

Fall Real Analysis

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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.

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 $\gamma \notin B$.

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, $\inf(B) = \alpha$.

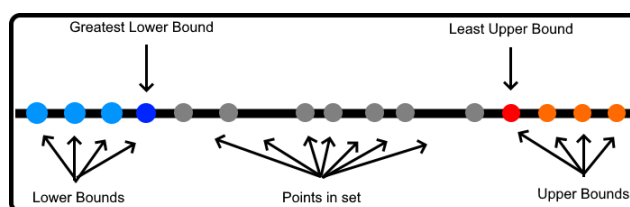


Figure 1: Infimum, Supremum, & Bounds

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 $0x + 0x = (0+0)x = 0x$, then $0x = 0$.
- (j) If $x, y \neq 0$, then $xy \neq 0$
Proof
 Suppose $xy = 0$, then $\frac{1}{y}\frac{1}{x}xy = \frac{1}{y}1y = \frac{1}{y}y = 1$.
 $xy = 0 = 1$ is a contradiction.
- (k) $(-x)y = -(xy) = x(-y)$
Proof
 $xy + (-x)y = (x+(-x))y = 0y = 0$.
 Then by part (c), $(-x)y = -(xy)$.
 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 $x > 0$, $-x < 0$ 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

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

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

- (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 a 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 by \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 $0 < s < t$, $s^n < t^n$.

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

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 $t_1 = \frac{x}{x+1} < 1$ and $< x$ 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 $y^n = x$.

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 3.3.1: 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 3.3.2: 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 3.3.3: Form $a + bi$

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

Proof

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

Definition 3.3.4: Conjugate

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

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

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

Proof

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

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

Proof

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

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

Proof

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

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

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

Proof

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

Definition 3.3.5: Absolute Value

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

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

$$(a) \quad \text{If } z \neq 0, \text{ then } |z| > 0.$$

Proof

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

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

Proof

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

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

Proof

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

$$(d) \quad |\operatorname{Re}(z)| \leq |z|$$

Proof

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

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

Proof

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

4 Euclidean Spaces

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

$$\mathbf{x} \cdot \mathbf{y} = x_1y_1 + \dots + x_ky_k \in \mathbb{R}$$

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:

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

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 $\sum z_i \overline{z_i} = \sum |z_i|^2 = |z|^2$. Thus:

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

Thus, $|z \cdot w| \leq |z||w|$.

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

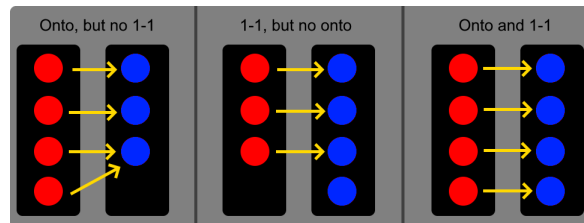
$$|x - y| = |x - z + z - y| \leq |x - z| + |z - y| = |x - z| + |y - z|$$

4.3 Cardinality**Definition 4.3.1: 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 4.3.2: 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 4.3.3: 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 $A \sim \mathbb{Z}_+ = J$
- A is **uncountable** if A is not finite or countably infinite
- A is **at most countable** if A is finite or countably infinite.

Example 4.3.4

\mathbb{Z} is countably infinite

Proof

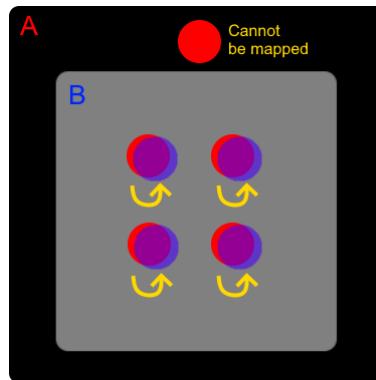
Let $f: \mathbb{Z}_+ \rightarrow \mathbb{Z}$

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

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

Definition 4.3.5: Pigeonhole Principle

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

**Theorem 4.3.6: 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.



5 Metric Spaces

5.1 Set of Sets

Definition 5.1.1: Union and Intersection

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

- $E = \cup_{x=1}^n E_x$ only if for every $x \in E$, $x \in E_x$ for at least one $x \in \Omega$.
- $P = \cap_{x=1}^n E_x$ 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 $(x \in B \text{ or/and } x \in C)$.

- 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 $(x \in B \text{ or/and } x \in C)$.

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 $(x \in B \text{ and } x \in C)$.

- 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 $(x \in B \text{ and } x \in C)$.

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 5.1.2: Union of countably infinite sets is countably infinite

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

Proof

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

$$\begin{pmatrix} x_{11} & x_{12} & x_{13} & \dots \\ x_{21} & x_{22} & x_{23} & \dots \\ x_{31} & x_{32} & x_{33} & \dots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

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 $\widetilde{E}_n = E_n - \cup_{m=1}^{\infty} E_m$ where $m \neq n$. Thus, $S = \cup_{n=1}^{\infty} \widetilde{E}_n$.

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

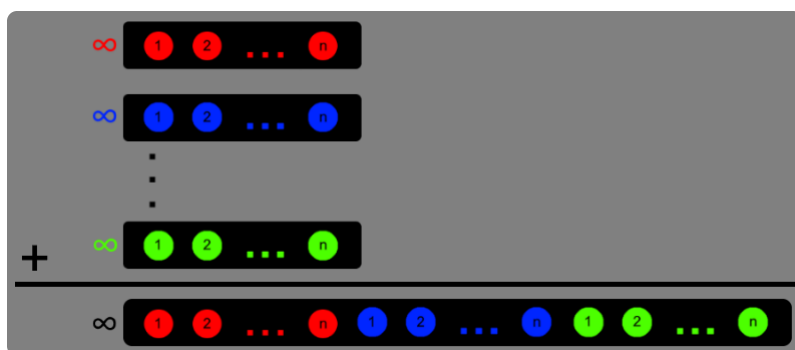
Thus, for each \widetilde{E}_n , there is a 1-1 mapping $\delta_n: \widetilde{E}_n \rightarrow A \subset \mathbb{Z}_+$.

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 5.1.3: 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 5.1.4: \mathbb{Q} is countably infinite

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 5.1.3**, \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 5.1.5: 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.

5.2 Metric Spaces**Definition 5.2.1: Metric Spaces**

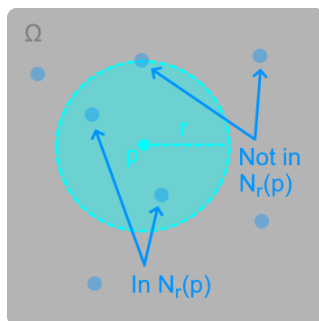
A set X is a metric space if for any $p, q \in X$, there is an associated $d(p, q) \in \mathbb{R}$ such that:

- $d(p, q) > 0$ 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 $r \in \mathbb{R}$.

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

Definition 5.2.2: 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 such that $d(q, p) < r$

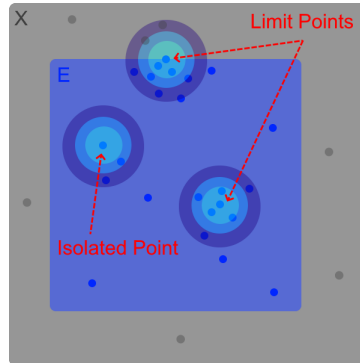
**(b) Limit Points and Closed Sets**

Closed set E contains all p 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 $q \neq p \in E$

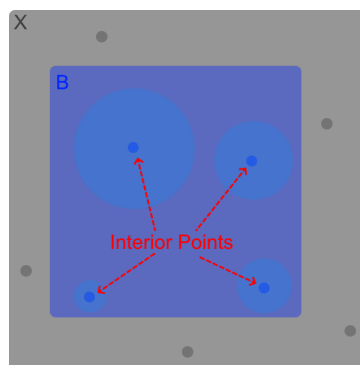
- Isolated Points
If $p \in E$ is not a limit point of E
- Closed
If every limit point p of E is a $p \in E$



(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 $N_r(p) \subset E$
- 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 $p \in E$

Theorem 5.2.3: $N_r(p)$ is open

Every neighborhood is an open set.

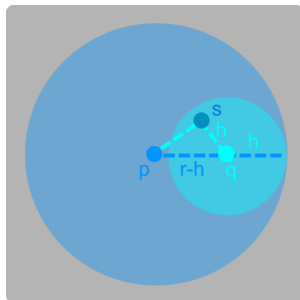
Proof

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

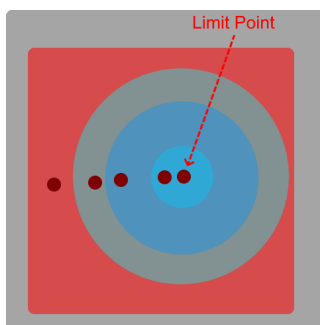
If p is a limit point of set E , then every $N_r(p)$ contains infinitely many $q \in E$.

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 5.2.5: Limit points do not exist in finite sets**

A finite set has no limit points.

Proof

Let p be a limit point of finite set E . By **theorem 5.2.4**, 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 5.2.6: Complement of union of sets = Intesection of complement of sets

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 5.2.7: 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 5.2.8: Closed set \rightarrow Open complement

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

Proof

From **theorem 5.2.7**, let $E = F^c$.

5.3

References