

# Lecture 24 – The Origin of Computer Science

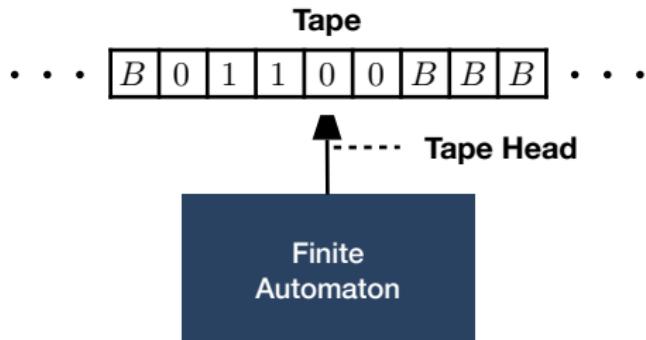
## COSE215: Theory of Computation

Jihyeok Park

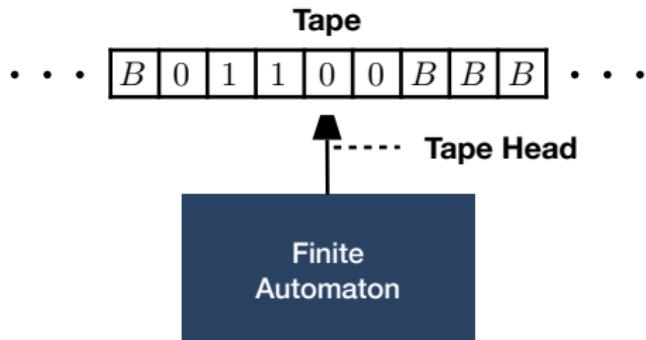


2024 Spring

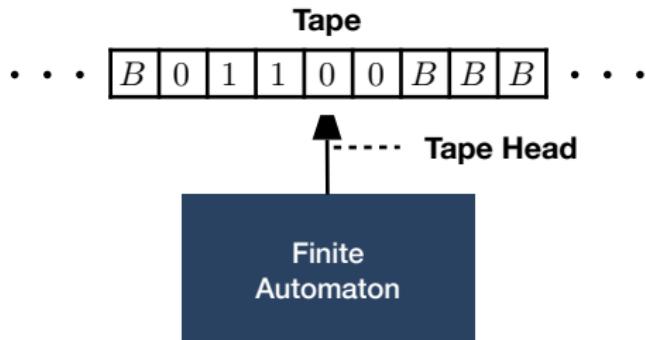
## Recall



- 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**.



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- Why did **Alan Turing** invent the **TM**?



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- 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**?

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## 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

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# Gödel's Incompleteness Theorem

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(1862 – 1943)



I argue that any **mathematical statement** is **True** or **False!**

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## Russell's Paradox

Really? How about the following statement? **True** or **False**?

Let  $R = \{x \mid x \notin x\}$ , then  $R \in R$ ?



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Okay.. Then, let's **add more axioms** to avoid such paradoxes!  
(e.g., **ZFC** - Zermelo–Fraenkel set theory with Axiom of Choice)

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## 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.

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  - The set of **non-negative even numbers** is **countably infinite**.

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

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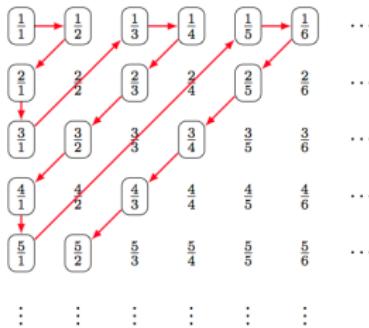
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- The set of **rational numbers** is **countably infinite**.



# 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	.	<b>3</b>	1	4	1	5	9	2	6	5	3
2	0	.	3	<b>7</b>	3	7	3	7	3	7	3	7
3	0	.	1	4	<b>2</b>	8	5	7	1	4	2	8
4	0	.	7	0	7	<b>1</b>	0	6	7	8	1	1
5	0	.	3	7	5	0	<b>0</b>	0	0	0	0	0
$\vdots$	$\vdots$											

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

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- 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	

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- 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,  $\text{encode}(0=0) = 2^6 \times 3^5 \times 5^6 = 243,000,000$ .

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- Gödel used this idea to encode **formulas** and **proofs** in **first-order logic**, and then proved his famous **Incompleteness Theorem**.<sup>1</sup>

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I argue another one: there always exists an **algorithm** that takes a statement as an input and **decides** whether it is **True** or **False**!

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



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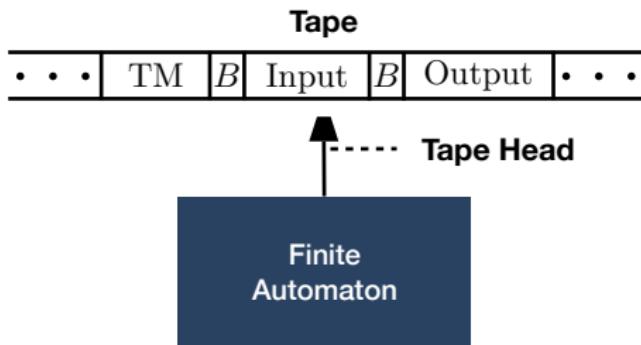
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- **Turing Machine** is the origin of **computers**.
- **Lambda Calculus** is the origin of **programming languages**.

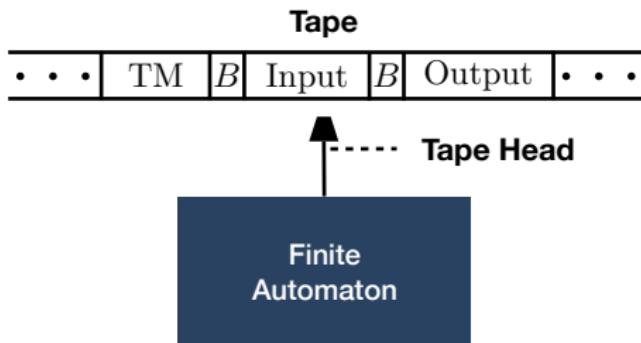
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- UTM was **the most important invention in computer science** because it was the first time we can write a **program (software)** instead of building a new **machine (hardware)** to solve a new problem.

# Disproof using Turing Machine

- Assume a TM  $A$  solves the **Decision Problem**.

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- Consider the following enumeration of TMs:

$H(M_i, w_i)$	$w_1$	$w_2$	$w_3$	$\dots$
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- Consider the TM  $F$  s.t.  $\forall i. F(w_i) = \begin{cases} \text{loop} & \text{if } H(M_i, w_i) = \text{halt} \\ \text{halt} & \text{otherwise} \end{cases}$

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- 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)**:

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

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

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## 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).

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- For example,  $(\lambda x. x + 1) \ 1$  and  $2$  are equivalent in LC because they have the same normal form.
- 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.

# Contents

## 1. Gödel's Incompleteness Theorem

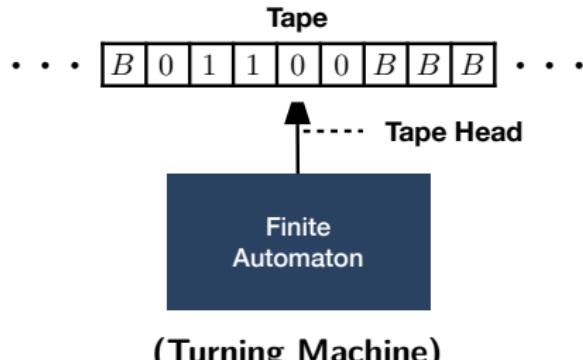
Example: Continuum Hypothesis  
Gödel Numbering

## 2. Entscheidungsproblem – Decision Problem

Disproof using Turing Machine  
Disproof using Lambda Calculus

## 3. Church-Turing Thesis

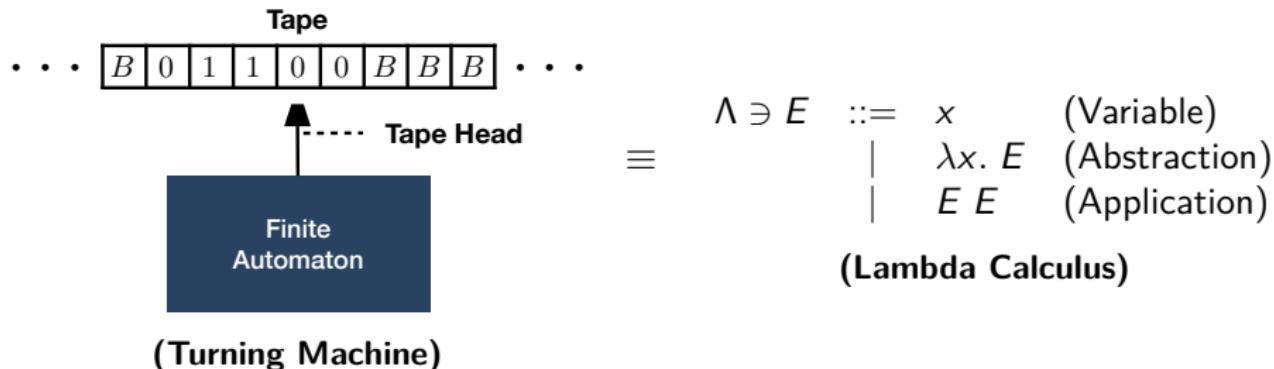
# Church-Turing Thesis


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

**(Lambda Calculus)**

- **LC** has the same computational power as **TMs**. (**Turing Complete**)

# 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

## 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

# Next Lecture

- Undecidability

Jihyeok Park  
[jihyeok\\_park@korea.ac.kr](mailto:jihyeok_park@korea.ac.kr)  
<https://plrg.korea.ac.kr>