Notes for Mathematical Analysis

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Chapter 1

Set Theory

1.1 Countability of Sets

Definition 1.1.1. A set A is said to be *countable* iff there is a bijection $f : I \to A$ with $I \subseteq \mathbb{N}$.

A is said to be *uncountable* iff for any injection $f : I \to A$ with $I \supseteq \mathbb{N}$, f is not surjection.

Definition 1.1.2. The *cardinal number* of a set A, denoted $|A|$ or $\#A$, is defined to the quantity of it elements.

Customarily, we write $\aleph_0$ for $|\mathbb{N}|$, and $\mathfrak{c}$ for $|\mathbb{R}|$.

Definition 1.1.3. Given A and B as sets, we define the following:

(i) $|A| = |B|$ iff there is a bijection $f : A \to B$;

(ii) $|A| \leq |B|$ iff there is an injection $g : A \to B$;

(iii) $|A| < |B|$ iff for any injection $g : A \to B$, g is not surjection.

Definition 1.1.4. A set A is said to be *finite* iff $|A| < \aleph_0$; it is *infinite* iff $|A| \geq \aleph_0$.

By 1.1.3, A is finite iff for all injection $f : A \to \mathbb{N}$, f is not surjection. Respectively, A is infinite iff there exists injection $f : \mathbb{N} \to A$.

Proposition 1.1.1. For any countable set A, $|A| \leq \aleph_0$.

Proof. If A is finite, i.e., $|A| < \aleph_0$, it is clearly countable.

If A is infinite, by Definition 1.1.4, $|A| \geq \aleph_0$. As A is countable, there must be an bijective $f : I \to A$ with $I \subseteq \mathbb{N}$, then (iii) in Definition 1.1.3 fails, so $|A| = \aleph_0$. $\square$

Proposition 1.1.2. For any set A, A is uncountable iff $|A| > \aleph_0$.

Proof. By Definition 1.1.1, A is uncountable iff for any injection $f : I \to A$ with $I \supseteq \mathbb{N}$, f is not surjection. This holds iff for any $I \subseteq \mathbb{N}$, $|I| < |A|$. $\mathbb{N} \subseteq \mathbb{N}$, Thus $\aleph_0 < |A|$. $\square$

Proposition 1.1.3. The subsets of any countable sets are countable.

Proof. Clearly, by intuition or by Definition 1.1.3, for any sets A and B, $A \subseteq B$ implies $|A| \leq |B|$. By Proposition 1.1.2, B is countable iff $|B| \leq \aleph_0$. Then we have $|A| \leq \aleph_0$. This holds iff A is countable. $\square$

Proposition 1.1.4. The super sets of any uncountable sets are uncountable.

Proof. Let A be an uncountable set. $|A| > \aleph_0$ implies that for any $B \supseteq A$, $|B| > |A| > \aleph_0$. Thus, by Proposition 1.1.2. $\square$

Proposition 1.1.5. The Cartesian product of countable sets is countable.

Proof. If A or B is empty, $A \times B$ is empty. The empty set is countable.

Let A and B be both infinite countable, then there exist $f : \mathbb{N} \to A$ and $g : \mathbb{N} \to B$. Let $h : \mathbb{N} \to \mathcal{P}(A \times B)$ defined by

$$h(x) = \begin{cases} \{(f_0, g_0)\} & x = 0 \\ \{(f_0, g_1), (f_1, g_0)\} & x = 1 \\ \{(f_0, g_2), (f_1, g_1), (f_2, g_0)\} & x = 2 \\ \{(f_0, g_3), (f_1, g_2), (f_2, g_1), (f_3, g_0)\} & x = 3 \\ \vdots & \vdots \end{cases}$$

Now we have

$$A \times B = \bigcup_{x=0}^{\infty} f(x).$$

Thus,

$$|A \times B| = \left| \bigcup_{x=0}^{\infty} f(x) \right| = \sum_{x=0}^{\infty} (x+1).$$

Clearly,

$$\aleph_0 = |\{0\} \cup \{1,2\} \cup \{3,4,5\} \cup \ldots| = |A \times B|.$$

Thus, $A \times B$ is countable. □

Proposition 1.1.6. The countable unions of countable sets is countable.

Proof. Similar to Proposition 1.1.5. □

Proposition 1.1.7. If A is a countable set but B is not, then $B \setminus A$ is uncountable.

Proof. If $B \setminus A$ is countable, $B \setminus A \cup A$ must be countable. Then $B \subseteq B \setminus A \cup A$ is also countable, contradicted to the condition. □

Proposition 1.1.8. There is no countably infinite $\mathcal{P}(X)$ for any set X.

Proof. As $\aleph_0$ is the smallest infinite cardinal number, let $X = \mathbb{N}$. Let

$$\mathcal{U} = \left\{ U = \bigcup_{i=0}^{\infty} \{x_i \in \{2i, 2i+1\}\} \right\} \subseteq \mathcal{P}(X).$$

Suppose $\mathcal{U}$ is countable, then there is a list

$$\mathcal{W} = \bigcup_{k=0}^{\infty} \{U_k = \{x_{k,i}\}\} \supseteq \mathcal{U}.$$

Now construct a new set

$$W = \{w_i\}_{i=0}^{\infty}$$

where for all $i \in \mathbb{N}$, $w_i = 2i$ if $x_{i,i} = 2i+1$, and $w_i = 2i+1$ if $x_{i,i} = 2i$. Now we have $W \in \mathcal{U}$ but $W \notin \mathcal{W}$, which is contradicted to the condition. Thus $\mathcal{U}$ is not countable, thus $\mathcal{P}(X) \supseteq \mathcal{U}$ is not either. □

Proposition 1.1.9. $\mathbb{R}$ is uncountable.

Proof. Similar to Proposition 1.1.8. □