

Fall Real Analysis

Azure

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Contents

1	Day 1: The Real Number System	4
1.1	Number Systems	4
1.2	Real Number System	4
1.3	Least Upper Bound Property	5
2	Day 2: Fields and Order	6
2.1	Greatest Upper Bound Property	6
2.2	Fields	6
2.3	Ordered Fields	7
3	Day 3: Roots and the Complex Field	9
3.1	n th Root	9
3.2	Decimals	10
3.3	Extended Reals	10
3.4	Complex Numbers	10
4	Day 4: Euclidean Spaces & Cauchy-Schwarz	12
4.1	Euclidean Spaces	12
4.2	Cauchy-Schwarz	12
5	Day 5: Existence of \mathbb{R}	14
6	Day 6: Cardinality	16
6.1	Cardinality	16
6.2	Set of Sets	17
7	Day 7: Metric Spaces and Closed/Open	20
7.1	Metric Spaces	20
7.2	Intervals and Balls	24
8	Day 8: Open Relative and Compact	25
8.1	Closure	25
8.2	Open Relative	25
8.3	Compact Sets	26
9	Day 9: Perfect & Connected Sets	30
9.1	Perfect Sets	30
9.2	Connected Sets	31

10 Day 10: Convergence & Cauchy Sequences	32
10.1 Convergent Sequences	32
10.2 Subsequences	34
10.3 Cauchy Sequences	35

1 The Real Number System

1.1 Number Systems

Natural : $\mathbb{N} = \{1, 2, 3, \dots\}$

Integer : $\mathbb{Z} = \{-2, -1, 0, 1, 2, \dots\}$

Rational : $\mathbb{Q} = \frac{p}{q}$ where $p, q \in \mathbb{N}$

*** \mathbb{Q} is countable, but fails to have the least upper bound property ***

Example 1.1.1

Let $\alpha \in \mathbb{R}$ where $\alpha^2 = 2$. Then α cannot be rational.

Proof

Let $\alpha = \frac{p}{q}$ where p and q cannot both be even.

Let set $A = \{x \in \mathbb{Q} \text{ for } x^2 < 2\}$ where $A \neq \emptyset$ and 2 is an upper bound for A .

But, A has no least upper bound in \mathbb{Q} , but A has a least upper bound in \mathbb{R} .

1.2 Real Number System

\mathbb{R} is the unique ordered field with the least upper bound property.

Also, \mathbb{R} exists and unique.

Definition 1.2.1: Order

Let S be a set. An order on S is a relation $<$ satisfying two axioms:

- **Trichotomy**: For all $x, y \in S$, only one holds true:
 - $x < y$
 - $x = y$
 - $x > y$
- **Transitivity**: If $x < y$ and $y < z$, then $x < z$.

Definition 1.2.2: Ordered Set

An ordered set is a set with an order.

Definition 1.2.3: Bounds

Let S be an ordered set and $E \subset S$.

An upper bound of E is a $\beta \in S$ if $x \leq \beta$ for all $x \in E$.

If such a β exists, then E is bounded from above.

A lower bound of E is a $\alpha \in S$ if $x \geq \alpha$ for all $x \in E$.

If such a α exists, then E is bounded from below.

Definition 1.2.4: Infimum & Supremum

Let S be an ordered set.

Let $E \subset S$ be bounded from above. Least upper bound $\beta \in S$ exists if:

- β is an upper bound for E
- If $\gamma < \beta$, then γ is not an upper bound for E .

Then $\beta = \sup(E)$.

Let $E \subset S$ be bounded from below. Greatest lower bound $\alpha \in S$ exists if:

- α is a lower bound for E
- If $\gamma > \alpha$, then γ is not a lower bound for E .

Then $\alpha = \inf(E)$.

Example 1.2.5

Let $S = (1, 2) \cup [3, 4) \cup (5, 6)$ with the order $<$ from \mathbb{R} . For subsets E of S :

- $E = (1, 2)$ is bounded above and $\sup(E) = 2$
- $E = (5, 6)$ is not bounded above so $\sup(E) = \text{DNE}$
- $E = [3, 4)$ is bounded below $\inf(E) = 3$ and $\sup(E) = \text{DNE}$

Observations on the Least Upper Bound

If $\sup(E)$ exists, it may or may not exist in S .

If $\sup(E)$ exists, then $\sup(E)$ is unique. If $\gamma \neq \alpha$, then $\gamma < \alpha$ or $\gamma > \alpha$.

1.3 Least Upper Bound Property**Theorem 1.3.1: Least Upper Bound Property**

An ordered set S has a least upper bound property if:

For every nonempty subset $E \subset S$ that is bounded from above:
 $\sup(E)$ exists in S .

Example 1.3.2

\mathbb{Q} doesn't have a least upper bound property. For example, $z = \sqrt{2}$.

Proof

Let $z = y - \frac{y^2-2}{y+2} = \frac{2y+2}{y+2}$, then take $z^2 - 2 = \frac{2(y^2-2)}{(y+2)^2}$.

Let set $A = \{y > 0 \in \mathbb{Q} \text{ where } y^2 < 2\}$ and set $B = \{y > 0 \in \mathbb{Q} \text{ where } y^2 > 2\}$

- If $y^2 - 2 < 0$, then $z > y$ where $z \in A$. So, y is not an upper bound.
 Since for any y , there is $z > y$ where $z \in A$, then $\sup(A)$ doesn't exist in \mathbb{Q} .
- If $y^2 - 2 > 0$, then $z < y$ where $z \in B$. So, y is an upper bound, but not $\sup(E)$.
 Since for any y , there is $z < y$ where $z \in B$, then $\inf(B)$ doesn't exist in \mathbb{Q} .

Thus, \mathbb{Q} doesn't have the least upper bound or greatest lower bound property.

2 Day 2: Fields

2.1 Greatest Upper Bound Property

Theorem 2.1.1: Least Upper Bound + Lower Bound implies Greatest Upper Bound

Let S be an ordered set with the least upper bound property.

Let non-empty $B \subset S$ be bounded below.

Let L be the set of all lower bounds of B .

Then $\alpha = \sup(L)$ exists in S .

Proof

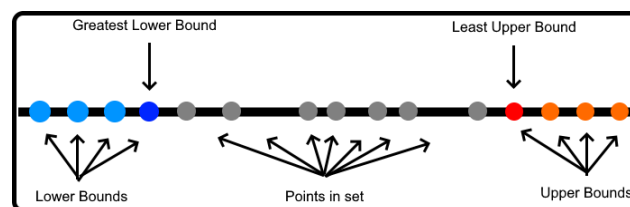
L is non-empty since B is bounded from below.

Thus, by the least upper bound property of S , $\alpha = \sup(L)$ exists in S .

We claim that $\alpha = \inf(B)$.

If $\gamma < \alpha$, then γ is not an upper bound for L so $\gamma \notin B$ since all upper bounds for L are in B . Thus, for every $x \in B$, $\alpha \leq x$.

If $\gamma \geq \alpha$, then γ is an upper bound of L so $\gamma \in B$. Thus, $\inf(B) = \alpha$.



2.2 Fields

Addition Axioms

- If $x, y \in F$, then $x+y \in F$
- $x+y = y+x$ for all $x, y \in F$
- $(x+y)+z = x+(y+z)$ for all $x, y, z \in F$
- There exists $0 \in F$ such that $0+x = x$ for all $x \in F$
- For every $x \in F$, there is $-x \in F$ where $x+(-x) = 0$

Multiplicative Axioms

- If $x, y \in F$, then $xy \in F$
- $yx = xy$ for all $x, y \in F$
- $(xy)z = x(yz)$ for all $x, y, z \in F$
- There exists $1 \neq 0 \in F$ such that $1x = x$ for all $x \in F$
- If $x \neq 0 \in F$, there is $\frac{1}{x} \in F$ where $x(\frac{1}{x}) = 1$

Distributive Law

$x(y+z) = xy + xz$ hold for all $x, y, z \in F$.

Propositions 2.2.1

- (a) If $x+y = x+z$, then $y = z$

Proof

$$y = 0+y = (-x)+x+y = (-x)+x+z = 0+z = z$$

- (b) If $x+y = x$, then $y = 0$

Proof

From (a), let $z = 0$.

- (c) If $x+y = 0$, then $y = -x$

Proof

From (a), let $z = -x$.

- (d) $-(-x) = x$

Proof

From (c), let $x = -x$ and $y = x$.

- (e) If $x \neq 0$ and $xy = xz$, then $y = z$

Proof

$$y = 1y = \frac{1}{x}xy = \frac{1}{x}xz = 1z = z$$

- (f) If $x \neq 0$ and $xy = x$, then $y = 1$

Proof

From (e), let $z = 1$.

- (g) If $x \neq 0$ and $xy = 1$, then $y = \frac{1}{x}$

Proof

From (e), let $z = \frac{1}{x}$.

- (h) If $x \neq 0$, then $\frac{1}{1/x} = x$

Proof

From (g), let $x = \frac{1}{x}$ and $y = x$.

- (i) $0x = 0$

Proof

Since $0x + 0x = (0+0)x = 0x = 0x + 0$, then $0x = 0$.

- (j) If $x, y \neq 0$, then $xy \neq 0$

Proof

Suppose $xy = 0$, then $1 = \frac{1}{y}\frac{1}{x}xy = \frac{1}{y}\frac{1}{x}0 = 0$.

$0 = 1$ is a contradiction.

- (k) $(-x)y = -(xy) = x(-y)$

Proof

$$xy + (-x)y = (x+(-x))y = 0y = 0.$$

Then by part (c), $(-x)y = -(xy)$.

$$\text{Similarly, } xy + x(-y) = x(y+(-y)) = x0 = 0.$$

Then by part (c), $x(-y) = -(xy)$.

- (l) $(-x)(-y) = xy$

Proof

By part (k), then $(-x)(-y) = -[x(-y)] = -[-(xy)]$.

By part (d), $-[-(xy)] = xy$.

2.3 Ordered Fields

An ordered field F is a field F which is also an ordered set for all $x, y, z \in F$.

- If $y < z$, then $y+x < z+x$
- If $x, y > 0$, then $xy > 0$

Definition 2.3.1: \mathbb{Q} and \mathbb{R} are ordered fields

\mathbb{Q} , \mathbb{R} are ordered fields, but \mathbb{C} is not an ordered field since $i^2 = -1 \not> 1$.

Propositions 2.3.2

Let F be an ordered field. For all $x, y, z \in F$.

- (a) If $x > 0$, then $-x < 0$ and vice versa

Proof

$$-x = -x + 0 < -x + x = 0$$

- (b) If $x > 0$ and $y < z$, then $xy < xz$

Proof

$$\text{Since } z - y > 0, \text{ then } 0 < x(z - y) = xz - xy$$

- (c) If $x < 0$ and $y < z$, then $xy > xz$

Proof

$$\text{Since } -x > 0 \text{ and } z - y > 0, \text{ then } 0 < -x(z - y) = xy - xz$$

- (d) If $x \neq 0$, $x^2 > 0$

Proof

$$\text{If } x > 0, \text{ then } x^2 = x \cdot x > 0$$

$$\text{If } x < 0, \text{ then } (-x)^2 = (-x) \cdot (-x) = x \cdot x = x^2 > 0$$

- (e) If $0 < x < y$, then $0 < 1/y < 1/x$

Proof

$$\text{Since } (\frac{1}{y})y = 1 > 0, \text{ then } (\frac{1}{y}) > 0$$

$$\text{Since } x < y, \text{ then } \frac{1}{y} = (\frac{1}{y})(\frac{1}{x})x < (\frac{1}{y})(\frac{1}{x})y = \frac{1}{x}$$

Theorem 2.3.3: \mathbb{R} is an ordered field with $<$

There exists a unique ordered field \mathbb{R} with the least upper bound property.

Also, $\mathbb{Q} \subset \mathbb{R}$ so \mathbb{Q} is also an ordered field.

Theorem 2.3.4

For all $x, y \in \mathbb{R}$:

- **Archimedean Property:** If $x > 0$, there is $n \in \mathbb{Z}$ such that $nx > y$.

Proof

Fix $x > 0$. Suppose there is a y such that the property fails.

Let $A = \{ nx : n = 1, 2, 3, \dots \}$.

Then, A is nonempty and bounded from above by y .

Then by the least upper bound property of \mathbb{R} , $\alpha = \sup(A)$ exists in \mathbb{R} .

Since $x > 0$, then $-x < 0$ so $\alpha - x < \alpha - 0 = \alpha$.

So $\alpha - x$ is not an upper bound of A .

So there is a $mx \in A$ such that $mx > \alpha - x$.

Then $\alpha < (m+1)x$, but $(m+1)x \in A$ contradicting α is an upper bound for A .

- **\mathbb{Q} is dense in \mathbb{R} :** If $x < y$, there is a $p \in \mathbb{Q}$ such that $x < p < y$.

Proof

Since $x < y$, then $y - x > 0$. Then by the Archimedean Property, there exists a $n \in \mathbb{Z}$ such that $n(y - x) > 1$. Thus, $ny > nx + 1 > nx$

By the well-ordering principle, there is a smallest $m \in \mathbb{Z}_+$ such that $m > nx$.

Then, $m > nx \geq m - 1$ so $nx + 1 \geq m > nx$.

Since $ny > nx + 1 \geq m > nx$, then $y > m/n > x$.

3 Roots & Complex Field

3.1 nth Root

- (a) If $0 < t \leq 1$, then $t^n \leq t$.

Proof

Since $t > 0$ and $t \leq 1$, then $t^2 \leq t$.

Since $t^2 \leq t$, then $t^3 \leq t^2$ so $t^3 \leq t^2 \leq t$.

Applying the process n times, then $t^n \leq t$.

- (b) If $t \geq 1$, $t^n \geq t$.

Proof

Since $0 < 1 \leq t$, then $t \leq t^2$.

Since $t \leq t^2$, then $t^2 \leq t^3$ so $t \leq t^2 \leq t^3$.

Applying the process n times, $t \leq t^n$.

- (c) If $0 < s < t$, then $s^n < t^n$.

Proof

$$\underbrace{s \cdot s \cdot \dots \cdot s}_n < t \cdot s \cdot \dots \cdot s < t \cdot t \cdot \dots \cdot s < \dots < \underbrace{t \cdot \dots \cdot t}_n$$

Theorem 3.1.1: $y^n = x$ has a unique y

Fix $n \in \mathbb{Z}_+$. For every $x > 0$, there exists a unique $y \in \mathbb{R}$ such that $y^n = x$.

Also, such a y is written as $y = \sqrt[n]{x} = x^{\frac{1}{n}}$.

Proof

Uniqueness:

y is unique since if $y_1 < y_2$, then $x = y_1^n < y_2^n \neq x$.

Existence:

Let set $A = \{ t > 0 : t^n < x \}$.

$A \neq \emptyset$ since let $t_1 = \frac{x}{x+1} < 1$ so $t_1 < x$ and thus, $0 < t_1^n < t_1 < x$ so $t_1 \in A$.

A is bounded above since if $t \geq x+1$, then $t > 1$ so $t^n \geq t \geq x+1 > x$ so $t \notin A$.

So $x+1$ is an upper bound of A .

Thus by the least upper bound property, $y = \sup(A)$ exists.

For $y^n = x$, show $y^n < x$ and $y^n > x$ cannot hold true.

*** (Not an upper bound of A if $<$ and not a least upper bound of A if $>$)***

For $0 < \alpha < \beta$:

$$\beta^n - \alpha^n = (\beta - \alpha) \underbrace{(\beta^{n-1} + \beta^{n-2}\alpha + \dots + \alpha^{n-1})}_{\substack{\beta^{n-1} < \beta^{n-1} < \beta^{n-1}}} < (\beta - \alpha)n\beta^{n-1}$$

Suppose $y^n < x$. Pick $0 < h < 1$ and $h < \frac{x - y^n}{n(y+1)^{n-1}}$.

From inequality, let $\beta = y+h$ and $\alpha = y$

$$(y+h)^n - y^n < hn(y+h)^{n-1} < hn(y+1)^{n-1} < x - y^n$$

Thus, $(y+h)^n < x$ so $y+h \in A$ and thus, not an upper bound of A which is a contradiction since $y = \sup(A)$.

Suppose $y^n > x$. Pick $0 < k = \frac{y^n - x}{ny^{n-1}} < \frac{y^n}{ny^{n-1}} = \frac{1}{n}y < y$.

Consider $t \geq y-k$, then: $y^n - t^n \leq y^n - (y-k)^n < kny^{n-1} = y^n - x$

Thus, $t^n > x$ so $t \notin A$.

Thus, $y-k$ is an upper bound of A which is a contradiction since $y = \sup(A)$.

Since $y^n < x$ and $y^n > x$, then $y^n = x$.

Corollary 3.1.2: n-th root of product = product of n-th root

If $a, b > 0$ and $n \in \mathbb{Z}_+$, then $(ab)^{\frac{1}{n}} = a^{\frac{1}{n}} b^{\frac{1}{n}}$.

Proof

Let $A = a^{\frac{1}{n}}$ and $B = b^{\frac{1}{n}}$.

Then by **theorem 3.1.1**, since A is a solution to $y_1^n = a$, then $A^n = a$.

Similarly, B is a solution of $y_2^n = b$ so $B^n = b$. Thus:

$$\begin{aligned} ab &= A^n B^n = A_1 A_2 \dots A_n B_1 B_2 \dots B_n \\ &= A_1 A_2 \dots B_1 A_n B_2 \dots B_n = \dots = A_1 B_1 A_2 \dots A_{n-1} A_n B_3 \dots B_n \\ &= \dots = A_1 B_1 A_2 B_2 \dots A_n B_n = (AB)^n \end{aligned}$$

Then again by **theorem 3.1.1**, there is a unique $(ab)^{\frac{1}{n}} = AB = a^{\frac{1}{n}} b^{\frac{1}{n}}$.

3.2 Decimals

Let n_0 be the largest integer such that $n_0 \leq x$ for $x > 0 \in \mathbb{R}$.

Then let n_k be the largest integer such that $d_k = n_0 + \frac{n_1}{10} + \dots + \frac{n_k}{10^k} \leq x$

Let E be the set of d_k for $k = 0, 1, \dots, \infty$. Then, $x = \sup(E)$.

3.3 Extended Reals

The extended real number system consist of \mathbb{R} and $\pm\infty$ such that:

$$-\infty < x < \infty \quad \text{for every } x \in \mathbb{R}$$

with the properties:

- $x \pm \infty = \pm\infty$
- $x / \pm\infty = 0$
- If $x > 0$, then $x(\pm\infty) = \pm\infty$
- If $x < 0$, then $x(\pm\infty) = \mp\infty$

3.4 Complex Numbers**Definition 3.4.1: Complex**

A complex number is an ordered pair (a, b) where $a, b \in \mathbb{R}$. For $x, y \in \mathbb{C}$

- $x + y = (a, b) + (c, d) = (a + c, b + d)$
- $xy = (a, b)(c, d) = (ac - bd, ad + bc)$
- $\frac{1}{x} = (a^2 + b^2)^{-1}(a, -b)$

Thus, the axioms form a field where $(0, 0) = 0$ and $(1, 0) = 1$ and $(0, 1) = i$.

Definition 3.4.2: Imaginary i

Let $i = (0, 1)$. Then, $i^2 = -1$.

Proof

$$i^2 = (0, 1)(0, 1) = (0 - 1, 0 + 0) = (-1, 0) = -1$$

Definition 3.4.3: Form $a + bi$

$$(a, b) = a + bi$$

Proof

$$(a, b) = (a, 0) + (0, b) = (a, 0) + (b, 0)(0, 1) = a + bi$$

Definition 3.4.4: Conjugate

Let conjugate: $\bar{z} = a - bi$ where $\text{Re}(z) = a$, $\text{Im}(z) = b$

Let $z = (a,b)$ and $w = (c,d)$:

(a) $\overline{z+w} = \bar{z} + \bar{w}$

Proof

$$\overline{z+w} = \overline{(a+c, b+d)} = (a+c, -b-d) = (a, -b) + (c, -d) = \bar{z} + \bar{w}$$

(b) $\overline{zw} = \bar{z} \bar{w}$

Proof

$$\overline{zw} = \overline{(ac-bd, ad+bc)} = (ac-bd, -ad-bc) = (a, -b) (c, -d) = \bar{z} \bar{w}$$

(c) $z + \bar{z} = 2 \text{Re}(z)$ $z - \bar{z} = 2i \text{Im}(z)$

Proof

$$z + \bar{z} = (a,b) + (a,-b) = (2a, 0) = 2 \text{Re}(z)$$

$$z - \bar{z} = (a,b) - (a,-b) = (0, 2b) = (0, 2) b = 2i \text{Im}(z)$$

(d) $z\bar{z} \geq 0$

Proof

$$z\bar{z} = (a,b)(a,-b) = (a^2 + b^2, -ab+ab) = a^2 + b^2 \geq 0$$

Definition 3.4.5: Absolute Value

Let absolute value: $|z| = \sqrt{z\bar{z}}$

Let $z = (a,b)$ and $w = (c,d)$:

(a) If $z \neq 0$, then $|z| > 0$.

Proof

$$\sqrt{z\bar{z}} = \sqrt{a^2 + b^2} \geq 0 \text{ where } |z| = 0 \text{ only if } a, b = 0 \text{ so only if } z = (0,0).$$

(b) $|\bar{z}| = |z|$

Proof

$$|\bar{z}| = \sqrt{a^2 + (-b)^2} = \sqrt{a^2 + b^2} = |z|$$

(c) $|zw| = |z| |w|$

Proof

$$\begin{aligned} |zw| &= |(ac-bd, ad+bc)| = \sqrt{(ac-bd)^2 + (ad+bc)^2} \\ &= \sqrt{a^2c^2 + b^2d^2 + a^2d^2 + b^2c^2} = \sqrt{(a^2 + b^2)(c^2 + d^2)} \\ &= \sqrt{a^2 + b^2} \sqrt{c^2 + d^2} = |z| |w| \end{aligned}$$

(d) $|\text{Re}(z)| \leq |z|$

Proof

$$|\text{Re}(z)| = |a| = \sqrt{a^2} \leq \sqrt{a^2 + b^2} = |z|$$

(e) $|z+w| \leq |z| + |w|$

Proof

$$\begin{aligned} |z+w|^2 &= (z+w)(\overline{z+w}) = (z+w)(\bar{z} + \bar{w}) = z\bar{z} + z\bar{w} + w\bar{z} + w\bar{w} \\ &= |z|^2 + |w|^2 + 2 \text{Re}(z\bar{w}) \leq |z|^2 + |w|^2 + 2|z\bar{w}| \\ &= |z|^2 + |w|^2 + 2|z||w| = (|z| + |w|)^2 \end{aligned}$$

4 Euclidean Spaces & Cauchy-Schwarz

4.1 Euclidean Spaces

For each positive integer k , let \mathbb{R}^k be the set of all ordered k -tuples:

$$\mathbf{x} = (x_1, \dots, x_k) \quad \text{for each } x_i \in \mathbb{R}$$

with the properties:

- $\mathbf{x} + \mathbf{y} = (x_1 + y_1, \dots, x_k + y_k) \in \mathbb{R}^k$
- $c\mathbf{x} = (cx_1, \dots, cx_k) \in \mathbb{R}^k$

So, \mathbb{R}^n has a vector space structure. Similarly, for \mathbb{C}^n .

Definition 4.1.1: Inner Product for \mathbb{R}^k

$$\mathbf{x} \cdot \mathbf{y} = x_1 y_1 + \dots + x_k y_k \in \mathbb{R}$$

Definition 4.1.2: Norm

$$|\mathbf{x}| = \sqrt{\mathbf{x} \cdot \mathbf{x}} = \sqrt{\sum_{i=1}^n x_i^2}$$

Definition 4.1.3: Extension to \mathbb{C}^k

For $\mathbf{z}, \mathbf{w} \in \mathbb{C}^n$

- $\mathbf{z} \cdot \mathbf{w} = z_1 \overline{w_1} + \dots + z_k \overline{w_k}$
- $\mathbf{z} \cdot \mathbf{z} = z_1 \overline{z_1} + \dots + z_k \overline{z_k} = |z_1|^2 + \dots + |z_n|^2 = |\mathbf{z}|^2$

4.2 Cauchy-Schwarz

Theorem 4.2.1: Cauchy-Schwarz

If $\alpha_1, \dots, \alpha_n \in \mathbb{C}$ and $b_1, \dots, b_n \in \mathbb{C}$, then:

$$|\sum_{j=1}^n \alpha_j \overline{b_j}|^2 \leq \sum_{j=1}^n |\alpha_j|^2 \sum_{j=1}^n |b_j|^2$$

Proof

Let $A = \sum |\alpha_j|^2$ and $B = \sum |b_j|^2$ and $C = \sum \alpha_j \overline{b_j}$.

If $B = 0$, then $b_1 = \dots = b_n = 0$. Thus, $0 \leq A(0)$ holds true.

Suppose $B > 0$. Then:

$$\begin{aligned} \sum |Ba_j - Cb_j|^2 &= \sum (Ba_j - Cb_j) \overline{(Ba_j - Cb_j)} = \sum (Ba_j - Cb_j) (\overline{B} \overline{a_j} - \overline{C} \overline{b_j}) \\ &= \sum (Ba_j - Cb_j) (\overline{B} \overline{a_j} - \overline{C} \overline{b_j}) = \sum B^2 \overline{a_j} a_j - B \overline{C} a_j \overline{b_j} - B C \overline{a_j} b_j + C \overline{C} b_j \overline{b_j} \\ &= B^2 \sum |a_j|^2 - B \overline{C} \sum a_j \overline{b_j} - B C \sum \overline{a_j} b_j + |C|^2 \sum |b_j|^2 \\ &= B^2 A - B \overline{C} C - B C \overline{C} + |C|^2 B = B^2 A - 2|C|^2 B + |C|^2 B = B^2 A - |C|^2 B \\ &= B(AB - |C|^2) \end{aligned}$$

Since $|Ba_j - Cb_j| \geq 0$, then $B(AB - |C|^2) \geq 0$.

Since $B > 0$, then $AB - |C|^2 \geq 0$ so $AB \geq |C|^2$.

Definition 4.2.2: Consequence of the Cauchy-Schwarz

Since $|z_i|^2 = z_i \overline{z_i}$, then $\sum z_i \overline{z_i} = \sum |z_i|^2 = |\mathbf{z}|^2$. Thus:

$$|\mathbf{z} \cdot \mathbf{w}|^2 = |\sum z_i \overline{w_i}|^2 \leq \sum |z_i|^2 \sum |w_i|^2 = |\mathbf{z}|^2 |\mathbf{w}|^2$$

Thus, $|\mathbf{z} \cdot \mathbf{w}| \leq |\mathbf{z}| |\mathbf{w}|$.

Propositions 4.2.3

Let $x, y, z \in \mathbb{R}^k$ where $\alpha \in \mathbb{R}$:

- (a) $|x| \geq 0$ where $|x| = 0$ only if $x = 0$

Proof

$$|x| = \sqrt{\sum_{i=1}^k x_i^2} \geq 0 \text{ where } |x| = 0 \text{ only if } x_1 = \dots = x_k = 0$$

- (b) $|\alpha x| = |\alpha||x|$

Proof

$$|\alpha x| = \sqrt{\sum_{i=1}^k (\alpha x_i)^2} = \sqrt{\alpha^2} \sqrt{\sum_{i=1}^k x_i^2} = |\alpha||x|$$

- (c) $|x + y| \leq |x| + |y|$

Proof

$$\begin{aligned} |x + y|^2 &= (x + y) \cdot (x + y) = |x|^2 + 2(x \cdot y) + |y|^2 \\ &\leq |x|^2 + 2|x||y| + |y|^2 = (|x| + |y|)^2 \end{aligned}$$

- (d) $|x - y| \leq |x - z| + |y - z|$

Proof

$$|x - y| = |x - z + z - y| \leq |x - z| + |z - y| = |x - z| + |y - z|$$

5 Construction of \mathbb{R} : **Theorem 2.3.3**

There exists an ordered field \mathbb{R} which has the least upper bound property.
Also, \mathbb{R} contains \mathbb{Q} as a subfield.

Definition 5.1: Cuts

Define a cut as any set $\alpha \subset \mathbb{Q}$ with the properties:

- α is not empty and $\alpha \neq \mathbb{Q}$
- If $p \in \alpha$ and $q \in \mathbb{Q} < p$, then $q \in \alpha$
- If $p \in \alpha$, then $p < r \in \mathbb{Q}$ for some $r \in \alpha$

Proposition 5.2: Order of $\mathbb{R} \rightarrow$ ordered set \mathbb{R}

Define $\alpha < \beta$ if α is a proper subset of β .

- If $\alpha \not\subseteq \beta$, then β is not a subset of α .
Then there is a $p \in \beta$ such that $p \notin \alpha$.
Then for any $q \in \alpha$, $q < p$ and thus, $q \in \beta$.
Thus, $\alpha \subset \beta$ and since $\alpha \neq \beta$, then $\alpha < \beta$.
- If $\alpha \not\subseteq \beta$ and $\alpha \not\supset \beta$, then either $\alpha = \beta$ or $\alpha \neq \beta$.
If $\alpha \neq \beta$, there are p, q such that $p \in \alpha$, but $p \notin \beta$ and $q \in \beta$, but $q \notin \alpha$.
But if $p \notin \beta$, then for any $b \in \beta$, $b < p$. Thus, $q < p$.
Similarly, if $q \notin \alpha$, then for any $a \in \alpha$, $a < q$. Thus, $p < q$.
Thus, there is a contradiction since $p > q$ and $p < q$ so $\alpha = \beta$.
- If $\alpha \not\subseteq \beta$, then α is not a subset of β .
Then there is a $p \in \alpha$ such that $p \notin \beta$.
Then for any $q \in \beta$, $q < p$ and thus, $q \in \alpha$.
Thus, $\beta \subset \alpha$ and since $\alpha \neq \beta$, then $\beta < \alpha$.
- If $\alpha < \beta$ and $\beta < \gamma$, then since α is a proper subset of β and β is a proper subset of γ , then α is a proper subset of γ . Thus, $\alpha < \gamma$.

Thus, \mathbb{R} is an ordered set with such an order $<$.

Proposition 5.3: Least Upper Bound of $\mathbb{R} \rightarrow$ Least Upper Bound Property

Let $A \subset \mathbb{R}$ and β be an upper bound for A . Let γ be the union of all $\alpha \in A$.
Thus, $p \in \gamma$ if and only if $p \in \alpha$ for some $\alpha \in A$.

γ defines a cut since:

- Since A is nonempty, there exists a $\alpha_0 \in A$ where α_0 is nonempty.
Since α_0 is nonempty, then γ is nonempty.
Since every $\alpha \in A$ is $\alpha < \beta$, then $\gamma < \beta$ so $\gamma \subset \beta$ and thus, $\gamma \neq \mathbb{Q}$.
- If $p \in \gamma$, then $p \in \alpha_1$ for some $\alpha_1 \in A$. If $q < p$, then $q \in \alpha_1$ so $q \in A$.
- If $p \in \gamma$, then $p \in \alpha_1$ for some $\alpha_1 \in A$. Thus, there is a $r \in \alpha_1$ such that $r > p$ so $r \in \gamma$. Thus, there is a $r \in \gamma$ where $r > p$.

Since γ defines a cut, then $\gamma \in \mathbb{R}$. Since every $\alpha \in A \subset \gamma$, then $\alpha \leq \gamma$ so γ is an upper bound for A .

Suppose $\delta < \gamma$. Then there is a $s \in \gamma$ such that $s \notin \delta$. Since $s \in \gamma$, then there is a $\alpha \in A$ such that $s \in \alpha$. Since $\delta < \alpha$, then δ is not an upper bound of A .

Thus, $\gamma = \sup(A)$.

Proposition 5.4: \mathbb{R} is a field

If $\alpha, \beta \in \mathbb{R}$, define $\alpha + \beta$ as the set of all sums $r + s$ where $r \in \alpha$ and $s \in \beta$. Also, let 0^* be the set of all negative rational numbers which is a cut since:

- 0^* is nonempty and $0^* \neq \mathbb{Q}$
- If $p \in 0^*$, then any $q \in \mathbb{Q} < p$ is a negative rational and thus, $q \in 0^*$.
- Since \mathbb{Q} is dense in \mathbb{R} , then for any $p \in 0^*$, there is a $r \in \mathbb{Q}$ where $p < r < 0$ so r is a negative rational so $r \in 0^*$.

$\alpha + \beta \in \mathbb{R}$ since $\alpha + \beta$ is a cut:

- $\alpha + \beta$ is non-empty since α, β are non-empty. Take $r' \notin \alpha, s' \notin \beta$, then $r' + s' > r + s$ for $r \in \alpha, s \in \beta$. Thus, $r' + s' \notin \alpha + \beta$ so $\alpha + \beta \neq \mathbb{Q}$.
- If $p \in \alpha + \beta$, then $p = r + s$ where $r \in \alpha$ and $s \in \beta$.
If $q < p$, then $q - s < p - s = (r + s) - s = r$ so $q - s \in \alpha$.
Since $q - s \in \alpha$ and $s \in \beta$, then $(q - s) + s = q \in \alpha + \beta$.
- If $r \in \alpha$, then there is a $t \in \alpha$ such that $t > r$. Let $s \in \beta$.
Thus, for any $p = r + s \in \alpha + \beta$, there is a $q = t + s \in \alpha + \beta$ such that $p = r + s < t + s = q$.

$\alpha + \beta = \beta + \alpha$

If $p = r + s \in \alpha + \beta$ where $r \in \alpha, s \in \beta$, then $s + r = r + s = p \in \beta + \alpha$.

$(\alpha + \beta) + \gamma = \alpha + (\beta + \gamma)$

If $r \in \alpha, s \in \beta, t \in \gamma$, then $r + s + t = (r + s) + t \in (\alpha + \beta) + \gamma$ and $r + s + t = r + (s + t) \in \alpha + (\beta + \gamma)$.

$\alpha + 0^* = \alpha$

If $r \in \alpha, s \in 0^*$, then $r + s < r$. Thus, $r + s \in \alpha$. Thus, $\alpha + 0^* \subset \alpha$.

If $p \in \alpha$, there is a $r \in \alpha$ where $r > p$. Thus, $p - r \in 0^*$.

Since $p = r + (p - r) \in \alpha + 0^*$, then $\alpha \subset \alpha + 0^*$. Thus, $\alpha + 0^* = \alpha$.

There is a $-\alpha$ such that $\alpha + (-\alpha) = 0^*$

Fix $\alpha \in \mathbb{R}$. Let set β be all p where there is $r > 0$ such that $-p - r \notin \alpha$.

$\beta \in \mathbb{R}$ since β is a cut:

- If $s \notin \alpha$ and $p = -s - 1$, then $-p - 1 \notin \alpha$. Thus, $p \in \beta$ so β is nonempty. If $q \in \alpha$, then $-q \notin \beta$ so $\beta \neq \mathbb{R}$.
- If $p \in \beta$, let $r > 0$ so $-p - r \notin \alpha$. If $q < p$, then $-q - r > -p - r$ and thus, $-q - r \notin \alpha$ so $q \in \beta$.
- If $p \in \beta$, let $t = p + (r/2)$. Then $-t - (r/2) = -p - r \notin \alpha$ and thus, $t \in \beta$ where $p < t$.

If $r \in \alpha, s \in \beta$, then $s \notin \alpha$. Thus, $r < -s$ so $r + s < 0$. Thus, $\alpha + \beta \subset 0^*$.

Let $v \in 0^*$ and let $w = -v/2$ so $w > 0$.

Thus, by the Archimedean property, there is an integer n such that $nw \in \alpha$, but $(n+1)w \notin \alpha$. Let $p = -(n+2)w$ so $-p - w = (n+1)w \notin \alpha$ so $p \in \beta$.

Then, $v = -2w = nw + -nw - 2w = nw + -(n+2)w = nw + p \in \alpha + \beta$.

Since $v \in 0^*$, then $0^* \subset \alpha + \beta$. Thus, $\alpha + \beta = 0^*$. Then, let $-\alpha = \beta$.

Thus, if $\alpha, \beta, \gamma \in \mathbb{R}$ and $\beta < \gamma$, then $\alpha + \beta < \alpha + \gamma$.

Thus, if $\alpha > 0^*$, then $-\alpha = -\alpha + 0^* < -\alpha + \alpha = 0^*$ so $-\alpha < 0^*$.

If $\alpha, \beta \in \mathbb{R}_+$, define $\alpha\beta$ as the set of all p such that $p \leq rs$ for $r \in \alpha, s \in \beta$.

Define 1^* as the set of all $q < 1$. Then all multiplication axioms holds with similar proofs as addition. Also, note since $\alpha, \beta > 0^*$, then $\alpha\beta > 0^*$.

Also, $\alpha(\beta + \gamma) = \alpha\beta + \alpha\gamma$ holds through cases were $\alpha, \beta, \gamma >, < 0^*$.

6 Cardinality

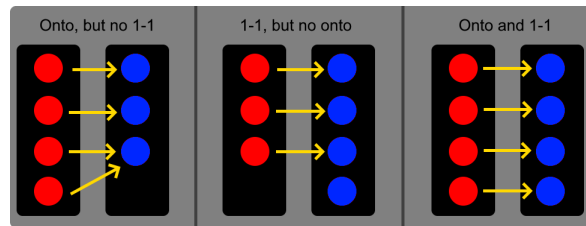
6.1 Cardinality

Definition 6.1.1: Onto and 1-1 Mapping

Suppose for every $x \in A$, there is an associated $f(x) \in B$.

Then f maps A into $B = f: A \rightarrow B$.

- If $f(A) = B$, then f maps A onto B .
- If for each $y \in B$, $f^{-1}(y)$ consist of at most one $x \in A$ where $f^{-1}(y_1) = x_1 \neq x_2 = f^{-1}(y_2)$ for $y_1 \neq y_2$, then f is a 1-1 mapping of A into B .



Definition 6.1.2: 1-1 Correspondence

Sets A and B are equivalent (have the same cardinality) if there is a 1-1 onto function $f: A \rightarrow B$. (1-1 correspondence between A and B) Then:

$$A \sim B$$

If $f: A \rightarrow B$ is 1-1 and onto, then there is a $f^{-1}: B \rightarrow A$ that is 1-1 and onto.

Definition 6.1.3: Countability

- A is finite if $A \sim J_n = \{0, 1, \dots, n\}$ for some $n \in \mathbb{N}$
- A is infinite if A is not finite
- A is countably infinite if $A \sim J = \mathbb{Z}_+$
- A is uncountable if A is not finite or countably infinite
- A is at most countable if A is finite or countably infinite

Example 6.1.4

\mathbb{Z} is countably infinite

Proof

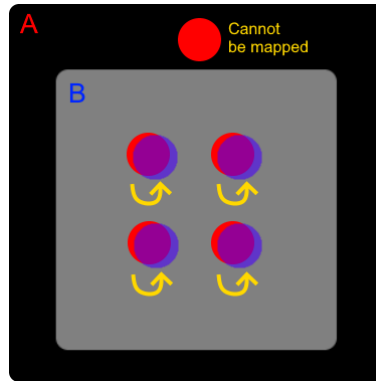
Let $f: \mathbb{Z}_+ \rightarrow \mathbb{Z}$

$$f(n) = \begin{cases} \frac{n}{2} & n \text{ is even} \\ -\frac{n-1}{2} & n \text{ is odd} \end{cases}$$

So $1 \mapsto 0$, $2 \mapsto 1$, $3 \mapsto -1$, $4 \mapsto 2$, $5 \mapsto -2$, etc. Thus, $\mathbb{Z} \sim \mathbb{Z}_+$.

Definition 6.1.5: Pigeonhole Principle

If A is finite, A is not equivalent to any proper set of A .

**Theorem 6.1.6: Infinite subsets of countable sets are countable**

An infinite subset E of a countably infinite set A is countably infinite.

Proof

Let $E \subset A$ be an infinite subset. For every distinct $x_i \in A$, let $x = \{x_1, x_2, \dots\}$.

Let n_1 be smallest integer such that $x_{n_1} \in E$.

Then let n_2 be the smallest integer where $n_2 > n_1$ such that $x_{n_2} \in E$.

Repeat the process to create sequence $f(k) = \{x_{n_1}, x_{n_2}, \dots, x_{n_k}, \dots\}$.

Thus, there is a 1-1 correspondence between E and \mathbb{Z}_+ so E is countably infinite.

**6.2 Set of Sets****Definition 6.2.1: Union and Intersection**

Let sets Ω, B be such that for each $x \in \Omega$, there is an associated $E_x \subset B$.

- $E = \bigcup_{x=1}^n E_x$ only if for every $x \in E$, $x \in E_x$ for at least one $x \in \Omega$.
- $P = \bigcap_{x=1}^n E_x$ only if for every $x \in P$, $x \in E_x$ for all $x \in \Omega$.

with properties:

- | | |
|---|---|
| (a) $A \cup B = B \cup A$ | $A \cap B = B \cap A$ |
| (b) $(A \cup B) \cup C = A \cup (B \cup C)$ | $(A \cap B) \cap C = A \cap (B \cap C)$ |
| (c) $A \subset A \cup B$ | $(A \cap B) \subset A$ |
| (d) If $A \subset B$, then $A \cup B = B$ and $A \cap B = A$ | |

Proof

If $x \in A \cup B$, then $x \in A$ or/and $x \in B$.

- If $x \in A$, since $A \subset B$, then $x \in B$. Then, $(A \cup B) \subset B$.
- If $x \in B$, then immediately $(A \cup B) \subset B$.

If $x \in B$, then $x \in A \cup B$ so $B \subset (A \cup B)$. Thus, $A \cup B = B$.

If $x \in A \cap B$, then $x \in A$ and $x \in B$. Thus, $(A \cap B) \subset A$.

If $x \in A$, since $A \subset B$, then $x \in B$ so $x \in A \cap B$. Thus, $A \subset (A \cap B)$.

Thus, $A \cap B = A$.

$$(e) A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$$

Proof

If $x \in A \cap (B \cup C)$, then $x \in A$ and ($x \in B$ or/and $x \in C$).

- If $x \in B$, then $x \in (A \cap B)$ so $x \in (A \cap B) \cup (A \cap C)$.
- If $x \in C$, then $x \in (A \cap C)$ so $x \in (A \cap B) \cup (A \cap C)$.

Thus, $A \cap (B \cup C) \subset (A \cap B) \cup (A \cap C)$.

If $x \in (A \cap B) \cup (A \cap C)$, then $x \in A$ and ($x \in B$ or/and $x \in C$).

Thus, $(A \cap B) \cup (A \cap C) \subset A \cap (B \cup C)$.

Thus, $A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$.

$$(f) A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$$

Proof

If $x \in A \cup (B \cap C)$, then $x \in A$ or/and ($x \in B$ and $x \in C$).

- If $x \in A$, then $x \in (A \cup B)$ and $x \in (A \cup C)$ so $A \cup (B \cap C) \subset (A \cup B) \cap (A \cup C)$.
- If $x \in B, C$, then $x \in (A \cup B)$ and $x \in (A \cup C)$ so $A \cup (B \cap C) \subset (A \cup B) \cap (A \cup C)$.

If $x \in (A \cup B) \cap (A \cup C)$, then $x \in A$ or/and ($x \in B$ and $x \in C$).

Thus, $(A \cup B) \cap (A \cup C) \subset A \cup (B \cap C)$.

Thus, $A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$.

Theorem 6.2.2: Union of countably infinite sets is countably infinite

If E_1, E_2, \dots are countably infinite sets, then $S = \bigcup_{n=1}^{\infty} E_n$ is countably infinite.

Proof

For each E_n , there is a sequence $\{x_{n1}, x_{n2}, \dots\}$. Then construct an array as such:

$$\begin{pmatrix} x_{11} & x_{12} & \dots \\ x_{21} & x_{22} & \dots \\ \vdots & \vdots & \ddots \end{pmatrix}$$

Take elements diagonally, then sequence $S^* = \{x_{11}; x_{21}, x_{12}; x_{31}, x_{32}, x_{23}; \dots\}$.

Since $S^* \sim S$ so S is at most countable and S is infinite since E_1, E_2, \dots are infinite, then S cannot be finite and thus, countably infinite.

Alternative Proof

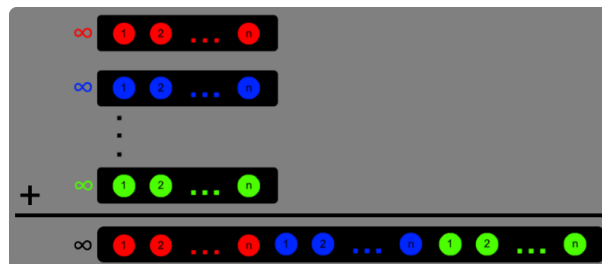
For each E_n , let set $\widetilde{E}_n = E_n - \bigcup_{m=1}^{n-1} E_m$ where $m \neq n$. Thus, $S = \bigcup_{n=1}^{\infty} \widetilde{E}_n$.

Since each E_n is countably infinite, there exists a 1-1 mapping $\delta_n: E_n \rightarrow \mathbb{Z}_+$.

Thus, for each \widetilde{E}_n , there is a 1-1 mapping $\delta_n: \widetilde{E}_n \rightarrow A \subset \mathbb{Z}_+$.

Let p_1, p_2, \dots be distinct primes. Since for $s \in S$, there exists a unique \widetilde{E}_i such that $s \in \widetilde{E}_i$, then let $f(s) = p_1^{\delta_1(s)} p_2^{\delta_2(s)} \dots$ where $p_k^{\delta_k(s)} = 1$ if $k \neq i$.

Then, by the Fundamental theorem of arithmetic, f maps s to a unique $z \in \mathbb{Z}_+$ and thus, f is a 1-1 function so S is at most countable. Since any $E_n \subset S$ is countably infinite, then S cannot be finite and thus, S is countably infinite.



Theorem 6.2.3: The set of countable n-tuples are countable

Let A be a countably infinite set and B_n be the set of all n -tuples (a_1, \dots, a_n) where $a_k \in A$. Then B_n is countably infinite.

Proof

The base case B_1 is countably infinite since $B_1 = A$.

Suppose B_{n-1} is countably infinite. Then for every $x \in B$:

$$x = (b, a) \quad b \in B_{n-1} \text{ and } a \in A$$

Since for every fixed b , $(b, a) \sim A$ and thus, countably infinite.

Since B is a set of countably infinite sets, then B_n is countably infinite.

Definition 6.2.4: \mathbb{Q} is countable

The set of rational numbers, \mathbb{Q} , is countably infinite.

Proof

Since elements of \mathbb{Q} are of form $\frac{a}{b}$ which is a 2-tuple, then by the **theorem 6.2.3**, \mathbb{Q} is countably infinite.

Alternative Proof

For every $x \in \mathbb{Q}$, let $x = (-1)^i \frac{p}{q}$ where $p, q \in \mathbb{Z}_+$.

Let $f(x) = 2^i 3^p 5^q$. Then by the Fundamental theorem of arithmetic, f is a 1-1 mapping of x to $E \subset \mathbb{Z}_+$.

Thus, \mathbb{Q} is at most countable, but since $p, q \in \mathbb{Z}_+$, then \mathbb{Q} cannot be finite and thus, is countably infinite.

Example 6.2.5: Sequences of 0 and 1 are uncountable

Let A be the set of all sequences whose elements are digits 0 and 1. Then A is uncountable.

Proof: Cantor's Diagonalization Proof

Let set E be a countably infinite subset of A which consist of sequences s_1, s_2, \dots

Then construct a sequence s as follows:

If the n -th digit in s_n is 1, then let the n -th digit of s be 0 and vice versa.

Thus, s differs from every $s_n \in E$ so $s \notin E$.

But, $s \in A$ so E is a proper subset of A .

Thus, every countably infinite subset of A is a proper subset of A .

If A is countably infinite, then A is a proper subset of A which is a contradiction.

7 Metric Spaces & Closed/Open

7.1 Metric Spaces

Definition 7.1.1: Metric Spaces

A set X is a metric space if for any $p, q \in X$, there is an associated $d(p, q) \in \mathbb{R}$ such that:

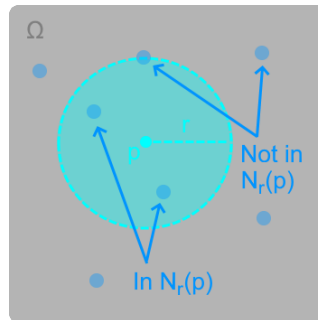
- $d(p, q) > 0$ if $p \neq q$
- $d(p, q) = 0$ if and only if $p = q$
- **Symmetry**: $d(p, q) = d(q, p)$
- **Triangle Inequality**: $d(p, q) \leq d(p, r) + d(r, q)$ for any $r \in X$.

For euclidean spaces \mathbb{R}^k , $d(x, y) = |x - y|$ where $x, y \in \mathbb{R}^k$.

Definition 7.1.2: Types of Points and Sets

(a) Neighborhood

For $p \in \mathbb{R}^k$ and $r > 0$, $N_r(p)$ is the set of all $q \in X$ where $d(q, p) < r$



(b) Limit Points and Closed Sets

Closed set E contains all $p \in X$ where every $N_r(p)$ contains a $q \neq p \in E$

• Limit Points

For point $p \in X$, every $N_r(p)$ contains a $q \neq p \in E$

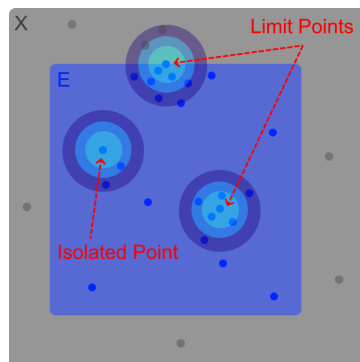
The set of all limit points of $E = E'$

• Isolated Points

If $p \in E$ is not a limit point of E

• Closed

If every limit point p of E is a $p \in E$



(c) Interior Points and Open Sets

Open set E contains all its p which has a $N_r(p) \subset E$

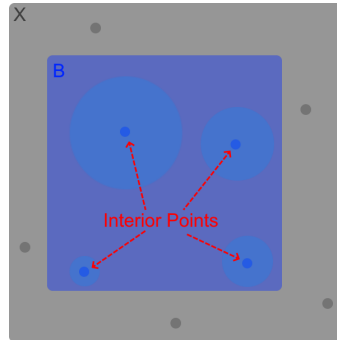
- Interior Point

For $p \in X$, there is a $N_r(p) \subset E$

The set of all interior points = E°

- Open

If every $p \in E$ is an interior point of E



(d) More about Sets

- Bounded

If there is $M \in \mathbb{R}$, $q \in X$ such that $d(p, q) < M$ for all $p \in E$

- Complement

From E , E^c is the set of all $p \in X$ such that $p \notin E$

- Perfect

If E is closed and if every $p \in E$ is a limit point of E

- Dense

If every $p \in X$ is a limit point of E or/and $p \in E$

- Boundary Point

For $p \in X$, if every $N_r(p)$ contains a $x \in E$ and $y \in E^c$

The set of all boundary points = ∂E

For a metric space X , $\{X, \emptyset\}$ are both open and closed.

Theorem 7.1.3: $N_r(p)$ is open

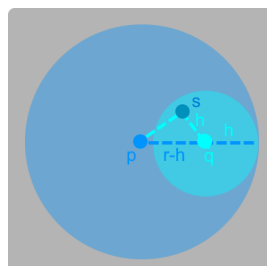
Every neighborhood is an open set.

Proof

Let $q \in N_r(p)$. Then there is a $h > 0 \in \mathbb{R}$ such that $d(q, p) = r - h$.

Then for any $s \in N_h(q)$, $d(s, p) \leq d(s, q) + d(q, p) = h + (r - h) = r$.

Thus, for any $q \in N_r(p)$, there exists a $N_h(q) \subset N_r(p)$.



Theorem 7.1.4: If a set has a limit point, there are infinite $q \in E$ in $N_r(p)$

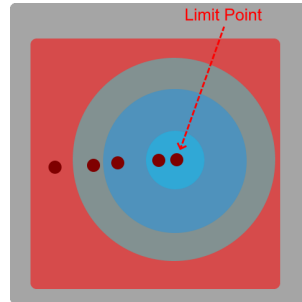
If p is a limit point of set E , then every $N_r(p)$ contains infinitely many $q \in E$.

Proof

Suppose there is $N_{r_1}(p)$ which contains finitely many $q = \{q_1, \dots, q_n\}$.

Let $r = \min_{m \in [1, n]} d(p, q_m)$. Then $N_r(p)$ contains no $q \in E$ such that $q \neq p$.

So, p is not a limit point of E which is a contradiction since p is a limit point of E .



Corollary 7.1.5: Limit points do not exist in finite sets

A finite set E has no limit points. Since $\emptyset \in A$, all finite set must be closed.

Proof

Let p be a limit point of finite set E . By **theorem 7.1.4**, then any $N_r(p)$ contain infinite $q \in E$ so E is an infinite set which is a contradiction since E is finite.

So p cannot be limit point of E and thus, E has no limit points.

Theorem 7.1.6: De Morgan's Laws

Let E_1, E_2, \dots be a collection of sets. Then, $(\cup E_x)^c = \cap (E_x^c)$.

Proof

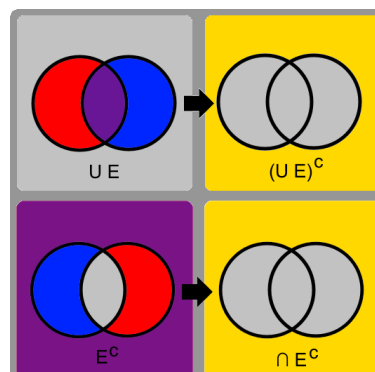
If $p \in (\cup E_x)^c$, then $p \notin (\cup E_x)$.

Thus, $p \notin E_x$ for any x so $p \in E_x^c$ for all x . Thus, $p \in \cap (E_x^c)$ so $(\cup E_x)^c \subset \cap (E_x^c)$.

If $p \in \cap (E_x^c)$, then $p \in E_x^c$ for all x .

Thus, $p \notin E_x$ for any x so $p \notin \cup E_x$. Thus, $p \in (\cup E_x)^c$ so $\cap (E_x^c) \subset (\cup E_x)^c$.

Thus, $(\cup E_x)^c = \cap (E_x^c)$.



Theorem 7.1.7: Open set \rightarrow Closed complement

A set E is open if and only if E^c is closed.

Proof

Suppose E is open. Let x be a limit point of E^c .

Then for every $r > 0$, $N_r(x)$ must contain a $p \in E^c$ such that $p \neq x$.

Then, $N_r(x) \not\subset E$ so x is not an interior point of E and thus, $x \notin E$ so $x \in E^c$.

Since any limit point x of E^c is a $x \in E^c$, then E^c is closed.

Suppose E^c is closed. Let $x \in E$.

Since $x \notin E^c$, x is not a limit point of E^c .

Then there exists a $r > 0$ such that any $p \in N_r(x)$ is not in E^c .

Thus, every $p \in N_r(x)$ is $p \in E$ so $N_r(x) \subset E$ and thus, x is an interior point of E .

Since any $x \in E$ is an interior point of E , then E is open.

Corollary 7.1.8: Closed set \rightarrow Open complement

A set F is closed if and only if F^c is open.

Proof

From **theorem 7.1.7**, let $E = F^c$.

Theorem 7.1.9: Union open \rightarrow open and Intersection closed \rightarrow closed

- (a) If $\{G_x\}$ is a finite or infinite collection of open sets, then $\cup G_x$ is open.

Proof

If $p \in \cup G_x$, then $p \in G_x$ for at least one x . Let \bar{x} be such an x .

Since $G_{\bar{x}}$ is open, then p is an interior point of $G_{\bar{x}}$ and thus, there is a $N_r(p)$ such that $N_r(p) \subset G_{\bar{x}} \subset \cup G_x$. So p is an interior point of $\cup G_x$.

Since any $p \in \cup G_x$ is an interior point, then $\cup G_x$ is open.

- (b) If $\{F_x\}$ is a finite or infinite collection of closed sets, then $\cap F_x$ is closed.

Proof

By **theorem 7.1.7**, any F_x^c is open. Since $\{F_x^c\}$ is a finite or infinite collection of open set, then by part (a), $\cup F_x^c$ is open.

Thus, again by **theorem 7.1.7**, $(\cup F_x^c)^c$ is closed.

By **theorem 7.1.6**, $(\cup F_x^c)^c = \cap (F_x^c)^c = \cap F_x$.

- (c) If G_1, \dots, G_n is a finite collection of open sets, then $\cap_{x=1}^n G_x$ is open.

Proof

If $p \in \cap_{x=1}^n G_x$, then $p \in G_x$ for all G_x for $x = \{1, 2, \dots, n\}$.

Since each G_x is open, then for any G_x , there is a $N_{r_x}(p) \subset G_x$.

Let $r = \min(r_1, r_2, \dots, r_n)$. Thus, $p \in N_r(p) \subset N_{r_x}(p)$ for all x .

So, $N_r(p) \subset \cap_{x=1}^n G_x$ and thus, p is an interior point of $\cap_{x=1}^n G_x$ so $\cap_{x=1}^n G_x$ is open.

Infinite + Closed: $G_i = (-1/i, 1/i)$

Infinite + Open: $G_i = (-i, i)$

- (d) If F_1, \dots, F_n is a finite collection of closed sets, then $\cup_{x=1}^n F_x$ is closed.

Proof

By **theorem 7.1.7**, any F_x^c is open. Since F_1^c, \dots, F_n^c is a finite collection of open set, then by part (c), $\cap_{x=1}^n F_x^c$ is open.

Thus, again by **theorem 7.1.7**, $(\cap_{x=1}^n F_x^c)^c$ is closed.

By **theorem 7.1.6**, $(\cap_{x=1}^n F_x^c)^c = \cup_{x=1}^n (F_x^c)^c = \cup_{x=1}^n F_x$.

Infinite + Closed: $F_i = [-1/i, 1/i]$

Infinite + Open: $F_i = [1/i, \infty)$

Theorem 7.1.10: E' is closed

Let $E \subset X$. Then, $(E')' \subset E'$. Thus, E' is closed.

Proof

If $x \in (E')'$, then for every $N_{r_1}(x)$, there is a $y \neq x$ where $y \in E'$.

Since $y \in E'$, then for every $N_{r_2}(y)$, there is a $z \neq y$ where $z \in E$.

Let $r = r_1 + r_2$.

Then for every $N_r(x)$, there exists a $z \neq x$ where $z \in E$. Thus, $x \in E'$ so $(E')' \subset E'$.

Theorem 7.1.11: E° is open

Let $E \subset X$. Then, E° is open.

Proof

If $p \in E^\circ$, there is a $r > 0$ such that $N_r(p) \subset E$.

Then for $0 < s < r$, $N_s(p) \subset N_r(p)$ so any $q \in N_s(p)$ is $q \in E^\circ$.

Since any $p \in E^\circ$ have a $N_s(p) \subset E^\circ$, then E° is open.

7.2 Intervals and Balls**Definition 7.2.1: Segments and Intervals**

In \mathbb{R} , a **segment** is an open interval $(a,b) = \{x \in \mathbb{R} : a < x < b\}$

In \mathbb{R} , a **interval** is a closed interval $[a,b] = \{x \in \mathbb{R} : a \leq x \leq b\}$

Definition 7.2.2: Open Balls

In \mathbb{R}^k , an **open ball** of radius $r > 0$ centered at p is:

$$N_r(p) = \{x \in \mathbb{R}^k : |x - p| < r\} = \{x \in \mathbb{R}^k : d(x,p) < r\}$$

A **closed ball** has $d(x,p) \leq r$.

Definition 7.2.3: Convex

$E \subset \mathbb{R}^k$ is **convex** if for all $x, y \in E$ and $t \in [0,1]$, $tx + (1-t)y \in E$.

Example 7.2.4: Balls are convex

Balls in \mathbb{R}^k are convex.

Proof

Let $x, y \in$ open ball $N_r(p)$. Let $z = tx + (1-t)y$ for $t \in [0,1]$.

Since $|x - p| < r$ and $|y - p| < r$:

$$\begin{aligned} |z - p| &= |tx + (1-t)y - p| = |tx + (1-t)y - tp + (t-1)p| \\ &= |t(x-p) + (1-t)(y-p)| \leq t|x-p| + (1-t)|y-p| \\ &< tr + (1-t)r = r \end{aligned}$$

Thus, $z \in N_r(p)$ so balls are convex. Same proof applies to closed balls.

Definition 7.2.5: Dense

$E \subset X$ is dense if every $x \in X$ is either in E or a limit point of E .

Example 7.2.6: \mathbb{Q} is dense in \mathbb{R}

Let $X = \mathbb{R}$. Then, $E = \mathbb{Q}$ is dense in \mathbb{R} .

Proof

Fix $x \in \mathbb{R}$ and $r > 0$. There is a $q \in \mathbb{Q}$ such that $x-r < q < x$. So for any $r > 0$ and $q \in \mathbb{Q}$, $q \neq x$ and $q \in N_r(x)$. Thus, every $x \in \mathbb{R}$ is a limit point of \mathbb{Q} .

8 Closure, Open Relative, & Compact

8.1 Closure

Definition 8.1.1: Closure

Let $E \subset$ metric space X and E' be the set of all limit points of E in X .

Then the closure of E : $\overline{E} = E \cup E'$

with the properties:

- (a) \overline{E} is closed
- (b) $E = \overline{E}$ if and only if E is closed
- (c) $\overline{E} \subset F$ for every closed $F \subset X$ such that $E \subset F$

Proof

Suppose $x \in X$, but $x \notin \overline{E}$. Thus, $x \in \overline{E}^c$.

Thus, there is a $N_r(x) \subset \overline{E}^c$ since else there is always a $p \in N_r(x)$ where $p \in \overline{E}$ so x is a limit point of \overline{E} so $x \in \overline{E}$. Thus, \overline{E}^c is open so \overline{E} is closed by [theorem 7.1.7](#).

If $E = \overline{E}$, then by part (a), E is closed.

If E is closed, then $E' \subset E$ so $E = E \cup E' = \overline{E}$.

If closed set F , then $F' \subset F$ and since $E \subset F$, then $E' \subset F' \subset F$. Thus, $\overline{E} \subset F$.

Theorem 8.1.2: $\sup(E) \in \overline{E}$

Let non-empty set of real numbers, E , be bounded above. Let $y = \sup(E)$.

Then, $y \in \overline{E}$. Thus, $y \in E$ if E is closed and $y \notin E$ if E is open in \mathbb{R} .

Proof

If $y \in E$, then $y \in \overline{E}$. Suppose $y \notin E$.

For every $h > 0$, there exists a $x \in E$ such that $y-h < x < y$ otherwise $y-h$ is an upper bound for E which is a contradiction since $y = \sup(E)$.

Thus, y is a limit point of E so $y \in E'$.

If E is closed, then $y \in E$ since $y \in E'$. Also, $y \in \overline{E}$.

If E is open, then any $N_r(y) \not\subset E$ since $N_r(y)$ in \mathbb{R} must contain a $\gamma > y$ so $y \notin E^o$.

8.2 Open Relative

Definition 8.2.1: Open Relative

Suppose $E \subset Y \subset$ metric space X .

Then E is open relative to Y if for each $p \in E$, there is an $r > 0$ such that for any $q \in Y$, then $q \in E$ if $d(q,p) < r$.

Theorem 8.2.2: E is open relative to $Y \subset X$ if $E = Y \cap G$ and G is open in X

Suppose $E \subset Y \subset X$.

E is open relative to Y if and only if $E = Y \cap G$ for some open $G \subset X$.

Proof:

Suppose E is open relative to Y .

Then for each $p \in E$, there is a $r_p > 0$ such that for any $q \in Y$ where $d(p, q) < r_p$, then $q \in E$.

Since $Y \subset X$, let V_p be the set of all $q \in X$ such that $d(p, q) < r_p$ and define $G = \bigcup_{p \in E} V_p$. Since V_p is open by [theorem 7.1.3](#), then by [theorem 7.1.9a](#), open $G \subset X$. Since $p \in V_p$ for all $p \in E$, then $E \subset G \cap Y$. Also, by construction, then $V_p \cap Y \subset E$ so $G \cap Y \subset E$. Thus, $E = Y \cap G$.

If G is open in X and $E = G \cap Y$, then every $p \in E$ has a $V_p \subset G$.

Then, $V_p \cap Y \subset G \cap Y = E$ so E is open relative to Y .

8.3 Compact Sets

Definition 8.3.1: Open Cover

An open cover of set $E \subset X$ is a collection of open $G_1, G_2, \dots \subset X$ such that $E \subset \bigcup G_i$.

Definition 8.3.2: Compact

$K \subset X$ is compact if every open cover of K contains a finite subcover.

If G_1, G_2, \dots is an open cover of K , then $K \subset \bigcup_{i=1}^n G_i$ for some n .

Theorem 8.3.3: A compact set is compact in every metric space

Suppose $K \subset Y \subset X$.

Then K is compact relative to X if and only if K is compact relative to Y .

Proof

Suppose K is compact relative to X .

Let V_1, V_2, \dots be sets open relative to Y such that $K \subset \bigcup V_x$. Then by [theorem 8.2.2](#) for each V_x , there is a G_x open relative to X where $V_x = Y \cap G_x$.

Since K is compact relative to X , then there is a n such that $K \subset G_{x_1} \cup \dots \cup G_{x_n}$.

Thus, $K = K \cap Y \subset (\bigcup_{i=1}^n G_{x_i}) \cap Y = (\bigcup_{i=1}^n (G_{x_i} \cap Y)) = \bigcup_{i=1}^n V_{x_i}$.

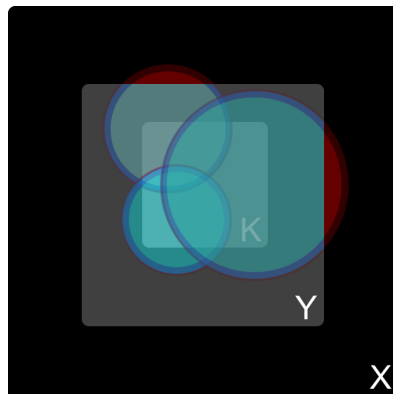
Since there are open V_{x_1}, \dots, V_{x_n} where $K \subset \bigcup_{i=1}^n V_{x_i}$ so K is compact relative to Y .

Suppose K is compact relative to Y .

Let open $G_1, G_2, \dots \subset X$ such that $X \subset \bigcup G_x$. For each G_x , let $V_x = Y \cap G_x \subset Y$.

Since K is compact relative to Y , there is a n such that $K \subset \bigcup_{i=1}^n V_{x_i}$.

Thus, $K \subset \bigcup_{i=1}^n V_{x_i} = \bigcup_{i=1}^n (Y \cap G_{x_i}) \subset \bigcup_{i=1}^n G_{x_i}$ so K is compact relative to X .



Theorem 8.3.4: A compact set is closed

Compact subsets of metric spaces are closed.

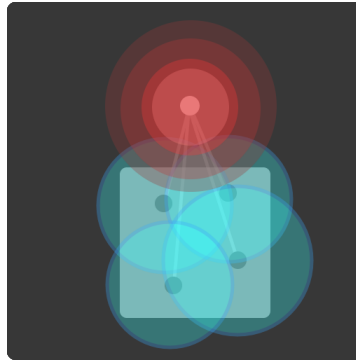
Proof

Let compact $K \subset X$. Suppose $p \in X$, but $p \notin K$ so $p \in K^c$.

If $q \in K$, let W_q be a neighborhood of q with $r < \frac{1}{2}d(p,q)$. Let $V_{p,q}$ be a neighborhood of p with $r < \frac{1}{2}d(p,q)$. Since K is compact, then there are finite points q_1, \dots, q_n such that $K \subset W$ where $W = W_{q_1} \cup \dots \cup W_{q_n}$.

Let $V = V_{p,q_1} \cap \dots \cap V_{p,q_n}$, then $K \cap V \subset W \cap V = \emptyset$ so $V \subset K^c$.

Since there is a neighborhood V for $p \in K^c$ where $V \subset K^c$, then every $p \in K^c$ is an interior point so K^c is open. Then by [theorem 7.1.7](#), K is closed.

**Theorem 8.3.5: If closed $E \subset$ compact set K , E is compact**

Closed subsets of compact sets are compact.

Proof

Suppose $F \subset K \subset X$ where F is closed relative to X and K is compact.

Let V_1, V_2, \dots be an open cover for F . Let open set F^c be all $k \in K$ where $k \notin F$.

$$K = F \cup F^c \subset V_1 \cup V_2 \cup \dots \cup F^c$$

Thus, $V_1 \cup V_2 \cup \dots \cup F^c$ is an open cover for K .

Since K is compact, there is a finite subcover Ω that covers K and thus, finite subcover Ω covers $F \cup F^c$.

Remove F^c from Ω . Since finite subcover $\Omega - F^c$ covers F , then F is compact.

Corollary 8.3.6: Closed $F \cap$ compact $K =$ compact

If F is closed and K is compact, then $F \cap K$ is compact.

Proof

Since K is compact, then K is closed by [theorem 8.3.4](#).

Then, by [7.1.9b](#), $F \cap K$ is closed.

Since $F \cap K \subset K$, then by [theorem 8.3.5](#), $F \cap K$ is compact.

Theorem 8.3.7: Nonempty $\cap_{i=1}^n K_i \rightarrow$ nonempty $\cap K_i$

For compact sets $K_1, K_2, \dots \subset X$ where any intersection of finite K_i is nonempty, then $\cap K_i$ is nonempty.

Proof

Fix K_1 . If there is a $k \in K_1$ where $k \in K_i$ for all i , then $k \in \cap K_i$ so $\cap K_i \neq \emptyset$.

Suppose for every $k \in K_1$, $k \notin K_i$ for some i .

Then for every $k \in K_1$, there is a K_i such that $p \notin K_i$ so $p \in K_i^c$.

Thus, K_2^c, K_3^c, \dots form an open cover for K_1 .

Since K_1 is compact, there is a n where $K_1 \subset K_{i_1}^c \cup \dots \cup K_{i_n}^c$.

But then, $K_1 \cap K_{i_1} \cap \dots \cap K_{i_n} = \emptyset$ which is a contradiction.

Corollary 8.3.8: Nonempty K_i where $K_{i+1} \subset K_i \rightarrow$ nonempty $\cap K_i$

If K_1, K_2, \dots is a sequence of nonempty compact sets such that $K_{i+1} \subset K_i$, then $\cap K_i$ is nonempty.

Proof

Since each K_i is nonempty and if $i_1 < \dots < i_n$, then $K_{i_1} \cap \dots \cap K_{i_n} = K_{i_n}$ is nonempty, then by **theorem 8.3.7**, $\cap K_i$ is nonempty.

Theorem 8.3.9: Nonempty intervals I_n where $I_{n+1} \subset I_n \rightarrow$ nonempty $\cap I_n$

If I_1, I_2, \dots is a sequence of intervals in \mathbb{R}^1 such that $I_{n+1} \subset I_n$, then $\cap I_n$ is nonempty.

Proof

Let $I_n = [a_n, b_n]$ and thus, each I_n is nonempty. If $n_1 < \dots < n_m$, then

$I_{n_1} \cap \dots \cap I_{n_m} = [a_{n_m}, b_{n_m}]$ is nonempty. Thus, by **theorem 8.3.7**, $\cap I_n$ is nonempty.

Theorem 8.3.10: $p \in E'$ exists if infinite $E \subset$ compact K

If E is an infinite subset of compact set K , then E has a limit point in K .

Proof

If no $p \in K$ is a $p \in E'$, then each p would have a neighborhood V_p contains at most $p \in E$ if $p \in E$. Thus, there is no finite subcover that covers E and thus, there is no finite subcover that covers K since $E \subset K$ which contradicts K is compact.

Definition 8.3.11: K-cells

The set of all $x = (x_1, \dots, x_k) \in \mathbb{R}^k$ where $x_i \in [a_i, b_i]$ for fixed $a_i, b_i \in \mathbb{R}$.

Theorem 8.3.12: K-cells are compact

Every k -cell is compact.

Proof

Let k -cell I consists of all $x = (x_1, \dots, x_k)$ where $x_i \in [a_i, b_i]$ for fixed $a_i, b_i \in \mathbb{R}$.

Let $\delta = \sqrt{\sum_{i=1}^k (b_i - a_i)^2}$. Thus, $|x - y| \leq \delta$ for $x, y \in I$.

Suppose there exists an open cover G_1, G_2, \dots of I which contain no finite subcover.

Let $c_i = \frac{a_i + b_i}{2}$. Then each interval splits into $[a_i, c_i]$ and $[c_i, b_i]$ for $i \in [1, k]$ so there now exists 2^k k -cells Q_i whose union is I .

At least one Q_i cannot be covered else I would be covered. Then subdivide Q_i as before and repeating the process so $Q_{i+1} \subset Q_i$ and each are not covered.

However, there is a point $x^* \in Q_{i_j}$ for all j such that $N_r(x^*) \subset G$ so Q_{i_1} is covered which is a contradiction.

Theorem 8.3.13: Heine-Borel Theorem

If a set $E \subset \mathbb{R}^k$ has one of the three properties, then it has the other two:

- (a) E is closed and bounded
- (b) E is compact
- (c) Every infinite subset of E has a limit point in E

Proof

Suppose E is closed and bounded.

Then there exists a $M \in \mathbb{R}$ and $q \in \mathbb{R}^k$ such that $d(p, q) < M$ for all $p \in E$.

Thus, there is a k -cell $K = [-M + q_1, q_1 + M] \times \dots \times [-M + q_k, q_k + M]$ such that $E \subset K$. Then by **theorem 8.3.12**, K is compact and thus by **theorem 8.3.5**, E is compact so (a) \rightarrow (b).

Then by **theorem 8.3.10**, any infinite subset of E has a limit point in E so (b) \rightarrow (c). Suppose E is not bounded.

Then there exists $p \in E$ such that $d(p, q) > M$ for any $M \in \mathbb{R}$ and $q \in \mathbb{R}^k$.

Let $S \subset E$ be such points p .

Then S is infinite else there is a maximal p and thus, p is bounded. Thus, S is infinite and contains no limit points in E since any $d(p_1, p_2) > M$ which contradicts that every infinite subset of E has a limit point in E . Thus, E is bounded.

Suppose E is not closed.

Then there exists a $p \in E'$, but $p \notin E$. Since p is a limit point, then there is a $q \in E$ such that $\frac{1}{n+1} < d(q, p) < \frac{1}{n}$ for $n = \{1, 2, \dots\}$.

Let $S \subset E$ be such points q .

Thus, p is the only limit point of S since for $r < \frac{1}{n}$, any $N_r(q_i)$ contains no points of S other than q_i since $d(q_i, q_j) > \frac{1}{n}$ for any $q_1, q_2 \in S$.

Thus, S is infinite, but the only $p \in S'$ is $p \notin E$ which contradicts that every infinite subset of E has a limit point in E . Thus, E is closed. So, (c) \rightarrow (a).

Theorem 8.3.14: Weierstrass Theorem

Every bounded infinite set $E \subset \mathbb{R}^k$ has a limit point in \mathbb{R}^k .

Proof

Since E is bounded, then there exists a k -cell K such that $E \subset K$. Since K is compact, then by **theorem 8.3.10**, E has a limit point in K and thus, in \mathbb{R}^k .

9 Perfect and Connected Sets

9.1 Perfect Sets

Definition 9.1.1: Perfect Set

$E \subset X$ is perfect if E is closed and if every $p \in E$ is $p \in E'$.

Theorem 9.1.2: Perfect sets are uncountable

Let P be a nonempty perfect set in \mathbb{R}^k . Then, P is uncountable.

Proof

Since P has limit points, then by [theorem 7.1.4](#), P is infinite.

Suppose P is countable. Then let $x_1, x_2, \dots \in P$.

Let V_i be a neighborhood of x_i where $y \in V_i$ for any $y \in \mathbb{R}^k$ such that $|y - x_i| < r$. Thus, the $\overline{V_i}$ is the set of all $y \in \mathbb{R}^k$ such that $|y - x_i| \leq r$.

Since every x_i are limit points, then any $V_i \cap P$ is not empty where there is a V_{i+1}

$$(a) \overline{V_{i+1}} \subset V_i$$

$$(b) x_i \notin \overline{V_{i+1}}$$

$$(c) V_{i+1} \cap P \text{ is nonempty}$$

Let $K_i = \overline{V_i} \cap P$. Since $\overline{V_i}$ is closed and bounded, then by [theorem 8.3.11](#), $\overline{V_i}$ is compact. Since $x_i \notin K_{i+1}$, then no $x_i \in P$ is $x_i \in \cap K_i$. Since $K_n \subset P$, then $\cap K_i$ is nonempty which contradicts [corollary 8.3.8](#) since each K_i is empty and $K_{i+1} \subset K_i$.

Corollary 9.1.3: \mathbb{R} is not countable

Every interval $[a, b]$ is uncountable. Thus, \mathbb{R} is uncountable.

Proof

Since $[a, b]$ is closed and every $p \in [a, b]$ is a limit point, then nonempty set $[a, b]$ is perfect. Thus, by [theorem 9.1.2](#), $[a, b]$ is uncountable.

Definition 9.1.4: Cantor Sets

There exists perfect segments in \mathbb{R}^1 which contain no segment.

Let $E_0 = [0, 1]$.

For E_1 , remove $(\frac{1}{3}, \frac{2}{3})$. Thus, $E_1 = [0, \frac{1}{3}] \cup [\frac{2}{3}, 1]$.

For E_2 , remove $(\frac{1}{9}, \frac{2}{9})$ and $(\frac{7}{9}, \frac{8}{9})$. Thus, $E_2 = [0, \frac{1}{9}] \cup [\frac{2}{9}, \frac{3}{9}] \cup [\frac{6}{9}, \frac{7}{9}] \cup [\frac{8}{9}, 1]$.

Continuing such a sequence, the set of compact sets E_n are such that:

$$(a) E_{n+1} \subset E_n$$

$$(b) E_n \text{ is the union of } 2^n \text{ intervals each of length } 3^{-n}.$$

$P = \cap E_n$ is called the Cantor set. P is compact and nonempty.

Thus, any segment of form $(\frac{3k+1}{3^m}, \frac{3k+2}{3^m})$ where $k, m \in \mathbb{Z}_+$ has no points in common with P . Since any segment (a, b) contain a segment of such a form since $3^{-m} < \frac{b-a}{6}$, then P contains no segment.

Let $x \in P$ and segment S contain x . Let I_n be an interval of E_n containing x . Then choose a large enough n so $I_n \subset S$.

Let x_n be an endpoint of I_n where $x_n \neq x$ and thus, x is a limit point. Since P is closed and every $p \in P$ is $p \in P'$, then P is perfect.

9.2 Connected Sets

Definition 9.2.1: Connected Set

$A, B \subset X$ are separated if both $A \cap \overline{B}$ and $\overline{A} \cap B$ are empty.

$E \subset X$ is connected if E is not the union of two nonempty separated sets.

Separated sets are disjoint, but disjoint sets need not be separated.

Theorem 9.2.2: All points between points in connected sets exists

$E \subset \mathbb{R}^1$ is connected if and only if:

If $x, y \in E$ and $x < z < y$, then $z \in E$.

Proof

If there exists $x, y \in E$ and $z \in (x, y)$ such that $z \notin E$, then $E = A_z \cup B_z$ where $A_z = E \cap (-\infty, z)$ and $B_z = E \cap (z, \infty)$.

Since $x \in A_z$ and $y \in B_z$, then A and B are nonempty. Since $A_z \subset (-\infty, z)$ and $B_z = (z, \infty)$, then A_z and B_z are separated. Thus, E is not connected.

Suppose E is not connected. Then, there are nonempty separated sets A and B such that $A \cup B = E$. Pick $x \in A$, $y \in B$ where $x < y$. Let $z = \sup(A \cap [x, y])$.

Since, $z \in \overline{A}$ so $z \notin B$, then $x \leq z < y$. If $z \notin A$, then $x < z < y$ so $z \notin E$.

If $z \in A$, then $z \notin \overline{B}$ and thus, there exists a z_1 such that $z < z_1 < y$ and $z_1 \notin B$. Then, $x < z_1 < y$ so $z_1 \notin E$.

10 Convergent and Cauchy Sequences

10.1 Convergent Sequences

Definition 10.1.1: Convergent Sequence

A sequence $\{x_n\}$ in metric space X converge if there is a $x \in X$ such that:

For every $\epsilon > 0$, there is a $N \in \mathbb{Z}$ such that for all $n \geq N$, $d(x_n, x) < \epsilon$

Then, $\{x_n\}$ converges to x : $\lim_{n \rightarrow \infty} x_n = x$

If $\{x_n\}$ does not converge, then it diverges.

Example 10.1.2

- (a) Let $x_n = \frac{1}{n}$ in \mathbb{R}^2 . Then, $\lim_{n \rightarrow \infty} x_n = 0$

Proof

For $\epsilon > 0$, there is a $\frac{1}{N} < \epsilon$. Then:

$$d(x_n, 0) = |x_n - 0| = \frac{1}{n} < \frac{1}{N} < \epsilon$$

- (b) Let $x_n = (-1)^n + \frac{1}{n}$ in \mathbb{R}^2 . Then, $\{x_n\}$ diverges.

Proof

$$\lim_{n \rightarrow \infty} x_n = \lim_{n \rightarrow \infty} (-1)^n + \lim_{n \rightarrow \infty} \frac{1}{n} = \lim_{n \rightarrow \infty} (-1)^n$$

Since $(-1)^n$ alternates between -1 and 1, then $\{x_n\}$ diverges.

Theorem 10.1.3: A convergent sequence is unique

- (a) $\{p_n\}$ converges to $p \in X$ if and only if every $N_r(p)$ contains p_n for all, but finitely many n .

Proof

Suppose $p_n \rightarrow p$. Then for $N_\epsilon(p)$, any $q \in X$ such that $d(q, p) < \epsilon$ is $q \in N_\epsilon(p)$. Since $p_n \rightarrow p$, there is a N such that for $n \geq N$, $d(p_n, p) < \epsilon$.

Thus, for $n \geq N$, $p_n \in N_\epsilon(p)$.

Suppose every $N_r(p)$ contains p_n for all, but finitely many n .

For $\epsilon > 0$, let $N_\epsilon(p)$ be the set of all $q \in X$ such that $d(p, q) < \epsilon$. Thus, there exists an N such that $p_n \in N_\epsilon(p)$ if $n \geq N$.

Thus, $d(p_n, p) < \epsilon$ so $p_n \rightarrow p$.

- (b) If $p, p' \in X$ and $\{p_n\}$ converges to p and p' , then $p = p'$.

Proof

For $\epsilon > 0$, there exists N, N' such that:

$$d(p_n, p) < \frac{\epsilon}{2} \text{ for } n \geq N \quad d(p_n, p') < \frac{\epsilon}{2} \text{ for } n \geq N'$$

Then for $n \geq \max(N, N')$:

$$d(p, p') \leq d(p, p_n) + d(p_n, p') < \epsilon$$

Thus, $p = p'$.

- (c) If $\{p_n\}$ converges, then $\{p_n\}$ is bounded.

Proof

If $\{p_n\} \rightarrow p$, there is a N such that for $n > N$, $d(p_n, p) < 1$.

Let $r = \max(1, d(p_1, p), \dots, d(p_N, p))$. Thus for all n , $d(p_n, p) \leq r$.

- (d) If $E \subset X$ and $p \in E'$, there is a $\{p_n\}$ in E such that $p = \lim_{n \rightarrow \infty} p_n$.

Proof

Since $p \in E'$, then for each $n \in \mathbb{Z}_+$, there is a $p_n \in E$ such that $d(p_n, p) < \frac{1}{n}$. For $\epsilon > 0$, there is a $\frac{1}{N} < \epsilon$ so for $n \geq N$, $d(p_n, p) < \frac{1}{n} < \frac{1}{N} < \epsilon$.

Thus, $p = \lim_{n \rightarrow \infty} p_n$.

Theorem 10.1.4: Arithmetic Operations for Sequences

Suppose $\{s_n\}, \{t_n\} \in \mathbb{C}$ where $\lim_{n \rightarrow \infty} s_n = s$ and $\lim_{n \rightarrow \infty} t_n = t$.

(a) $\lim_{n \rightarrow \infty} s_n + t_n = s + t$

Proof

For $\epsilon > 0$, there exists N_1, N_2 such that

$$|s_n - s| < \frac{\epsilon}{2} \text{ for } n \geq N_1 \quad |t_n - t| < \frac{\epsilon}{2} \text{ for } n \geq N_2$$

If $N = \max(N_1, N_2)$, then for $n \geq N$:

$$|s_n + t_n - s + t| \leq |s_n - s| + |t_n - t| < \epsilon$$

(b) $\lim_{n \rightarrow \infty} cs_n = cs$ and $\lim_{n \rightarrow \infty} c + s_n = c + s$

Proof

For $\epsilon > 0$, there exists a N such that

$$|s_n - s| < \frac{\epsilon}{c} \text{ for } n \geq N$$

$$|cs_n - cs| \leq c \cdot |s_n - s| < \epsilon$$

(c) $\lim_{n \rightarrow \infty} s_n t_n = st$

Proof

$$\text{Note } s_n t_n - st = (s_n - s)(t_n - t) + t(s_n - s) + s(t_n - t).$$

For $\epsilon > 0$, there exists N_1, N_2 such that

$$|s_n - s| < \sqrt{\epsilon} \text{ for } n \geq N_1 \quad |t_n - t| < \sqrt{\epsilon} \text{ for } n \geq N_2$$

If $N = \max(N_1, N_2)$, then for $n \geq N$, $|(s_n - s)(t_n - t)| < \epsilon$.

Thus, $\lim_{n \rightarrow \infty} (s_n - s)(t_n - t) = 0$.

$$\begin{aligned} \lim_{n \rightarrow \infty} (s_n t_n - st) &= \lim_{n \rightarrow \infty} (s_n - s)(t_n - t) + t(s_n - s) + s(t_n - t) \\ &= 0 + t \cdot 0 + s \cdot 0 = 0 \end{aligned}$$

(d) $\lim_{n \rightarrow \infty} \frac{1}{s_n} = \frac{1}{s}$ where $s_n, s \neq 0$

Proof

Choose m such that $|s_n - s| < \frac{1}{2}|s|$ if $n \geq m$ so $|s_n| > \frac{1}{2}|s|$ for $n \geq m$.

For $\epsilon > 0$, there is a $N > m$ such that for $n \geq N$, $|s_n - s| < \frac{1}{2}|s|^2\epsilon$.

Thus, for $n \geq N$, $|\frac{1}{s_n} - \frac{1}{s}| = \frac{s_n - s}{s_n s} < \frac{2}{|s|^2}|s_n - s| < \epsilon$.

Theorem 10.1.5: Extension to \mathbb{R}^k

(a) Suppose $x_n \in \mathbb{R}^k$ and $x_n = (\alpha_{n1}, \dots, \alpha_{nk})$. Then $\{x_n\}$ converges to $x = (\alpha_1, \dots, \alpha_k)$ if and only if $\lim_{n \rightarrow \infty} \alpha_{ni} = \alpha_i$ for $i \in [1, k]$.

Proof

Suppose $\{x_n\}$ converges to $x = (\alpha_1, \dots, \alpha_k)$.

Since for any $i \in [1, k]$, $|\alpha_{ni} - \alpha_i| \leq |x_n - x| < \epsilon$. Then, $\lim_{n \rightarrow \infty} \alpha_{ni} = \alpha_i$.

Suppose $\lim_{n \rightarrow \infty} \alpha_{ni} = \alpha_i$ for $i \in [1, k]$.

Then for $\epsilon > 0$, there is an N such that for $n \geq N$:

$$|\alpha_{ni} - \alpha_i| < \frac{\epsilon}{\sqrt{k}} \text{ for } i \in [1, k]$$

$$|x_n - x| = \sqrt{\sum_{i=1}^k |\alpha_{ni} - \alpha_i|^2} < \sqrt{k \cdot \left(\frac{\epsilon}{\sqrt{k}}\right)^2} = \epsilon$$

(b) Suppose $\{x_n\}, \{y_n\} \in \mathbb{R}^k$ and $\{\beta_n\} \in \mathbb{R}$ and $x_n \rightarrow x$, $y_n \rightarrow y$, $\beta_n \rightarrow \beta$.
 $\lim_{n \rightarrow \infty} x_n + y_n = x + y \quad \lim_{n \rightarrow \infty} x_n \cdot y_n = x \cdot y \quad \lim_{n \rightarrow \infty} \beta_n x_n = \beta x$

Proof

By part a, then $\lim_{n \rightarrow \infty} x_{ni} + y_{ni} = x_i + y_i$ so $\{x_n + y_n\} \rightarrow x + y$.

Also, $\lim_{n \rightarrow \infty} \sum_{i=1}^k x_{ni} y_{ni} = \sum_{i=1}^k x_i y_i$ so $\{x_n \cdot y_n\} \rightarrow x \cdot y$.

Also, $\lim_{n \rightarrow \infty} \beta_i x_{ni} = \beta_i x_i$ so $\{\beta_n x_n\} \rightarrow \beta x$.

10.2 Subsequences

Definition 10.2.1: Subsequence

For sequence $\{p_n\}$, let $\{n_k\} \in \mathbb{Z}_+$ where $n_k < n_{k+1}$.

Then $\{p_{n_k}\}$ is a subsequence of $\{p_n\}$.

If $\{p_{n_k}\}$ converges, then its limit is called a subsequential limit.

Theorem 10.2.2: $\{p_n\} \rightarrow p \iff \{p_{n_k}\} \rightarrow p$

$\{p_n\}$ converges to p if and only if every subsequence converges to p .

Proof

Suppose $\{p_n\}$ converges to p .

Then for $\epsilon > 0$, there is a N such that for $n \geq N$, $|p_n - p| < \epsilon$.

Let $\{p_{n_k}\}$ be a subsequence of $\{p_n\}$.

Then for $n_k \geq N$, $|p_{n_k} - p| < \epsilon$. Thus, every $\{p_{n_k}\} \rightarrow p$.

Suppose every subsequence converges to p .

Since $\{p_n\}$ is a subsequence of itself, then $\{p_n\}$ converges to p .

Theorem 10.2.3: $\{p_n\}$ in compact space have $\{p_{n_k}\} \rightarrow p$

- (a) If $\{p_n\}$ is a sequence in a compact metric space X , then some subsequence converges to $p \in X$.

Proof

Let E be the range of $\{p_n\}$.

If E is finite, there is a $p \in E$ and sequence $\{n_k\}$ with $n_k < n_{k+1}$ such that $p_{n_1} = p_{n_2} = \dots = p$. Thus, $\{p_{n_k}\} \rightarrow p$.

If E is infinite, then by [theorem 8.3.10](#), then there exists a $p \in X$.

Then choose n_k such that $d(p_{n_k}, p) < \frac{1}{k}$. Thus, $\{p_{n_k}\} \rightarrow p$.

- (b) Every bounded sequence in \mathbb{R}^k contains a convergent subsequence.

Proof

Since every bounded set lies in a compact space in \mathbb{R}^k , then by part a, every bounded sequence contains a convergent subsequence.

Theorem 10.2.4: The set of subsequential limits is closed

The subsequential limits of $\{p_n\}$ in metric space X form a closed subset of X .

Proof

Let E be the range of the set of all subsequential limits of $\{p_n\}$.

If E is empty, then E is closed. If E is finite, then E' is empty so E is closed.

Suppose E is infinite. Then, let $q \in E'$.

Choose n_1 so $p_{n_1} \neq q$. Let $\frac{\epsilon}{2} = d(p_{n_1}, q)$.

Since $q \in E'$, there is a $x \in E$ where $d(x, q) < \frac{\epsilon}{2}$.

Since $x \in E$, then there is a $\{p_{n_k}\} \rightarrow x$ so $d(p_{n_k}, x) < \frac{\epsilon}{2}$.

Thus, $d(p_{n_k}, q) \leq d(p_{n_k}, x) + d(x, q) < \epsilon$ so q is a subsequential limit of $\{p_n\}$.

Thus, $q \in E$ so E is closed.

10.3 Cauchy Sequences

Definition 10.3.1: Metric Spaces

Sequence $\{p_n\} \in X$ is a Cauchy sequence if:

For every $\epsilon > 0$, there is a $N \in \mathbb{Z}$ such that for all $n, m \geq N$, $d(p_n, p_m) < \epsilon$

Let nonempty $E \subset X$ and $S \subset \mathbb{R}$ of $d(p, q)$ where $p, q \in E$.

Let $\sup(S) = \text{diam}(E)$. If $\{p_n\} \in X$, and $p_N, p_{N+1}, \dots \in E_N$, then $\{p_n\}$ is a Cauchy sequence if and only if $\lim_{N \rightarrow \infty} \text{diam}(E_N) = 0$.

Theorem 10.3.2: Cauchy sequences and its closure have the same diam

- (a) If $\overline{E} \subset X$, then $\text{diam}(\overline{E}) = \text{diam}(E)$.

Proof

Since $E \subset \overline{E}$, then $\text{diam}(E) \leq \text{diam}(\overline{E})$.

For $\epsilon > 0$, let $p, q \in E$.

Thus, there are $p', q' \in E$ such that $d(p', p) < \epsilon$ and $d(q', q) < \epsilon$. Thus:

$d(p, q) \leq d(p, p') + d(p', q') + d(q', q) < 2\epsilon + d(p', q') \leq 2\epsilon + \text{diam}(E)$.

Thus, $\text{diam}(\overline{E}) \leq 2\epsilon + \text{diam}(E)$ so $\text{diam}(\overline{E}) = \text{diam}(E)$.

- (b) If K_n is a sequence of compact sets of X such that $K_{n+1} \subset K_n$ and $\lim_{n \rightarrow \infty} \text{diam}(K_n) = 0$, then $\cap K_n$ consist of only one point.

Proof

Let $K = \cap K_n$. Since K_n is a sequence of compact sets, then by **Corollary 8.3.8**, K is nonempty.

If K contains more than one point, then $\text{diam}(K) > 0$.

But since $K \subset K_n$, then $\text{diam}(K) \leq \text{diam}(K_n)$ which contradicts that $\text{diam}(K_n) \rightarrow 0$.

Theorem 10.3.3: Cauchy sequences are convergent

- (a) In every metric space, every convergent sequence is a Cauchy sequence.

Proof

- (b) If $\{p_n\}$ is a Cauchy sequence in compact metric space X , then $\{p_n\}$ converges to some $p \in X$.

Proof

- (c) In \mathbb{R}^k , every Cauchy sequence converges.

Proof

References