{2} \\ &= \frac{2xy + x^2 - 2xy + y^2}{2} \\ &= \frac{x^2 + y^2}{2}\end{aligned}$$

as desired. □

(b) If $\mathbf{x}, \mathbf{y} \in \mathbb{R}^n$, then $|x_1y_1 + \cdots + x_ny_n| \leq \|\mathbf{x}\| \cdot \|\mathbf{y}\|$.

Proof. Suppose first that $\|\mathbf{x}\| = \|\mathbf{y}\| = 1$. Then by Definition 18.6, $\|\mathbf{x}\| = 1 = \sqrt{x_1^2 + \cdots + x_n^2}$, from which it follows that $1 = x_1^2 + \cdots + x_n^2$. Therefore, we have that

$$\begin{aligned}
 |x_1y_1 + \cdots + x_ny_n| &\leq |x_1y_1| + \cdots + |x_ny_n| && \text{Lemma 8.8} \\
 &= |x_1||y_1| + \cdots + |x_n||y_n| \\
 &\leq \frac{|x_1|^2 + |y_1|^2}{2} + \cdots + \frac{|x_n|^2 + |y_n|^2}{2} && \text{Lemma 18.9a} \\
 &= \frac{x_1^2 + y_1^2}{2} + \cdots + \frac{x_n^2 + y_n^2}{2} \\
 &= \frac{(x_1^2 + \cdots + x_n^2) + (y_1^2 + \cdots + y_n^2)}{2} \\
 &= \frac{1 + 1}{2} \\
 &= 1
 \end{aligned}$$

as desired.

Now let \mathbf{x}, \mathbf{y} be arbitrary elements of \mathbb{R}^n . Consider the vectors $\mathbf{u}_x, \mathbf{u}_y$ defined by $\mathbf{u}_x = \frac{\mathbf{x}}{\|\mathbf{x}\|}$ and $\mathbf{u}_y = \frac{\mathbf{y}}{\|\mathbf{y}\|}$. By the proof of the first case, we have that

$$\begin{aligned}
 |x_1y_1 + \cdots + x_ny_n| &= \|\mathbf{x}\| \cdot \|\mathbf{y}\| \cdot \left| \frac{x_1y_1}{\|\mathbf{x}\| \cdot \|\mathbf{y}\|} + \cdots + \frac{x_ny_n}{\|\mathbf{x}\| \cdot \|\mathbf{y}\|} \right| \\
 &= \|\mathbf{x}\| \cdot \|\mathbf{y}\| \cdot |u_{x_1}u_{y_1} + \cdots + u_{x_n}u_{y_n}| \\
 &\leq \|\mathbf{x}\| \cdot \|\mathbf{y}\| \cdot 1 \\
 &= \|\mathbf{x}\| \cdot \|\mathbf{y}\|
 \end{aligned}$$

as desired. □

Theorem 18.10. If $\mathbf{x}, \mathbf{y} \in \mathbb{R}^n$ and $\lambda \in \mathbb{R}$, then

(a) $\|\mathbf{x}\| \geq 0$. Moreover, $\|\mathbf{x}\| = 0$ if and only if $\mathbf{x} = \mathbf{0}$.

Proof. Let \mathbf{x} be an arbitrary element of \mathbb{R}^n .

We first prove that $\|\mathbf{x}\| \geq 0$. By Lemma 7.26, $x_i^2 \geq 0$ for all $i \in [n]$. Thus, by Definition 7.21, $x_1^2 + \cdots + x_n^2 \geq 0$. Therefore, we have by Definition 18.6 that $\|\mathbf{x}\| = \sqrt{x_1^2 + \cdots + x_n^2} \geq 0$, as desired.

We now prove that $\|\mathbf{x}\| = 0$ if and only if $\mathbf{x} = \mathbf{0}$. Suppose first that $\|\mathbf{x}\| = 0$. Then by Definition 18.6 and Script 7, $x_1^2 + \cdots + x_n^2 = 0$. Now suppose for the sake of contradiction that $\mathbf{x} \neq \mathbf{0}$. Then there exists an x_i such that $x_i \neq 0$. Thus, by Lemma 7.26, $x_i^2 > 0$. Additionally, $x_j^2 \geq 0$ for all $j \in [n]$. Thus, we have that $0 < x_i^2 \leq x_1^2 + \cdots + x_n^2$. But by Definition 3.1, this implies that $x_1^2 + \cdots + x_n^2 \neq 0$, a contradiction.

Now suppose that $\mathbf{x} = \mathbf{0}$. Then by Definition 18.6, $\|\mathbf{x}\| = \sqrt{0^2 + \cdots + 0^2} = 0$, as desired. □

(b) $\|\lambda\mathbf{x}\| = |\lambda| \cdot \|\mathbf{x}\|$.

Proof. Let λ be an arbitrary element of \mathbb{R} , and let \mathbf{x} be an arbitrary element of \mathbb{R}^n . Then we have that

$$\begin{aligned}
 \|\lambda\mathbf{x}\| &= \sqrt{(\lambda x_1)^2 + \cdots + (\lambda x_n)^2} && \text{Definition 18.6} \\
 &= |\lambda| \cdot \sqrt{x_1^2 + \cdots + x_n^2} \\
 &= |\lambda| \cdot \|\mathbf{x}\| && \text{Definition 18.6}
 \end{aligned}$$

as desired. □

$$(c) \|\mathbf{x} + \mathbf{y}\| \leq \|\mathbf{x}\| + \|\mathbf{y}\|.$$

Proof. Let \mathbf{x}, \mathbf{y} be arbitrary elements of \mathbb{R}^n . Then we have that

$$\begin{aligned} \|\mathbf{x} + \mathbf{y}\| &= \sqrt{(x_1 + y_1)^2 + \cdots + (x_n + y_n)^2} && \text{Definition 18.6} \\ &= \sqrt{x_1^2 + \cdots + x_n^2 + 2x_1y_1 + \cdots + 2x_ny_n + y_1^2 + \cdots + y_n^2} \\ &\leq \sqrt{\|\mathbf{x}\|^2 + 2\|\mathbf{x}\|\|\mathbf{y}\| + \|\mathbf{y}\|^2} && \text{Lemma 18.9} \\ &= \sqrt{(\|\mathbf{x}\| + \|\mathbf{y}\|)^2} \\ &= \|\mathbf{x}\| + \|\mathbf{y}\| \end{aligned}$$

as desired. \square

Corollary 18.11. If $\mathbf{x}, \mathbf{y}, \mathbf{z} \in \mathbb{R}^n$ and $\lambda \in \mathbb{R}$, then

$$(a) \|\mathbf{x} - \mathbf{z}\| \leq \|\mathbf{x} - \mathbf{y}\| + \|\mathbf{y} - \mathbf{z}\|.$$

$$(b) \left| \|\mathbf{x}\| - \|\mathbf{y}\| \right| \leq \|\mathbf{x} - \mathbf{y}\|.$$

Proof. The proofs are symmetric to those of Lemma 8.8. \square

7/10: The next goal is to “topologize” \mathbb{R}^n . To discuss topology on \mathbb{R}^n , we first need to introduce notions for \mathbb{R}^n that are analogous to open and closed intervals for \mathbb{R} .

Remark 18.12. For $\mathbf{x} = (x_1, \dots, x_n) \in \mathbb{R}^n$ and $\mathbf{y} = (y_1, \dots, y_m) \in \mathbb{R}^m$, we identify $(\mathbf{x}, \mathbf{y}) \in \mathbb{R}^n \times \mathbb{R}^m$ with $(x_1, \dots, x_n, y_1, \dots, y_m) \in \mathbb{R}^{n+m}$. So if $A \subset \mathbb{R}^n$ and $B \subset \mathbb{R}^m$, we can consider $A \times B$ to be a subset of \mathbb{R}^{n+m} .

If also $C \in \mathbb{R}^k$, then $(A \times B) \times C$ and $A \times (B \times C)$ correspond to the same subset of \mathbb{R}^{n+m+k} under this identification; we write $A \times B \times C$ for this set.

Definition 18.13. An **open rectangle** in \mathbb{R}^n is a set of the form $(a_1, b_1) \times \cdots \times (a_n, b_n)$, a product of open intervals. Similarly, a **closed rectangle** in \mathbb{R}^n is a set of the form $[a_1, b_1] \times \cdots \times [a_n, b_n]$. We allow the possibility that $a_j = b_j$ (where $[a_j, a_j] = \{a_j\}$). If there is at least one j with $a_j = b_j$, then we say that the rectangle is **degenerate**; otherwise, we say that the rectangle is **non-degenerate**.

Definition 18.14. A subset $U \subset \mathbb{R}^n$ is **open** if for all $\mathbf{x} \in U$, there exists an open rectangle R such that $\mathbf{x} \in R \subset U$. A subset $C \subset \mathbb{R}^n$ is **closed** if its complement is open.

Exercise 18.15. Decide whether each of the following is an open set in \mathbb{R}^2 .

$$(a) \{(x_1, x_2) \mid x_1, x_2 \in \mathbb{R}, x_1 > 0, x_2 > 0\}.$$

Proof. To prove that $U = \{(x_1, x_2) \mid x_1, x_2 \in \mathbb{R}, x_1 > 0, x_2 > 0\}$ is open, Definition 18.14 tells us that it will suffice to show that for all $\mathbf{x} \in U$, there exists an open rectangle R such that $\mathbf{x} \in R \subset U$. Let \mathbf{x} be an arbitrary element of U . Then by the definition of U , $0 < x_1$ and $0 < x_2$. It follows by Theorem 5.2 and Corollary 6.12, there exist a_1, b_1, a_2, b_2 such that $0 < a_1 < x_1 < b_1$ and $0 < a_2 < x_2 < b_2$. Thus, by Equations 8.1, $x_1 \in (a_1, b_1)$ and $x_2 \in (a_2, b_2)$. Consequently, if we let $R = (a_1, b_1) \times (a_2, b_2)$, Definition 18.13 guarantees that R is an open rectangle. Additionally, Definition 1.15 asserts that $(x_1, x_2) = \mathbf{x} \in R$, as desired. Additionally, if \mathbf{y} is any vector in R , then by the definition of R , $0 < a_1 < y_1$ and $0 < a_2 < y_2$. Thus, by transitivity, $\mathbf{y} \in U$. Therefore, by Definition 1.3, $R \subset U$, as desired. \square

$$(b) \{(x, 0) \mid x \in \mathbb{R}\}.$$

Proof. To prove that $U = \{(x, 0) \mid x \in \mathbb{R}\}$ is not open, Definition 18.14 tells us that it will suffice to find an $\mathbf{x} \in U$ such that for all open rectangles R containing \mathbf{x} , $R \not\subset U$. Let $\mathbf{x} = (0, 0)$, and let R be an arbitrary open rectangle containing \mathbf{x} . By Definitions 18.13 and 1.15 along with Equations 8.1, $a_1 < 0 < b_1$ and $a_2 < 0 < b_2$. Thus, by consecutive applications of Theorem 5.2, there exist points $y_1, y_2 \in \mathbb{R}$ such that $a_1 < y_1 < 0$ and $a_2 < y_2 < 0$. It follows that $\mathbf{y} = (y_1, y_2) \in R$. However, since $y_2 \neq 0$ by Definition 3.1, $\mathbf{y} \notin U$. Therefore, by Definition 1.3, $R \not\subset U$, as desired. \square

Exercise 18.16. Show that if R_1, \dots, R_m are open rectangles containing $\mathbf{x} \in \mathbb{R}^n$, then $R = R_1 \cap \dots \cap R_m$ is an open rectangle containing $\mathbf{x} \in \mathbb{R}^n$. If $R = (a_1, b_1) \times \dots \times (a_n, b_n)$, derive formulas for a_i and b_i in terms of the corresponding quantities for R_1, \dots, R_m .

Proof. Let $R_i = (r_{ij}, s_{ij})_{j=1}^n$ for all $i \in [m]$. To prove that $R = \bigcap_{i=1}^m R_i$ is an open rectangle containing \mathbf{x} , Definitions 18.13 and 1.15 tell us that it will suffice to show that R is the Cartesian product of open intervals, each containing its respective x_j . Since $\mathbf{x} \in R_i$ for all $i \in [m]$, we have by Definition 1.15 that $x_j \in (r_{ij}, s_{ij})$ for all $i \in [m]$, $j \in [n]$. Thus, by Corollary 3.19, $\bigcap_{i=1}^m (r_{ij}, s_{ij})$ is a region (hence an open interval by Corollary 4.11 and Lemma 8.3) containing x_j for all $j \in [n]$. Therefore, since $R = \bigcap_{i=1}^m R_i = \prod_{i=1}^n (\bigcap_{i=1}^m (r_{ij}, s_{ij}))$ by Script 1, we have that R is the Cartesian product of open intervals, each containing its respective x_j , as desired.

Let $a_j = \max_{i=1}^m (r_{ij})$ and let $b_j = \min_{i=1}^m (s_{ij})$ for all $j \in [n]$. To prove that $R = (a_j, b_j)_{j=1}^n$, Definition 1.2 tells us that it will suffice to show that every $\mathbf{x} \in R$ is an element of $(a_j, b_j)_{j=1}^n$ and vice versa. Suppose first that \mathbf{x} is an arbitrary element of R . Then by Definition 1.6, $\mathbf{x} \in R_i$ for all $i \in [m]$. It follows by Definition 1.15 that $x_j \in (r_{ij}, s_{ij})$ for all $i \in [m]$, $j \in [n]$, including the j, j' for which r_{ij} is at its maximum and $s_{ij'}$ is at its minimum. In other words, $x_j \in (a_j, b_j)$ for all $j \in [n]$. Therefore, by Definition 1.15, $\mathbf{x} \in (a_j, b_j)_{j=1}^n$, as desired. The proof is symmetric in the other direction. \square

Definition 18.17. The **open ball** (in \mathbb{R}^n with center \mathbf{p} and radius $r > 0$) is defined as

$$B(\mathbf{p}, r) = \{\mathbf{x} \in \mathbb{R}^n \mid \|\mathbf{x} - \mathbf{p}\| < r\}$$

The **closed ball** (in \mathbb{R}^n with center \mathbf{p} and radius $r > 0$) is defined as

$$\bar{B}(\mathbf{p}, r) = \{\mathbf{x} \in \mathbb{R}^n \mid \|\mathbf{x} - \mathbf{p}\| \leq r\}$$

Remark 18.18. In \mathbb{R}^1 , an open rectangle is also an open ball, and vice versa.

The following results illustrate how open rectangles and open balls in \mathbb{R}^n are “compatible” with each other.

Lemma 18.19. Fix $\mathbf{x} \in \mathbb{R}^n$.

(a) If R is an open rectangle containing \mathbf{x} , then there exists $r > 0$ such that $B(\mathbf{x}, r) \subset R$.

Proof. Since $\mathbf{x} \in R$, Definitions 18.13 and 1.15 tell us that $x_i \in (a_i, b_i)$ for all $i \in [n]$. Additionally, we know by Corollary 4.11 and Lemma 8.3 that each (a_i, b_i) is an open interval. Combining the last two results, we have by Lemma 8.10 that for each $i \in [n]$, there exists $\delta_i > 0$ such that $(x_i - \delta_i, x_i + \delta_i) \subset (a_i, b_i)$. Let $r = \min\{\delta_i\}_{i=1}^n$.

To prove that $B(\mathbf{x}, r) \subset R$, Definition 1.3 tells us that it will suffice to show that every $\mathbf{y} \in B(\mathbf{x}, r)$ is an element of R . Let \mathbf{y} be an arbitrary element of $B(\mathbf{x}, r)$. Then by Definition 18.17, $\|\mathbf{y} - \mathbf{x}\| < r$. It follows that

$$\begin{aligned} |y_i - x_i| &= \sqrt{(y_i - x_i)^2} \\ &\leq \sqrt{(y_1 - x_1)^2 + \dots + (y_n - x_n)^2} && \text{Lemma 7.26} \\ &= \|\mathbf{y} - \mathbf{x}\| && \text{Definition 18.6} \\ &< r \end{aligned}$$

for all $i \in [n]$. Thus, by the definition of r , $|y_i - x_i| \leq \delta_i$ for all $i \in [n]$. Consequently, by Exercise 8.9 and Definition 1.3, $y_i \in (a_i, b_i)$ for all $i \in [n]$. Therefore, by Definitions 1.15 and 18.13, $\mathbf{y} \in R$, as desired. \square

(b) If B is an open ball containing \mathbf{x} , then there exists an open rectangle R such that $\mathbf{x} \in R \subset B$.

Lemma. If $\mathbf{x} \in \mathbb{R}^n$, then $\|\mathbf{x}\| \leq \sum_{i=1}^n |x_i|$.

Proof. By Definition 18.2, we can decompose \mathbf{x} into the sum of n unit vectors \mathbf{u}_i (where \mathbf{u}_i points one unit in the i^{th} direction), each scaled by x_i ; symbolically, let $\mathbf{x} = \sum_{i=1}^n x_i \mathbf{u}_i$. Therefore,

$$\begin{aligned}
 \|\mathbf{x}\| &= \left\| \sum_{i=1}^n x_i \mathbf{u}_i \right\| \\
 &= \sum_{i=1}^n \|x_i \mathbf{u}_i\| && \text{Theorem 18.10c} \\
 &= \sum_{i=1}^n |x_i| \cdot \|\mathbf{u}_i\| && \text{Theorem 18.10b} \\
 &= \sum_{i=1}^n |x_i| \cdot \sqrt{1^2} && \text{Definition 18.6} \\
 &= \sum_{i=1}^n |x_i|
 \end{aligned}$$

as desired. \square

Proof of Lemma 18.19b. Suppose $\mathbf{x} \in B(\mathbf{y}, r)$. Then by Definition 18.17, $\|\mathbf{x} - \mathbf{y}\| < r$. Thus, we can define $r' = r - \|\mathbf{x} - \mathbf{y}\|$ such that $r' > 0$. With this term defined, we can let $R = (x_i - \frac{r'}{n}, x_i + \frac{r'}{n})_{i=1}^n$.

To prove that $\mathbf{x} \in R$, Definition 18.13 tells us that it will suffice to show that $x_i \in (x_i - \frac{r'}{n}, x_i + \frac{r'}{n})$ for all $i \in [n]$. But since $|x_i - x_i| = 0 < \frac{r'}{n}$ for all $i \in [n]$, Exercise 8.9 asserts that this is true.

To prove that $R \subset B$, Definition 1.3 tells us that it will suffice to show that every $\mathbf{z} \in R$ is an element of B . Let \mathbf{z} be an arbitrary element of R . Then by Definition 18.13, $z_i \in (x_i - \frac{r'}{n}, x_i + \frac{r'}{n})$ for all $i \in [n]$. It follows by Exercise 8.9 that $|z_i - x_i| < \frac{r'}{n}$ for all $i \in [n]$. Consequently,

$$\begin{aligned}
 \|\mathbf{z} - \mathbf{y}\| &\leq \|\mathbf{z} - \mathbf{x}\| + \|\mathbf{x} - \mathbf{y}\| && \text{Corollary 18.11} \\
 &\leq \sum_{i=1}^n |z_i - x_i| + \|\mathbf{x} - \mathbf{y}\| && \text{Lemma} \\
 &< \sum_{i=1}^n \frac{r'}{n} + \|\mathbf{x} - \mathbf{y}\| \\
 &= r' + \|\mathbf{x} - \mathbf{y}\| \\
 &= r - \|\mathbf{x} - \mathbf{y}\| + \|\mathbf{x} - \mathbf{y}\| \\
 &= r
 \end{aligned}$$

Therefore, by Definition 18.17, $\mathbf{z} \in B$, as desired. \square

Corollary 18.20. A set $U \subset \mathbb{R}^n$ is open if and only if for every $\mathbf{x} \in U$, there exists $r > 0$ such that $B(\mathbf{x}, r) \subset U$.

Proof. Suppose first that $U \subset \mathbb{R}^n$ is open. Let \mathbf{x} be an arbitrary element of U . By Definition 18.14, there exists an open rectangle R such that $\mathbf{x} \in R \subset U$. Therefore, by Lemma 18.19, there exists $r > 0$ such that $B(\mathbf{x}, r) \subset R \subset U$, as desired.

Now suppose that for all $\mathbf{x} \in U$, there exists $r > 0$ such that $B(\mathbf{x}, r) \subset U$. To prove that U is open, Definition 18.14 tells us that it will suffice to show that for all $\mathbf{x} \in U$, there exists an open rectangle R such that $\mathbf{x} \in R \subset U$. Let \mathbf{x} be an arbitrary element of U . Then there exists $r > 0$ such that $B(\mathbf{x}, r) \subset U$. Therefore, by Lemma 18.19, there exists an open rectangle R such that $\mathbf{x} \in R \subset B \subset U$, as desired. \square