Section 2.1. Metric Spaces and Normed Spaces

Here we seek to generalize notions of distance and length in $\mathbb{R}^n$ to abstract settings.

**Definition 1** A *metric space* is a pair $(X, d)$, where $X$ is a set and $d : X \times X \to \mathbb{R}_+$ a function satisfying

1. $d(x, y) \geq 0$, $d(x, y) = 0 \iff x = y \ \forall x, y \in X$
2. $d(x, y) = d(y, x) \ \forall x, y \in X$
3. *triangle inequality:* $d(x, z) \leq d(x, y) + d(y, z) \ \forall x, y, z \in X$

A function $d : X \times X \to \mathbb{R}_+$ satisfying 1-3 is called a *metric* on $X$.

A metric gives a notion of distance between elements of $X$.

**Definition 2** Let $V$ be a vector space over $\mathbb{R}$. A *norm* on $V$ is a function $\| \cdot \| : V \to \mathbb{R}_+$ satisfying

1. $\|x\| \geq 0 \ \forall x \in V$
2. $\|x\| = 0 \iff x = 0 \ \forall x \in V$
3. *triangle inequality:* $\|x + y\| \leq \|x\| + \|y\| \ \forall x, y \in V$
4. $\|\alpha x\| = |\alpha|\|x\| \ \forall \alpha \in \mathbb{R}, x \in V$

A *normed vector space* is a vector space over $\mathbb{R}$ equipped with a norm.
A norm gives a notion of length of a vector in $V$.

Example: In $\mathbb{R}^n$, the standard notion of distance between two vectors $x$ and $y$ measures the length of the difference $x - y$, i.e., $d(x, y) = \|x - y\| = \sqrt{\sum_{i=1}^{n}(x_i - y_i)^2}$.

In an abstract normed vector space, the norm can be used analogously to define a notion of distance.

**Theorem 3** Let $(V, \| \cdot \|)$ be a normed vector space. Let $d : V \times V \to \mathbb{R}_+$ be defined by

$$d(v, w) = \|v - w\|$$

Then $(V, d)$ is a metric space.

**Proof:** We must verify that $d$ satisfies all the properties of a metric.

1. Let $v, w \in V$. Then by definition, $d(v, w) = \|v - w\| \geq 0$ (why?), and

   $$d(v, w) = 0 \iff \|v - w\| = 0$$
   $$\iff v - w = 0$$
   $$\iff (v + (-w)) + w = w$$
   $$\iff v + ((-w) + w) = w$$
   $$\iff v + 0 = w$$
   $$\iff v = w$$

2. First, note that for any $x \in V$, $0 \cdot x = (0 + 0) \cdot x = 0 \cdot x + 0 \cdot x$, so $0 \cdot x = 0$. Then

   $$0 = 0 \cdot x = (1 - 1) \cdot x = 1 \cdot x + (-1) \cdot x = x + (-1) \cdot x,$$

   so we have $(-1) \cdot x = (-x)$. Then let $v, w \in V$.

   $$d(v, w) = \|v - w\|$$
   $$= \|(-1)(v + (-w))\|$$
   $$= \|(-1)v + (-1)(-w)\|$$
   $$= \|-v + w\|$$
   $$= \||w + (-v)\|$$
   $$= \|w - v\|$$
   $$= d(w, v)$$

3. Let $u, w, v \in V$.

   $$d(u, w) = \|u - w\|$$
   $$= \|u + (-v + v) - w\|$$
   $$= \|u - v + v - w\|$$
   $$\leq \|u - v\| + \|v - w\|$$
   $$= d(u, v) + d(v, w)$$
Thus $d$ is a metric on $V$. ■

Examples of Normed Vector Spaces

- $\mathbb{E}^n$: $n$-dimensional Euclidean space.
  
  $V = \mathbb{R}^n$, $\|x\|_2 = |x| = \sqrt{\sum_{i=1}^{n} (x_i)^2}$

- $V = \mathbb{R}^n$, $\|x\|_1 = \sum_{i=1}^{n} |x_i|$ (the “taxi cab” norm or $L^1$ norm)

- $V = \mathbb{R}^n$, $\|x\|_\infty = \max\{|x_1|, \ldots, |x_n|\}$ (the maximum norm, or sup norm, or $L^\infty$ norm)

- $C([0, 1])$, $\|f\|_\infty = \sup \{|f(t)| : t \in [0, 1]\}$

- $C([0, 1])$, $\|f\|_2 = \sqrt{\int_0^1 (f(t))^2 \, dt}$

- $C([0, 1])$, $\|f\|_1 = \int_0^1 |f(t)| \, dt$

Theorem 4 (Cauchy-Schwarz Inequality)
If $v, w \in \mathbb{R}^n$, then

\[
\left( \sum_{i=1}^{n} v_i w_i \right)^2 \leq \left( \sum_{i=1}^{n} v_i^2 \right) \left( \sum_{i=1}^{n} w_i^2 \right)
\]

\[
|v \cdot w|^2 \leq |v|^2 |w|^2
\]

\[
|v \cdot w| \leq |v||w|
\]

Proof: Read the proof in de La Fuente. ■

The Cauchy-Schwarz Inequality is essential in proving the triangle inequality in $\mathbb{E}^n$. Deriving the triangle inequality in $\mathbb{E}^n$ from the Cauchy-Schwarz inequality is a good exercise. The Cauchy-Schwarz inequality can also be viewed as a consequence of geometry in $\mathbb{R}^2$, in particular the law of cosines. Note that for $v, w \in \mathbb{R}^2$, $v \cdot w = |v||w| \cos \theta$ where $\theta$ is the angle between $v$ and $w$; see Figure 1.\(^1\)

Notice that a given vector space may have many different norms. As a trivial example, if $\| \cdot \|$ is a norm on a vector space $V$, so are $2\| \cdot \|$ and $3\| \cdot \|$ and $k\| \cdot \|$ for any $k > 0$. Less trivially, $\mathbb{R}^n$ supports many different norms as in the examples above. Different norms on a given vector space yield different geometric properties; for example, see Figure 2 for different norms on $\mathbb{R}^2$.

\(^1\)From the law of cosines, $(v-w) \cdot (v-w) = v \cdot v + w \cdot w - 2|v||w| \cos \theta$. On the other hand, $(v-w) \cdot (v-w) = v \cdot v - 2v \cdot w + w \cdot w$, so $v \cdot w = |v||w| \cos \theta$. 

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Figure 1: $\theta$ is the angle between $v$ and $w$.

**Definition 5** Two norms $\| \cdot \|$ and $\| \cdot \|^*$ on the same vector space $V$ are said to be Lipschitz-equivalent (or equivalent) if $\exists m, M > 0$ s.t. $\forall x \in V$,

$$m\|x\| \leq \|x\|^* \leq M\|x\|$$

Equivalently, $\exists m, M > 0$ s.t. $\forall x \in V, x \neq 0$,

$$m \leq \frac{\|x\|^*}{\|x\|} \leq M$$

If two norms are equivalent, then they define the same notions of convergence and continuity. For topological purposes, equivalent norms are indistinguishable. For example, suppose two norms $\| \cdot \|$ and $\| \cdot \|^*$ on the vector space $V$ are equivalent, and fix $x \in V$. Let $B_\varepsilon(x, \| \cdot \|)$ denote the $\| \cdot \|$-ball of radius $\varepsilon$ about $x$; similarly, let $B_\varepsilon(x, \| \cdot \|^*)$ denote the $\| \cdot \|^*$-ball of radius $\varepsilon$ about $x$. That is,

$$B_\varepsilon(x, \| \cdot \|) = \{ y \in V : \|x - y\| < \varepsilon \}$$

$$B_\varepsilon(x, \| \cdot \|^*) = \{ y \in V : \|x - y\|^* < \varepsilon \}$$

Then for any $\varepsilon > 0$,

$$B_{\frac{m}{M}}(x, \| \cdot \|) \subseteq B_\varepsilon(x, \| \cdot \|^*) \subseteq B_{\frac{M}{m}}(x, \| \cdot \|)$$

See Figure 3.

In $\mathbb{R}^n$ (or any finite-dimensional normed vector space), all norms are equivalent. This says roughly that, up to a difference in scaling, for topological purposes there is a unique norm in $\mathbb{R}^n$.

**Theorem 6** All norms on $\mathbb{R}^n$ are equivalent.\(^2\)

\(^2\)The statement of the theorem in de la Fuente (Theorem 10.8, p. 107) is correct, but the proof has a problem.
However, infinite-dimensional spaces support norms that are not equivalent. For example, on $C([0, 1])$, let $f_n$ be the function

$$f_n(t) = \begin{cases} 1 - nt & \text{if } t \in \left[0, \frac{1}{n}\right] \\ 0 & \text{if } t \in \left(\frac{1}{n}, 1\right] \end{cases}$$

Then

$$\frac{\|f_n\|_1}{\|f_n\|_\infty} = \frac{1}{2n} = \frac{1}{2n} \to 0$$

**Definition 7** In a metric space $(X, d)$, a subset $S \subseteq X$ is bounded if $\exists x \in X, \beta \in \mathbb{R}$ such that $\forall s \in S, d(s, x) \leq \beta$.

In a metric space $(X, d)$, define

$$B_\varepsilon(x) = \{y \in X : d(y, x) < \varepsilon\} = \text{open ball with center } x \text{ and radius } \varepsilon$$
$$B_\varepsilon[x] = \{y \in X : d(y, x) \leq \varepsilon\} = \text{closed ball with center } x \text{ and radius } \varepsilon$$

We can use the metric $d$ to define a generalization of “radius”. In a metric space $(X, d)$, define the **diameter** of a subset $S \subseteq X$ by

$$\text{diam}(S) = \sup\{d(s, s') : s, s' \in S\}$$

Similarly, we can define the distance from a point to a set, and distance between sets, as follows:

$$d(A, x) = \inf_{a \in A} d(a, x)$$
$$d(A, B) = \inf_{a \in A} d(B, a)$$
$$= \inf\{d(a, b) : a \in A, b \in B\}$$

Note that $d(A, x)$ cannot be a metric (since a metric is a function on $X \times X$, the first and second arguments must be objects of the same type); in addition, $d(A, B)$ does not define a metric on the space of subsets of $X$ (why?).\footnote{Another, more useful notion of the distance between sets is the Hausdorff distance, given by $d(A, B) = \max\{\sup_{a \in A} \inf_{b \in B} d(a, b), \sup_{b \in B} \inf_{a \in A} d(a, b)\}$.}

**Section 2.2. Convergence of Sequences in Metric Spaces**

**Definition 8** Let $(X, d)$ be a metric space. A sequence $\{x_n\}$ **converges** to $x$ (written $x_n \to x$ or $\lim_{n \to \infty} x_n = x$) if

$$\forall \varepsilon > 0 \ \exists N(\varepsilon) \in \mathbb{N} \text{ s.t. } n > N(\varepsilon) \Rightarrow d(x_n, x) < \varepsilon$$
Notice that this is exactly the same as the definition of convergence of a sequence of real numbers, except we replace the standard measure of distance $|\cdot|$ in $\mathbb{R}$ by the general metric $d$.

**Theorem 9 (Uniqueness of Limits)** In a metric space $(X, d)$, if $x_n \to x$ and $x_n \to x'$, then $x = x'$.

![Diagram](image)

**Proof:** Suppose $\{x_n\}$ is a sequence in $X$, $x_n \to x$, $x_n \to x'$, $x \neq x'$. Since $x \neq x'$, $d(x, x') > 0$.

Let

\[ \varepsilon = \frac{d(x, x')}{2} \]

Then there exist $N(\varepsilon)$ and $N'(\varepsilon)$ such that

\[ n > N(\varepsilon) \implies d(x_n, x) < \varepsilon \]
\[ n > N'(\varepsilon) \implies d(x_n, x') < \varepsilon \]

Choose

\[ n > \max\{N(\varepsilon), N'(\varepsilon)\} \]

Then

\[ d(x, x') \leq d(x, x_n) + d(x_n, x') \]
\[ < \varepsilon + \varepsilon \]
\[ = 2\varepsilon \]
\[ = d(x, x') \]
\[ d(x, x') < d(x, x') \]

a contradiction. ■

**Definition 10** An element $c$ is a *cluster point* of a sequence $\{x_n\}$ in a metric space $(X, d)$ if $\forall \varepsilon > 0$, $\{n : x_n \in B_\varepsilon(c)\}$ is an infinite set. Equivalently,

\[ \forall \varepsilon > 0, N \in \mathbb{N} \exists n > N \text{ s.t. } x_n \in B_\varepsilon(c) \]
Example:

\[ x_n = \begin{cases} 
1 - \frac{1}{n} & \text{if } n \text{ even} \\
\frac{1}{n} & \text{if } n \text{ odd} 
\end{cases} \]

For \( n \) large and odd, \( x_n \) is close to zero; for \( n \) large and even, \( x_n \) is close to one. The sequence does not converge; the set of cluster points is \( \{0, 1\} \).

If \( \{x_n\} \) is a sequence and \( n_1 < n_2 < n_3 < \cdots \) then \( \{x_{n_k}\} \) is called a subsequence.

Note that a subsequence is formed by taking some of the elements of the parent sequence, in the same order.

Example: \( x_n = \frac{1}{n} \), so \( \{x_n\} = \left(1, \frac{1}{2}, \frac{1}{3}, \ldots \right) \). If \( n_k = 2k \), then \( \{x_{n_k}\} = \left(\frac{1}{2}, \frac{1}{4}, \frac{1}{6}, \ldots \right) \).

**Theorem 11** (2.4 in De La Fuente, plus …) Let \( (X, d) \) be a metric space, \( c \in X \), and \( \{x_n\} \) a sequence in \( X \). Then \( c \) is a cluster point of \( \{x_n\} \) if and only if there is a subsequence \( \{x_{n_k}\} \) such that \( \lim_{k \to \infty} x_{n_k} = c \).

**Proof:** Suppose \( c \) is a cluster point of \( \{x_n\} \). We inductively construct a subsequence that converges to \( c \). For \( k = 1 \), \( \{n : x_n \in B_1(c)\} \) is infinite, so nonempty; let

\[ n_1 = \min \{n : x_n \in B_1(c)\} \]

Now, suppose we have chosen \( n_1 < n_2 < \cdots < n_k \) such that

\[ x_{n_j} \in B_{\frac{1}{j}}(c) \text{ for } j = 1, \ldots, k \]

\( \{n : x_n \in B_{\frac{1}{k+1}}(c)\} \) is infinite, so it contains at least one element bigger than \( n_k \), so let

\[ n_{k+1} = \min \left\{n : n > n_k, x_n \in B_{\frac{1}{k+1}}(c) \right\} \]

Thus, we have chosen \( n_1 < n_2 < \cdots < n_k < n_{k+1} \) such that

\[ x_{n_j} \in B_{\frac{1}{j}}(c) \text{ for } j = 1, \ldots, k, k+1 \]

Thus, by induction, we obtain a subsequence \( \{x_{n_k}\} \) such that

\[ x_{n_k} \in B_{\frac{1}{k}}(c) \]

Given any \( \varepsilon > 0 \), by the Archimedean property, there exists \( N(\varepsilon) > 1/\varepsilon \).

\[ k > N(\varepsilon) \Rightarrow x_{n_k} \in B_{\frac{1}{k}}(c) \]

\[ \Rightarrow x_{n_k} \in B_{\varepsilon}(c) \]

so

\[ x_{n_k} \to c \text{ as } k \to \infty \]
Conversely, suppose that there is a subsequence \( \{x_{n_k}\} \) converging to \( c \). Given any \( \varepsilon > 0 \), there exists \( K \in \mathbb{N} \) such that

\[
k > K \Rightarrow d(x_{n_k}, c) < \varepsilon \Rightarrow x_{n_k} \in B_\varepsilon(c)
\]

Therefore,

\[
\{n : x_n \in B_\varepsilon(c)\} \supseteq \{n_{K+1}, n_{K+2}, n_{K+3}, \ldots\}
\]

Since \( n_{K+1} < n_{K+2} < n_{K+3} < \cdots \), this set is infinite, so \( c \) is a cluster point of \( \{x_n\} \). ■

Section 2.3. Sequences in \( \mathbb{R} \) and \( \mathbb{R}^m \)

**Definition 12** A sequence of real number \( \{x_n\} \) is increasing (decreasing) if \( x_{n+1} \geq x_n \) \((x_{n+1} \leq x_n)\) for all \( n \).

**Definition 13** If \( \{x_n\} \) is a sequence of real numbers, \( \{x_n\} \) tends to infinity (written \( x_n \to \infty \) or \( \lim x_n = \infty \)) if

\[
\forall K \in \mathbb{R} \ \exists N(K) \text{ s.t. } n > N(K) \Rightarrow x_n > K
\]

Similarly define \( x_n \to -\infty \) or \( \lim x_n = -\infty \).

Notice we don’t say the sequence converges to infinity; the term “converge” is limited to the case of finite limits.

**Theorem 14 (Theorem 3.1’)** Let \( \{x_n\} \) be an increasing (decreasing) sequence of real numbers. Then \( \lim_{n \to \infty} x_n = \sup\{x_n : n \in \mathbb{N}\} \) \((\lim_{n \to \infty} x_n = \inf\{x_n : n \in \mathbb{N}\})\). In particular, the limit exists.

**Proof:** Read the proof in the book, and figure out how to handle the unbounded case. ■

**Lim Sups and Lim Infs:**

Consider a sequence \( \{x_n\} \) of real numbers. Let

\[
\alpha_n = \sup\{x_k : k \geq n\} = \sup\{x_n, x_{n+1}, x_{n+2}, \ldots\}
\]

\[
\beta_n = \inf\{x_k : k \geq n\}
\]

Either \( \alpha_n = +\infty \) for all \( n \), or \( \alpha_n \in \mathbb{R} \) and \( \alpha_1 \geq \alpha_2 \geq \alpha_3 \geq \cdots \). Either \( \beta_n = -\infty \) for all \( n \), or \( \beta_n \in \mathbb{R} \) and \( \beta_1 \leq \beta_2 \leq \beta_3 \leq \cdots \).

\(^4\)See the handout for this material.
Definition 15

\[
\begin{align*}
\limsup_{n \to \infty} x_n &= \begin{cases} 
+\infty & \text{if } \alpha_n = +\infty \text{ for all } n \\
\lim \alpha_n & \text{otherwise.}
\end{cases} \\
\liminf_{n \to \infty} x_n &= \begin{cases} 
-\infty & \text{if } \beta_n = -\infty \text{ for all } n \\
\lim \beta_n & \text{otherwise.}
\end{cases}
\end{align*}
\]

Theorem 16 Let \( \{x_n\} \) be a sequence of real numbers. Then

\[
\lim_{n \to \infty} x_n = \gamma \in \mathbb{R} \cup \{-\infty, \infty\} \iff \limsup_{n \to \infty} x_n = \liminf_{n \to \infty} x_n = \gamma
\]

Theorem 17 (Theorem 3.2, Rising Sun Lemma) Every sequence of real numbers contains an increasing subsequence or a decreasing subsequence or both.

Proof: Let

\[
S = \{ s \in \mathbb{N} : x_s > x_n \ \forall n > s \}
\]

Either \( S \) is infinite, or \( S \) is finite.

If \( S \) is infinite, let

\[
\begin{align*}
n_1 &= \min S \\
n_2 &= \min (S \setminus \{n_1\}) \\
n_3 &= \min (S \setminus \{n_1, n_2\}) \\
& \vdots \\
n_{k+1} &= \min (S \setminus \{n_1, n_2, \ldots, n_k\})
\end{align*}
\]

Then \( n_1 < n_2 < n_3 < \cdots \).

\[
\begin{align*}
x_{n_1} > x_{n_2} & \quad \text{since } n_1 \in S \text{ and } n_2 > n_1 \\
x_{n_2} > x_{n_3} & \quad \text{since } n_2 \in S \text{ and } n_3 > n_2 \\
& \vdots \\
x_{n_k} > x_{n_{k+1}} & \quad \text{since } n_k \in S \text{ and } n_{k+1} > n_k \\
& \vdots
\end{align*}
\]
so \( \{x_{n_k}\} \) is a strictly decreasing subsequence of \( \{x_n\} \).

If \( S \) is finite and nonempty, let \( n_1 = (\max S) + 1 \); if \( S = \emptyset \), let \( n_1 = 1 \). Then

\[
\begin{align*}
n_1 &\notin S \quad \text{so} \quad \exists n_2 > n_1 \text{ s.t. } x_{n_2} \geq x_{n_1} \\
n_2 &\notin S \quad \text{so} \quad \exists n_3 > n_2 \text{ s.t. } x_{n_3} \geq x_{n_2} \\
& \quad \vdots \\
n_k &\notin S \quad \text{so} \quad \exists n_{k+1} > n_k \text{ s.t. } x_{n_{k+1}} \geq x_{n_k} \\
& \quad \vdots
\end{align*}
\]

so \( \{x_{n_k}\} \) is a (weakly) increasing subsequence of \( \{x_n\} \).

**Theorem 18 (Thm. 3.3, Bolzano-Weierstrass)** Every bounded sequence of real numbers contains a convergent subsequence.

**Proof:** Let \( \{x_n\} \) be a bounded sequence of real numbers. By the Rising Sun Lemma, find an increasing or decreasing subsequence \( \{x_{n_k}\} \). If \( \{x_{n_k}\} \) is increasing, then by Theorem 3.1', \( \lim x_{n_k} = \sup \{x_{n_k} : k \in \mathbb{N}\} \leq \sup \{x_n : n \in \mathbb{N}\} < \infty \), since the sequence is bounded; since the limit is finite, the subsequence converges. Similarly, if the subsequence is decreasing, it converges.
Figure 2: The unit ball around 0 in different norms on $\mathbb{R}^2$: standard $\| \cdot \|_2$, $\| \cdot \|_1$ ($L^1$ or taxi cab norm) and $\| \cdot \|_\infty$ (sup norm or $L^\infty$ norm).
Figure 3: All norms on $\mathbb{R}^n$ are equivalent.