Finite and Infinite

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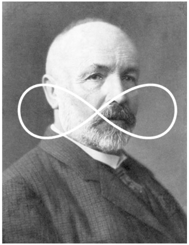

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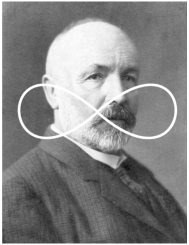

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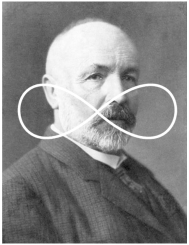

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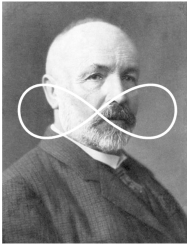

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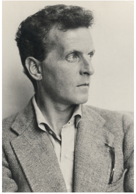
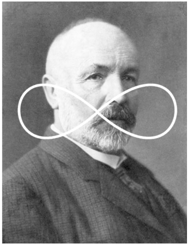


Ludwig Wittgenstein
(1889 – 1951)



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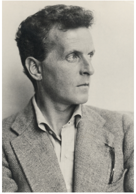

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From his paradise that Cantor with us unfolded, we hold our breath in awe; knowing, we shall not be expelled.

— *David Hilbert*

“没有人能把我们从 *Cantor* 创造的乐园中驱逐出去”

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MATHEMATIKER
BEGRÜNDER DER MENGENLEHRE
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TIK LIEGT IN IHRER FREIHEIT
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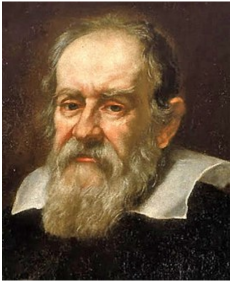
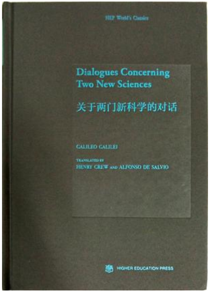
"The essence of mathematics lies in its freedom"



Galileo Galilei (1564 – 1642)



《关于两门新科学的对话》(1638)

"用我们有限的心智来讨论无限 $\cdots$"

$$S_1 = \{1, 2, 3, \cdots, n, \cdots\}$$

$$S_2 = \{1, 4, 9, \cdots, n^2, \cdots\}$$

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说到底，"等于"、"大于"和"小于"诸性质不能用于无限，而只能用于有限的数量。 — *Galileo Galilei*

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无穷数是不可能的。 — *Gottfried Wilhelm Leibniz*

这些证明一开始就期望那些数要具有有穷数的一切性质，或者甚至于把有穷数的性质强加于无穷。

相反，这些无穷数，如果它们能够以任何形式被理解的话，倒是由于它们与有穷数的对应，它们必须具有完全新的数量特征。

这些性质完全依赖于事物的本性，$\cdots$ 而并非来自我们的主观任意性或我们的偏见。

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Definition (Dedekind-infinite & Dedekind-finite (Dedekind, 1888))

A set A is Dedekind-infinite if there is a bijective function from A onto some proper subset B of A.

A set is Dedekind-finite if it is not Dedekind-infinite.

Comparing Sets

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$=$ $<$

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Function

$$=$$

Definition ($|A| = |B|$ ($A \approx B$) (1878))

Two sets of A and B are *equipotent* if there exists a *bijection* from A to B.

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$$\{1, 2, 3\} \quad \textit{vs.} \quad \{a, b, c\}$$

$$\{1, 2, 3, \cdots\} \quad \textit{vs.} \quad \{1, 3, 5, \cdots, 2, 4, 6, \cdots\}$$

Definition (Finite and Infinite)

For any set X,

Finite

$$\exists n \in \mathbb{N} : |X| = n \qquad (0 \in \mathbb{N})$$

Infinite ($\neg$ finite)

$$\forall n \in \mathbb{N} : |X| \neq n$$

Definition (Finite and Infinite)

For any set X,

Countably Infinite

$$|X| = |\mathbb{N}| \triangleq \aleph_0$$

Countable

(finite $\lor$ countably infinite)

Uncountably Infinite

$$(\neg \text{ finite}) \land \Big(\neg \text{ (countably infinite)}\Big)$$

$$(\neg \text{ countable})$$

Theorem ($\aleph_0$ (1874))

$$|\mathbb{Q}| = |\mathbb{N}|$$

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$|\mathbb{Q}| = |\mathbb{N}|$ (UD Problem 22.9)

$$q \in \mathbb{Q}^+ : a/b \; (a, b \in \mathbb{N}^+)$$

1/1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	⋯
2/1	2/2	2/3	2/4	2/5	2/6	2/7	2/8	⋯
3/1	3/2	3/3	3/4	3/5	3/6	3/7	3/8	⋯
4/1	4/2	4/3	4/4	4/5	4/6	4/7	4/8	⋯
5/1	5/2	5/3	5/4	5/5	5/6	5/7	5/8	⋯
6/1	6/2	6/3	6/4	6/5	6/6	6/7	6/8	⋯
7/1	7/2	7/3	7/4	7/5	7/6	7/7	7/8	⋯
8/1	8/2	8/3	8/4	8/5	8/6	8/7	8/8	⋯
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋱

$$|\mathbb{N}| = |\mathbb{Z}|$$

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$$|\mathbb{N}| = |\mathbb{N} \times \mathbb{N}|$$

$$|\mathbb{N}| = |\mathbb{Z}|$$

$$|\mathbb{N}| = |\mathbb{N} \times \mathbb{N}|$$

$$f : \mathbb{N} \times \mathbb{N} \to \mathbb{N} \qquad f(m,n) = n + \frac{(m+n)(m+n+1)}{2}$$

Theorem ($\mathbb{R}$ is uncountably infinite (1874) .)

$$|\mathbb{R}| \neq |\mathbb{N}| \qquad (|\mathbb{R}| > |\mathbb{N}|)$$

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Proof.

See UD Theorem 22.12. $\quad f : \mathbb{N} \xleftrightarrow[onto]{1-1} (0,1).$

$\square$

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□

Theorem (Cantor's Theorem (1891))

$$|X| \neq |2^X| \qquad (|X| < |2^X|)$$

Infinite Sequences of 0's and 1's (UD Problem 22.3)

Is the set of all infinite sequences of 0's and 1's finite, countably infinite, or uncountable?

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Nonproof.

$$f : \{\{0,1\}^*\} \to \mathbb{N}$$

$$f(x_0 x_1 \cdots) = \sum_{i=0}^{\infty} x_i 2^i$$

□

Theorem ($|\mathbb{R}|$ (1877))

$$|(0,1)| = |\mathbb{R}| = |\mathbb{R} \times \mathbb{R}| = |\mathbb{R}^{n \in \mathbb{N}}|$$

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"I see it, but I don't believe it !"

— Cantor's letter to Dedekind (1877).

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Q : Then, what is "dimension"?

$$<$$

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$|B| \leq |A|$ (Axiom of Choice)

Definition ($|A| < |B|$)

$$|A| < |B| \iff |A| \leq |B| \land |A| \neq |B|$$

Definition ($|A| < |B|$)

$|A| < |B| \iff |A| \le |B| \land |A| \neq |B|$

$$|\mathbb{N}| < |\mathbb{R}|$$

$$|X| < |2^X|$$

Definition (Countable Revisited)

X is countable:

$$\exists n \in \mathbb{N} : |X| = n \lor |X| = |\mathbb{N}|$$

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Subsets of Countable Set (UD Problem 22.6; UD Corollary 22.4)

Every subset B of a countable set A is countable.

Set Union (UD Problem 22.1)

Give an example, if possible, of

(c) a countably infinite collection of *pairwise disjoint* nonempty sets whose union is finite.

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$$|A| = n \implies |2^A| = 2^n$$

Slope (UD Problem 22.2 (e))

(e) the set of all lines with rational slopes

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$$|\mathbb{R}| \leq\ |\mathbb{Q} \times \mathbb{R}|\ \leq |\mathbb{R} \times \mathbb{R}| = |\mathbb{R}|$$

Q : Is "$\leq$" a partial order?

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$$|X| \leq |Y| \land |Y| \leq |X| \implies |X| = |Y|$$

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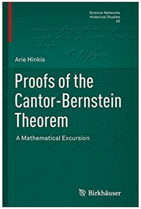

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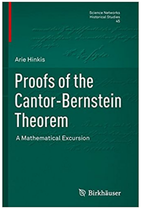

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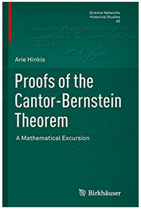

Q : *Is "$\leq$" a total order?*

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Theorem (PCC)

Principle of Cardinal Comparability (PCC) $\iff$ *Axiom of Choice*

Finite Sets

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“关于有穷，我原以为我是懂的”

Definition (Finite)

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Theorem (Pigeonhole Principle (UD Theorem 21.2))

$$f : \{1, \cdots, m\} \to \{1, \cdots, n\} \; (m, n \in \mathbb{N}^+, m > n)$$

f is not one-to-one.

$A \setminus \{a\}$ (UD Problem 21.15)

Let A be a nonempty finite set with $|A| = n$ and let $a \in A$.
Prove that $A \setminus \{a\}$ is finite and $|A \setminus \{a\}| = n - 1$.

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$$f : A \xleftrightarrow[onto]{1-1} \{1, \cdots, n\}$$

$$f|_{A \setminus \{a\}} : A \setminus \{a\} \xleftrightarrow[onto]{1-1} \{1, \cdots, n\} \setminus \{f(a)\}$$

$A \setminus \{a\}$ (UD Problem 21.15)

Let A be a nonempty finite set with $|A| = n$ and let $a \in A$.
Prove that $A \setminus \{a\}$ is finite and $|A \setminus \{a\}| = n - 1$.

$$f : A \xleftrightarrow[onto]{1-1} \{1, \cdots, n\}$$

$$f|_{A\setminus\{a\}} : A \setminus \{a\} \xleftrightarrow[onto]{1-1} \{1, \cdots, n\} \setminus \{f(a)\} \xleftrightarrow[onto]{1-1} \{1, \cdots, n-1\}$$

$|A| \le |B|$ (UD Problem 21.17)

A and B are finite sets and $f : A \to B$ is one-to-one.
Show that $|A| \le |B|$.

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By contradiction and the pigeonhole principle.

(UD Problem 21.16)

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(c) If two finite sets A and B satisfy $B \subseteq A$ and $|A| \leq |B|$, then $A = B$.

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By contradiction and (b).

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(No Axiom of Choice Here)

$f : A \to A$ (UD Problem 21.19)

Let A be a finite set.

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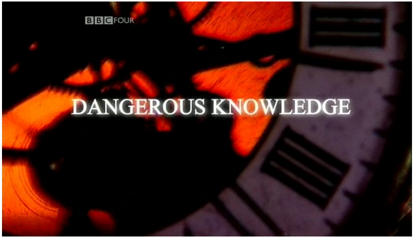
$$f(g(y)) = f(x) = y \implies f = g^{-1}$$

Dangerous Knowledge (BBC 2007)



Continuum Hypothesis (CH):

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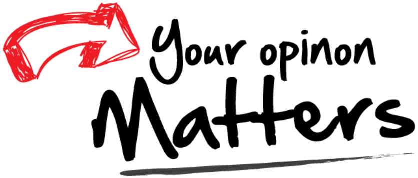
☞ Dangerous Knowledge (22:20)

Independence from ZFC:

Kurt Gödel (1940) CH cannot be disproved from ZF.

Paul Cohen (1964) CH cannot be proven from the ZFC axioms.


Thank
You!



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