

Columbia MA Math Camp

Real Analysis

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- In real analysis (and also in micro) we often need to use concepts related to limits and convergence
- By saying that a sequence of objects converges to a limiting object, we mean, roughly speaking, that the sequence will get "as close as we want" to the limit.
- To be able to talk about how close 2 objects are, we need the concept of distance.
- Metric spaces are the general framework that capture the concept of distance, but we will focus on Euclidean metric spaces
 - Pretty much the only thing economists work with
 - Easier to visualize

Euclidean Spaces

Sequences and Convergence

Open and Closed Sets

Defining Metric Spaces

Definition 1.1

Let X be a set, and $d : X \times X \rightarrow \mathbb{R}$ a function. We call d a **metric** on X if:

- **Positive Definiteness** : $d(x, y) \geq 0$ for all $x, y \in X$, and $d(x, y) = 0$ iff $x = y$
- **Symmetry** : $d(x, y) = d(y, x)$
- **Triangle Inequality** : $d(x, z) \leq d(x, y) + d(y, z)$ for all $x, y, z \in X$

A **metric space** (X, d) is a set X with a metric d defined on X

Example : A trivial example is the discrete metric :

$$d(x, y) = \begin{cases} 1 & \text{if } x \neq y \\ 0 & \text{if } x = y \end{cases}$$

Does this satisfy the properties of a metric? We will however focus on Euclidean metric spaces.

Discrete Metric is actually a metric

Discrete metric : $d(x, y) = \begin{cases} 0 & x = y \\ 1 & x \neq y \end{cases}$

Let us check that the discrete metric satisfies the 3 properties of a metric :

- (a) By definition $d(x, y) = 0$ iff $x = y$
- (b) Symmetric is also trivial
- (c) Take $x, y, z \in X$. If $x = y$, then $d(x, y) = 0 \leq d(x, z) + d(z, y)$. If $x \neq y$, then we must have $d(x, z) = 1$ OR $d(z, y) = 1$. In either case we have :

$$d(x, y) = 1 \leq d(x, z) + d(z, y)$$

Definition 1.2

In \mathbb{R}^n , the **Euclidean distance** is the function $d : \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R}^+$:

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

Euclidean distance satisfies the 3 properties that we mentioned earlier:

- $d(x, y) \geq 0$, and $d(x, y) = 0$ iff $x = y$
- $d(x, y) = d(y, x)$
- $d(x, y) \leq d(x, z) + d(z, y)$

Let us prove the first two properties. Triangle Inequality is hard to show - requires the Cauchy Schwarz inequality.

Euclidean metric proof

Fact 1

Prove that the Euclidean metric satisfies the first two properties of a metric

Proof.

(a) WTS that $d(x, y) = 0$ iff $x = y$ for any $x, y \in \mathbb{R}^n$.

(\implies) : If $d(x, y) = \sqrt{\sum_{i=1}^n (x_i - y_i)^2} = 0$, this implies $\sum_{i=1}^n (x_i - y_i)^2 = 0$. Since $(x_i - y_i)^2 \geq 0$ for each i which means that $(x_i - y_i)^2 = 0 \forall i$ and thus $x_i = y_i \forall i$. Thus $x = y$

(\impliedby) : If $x = y$, we have $x_i = y_i$ for each i . Therefore

$$d(x, y) = \sqrt{\sum_{i=1}^n (x_i - y_i)^2} = 0$$

(b) WTS that $d(x, y) = d(y, x)$. This follows from the fact that :

$$\sqrt{\sum_{i=1}^n (x_i - y_i)^2} = \sqrt{\sum_{i=1}^n (y_i - x_i)^2}$$

Definition 1.3

A subset S of \mathbb{R}^n is **bounded** if there exists $M \in \mathbb{R}$ such that for all $x \in S$, $d(0, x) \leq M$.

Note: We could have chosen any $a \in \mathbb{R}^n$ in the place of 0. Suppose S is bounded with respect to 0. Then for any $x \in S$ the triangle inequality tells us

$$d(a, x) \leq d(a, 0) + d(0, x) \leq d(a, 0) + M$$

Thus S is bounded with respect to a as well.

Definition 1.4

Let $S \subseteq \mathbb{R}$. A number $M \in \mathbb{R}$ is an **upper bound** of S if $s \leq M$ for every $s \in S$.

If no $M' < M$ is an upper bound of S , then M is called the **least upper bound** or **supremum** of S .

We make one important assumption about the real numbers: every bounded set of real numbers has a least upper bound. This is called the **least upper bound property**.

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Sequences: Definition

Formally, a **sequence** in a set X is a function from \mathbb{N} to X . We denote x_n the image of n , and (x_n) the sequence.

Less formally, a sequence is an **ordered collection** of elements (x_0, x_1, x_2, \dots) . Many problems in math boil down to understanding the long-term behavior of some sequence.

We typically write sequences as a formula or by enumerating the first few terms.

- $(x_n) = (n)_{n=0}^{\infty} : (0, 1, 2, 3, \dots)$
- $(x_n) = (1)_{n=0}^{\infty} : (1, 1, 1, 1, \dots)$
- $(x_n) = \left(\frac{1+(-1)^n}{2}\right)_{n=0}^{\infty} : (1, 0, 1, 0, \dots)$
- $(x_n) = \left(\frac{1}{n+1}\right)_{n=0}^{\infty} : (1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \dots)$

You'll also see people write things like $x_n = n$.

In \mathbb{R}^n we can define properties of sequences that rely on the notion of distance.

Definition 2.1

A sequence (x_n) of $S \subseteq \mathbb{R}^n$ is **bounded** iff $\{x_0, \dots, x_n, \dots\}$ is a bounded subset of \mathbb{R}^n .

Are the sequences $x_n = n$ and $x_n = 1/n$ bounded or unbounded?

- The sequence $x_n = n$ is not bounded. For any $M \in \mathbb{R}$, $d(x_n, 0) > M$ for $n > M$.
- The sequence $x_n = \frac{1}{n}$ is bounded: $d(x_n, 0) \leq 1$ for all n

Definition 2.2

A sequence (x_n) of $S \subseteq \mathbb{R}^n$ **converges to a limit** $\ell \in S$ iff for all $\epsilon > 0$, there exists an integer $N(\epsilon)$ such that for all $n \geq N(\epsilon)$

$$d(x_n, \ell) < \epsilon$$

We write $x_n \rightarrow \ell$ or $\lim_{n \rightarrow \infty} x_n = \ell$. If (x_n) does not converge, we say it **diverges**.

This definition is important, so let's unpack it a little:

- The sequence must eventually **get and remain** arbitrarily close to ℓ
- N can be different for each ϵ .
- We require $\ell \in S$. Consider $(x_n) = (1, \frac{1}{2}, \frac{1}{3}, \dots)$. What happens if $S = \mathbb{R}$? If $S = (0, 2)$?

Proposition 2.1

If a sequence (x_n) converges, then (x_n) is bounded.

Proof.

Assume $x_n \rightarrow \ell$.

- Take $\epsilon = 1$
- Since $x_n \rightarrow \ell$, by definition there exists $N \in \mathbb{N}$ such that for all $n \geq N$, $d(x_n, \ell) < 1$.

This proves that the sequence starting at N is bounded, but we need to deal with the first $N - 1$ terms.

- Define $M \equiv \max\{d(x_1, \ell), \dots, d(x_{N-1}, \ell), 1\}$
- For all n , $d(x_n, \ell) \leq M$



Limit (if exists) must be unique

Proposition 2.2

The limit of a sequence (x_n) is unique provided it exists i.e. if $x_n \rightarrow x$ and $x_n \rightarrow x'$, then $x = x'$

Proof.

We prove this by contradiction. Suppose $x \neq x'$. Thus it must be that $d(x, x') > 0$.

Consider $\varepsilon = \frac{d(x, x')}{2}$.

Because $x_n \rightarrow x$, there exists N such that $d(x_n, x) < \varepsilon$ for any $n > N$. Similarly, because $x_n \rightarrow x'$, there exists N' such that $d(x_n, x') < \varepsilon$ for any $n > N'$. Take $\hat{n} = \max\{N, N'\} + 1$ so that $\hat{n} > N$ and $\hat{n} > N'$. There $d(x_{\hat{n}}, x) < \varepsilon$ and $d(x_{\hat{n}}, x') < \varepsilon$. Thus it must be that :

$$d(x, x_{\hat{n}}) + d(x_{\hat{n}}, x') < 2\varepsilon = d(x, x')$$

which contradicts the triangle inequality of d . Thus we have reached a logical contradiction and therefore $x = x'$. □

Order of Limits are preserved in sequences

Proposition 2.3

In the Euclidean metric space (\mathbb{R}, d) , suppose there are 2 convergent sequences $x_n \rightarrow x$ and $y_n \rightarrow y$. If $x_n \leq y_n \forall n$, then prove that $x \leq y$

Proof.

We do this by contradiction. Suppose $x > y$ and set $\varepsilon = \frac{x-y}{2}$. Since $x_n \rightarrow x$ and $y_n \rightarrow y$, then by definition, $\exists N_x$ and N_y such that $|x_n - x| < \varepsilon$ and $|y_n - y| < \varepsilon \forall n > N_x$ and $n > N_y$. Take $\hat{n} > \max\{N_x, N_y\}$. Then we must have $|x_{\hat{n}} - x| < \varepsilon$ and $|y_{\hat{n}} - y| < \varepsilon$. Since $\varepsilon = \frac{x-y}{2}$, this implies, $x - \varepsilon = y + \varepsilon$

$$x_{\hat{n}} > x - \varepsilon = y + \varepsilon > y_{\hat{n}}$$

which contradicts $x_n \leq y_n \forall n$

□

Here is a result you'll show on your problem set:

Proposition 2.4

A sequence $(x^k) = (x_1^k, \dots, x_n^k)$ of \mathbb{R}^n converges to a limit x iff each component converges to the corresponding component of x in \mathbb{R} .

The result boils down to the fact that for all $j \in \{1, \dots, n\}$:

$$|x_j - x_j^k| \leq \left(\sum_{i=1}^n (x_j - x_j^i)^2 \right)^{\frac{1}{2}} \leq n \max_i |x_i - x_i^k|$$

Convergent sequences: results (cont.)

In general, working with the definition of convergence is cumbersome. There are some important results we'll use frequently

Proposition 2.5

Let (x_n) and (y_n) be sequences of \mathbb{R} . If $(x_n) \rightarrow x$ and $(y_n) \rightarrow y$:

- (a) $x_n + y_n \rightarrow x + y$
- (b) $x_n y_n \rightarrow xy$
- (c) $1/x_n \rightarrow 1/x$ if $x \neq 0$

Proof.

We'll show the second one and the rest will probably be on your problem set.



Proof of Property (b)

Proposition 2.6

Let (x_n) and (y_n) be sequences of \mathbb{R} . If $(x_n) \rightarrow x$ and $(y_n) \rightarrow y$ then $x_n y_n \rightarrow xy$

Proof.

Take any $\varepsilon > 0$. I want to find N such that $|x_n y_n - xy| < \varepsilon$ for any $n > N$.

Because (y_n) is convergent, it is bounded i.e. there exists M such that $|y_n| < M \forall n$.

Because $x_n \rightarrow x$, there exists N_x s.t $|x_n - x| < \frac{\varepsilon}{2M}$. Again since $y_n \rightarrow y$, there exists N_y such that $|y_n - y| < \frac{\varepsilon}{2(|x|+1)}$.

Let $N = \max\{N_x, N_y\}$ and I claim this is the N we need to find. This is because for any $n > N$,

$$\begin{aligned} |x_n y_n - xy| &= |(x_n - x)y_n + (y_n - y)x| \\ &\leq |x_n - x| |y_n| + |y_n - y| |x| \\ &< \frac{\varepsilon}{2M} \cdot M + \frac{\varepsilon}{2(|x|+1)} \cdot |x| \\ &< \frac{\varepsilon}{2} + \frac{\varepsilon}{2} = \varepsilon \end{aligned}$$



Definition 2.3

Let (x_n) be a sequence. A **subsequence** of (x_n) is a sequence (x_{n_k}) where $n_1 < n_2 < \dots$ is an increasing sequence of indices.

- (x_2, x_3, x_5, \dots) is a subsequence of (x_n)
- (x_4, x_3, x_2, \dots) is not (the terms are out of order).

Proposition 2.7

A sequence (x_n) converges to a limit ℓ iff all its subsequences converge to the same limit ℓ .

Proof.

(\Rightarrow) Assume $(x_n) \rightarrow \ell$ and consider a subsequence (x_{n_k}) of (x_n) . Fix $\epsilon > 0$. There exists $N \in \mathbb{N}$ such that for all $n \geq N$, $d(x_n, \ell) < \epsilon$. Take K such that $n_K \geq N$. Then for all $k \geq K$, $n_k \geq n_K \geq N$, so $d(x_{n_k}, \ell) < \epsilon$.

(\Leftarrow) Since (x_n) is a subsequence of itself, this implication is immediate. □

Proposition 2.8

Bolzano-Weierstrass Theorem *Every bounded sequence of real numbers has a convergent subsequence.*

Proof.

To do this, we will first prove :

- **Monotone Convergence Theorem** : Every increasing (decreasing) and bounded from above (below) real sequence is convergent in $(\mathbb{R},)$
- Every sequence in \mathbb{R} has a monotone subsequence.

Combining these 2 results, we get that the Bolzano-Weierstrass Theorem holds. □

Monotone Convergence Theorem

Proposition 2.9

Monotone Convergence Theorem *Every increasing (decreasing) and bounded from above (below) real sequence is convergent in (\mathbb{R}, d)*

Proof.

Take any increasing and bounded real sequence (x_n) . By the least upper bound property of \mathbb{R} , it has a l.u.b.

Let $x := \sup x_1, x_2, \dots$. We want to show $x_n \rightarrow x$. Take any $\varepsilon > 0$. Want to find N s.t. $d(x_n, x) < \varepsilon \forall n > N$. Since x is the lub $\implies x - \varepsilon$ is not an upper bound and therefore $\exists N$ s.t. $x_N > x - \varepsilon$. Therefore $\forall n > N$, it must be that :

$$x \geq x_n \geq x_N > x - \varepsilon$$

and therefore $|x_n - x| < \varepsilon$

The proof for a decreasing and bounded from below sequence (x_n) is completed by applying the proof above to $(-x_n)$. □

Every sequence in \mathbb{R} has a monotone subsequence

Proposition 2.10

Every sequence in \mathbb{R} has a monotone subsequence

Proof.

Take any sequence (x_n) in \mathbb{R} . Call the term x_n a dominant term if $x_n > x_m$ for all $m \geq n$.

- **Case 1 :** (x_n) has infinitely many dominant terms. Then these dominant terms constitute a decreasing sequence
- **Case 2 :** (x_n) has finitely many dominant terms. Let x_N be the last dominant term. Let $n_1 = N + 1$. So x_{n_1} is not a dominant term. This means there exists $n_2 > n_1$ s.t. $x_{n_2} > x_{n_1}$. Again x_{n_2} is not dominant which implies there exists n_3 st $x_{n_3} > x_{n_2}$ and so on. We thus obtain a strictly increasing sequence
- **Case 3 :** (x_n) has no dominant terms. We can let $n_1 = 1$ and then we're back in the previous case.



- When a sequence converges, its terms become closer and closer to the limit as n increases. As a by-product, the terms themselves become closer and closer together.
- The notion of a Cauchy sequence weakens the requirement of convergence by only requiring that the terms get closer together
 - Without necessarily converging to a limit.

Cauchy Sequences (contd)

- How do we actually know when a sequence converges? Do we have to calculate the limit?

$$a_n = \sum_{k=1}^n \frac{1}{k^2}$$

- Turns out the right notion is that of **Cauchy sequences**
- In many situations, we will show that Cauchy sequences are the same as convergent sequences which will help us show that a sequence is convergent without specifying the limit

Cauchy Sequences (cont.)

Definition 2.4

A sequence (x_n) is **Cauchy** iff:

$$\forall \epsilon > 0, \exists N(\epsilon) \in \mathbb{N} \text{ such that } \forall n, m \geq N(\epsilon), d(x_n, x_m) < \epsilon$$

- Not enough for subsequent terms to be close: **all** terms after a certain point must be close.
- Let's show (a_n) on the previous slide is Cauchy. Fix $\epsilon > 0$, and take $N > 1/\epsilon$:

$$\begin{aligned} d(x_n, x_m) &= \sum_{k=n+1}^m \frac{1}{k^2} < \sum_{k=n+1}^m \frac{1}{k(k-1)} \\ &= \sum_{k=n+1}^m \frac{1}{k-1} - \frac{1}{k} \\ &= \frac{1}{n} - \frac{1}{m} < \epsilon \end{aligned}$$

Proposition 2.11

If (x_n) is Cauchy, it is bounded

Proof.

There exists N such that $d(x_n, x_m) < 1$ for all $n, m \geq N$. In particular, $d(x_n, x_N) < 1$, so $\{x_n | n \geq N\}$ is bounded.

Since $\{x_n | n < N\}$ is also bounded, the whole sequence is bounded. □

Question: Is the reverse implication true? Counter-example?

Convergence of a subsequence implies convergence

Proposition 2.12

If a subsequence of a Cauchy sequence converges to ℓ , the sequence itself converges to ℓ .

Proof.

Let (x_n) be Cauchy, and suppose $x_{n_k} \rightarrow \ell$. Fix $\epsilon > 0$. Since (x_n) is Cauchy, there exists an N such that

$$d(x_n, x_m) < \epsilon/2, \forall n, m \geq N$$

Since $(x_{n_k}) \rightarrow \ell$, there exists K such that

$$d(x_{n_k}, \ell) < \epsilon/2, \forall k \geq K$$

Take k such that $N_k \geq \max(N, n_K)$. Then for all $n \geq N$:

$$d(x_n, \ell) < d(x_n, x_{n_k}) + d(x_{n_k}, \ell) < \epsilon/2 + \epsilon/2 = \epsilon$$

Thus $x_n \rightarrow \ell$.



Do Cauchy sequences converge?

Theorem 2.1

In \mathbb{R}^n a sequence converges iff it is Cauchy.

Proof.

(\Rightarrow) Suppose $x_n \rightarrow \ell$. Let $\epsilon > 0$. There exists N such that for all $n \geq N$, $d(x_n, \ell) < \epsilon/2$. Let $n, m \geq N$. By the triangle inequality,

$$d(x_n, x_m) \leq d(x_n, \ell) + d(\ell, x_m) < \epsilon/2 + \epsilon/2 = \epsilon$$

(\Leftarrow) Since Cauchy sequences are bounded, by Prop. 2.8, (x_n) has a convergent subsequence. From the result above, (x_n) converges. □

Definition 2.5

*Spaces in which Cauchy sequences converge are called **complete metric spaces***

Can you give an example of a Cauchy sequence which does not converge? (**Hint:** Impossible in \mathbb{R} .)

Do Cauchy sequences converge?

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Definition 2.5

*Spaces in which Cauchy sequences converge are called **complete metric spaces***

Can you give an example of a Cauchy sequence which does not converge? (**Hint:** Impossible in \mathbb{R} .)

Consider the rational numbers \mathbb{Q} and the sequence given by :

$$a_n = \left(1 + \frac{1}{n}\right)^n$$

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Open and Closed Sets

- Most of economics deals with sets: budget sets, indifference curves, production sets, the set of unbiased estimators, etc. It's useful to have well-defined language to describe the structure of sets.
- In addition, many common concepts and results (limits, continuity, existence of maxima, etc.) rely on the notion of open and closed sets.
- As a silly example consider the sets $S_1 = [0, 1]$ and $S_2 = (0, 1)$. The points 0 and 1 seem special: they are on the “edge” of both sets. The difference between S_1 and S_2 is whether they contain these points on the edge (turns out to be an important distinction!)

Open Balls

Definition 3.1

In \mathbb{R}^n , an **open ball** with center a and radius $r > 0$ is the subset of all points at a distance less than r from a :

$$B(a, r) = \{x \in \mathbb{R}^n \mid d(x, a) < r\}$$

Note: Even though I'm writing $d(x, a)$, I mean the Euclidean metric.

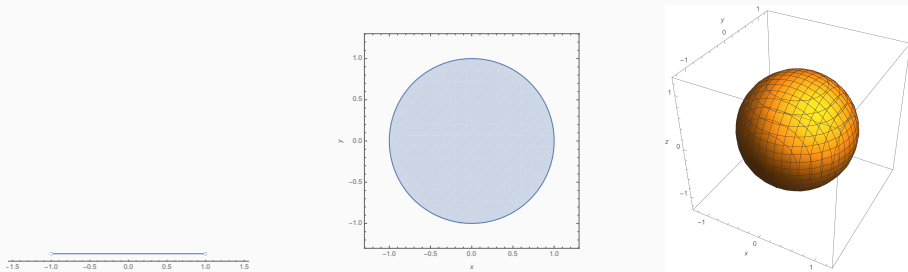


Figure 1: Open balls in \mathbb{R} , \mathbb{R}^2 , and \mathbb{R}^3

Definition 3.2

Let S be a subset of \mathbb{R}^n

- A point $a \in \mathbb{R}^n$ is an **interior point** of S if $\exists r > 0$ such that $B(a, r) \subseteq S$.
- The **interior** of S , noted $\text{int}(S)$ is the set of all its interior point.
- A subset S is an **open set** if all its points are interior points of S , i.e. if $\text{int}(S) = S$.
- Because an interior point of S always belongs to S , $\text{int}(S) \subseteq S$.
- To show a set is open, take an arbitrary point $s \in S$ and find a radius such that $B(s, r) \subseteq S$.

Proposition 3.1

Any open ball is an open set.

Proof.

Terminology is not a proof!

Consider an open ball $B(a, r)$. We will show every point is interior.

- Let $x \in B(a, r)$. We need to find a radius $R > 0$ such that $B(x, R) \subseteq B(a, r)$
- Define $R = r - d(a, x) > 0$
- Using the triangle inequality, for any $y \in B(x, R)$:

$$d(y, a) \leq d(y, x) + d(x, a) < r.$$



Proposition 3.2

- *Any union (possibly infinite) of open sets is an open set.*
- *Any finite intersection of open sets is an open set.*

Proof.

We will show the first result.

- Let $\{S_i\}$ be a family of open sets and $S \equiv \cup_i S_i$. Need to show $S = \text{int}(S)$.
- For any $x \in S$, $x \in S_i$ for some i .
- Since S_i is open, there exists $r > 0$ such that $B(x, r) \subseteq S_i$.
- But $S_i \subseteq S$, so $B(x, r) \subseteq S$, so $x \in \text{int}(S)$.



Definition 3.3

Let S be a subset of \mathbb{R}^n .

- A point $a \in \mathbb{R}^n$ is a **closure point** of S iff for any radius $r > 0$, the open ball $B(a, r)$ around a contains some point of S . In other words, for all $r > 0$, $B(a, r) \cap S \neq \emptyset$
- The **closure** of a subset S , $cl(S)$, is the set of all its closure points.
- A subset S is a **closed set** iff $cl(S) = S$.

A point that belongs to S is always a closure point of S , so $S \subseteq cl(S)$.

Proposition 3.3

- The complement of $\text{int}(S)$ is the closure of S^c : $(\text{int}(S))^c = \text{cl}(S^c)$.
- The complement of $\text{cl}(S)$ is the interior of S^c : $(\text{cl}(S))^c = \text{int}(S^c)$.

Proof.

We'll show the first result. The definition of $\text{int}(S)$ is:

$$a \in \text{int}(S) \Leftrightarrow \exists r > 0 : B(a, r) \subseteq S$$

Take the negation of each side of the equivalence:

$$a \in (\text{int}(S))^c \Leftrightarrow \forall r > 0 : B(a, r) \cap S^c \neq \emptyset$$

But the right-hand side is precisely the definition of belonging to $\text{cl}(S^c)$!



Links between open and closed sets (cont.)

An important theorem follows directly from the previous result

Theorem 3.1

A set S is open (closed) iff its complement is closed (open).

Proof.

Applying the previous result, we see

$$\begin{aligned} S \text{ is open} &\Leftrightarrow \text{int}(S) = S \text{ (defn)} \\ &\Leftrightarrow \text{cl}(S^c) = S^c \text{ (previous result)} \\ &\Leftrightarrow S^c \text{ is closed (defn)} \end{aligned}$$

A similar proof shows S is closed iff S^c is open.



Proposition 3.4

- *Any intersection (possibly infinite) of closed sets is a closed set.*
- *Any finite union of closed sets is a closed set.*

Proof.

We'll show the first result:

- For a collection of closed sets $\{S_i\}$, $\cap_i S_i = (\cup_i S_i^c)^c$ by Morgan's laws.
- Since S_i is closed, S_i^c is open.
- By Proposition 3.2, $\cup_i S_i^c$ is open.
- Therefore $(\cup_i S_i^c)^c$ is closed, finishing the proof.

