

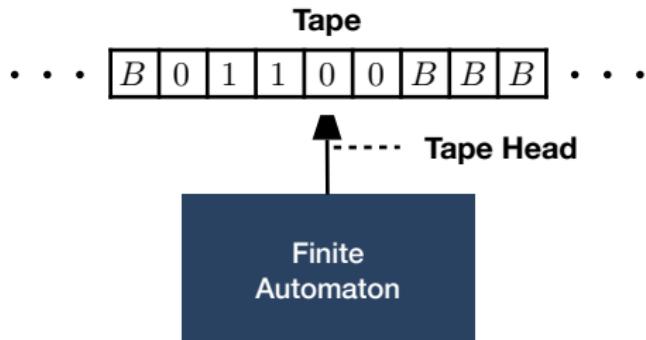
Lecture 24 – The Origin of Computer Science

COSE215: Theory of Computation

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2025 Spring



- A **Turing machine (TM)** is a finite automaton with a **tape**.
- A language accepted by a TM is **Recursively Enumerable**.
- A standard **TM** is the **most powerful model of computation**.
- Why did **Alan Turing** invent the **TM**?
- Why is TM the **origin of Computer Science**?

Contents

1. Gödel's Incompleteness Theorem

Example: Continuum Hypothesis
Gödel Numbering

2. Entscheidungsproblem – Decision Problem

Disproof using Turing Machine
Disproof using Lambda Calculus

3. Church-Turing Thesis

Contents

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Gödel Numbering

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Disproof using Lambda Calculus

3. Church-Turing Thesis

Gödel's Incompleteness Theorem

David Hilbert
(1862 – 1943)



I argue that any statement is **True** or **False**, not both (*Consistent*), and we can **PROVE** that any **True** statement (*Complete*)!

Russell's Paradox

Really? How about the following statement? **True** or **False**?
Let $R = \{x \mid x \notin x\}$, then $R \in R$?



Bertrand Russell
(1872 – 1970)

David Hilbert
(1862 – 1943)



We can always avoid such paradoxes by adding **more axioms!**
(e.g., **ZFC** - Zermelo–Fraenkel set theory with Axiom of Choice)

1st Gödel's Incompleteness Theorem (1931)

Unfortunately, I proved that there always exists a statement that is **True** but **Unprovable** under **any set of axioms**.



Kurt Gödel
(1906 – 1978)

Example: Continuum Hypothesis

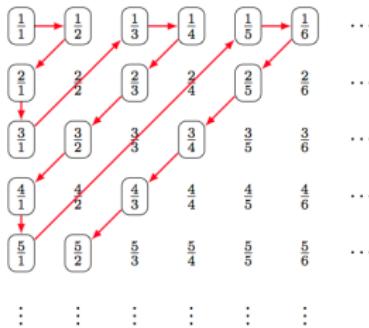
- **Cardinality:** The number of elements in a set.

$$|\{3, 42, 7\}| = 3$$

- A set is **countably infinite** if there is a **bijection** between the set and the set of natural numbers (the cardinality of natural numbers is \aleph_0).
 - The set of **non-negative even numbers** is **countably infinite**.

$$\mathbb{N} \xleftrightarrow[f]{f^{-1}} \{n \in \mathbb{N} \mid n \geq 0 \wedge n \equiv 0 \pmod{2}\} \text{ where } f(n) = 2n \text{ and } f^{-1}(n) = \frac{n}{2}$$

- The set of **rational numbers** is **countably infinite**.



Example: Continuum Hypothesis

- A set of **real numbers** between 0 and 1 is **uncountably infinite** and its cardinality ($\aleph_1 = 2^{\aleph_0}$) is strictly larger than the set of natural numbers ($\aleph_1 > \aleph_0$) because of **Cantor's diagonal argument**:

n	$f(n)$											
1	0	.	3	1	4	1	5	9	2	6	5	3
2	0	.	3	7	3	7	3	7	3	7	3	7
3	0	.	1	4	2	8	5	7	1	4	2	8
4	0	.	7	0	7	1	0	6	7	8	1	1
5	0	.	3	7	5	0	0	0	0	0	0	0
:	:											

- Continuum Hypothesis:** There is no set whose cardinality is strictly between \aleph_0 and \aleph_1 :

$$\nexists \aleph. \aleph_0 < \aleph < \aleph_1$$

- Kurt Gödel and Paul Cohen showed we **CANNOT** either prove or disprove the **Continuum Hypothesis** using the standard axioms of set theory, **ZFC** (Zermelo-Fraenkel set theory with the **Axiom of Choice**).

- **Gödel Numbering:** Assign a unique number to each symbol and string in a formal language.

Symbol	\sim	\vee	\supset	\exists	$=$	0	s	()	,	+
Number	1	2	3	4	5	6	7	8	9	10	11
Symbol	x	x	y	z	p	q	r	P	Q	R	
Number	12	13	14	15	16	17	18	19	20	21	

- We will use **prime numbers** to encode strings:

$$\text{encode}(x_1 \cdots x_n) = \prod_{i=1}^n p_i^{x_i}$$

where p_i is the i -th prime number.

- For example, $\text{encode}(0=0) = 2^6 \times 3^5 \times 5^6 = 243,000,000$.
- Gödel used this idea to encode **formulas** and **proofs** in **first-order arithmetic**, and then proved his famous **Incompleteness Theorem**.¹

¹https://en.wikipedia.org/wiki/Gödel's_incompleteness_theorems

Contents

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Gödel Numbering

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Disproof using Lambda Calculus

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David Hilbert
(1862 – 1943)



Entscheidungsproblem – “Decision Problem” (1928)

I also argue that there exists an **algorithm** that can **decide** any mathematical statement is **True** or **False (Decidable)**!

Disproof using “Turing Machine” (1936)

Inspired by **Gödel Numbering**, I defined “**Turing Machines**” as **computations** and proved such an algorithm does **not exist**.



Alan Turing
(1912 – 1954)

Disproof using “Lambda Calculus” (1936)

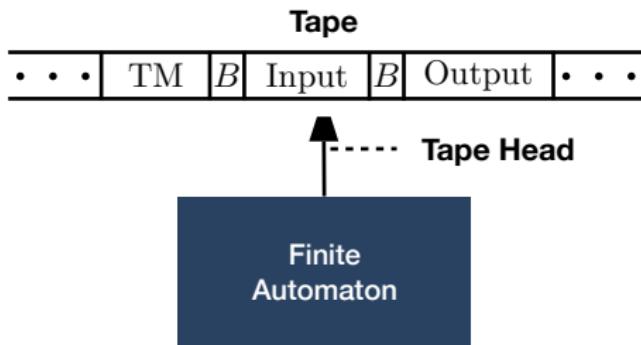
Independent of Turing Machines, I defined “**Lambda Calculus**” as **computation** and proved such an algorithm does **not exist**.



Alonzo Church
(1903 – 1995)

- **Turing Machine** is the origin of **computers**.
- **Lambda Calculus** is the origin of **programming languages**.

- Alan Turing's definition of computation – **Turing Machines (TMs)**.
- Inspired by **Gödel Numbering**, he defined an **encoding** of TMs that can be **enumerated by natural numbers**.
- Then, he defined a **Universal Turing Machine (UTM)** that can simulate any TM with any input:



- UTM was **the most important invention in computer science** because it was the first time we can write a **program (software)** instead of building a new **machine (hardware)** to solve a new problem.

- Assume a TM A solves the **Decision Problem**.
- We can build a TM H that solves the **Halting Problem** by using A :

$$\forall \text{TM } M. \forall w \in a^*. H(M, w) = \begin{cases} \text{halt} & \text{if } A(\text{"}M \text{ halts on } w\text{"}) \\ \text{loop} & \text{otherwise} \end{cases}$$

- Consider the following enumeration of TMs:

$H(M_i, w_i)$	w_1	w_2	w_3	\dots
M_1	halt	loop	halt	\dots
M_2	halt	halt	loop	\dots
M_3	loop	halt	halt	\dots
\vdots	\vdots	\vdots	\vdots	\ddots

- Consider the TM F s.t. $\forall i. F(w_i) = \begin{cases} \text{loop} & \text{if } H(M_i, w_i) = \text{halt} \\ \text{halt} & \text{otherwise} \end{cases}$
- Then, F is not in the enumeration (i.e., $F \neq M_i$ for all i). It contradicts the **enumerability of TMs**. So, **A does not exist.**

- Alonzo Church's definition of computation is the **Lambda Calculus (LC)**:

$$\begin{array}{lcl} \Lambda \ni E & ::= & x \quad (\text{Variable}) \\ & | & \lambda x. E \quad (\text{Abstraction}) \\ & | & E E \quad (\text{Application}) \end{array}$$

- **Computations** are done by **β -reduction**:

$$(\lambda x. E) E' \rightarrow E[x \mapsto E']$$

- For example,

$$(\lambda x. (\lambda y. x y)) z \rightarrow \lambda y. z y$$

- A **computable function** is a **lambda term**.
- If there is no more possible β -reduction, the term is in **normal form**.

- However, there is no **data structures** or **control flows** in LC.
- Surprisingly, we can **encode** them – **Church Encoding**:

Boolean Values and Operations

$$\text{true} = \lambda x. \lambda y. x$$

$$\text{false} = \lambda x. \lambda y. y$$

$$\text{and} = \lambda b_1. \lambda b_2. b_1 \ b_2 \ \text{false}$$

$$\text{or} = \lambda b_1. \lambda b_2. b_1 \ \text{true} \ b_2$$

Natural Numbers and Operations

$$0 = \lambda f. \lambda x. x$$

$$1 = \lambda f. \lambda x. f \ x$$

$$2 = \lambda f. \lambda x. f \ (f \ x)$$

$$3 = \lambda f. \lambda x. f \ (f \ (f \ x))$$

$$\text{plus} = \lambda n_1. \lambda n_2. \lambda f. \lambda x. n_1 \ f \ (n_2 \ f \ x)$$

$$\text{times} = \lambda n_1. \lambda n_2. \lambda f. \lambda x. n_1 \ (n_2 \ f) \ x$$

$$\text{exp} = \lambda n_1. \lambda n_2. n_2 \ n_1$$

Control Flows

$$\text{if} = \lambda b. \lambda e_1. \lambda e_2. b \ e_1 \ e_2$$

$$\text{Y} = \lambda f. (\lambda x. f \ (x \ x)) (\lambda x. f \ (x \ x))$$

Pairs

$$\text{pair} = \lambda x. \lambda y. \lambda f. f \ x \ y$$

$$\text{fst} = \lambda p. p \ (\lambda x. \lambda y. x)$$

$$\text{snd} = \lambda p. p \ (\lambda x. \lambda y. y)$$

Lists

$$\text{nil} = \lambda c. \lambda n. n$$

$$\text{cons} = \lambda h. \lambda t. \lambda c. \lambda n. c \ h \ (t \ c \ n)$$

$$\text{head} = \lambda l. l \ (\lambda h. \lambda t. h)$$

$$\text{isnil} = \lambda l. l \ (\lambda h. \lambda t. \text{false}) \ \text{true}$$

$$\begin{array}{ll} 0 = \lambda f. \lambda x. x & \text{plus} = \lambda n_1. \lambda n_2. \lambda f. \lambda x. n_1 f (n_2 f x) \\ 1 = \lambda f. \lambda x. f x & \text{times} = \lambda n_1. \lambda n_2. \lambda f. \lambda x. n_1 (n_2 f) x \\ 2 = \lambda f. \lambda x. f (f x) & \text{exp} = \lambda n_1. \lambda n_2. n_2 n_1 \\ 3 = \lambda f. \lambda x. f (f (f x)) & \end{array}$$

For example, we can compute $1 + 1$ as follows:

$$\begin{aligned} \text{plus } 1 \ 1 &= (\lambda n_1. \lambda n_2. \lambda f. \lambda x. n_1 f (n_2 f x)) \ 1 \ 1 \\ &\rightarrow \lambda f. \lambda x. 1 f (1 f x) \\ &= \lambda f. \lambda x. (\lambda f. \lambda x. f x) f ((\lambda f. \lambda x. f x) f x) \\ &\rightarrow \lambda f. \lambda x. (\lambda f. \lambda x. f x) f (f x) \\ &\rightarrow \lambda f. \lambda x. f (f x) \\ &= 2 \end{aligned}$$

The **normal form** (computational result) of $(\text{plus } 1 \ 1)$ is 2.

- Church proved that there is **no computable function** that can decide whether two **lambda terms** are **equivalent** or **not**:

$$\exists \text{eq?} \in \Lambda. \forall E_1, E_2 \in \Lambda. (\text{eq? } E_1 \ E_2) \rightarrow \begin{cases} \text{true} & \text{if } E_1 \equiv E_2 \\ \text{false} & \text{otherwise} \end{cases}$$

where $E_1 \equiv E_2$ means E_1 and E_2 are equivalent, i.e., they have the same **normal form** (computational result).

- For example, (plus 1 1) and (plus 0 2) are equivalent in LC because they have the same normal form 2.
- It means that there is no computable function that can **decide** whether a **lambda term** has a given **normal form** or not.
- We skip the proof here.

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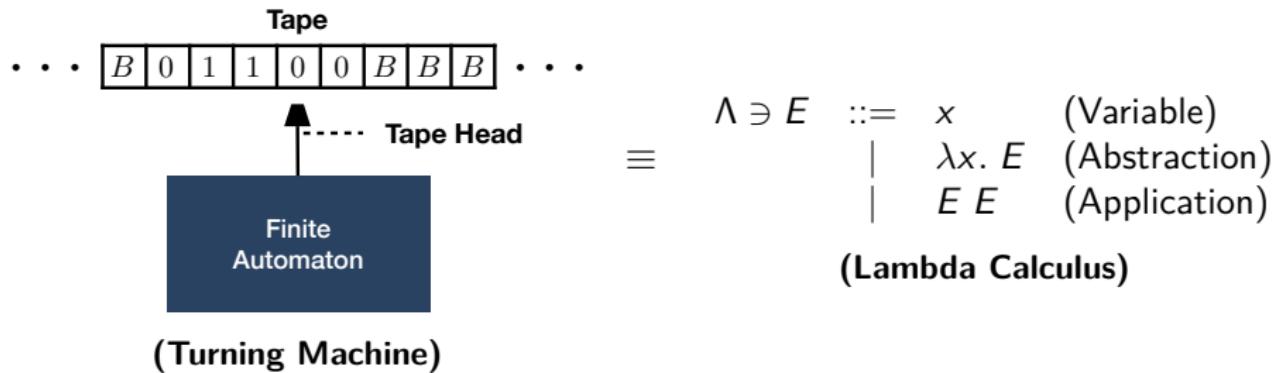
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Church-Turing Thesis



- **LC** has the same computational power as **TMs**. (**Turing Complete**)
- **Church-Turing Thesis:**
Any real-world computation can be translated into an equivalent computation involving a Turing machine or can be done using lambda calculus.

Summary

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Next Lecture

- Undecidability

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