Econ 204 2020

Lecture 3

Outline

1. Metric Spaces and Normed Spaces
2. Convergence of Sequences in Metric Spaces
3. Sequences in $\mathbf{R}$ and $\mathbf{R}^n$

Metric Spaces and Metrics

Generalize distance and length notions in $\mathbf{R}^n$

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

1. $d(x, y) \geq 0$, $d(x, y) = 0 \Leftrightarrow x = y \; \forall x, y \in X$

2. $d(x, y) = d(y, x) \; \forall x, y \in X$

3. triangle inequality*:*

$$d(x, z) \leq d(x, y) + d(y, z) \quad \forall x, y, z \in X$$

$$\begin{array}{ccccc} & & y & & \\ & \nearrow & & \searrow & \\ x & & \longrightarrow & & z \end{array}$$

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

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

Normed Spaces and Norms

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

1. $\|x\| \geq 0 \; \forall x \in V$

2. $\|x\| = 0 \Leftrightarrow x = 0 \; \forall x \in V$

3. triangle inequality*:*

$$\|x + y\| \leq \|x\| + \|y\| \; \forall x, y \in V$$

$$\begin{array}{ccccc} & & x & & \\ x & \nearrow & & \searrow & y \\ 0 & & \longrightarrow & & x+y \\ y & \searrow & & \nearrow & x \\ & & y & & \end{array}$$

4. $\|\alpha x\| = |\alpha|\|x\| \ \forall \alpha \in \mathbf{R}, x \in V$

A normed vector space *is a vector space over* $\mathbf{R}$ *equipped with a norm.*

A norm gives a notion of length of a vector in V.

Normed Spaces and Norms

Example: In $\mathbf{R}^n$, standard notion of distance between two vectors x and y measures length of 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 1. *Let* $(V, \|\cdot\|)$ *be a normed vector space. Let* $d : V \times V \Rightarrow \mathbf{R}_+$ *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

$$
\begin{aligned}
d(v, w) = 0 &\Leftrightarrow \|v - w\| = 0 \\
&\Leftrightarrow v - w = 0 \\
&\Leftrightarrow (v + (-w)) + w = w \\
&\Leftrightarrow v + ((-w) + w) = w \\
&\Leftrightarrow v + 0 = w \\
&\Leftrightarrow v = w
\end{aligned}
$$

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 $v, w \in V$.

$$\begin{aligned} d(v,w) &= \|v - w\| \\ &= |-1|\|v - w\| \\ &= \|(-1)(v + (-w))\| \\ &= \|(-1)v + (-1)(-w)\| \\ &= \|-v + w\| \\ &= \|w + (-v)\| \\ &= \|w - v\| \\ &= d(w,v) \end{aligned}$$

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

$$\begin{aligned} d(u,w) &= \|u-w\| \\ &= \|u+(-v+v)-w\| \\ &= \|u-v+v-w\| \\ &\leq \|u-v\|+\|v-w\| \\ &= d(u,v)+d(v,w) \end{aligned}$$

Thus d is a metric on V. $\square$

Normed Spaces and Norms

Examples

- $\mathbf{E}^n$: n-dimensional Euclidean space.

$$V = \mathbf{R}^n, \ \|x\|_2 = |x| = \sqrt{\sum_{i=1}^{n} (x_i)^2}$$

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

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

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

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

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

Normed Spaces and Norms

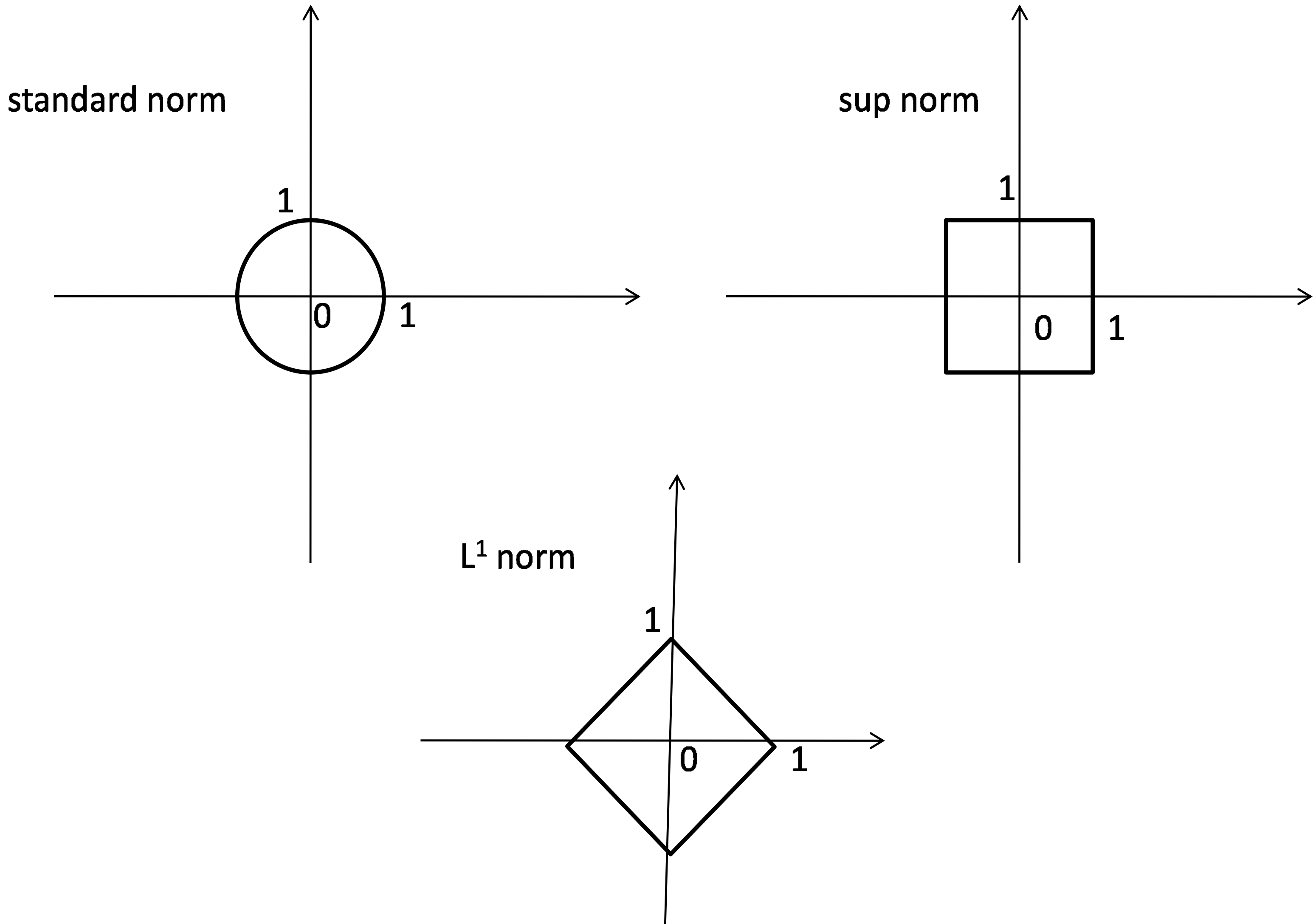
Theorem 2 (Cauchy-Schwarz Inequality)**.**
If $v, w \in \mathbf{R}^n$*, then*

$$
\begin{aligned}
\left(\sum_{i=1}^{n} v_i w_i\right)^2 &\leq \left(\sum_{i=1}^{n} v_i^2\right)\left(\sum_{i=1}^{n} w_i^2\right) \\
|v \cdot w|^2 &\leq |v|^2 |w|^2 \\
|v \cdot w| &\leq |v||w|
\end{aligned}
$$

Equivalent Norms

A given vector space may have many different norms: 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, $\mathbf{R}^n$ supports many different norms as in the examples above. Different norms on a given vector space yield different geometric properties.



unit balls around 0 in different norms

Equivalent Norms

Definition 3. *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.* $\forall x \in V, x \neq 0$*,*

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

Equivalent Norms

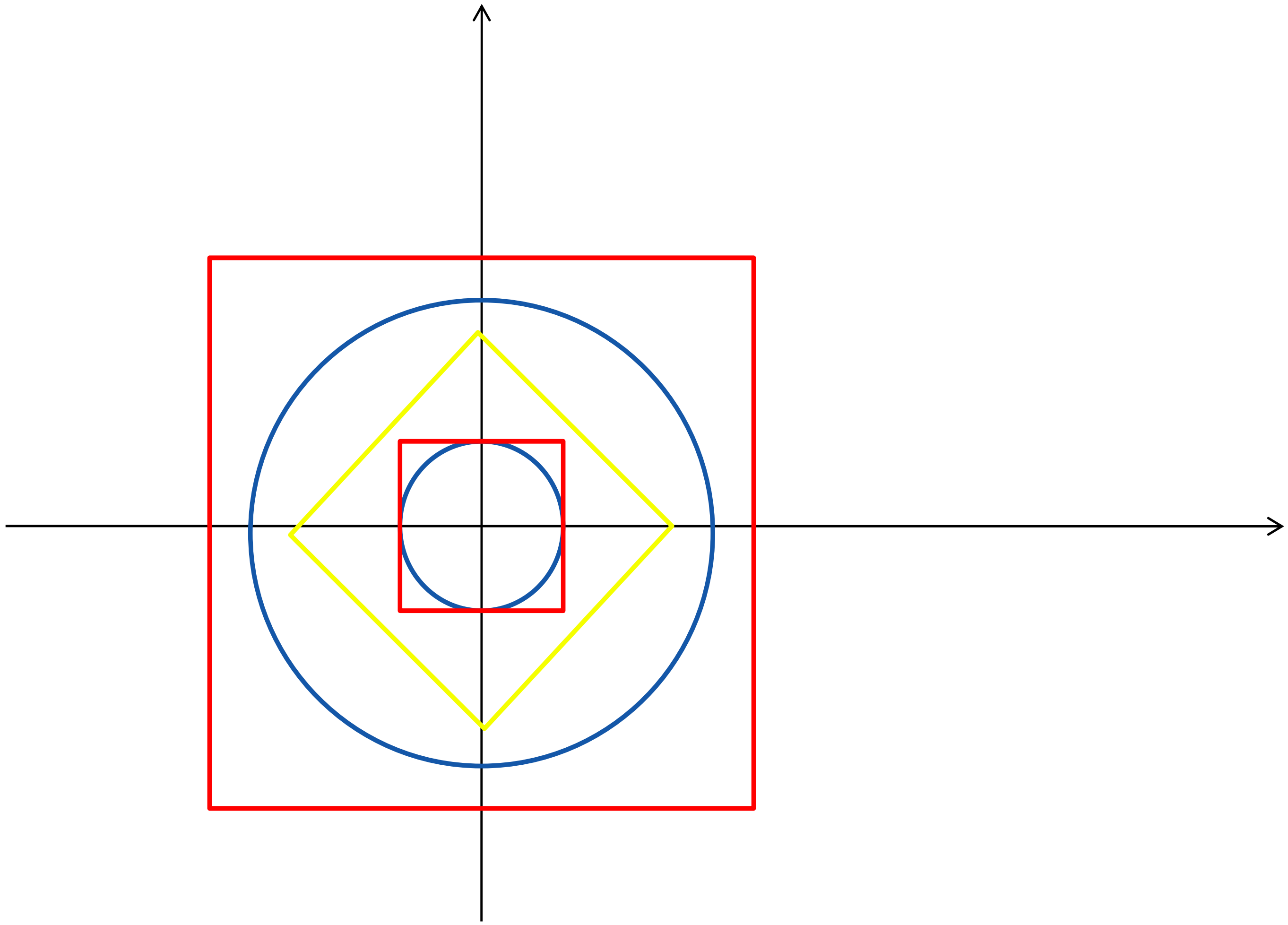
If two norms are equivalent, then they define the same notions of convergence and continuity. For topological purposes, equivalent norms are indistinguishable.

For example, suppose two norms $\|\cdot\|$ and $\|\cdot\|^*$ on the vector space V are equivalent, and fix $x \in V$. Let

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

Then for any $\varepsilon > 0$,

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



norms on **R**^{n} are equivalent

Equivalent Norms

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

Theorem 3. *All norms on $\mathbf{R}^n$ are equivalent.*

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

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

Metrics and Sets

Definition 4. *In a metric space* (X, d)*, a subset* $S \subseteq X$ *is* bounded *if* $\exists x \in X, \beta \in \mathbf{R}$ *such that* $\forall s \in S$*,* $d(s, x) \leq \beta$*.*

In a metric space (X, d), define

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

Metrics and Sets

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:

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

But $d(A, B)$ is **not** a metric.

Convergence of Sequences

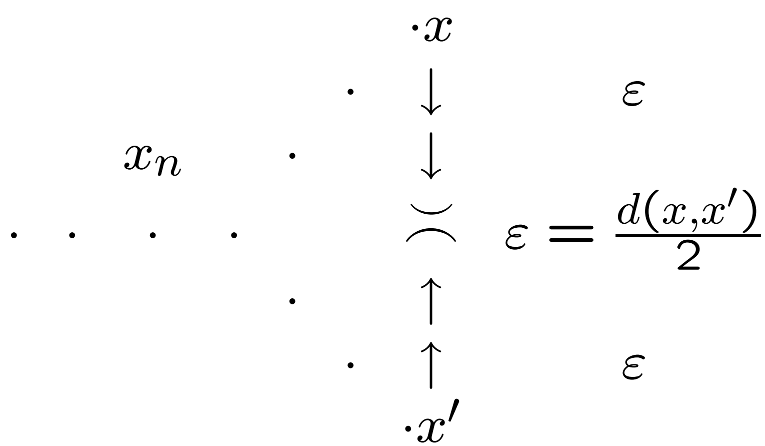
Definition 5. *Let* (X, d) *be a metric space. A sequence* $\{x_n\}$ converges *to* x *(written* $x_n \to x$ *or* $\lim_{n\to\infty} x_n = x$*) if*

$$\forall \varepsilon > 0\ \exists N(\varepsilon) \in \mathbf{N} \text{ s.t. } n > N(\varepsilon) \Rightarrow d(x_n, x) < \varepsilon$$

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 $\mathbf{R}$ by the general metric d.

Uniqueness of Limits

Theorem 4 (Uniqueness of Limits)**.** *In a metric space* (X, d)*, if* $x_n \to x$ *and* $x_n \to x'$*, then* $x = x'$*.*



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

$$n > N(\varepsilon) \;\Rightarrow\; d(x_n, x) < \varepsilon$$
$$n > N'(\varepsilon) \;\Rightarrow\; d(x_n, x') < \varepsilon$$

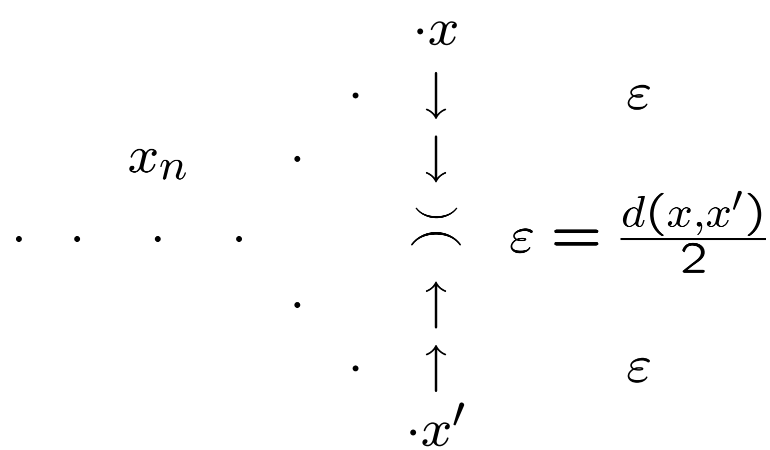
Choose

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

Then

$$
\begin{aligned}
d(x, x') &\leq d(x, x_n) + d(x_n, x') \\
&< \varepsilon + \varepsilon \\
&= 2\varepsilon \\
&= d(x, x') \\
d(x, x') &< d(x, x')
\end{aligned}
$$

a contradiction. $\square$


$\cdot x$
ε
x_n
$\varepsilon = \frac{d(x,x')}{2}$
ε
$\cdot x'$

Cluster Points

Definition 6. *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,*

$$\forall \varepsilon > 0, N \in \mathbf{N}\ \exists n > N \text{ s.t. } x_n \in B_\varepsilon(c)$$

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 $\{0, 1\}$.

Subsequences

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 $\{x_{n_k}\} = \left(\frac{1}{2}, \frac{1}{4}, \frac{1}{6}, \ldots\right)$.

Cluster Points and Subsequences

Theorem 5 (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 $N(\varepsilon) > 1/\varepsilon$.

$$\begin{aligned} k > N(\varepsilon) &\Rightarrow x_{n_k} \in B_{\frac{1}{k}}(c) \\ &\Rightarrow x_{n_k} \in B_{\varepsilon}(c) \end{aligned}$$

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 $K \in \mathbf{N}$ 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 $\{x_n\}$. $\square$

Sequences in $\mathbf{R}$ and $\mathbf{R}^m$

Definition 7. *A sequence of real numbers* $\{x_n\}$ *is* increasing (decreasing*) if* $x_{n+1} \geq x_n$ ($x_{n+1} \leq x_n$) *for all* n.

Definition 8. *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*

$$\forall K \in \mathbf{R}\ \exists N(K) \text{ s.t. } n > N(K) \Rightarrow x_n > K$$

Similarly define $x_n \to -\infty$ *or* $\lim x_n = -\infty$.

Increasing and Decreasing Sequences

Theorem 6 (Theorem 3.1'). *Let* $\{x_n\}$ *be an increasing (decreasing) sequence of real numbers. Then*

$$\lim_{n\to\infty} x_n = \sup\{x_n : n \in \mathbf{N}\}$$

$$\left(\lim_{n\to\infty} x_n = \inf\{x_n : n \in \mathbf{N}\} \right)$$

In particular, the limit exists.

Lim Sups and Lim Infs

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

$$\begin{aligned} \alpha_n &= \sup\{x_k : k \geq n\} \\ &= \sup\{x_n, x_{n+1}, x_{n+2}, \ldots\} \\ \beta_n &= \inf\{x_k : k \geq n\} \\ &= \inf\{x_n, x_{n+1}, x_{n+2}, \ldots\} \end{aligned}$$

Either $\alpha_n = +\infty$ for all n, or $\alpha_n \in \mathbf{R}$ and $\alpha_1 \geq \alpha_2 \geq \alpha_3 \geq \cdots$.

Either $\beta_n = -\infty$ for all n, or $\beta_n \in \mathbf{R}$ and $\beta_1 \leq \beta_2 \leq \beta_3 \leq \cdots$.

Lim Sups and Lim Infs

Definition 9.

$$\limsup_{n\to\infty} x_n = \begin{cases} +\infty & \textit{if } \alpha_n = +\infty \textit{ for all } n \\ \lim \alpha_n & \textit{otherwise.} \end{cases}$$

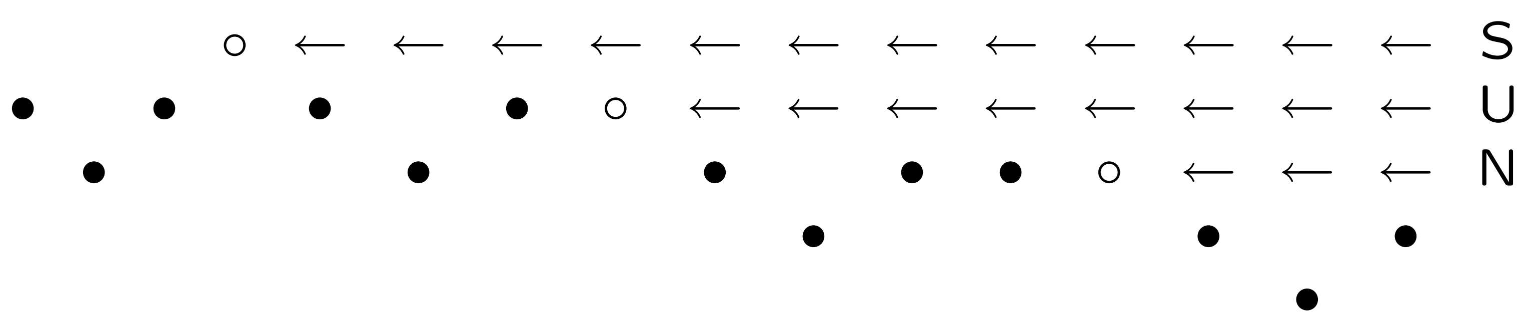
$$\liminf_{n\to\infty} x_n = \begin{cases} -\infty & \textit{if } \beta_n = -\infty \textit{ for all } n \\ \lim \beta_n & \textit{otherwise.} \end{cases}$$

Theorem 7. *Let $\{x_n\}$ be a sequence of real numbers. Then*

$$\lim_{n\to\infty} x_n = \gamma \in \mathbf{R} \cup \{-\infty, \infty\}$$
$$\Leftrightarrow \limsup_{n\to\infty} x_n = \liminf_{n\to\infty} x_n = \gamma$$

Increasing and Decreasing Subsequences

Theorem 8 (Theorem 3.2, Rising Sun Lemma)**.** *Every sequence of real numbers contains an increasing subsequence or a decreasing subsequence or both.*



Proof. Let

$$S = \{s \in \mathbf{N} : x_s > x_n \quad \forall n > s\}$$

Either S is infinite, or S is finite.

If S is infinite, let

$$\begin{aligned} n_1 &= \min S \\ n_2 &= \min (S \setminus \{n_1\}) \\ n_3 &= \min (S \setminus \{n_1, n_2\}) \\ &\vdots \\ n_{k+1} &= \min (S \setminus \{n_1, n_2, \ldots, n_k\}) \end{aligned}$$

Then $n_1 < n_2 < n_3 < \cdots$.

$$\begin{aligned} x_{n_1} > x_{n_2} &\quad \text{since } n_1 \in S \text{ and } n_2 > n_1 \\ x_{n_2} > x_{n_3} &\quad \text{since } n_2 \in S \text{ and } n_3 > n_2 \\ &\quad \vdots \\ x_{n_k} > x_{n_{k+1}} &\quad \text{since } n_k \in S \text{ and } n_{k+1} > n_k \\ &\quad \vdots \end{aligned}$$

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

$$\begin{array}{lcl} n_1 \notin S & \text{so} & \exists n_2 > n_1 \text{ s.t. } x_{n_2} \geq x_{n_1} \\ n_2 \notin S & \text{so} & \exists n_3 > n_2 \text{ s.t. } x_{n_3} \geq x_{n_2} \\ & \vdots & \\ n_k \notin S & \text{so} & \exists n_{k+1} > n_k \text{ s.t. } x_{n_{k+1}} \geq x_{n_k} \\ & \vdots & \end{array}$$

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

Bolzano-Weierstrass Theorem

Theorem 9 (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',

$$\lim x_{n_k} = \sup\{x_{n_k} : k \in \mathbf{N}\} \leq \sup\{x_n : n \in \mathbf{N}\} < \infty$$

since the sequence is bounded; since the limit is finite, the subsequence converges. Similarly, if the subsequence is decreasing, it converges. □