# COMP2012/G52LAC
# Languages and Computation
# Lecture 18
*Decidability and the Halting Problem*

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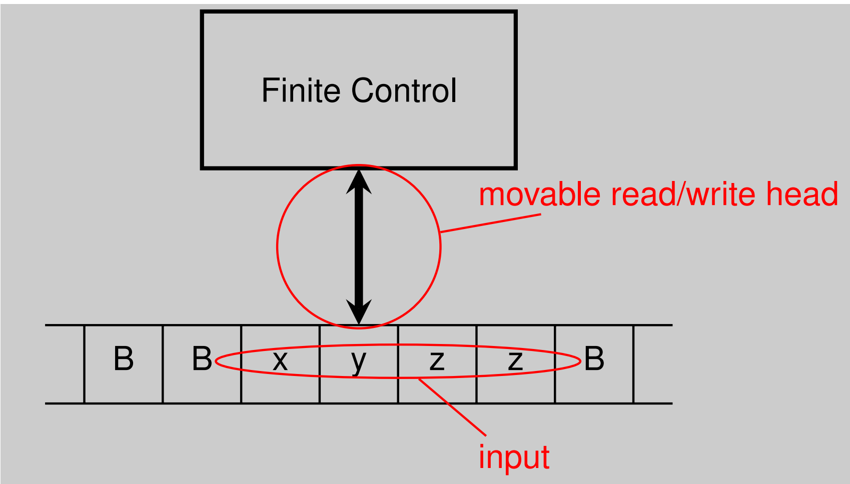
## Recap: Turing Machines (1)

- A Turing Machine (TM) is a mathematical model of a general-purpose computer.
- A TM is a generalisation of a PDA: TM = FA + infinite tape



## Recap: Turing Machines (2)






## Recap: Turing Machines (3)

- Mainly used to study the ***notion of computation***: what can computers do (given suffi- cient time and memory) and what can they not do.
- There are other notions of computation, such that the $\lambda$***-calculus***.
- All suggested notions of computation have so far proved to be equivalent.
- ***The Church-Turing Thesis***: “Every function which would naturally be regarded as ‘computable’ can be computed by a TM”.

# The Language of a TM (1)

$$L(M) = \{w \in \Sigma^* \mid (\epsilon, q_0, w) \overset{*}{\underset{M}{\vdash}} (\gamma_L, q, \gamma_R) \wedge q \in F\}$$

A TM stops if it reaches an accepting state.

A TM stops in a non-accepting state if the transition function returns $\mathrm{stop}$ for that state and current tape input.

However, it may also ***never*** stop!

This is unlike the machines lige DFAs, NFAs, PDAa.



# The Language of a TM (2)

If a particular TM $M$ ***always*** stops, either in an accepting or a non-accepting state, then $M$ ***decides*** $L(M)$.

Given that TMs model general purpose computers, it should not come as a surprise that they can loop. Consider e.g.

```
input x; while (x<10);
```

What may come as a surprise is that there are languages for which a TM ***necessarily*** cannot decide membership; i.e., will loop on some inputs.



# Recursive Language

$L$ is ***recursive*** if $L = L(M)$ for a TM $M$ such that

1. if $w \in L$, then $M$ accepts $w$ (and thus halts)
2. if $w \notin L$, then $M$ eventually halts without ever entering an accepting state.

Such a TM corresponds to an ***algorithm***: a well-defined sequence of steps that always produces an answer in finite space and time.

We also say that $M$ ***decides*** $L$.



# Recursively Enumerable (RE) Language

$L$ is ***recursivele enumerable (RE)*** if $L = L(M)$ for a TM $M$.

I.e., $M$ is ***not*** required to halt for $w \notin L$.

Such a TM corresponds to a ***semi-algorithm***.

Why “recursively enumerable”?

Because it is possible to construct a TM that enumerates all strings in such a language in some order. (But it will necessarily keep trying to enumerate strings forever.)

# Decidable and Undecidable

There are even languages that have no TM! The non-RE languages.

- Decidable: a language or problem (encoded as a language) that is recursive.
- Undecidable: a language or problem that is RE but not recursive, or non-RE.

Example of non-RE language: The set of all Turing machines accepting exactly 3 words.

(In fact, a simple cardinality argument shows that most languages are non-RE: there are “many more” languages than there are TMs.)



# Halting Problem

Famous example of a RE language that is not recursive; i.e. an undecidable language.

Informally: Can we write a program (TM) that takes the text of an ***arbitrary*** program and input to that program as input and decides whether the input program terminates on the given input or not?

Formulated as a language: Is there a TM that ***decides*** the language of terminating programs/TMs?

Proof sketch on whiteboard.



# Other Undecidable Problems

- Whether two programs (computable functions) are equal
- Whether a CFG is ambiguous
- Whether two CFGs are equivalent
- Rice’s Theorem: Whether the language of a given TM has some particular ***non-trivial*** property. (Non-trivial: holds for some but not all languages.)



# Rice’s Theorem (1)

(After Henry Gordon Rice; also known as the Rice-Myhill-Shapiro theorem.)

Let $C$ be a set of languages. Define

$$L_C = \{ \ M \mid L(M) \in C \ \}$$

where $M$ ranges over all TMs. Then either $L_C$ is empty, or it contains all TMs, or it is undecidable.

For example, $C$ might be the set of regular languages. As there are some TMs that recognise regular languages, but not all do, $L_C$ is undecidable in this case.

# Rice's Theorem (2)

Consequence: There are lots of really useful programs that cannot be implemented ***perfectly***.

E.g., virus detection: virus programs do exist, but not all programs are viruses; being a virus is a non-trivial property.

Caveat: Rice's theorem is concerned with properties of the ***language*** accepted by a TM, not about properties of the TM (code) itself. E.g., it is certainly decidable if a TM has at most 10 states.

`http://www.eecs.berkeley.edu/~luca/cs172/noterice.pdf`