Church–Turing Thesis

CSCI 3130 Formal Languages and Automata Theory

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Fall 2018

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A **computer** is a machine that manipulates data according to a list of instructions.
What is a computer?

def hello(name):
    print("Hello ", name)

world

Hello world

Google Now

Will it rain today?

No, rain is not expected today at Ma Liu Shui

Machine Learning algorithm

Environment

self driving
Turing machines

Can both **read** from and **write** to the tape

Head can move both **left** and **right**

Unlimited tape space

Has two special states **accept** and **reject**
Example

$L_1 = \{ w#w \mid w \in \{a, b\}^* \}$

Strategy:

Read and remember the first symbol
Cross it off
Read the first symbol past #
If they don’t match, reject
If they do, cross it off

_abbaa#abbaa
xbbaa#abbaa
xbbaa#abbaa
xbbaa#abbaa
Example

$L_1 = \{ w\#w \mid w \in \{a, b\}^* \}$

Strategy:

- Look for and remember the first uncrossed symbol
- Cross it off
- Read the first symbol past #
- If they do, cross it off, else reject
- At the end, there should be only x’s
  - if so, accept; otherwise reject
How Turing machines operate

Current state: \(q_1\)

Replace a with b, and move head left

New state: \(q_2\)
Computing devices: from practice to theory
Brief history of computing devices

Antikythera Mechanism (~100BC)

Abacus (Sumer 2700-2300BC, China 1200)

Babbage Difference engine (1840s)

Its reproduction

Brief history of computing devices: programmable devices

Z3 (Germany, 1941)

ENIAC (Pennsylvania, US, 1945)

Personal computers (since 1970s)

Mobile phones
Computation is universal

In principle, all computers have the same problem solving ability.

If an algorithm can be implemented on any realistic computer, then it can be implemented on a Turing machine.
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Turing machine

Quantum computing
DNA computing
Alan Turing

Alan Turing aged 16
(1912-1954)

Invented the **Turing Test** to tell apart humans from computers

Broke German encryption machines during World War II

**Turing Award** is the “Nobel prize of Computer Science”

**Turing’s motivation**: Understand the limitations of human computation by studying his “automatic machines”
Hilbert’s Entscheidungsproblem, 1928 reformulation

Entscheidungsproblem (Decision Problem)

“Write a program” to solve the following task:

Input: mathematical statement (in first-order logic)
Output: whether the statement is true

In fact, he didn’t ask to “write a program”, but to “design a procedure”

Examples of statements expressible in first-order logic:

Fermat’s last theorem: 
\[ x^n + y^n = z^n \]
has no integer solution for integer \( n \geq 3 \)

Twin prime conjecture:
There are infinitely many pairs of primes of the form \( p \) and \( p + 2 \)
Undecidability

Entscheidungsproblem (Decision Problem)

Design a procedure to solve the following task:

Input: mathematical statement (in first-order logic)
Output: whether the statement is true

Church (1935-1936) and Turing (1936-1937) independently showed the procedure that Entscheidungsproblem asks for cannot exist!

Definitions of procedure/algorithm:

λ-calculus (Church) and automatic machine (Turing)
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Intuitive notion of algorithms coincides with those implementable on Turing machines

Supporting arguments:

1. Turing machine is intuitive
2. Many independent definitions of “algorithms” turn out to be equivalent

References:

Alan Turing, “On Computable Numbers, with an Application to the Entscheidungsproblem”, 1937

Alonzo Church, “A Note on the Entscheidungsproblem”, 1936
A Turing Machine is \((Q, \Sigma, \Gamma, \delta, q_0, q_{\text{acc}}, q_{\text{rej}})\), where

- \(Q\) is a finite set of states
- \(\Sigma\) is the input alphabet, not containing the blank symbol \(\square\)
- \(\Gamma\) is the tape alphabet \((\Sigma \subseteq \Gamma)\) including \(\square\)
- \(q_0 \in Q\) is the initial state
- \(q_{\text{acc}}, q_{\text{rej}} \in Q\) are the accepting and rejecting states
- \(\delta\) is the transition function

\[
\delta : (Q \setminus \{q_{\text{acc}}, q_{\text{rej}}\}) \times \Gamma \to Q \times \Gamma \times \{L, R\}
\]

Turing machines are deterministic
A configuration consists of current state, head position, and tape contents.

Configuration (abbreviation)

\[ \text{ab } q_1 \text{ a} \]

\[ \text{abb } q_{\text{acc}} \]
Configurations

The start configuration of the TM on input $w$ is $q_0 w$

We say a configuration $C$ yields $C'$ if the TM can go from $C$ to $C'$ in one step

Example: $ab q_1 a$ yields $abb q_{acc}$

An accepting configuration is one that contains $q_{acc}$

A rejecting configuration is one that contains $q_{rej}$
The language of a Turing machine

A Turing machine $M$ accepts $x$ if there is a sequence of configurations $C_0, C_1, \ldots, C_k$ where

- $C_0$ is starting
- $C_i$ yields $C_{i+1}$
- $C_k$ is accepting

The language recognized by $M$ is the set of all strings that $M$ accepts.