

Introduction to Turing Machines

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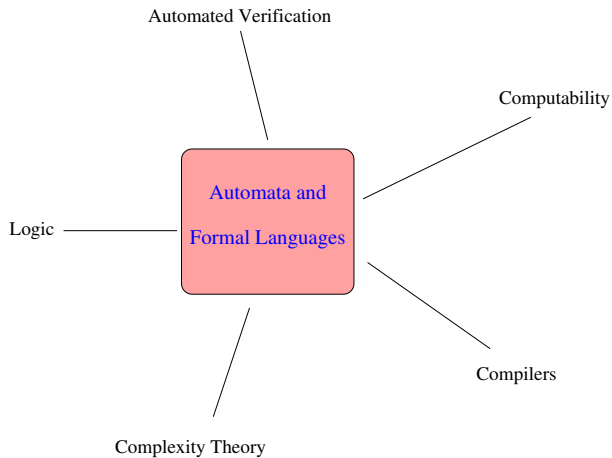
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Outline

- 1 Turing Machines
- 2 Formal definitions
- 3 Computability

Role of Automata Theory in other subjects



Brief history of logic and computability



David Hilbert 1928: Entscheidungsproblem (deciding validity of FO logic)



Kurt Godel

1929: Completeness of FO logic
 1931: Incompleteness of FO arithmetic
 1931: Primitive Recursive Functions



Alonzo Church

1936: Undecidability of Entscheidungsproblem using Lambda-calculus

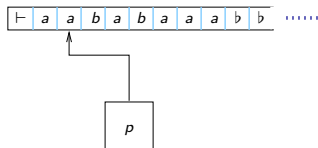
Alan Turing

1936: Undecidability of Entscheidungsproblem using TMs



Kleene, Rosser, Scott, Rabin, ...

How a Turing machine works



- Finite control
- Tape infinite to the right
- Each step: In current state p , read current symbol under the tape head, say a : Change state to q , replace current symbol by b , and move head left or right.

$$(p, a) \rightarrow (q, b, L/R).$$

How a Turing machine works

- Special designated **accept** state t and **reject** state r . These states are assumed to be “sink” states.
- TM accepts its input by entering state t .
- TM rejects its input by entering state r .
- TM never falls off the left end of the tape (i.e it always moves right on seeing ‘ \vdash ’).

Example TM for $a^n b^n c^n$

Exercise: TM for adding numbers in unary

Design a TM that accepts $\{1^m \# 1^n \# 1^{n+m} \mid m, n \geq 0\}$.

Turning machines more formally

A **Turing machine** is a structure of the form

$$M = (Q, A, \Gamma, s, \delta, \vdash, \flat, t, r)$$

where

- Q is a finite set of states,
- A is the input alphabet,
- Γ is the tape alphabet which contains A ,
- $s \in Q$ is the start state,
- $\delta : Q \times \Gamma \rightarrow Q \times \Gamma \times \{L, R\}$ is the (deterministic) transition relation,
- $\vdash \in \Gamma$ is the left-end marker.
- $\flat \in \Gamma$ is the blank tape symbol.
- $t \in Q$ is the accept state.
- $r \in Q$ is the reject state.

Configurations, runs, etc. of a Turing machine

- A **configuration** of M is of the form $(p, yb^\omega, n) \in Q \times \Gamma^\omega \times \mathbb{N}$, which says “ M is in state p , with “non-blank” tape contents y , and read head positioned at the n -th cell of the tape.
- Initial configuration of M on input w is $(s, \vdash wb^\omega, 0)$.
- 1-step transition of M : If $(p, a) \rightarrow (q, b, L)$ is a transition in δ , and $z(n) = a$: then

$$(p, z, n) \xrightarrow{1} (q, s_b^n(z), n - 1).$$

- Similarly, if $(p, a) \rightarrow (q, b, R)$ is a transition in δ , and $z(n) = a$: then

$$(p, z, n) \xrightarrow{1} (q, s_b^n(z), n + 1).$$

- M **accepts** w if $(s, \vdash wb^\omega, 0) \xrightarrow{*} (t, z, i)$, for some z and i .
- M **rejects** w if $(s, \vdash wb^\omega, 0) \xrightarrow{*} (r, z, i)$, for some z and i .

Language accepted by a Turing machine

- The Turing machine M is said to **halt** on an input if it eventually gets into state t or r on the input.
- Note that M may not get into either state t or r on a particular input w . In that case we say M **loops** on w .
- The language accepted by M is denoted $L(M)$ and is the set of strings accepted by M .
- A language $L \subseteq A^*$ is called **recursively enumerable** if it is accepted by some Turing machine M .
- A language $L \subseteq A^*$ is called **recursive** if it is accepted by some Turing machine M which **halts on all inputs**.

Computability and languages

- Notion of a function $f : \mathbb{N} \rightarrow \mathbb{N}$ being “computable” (informally if we can give a “finite recipe” or “algorithm” to compute $f(n)$ for a given n .)
- We say f is **computable** if we have a TM M that given $\vdash 0^n$ as input, outputs $0^{f(n)}$ on its tape, and halts.
- View f as a language

$$L_f = \{(n, f(n)) \mid n \in \mathbb{N}\}.$$

- Then f is computable iff L_f is recursive.