

## Week 6 at a glance

### Textbook reading: Chapter 3

Before Monday, Page 165-166 Introduction to Section 3.1.

Before Wednesday, Example 3.9 on page 173.

Before Friday, Page 184-185 Terminology for describing Turing machines.

For Week 7 Monday: Introduction to Chapter 4.

### We will be learning and practicing to:

- Clearly and unambiguously communicate computational ideas using appropriate formalism. Translate across levels of abstraction.
  - Use precise notation to formally define the state diagram of a Turing machine
  - Use clear English to describe computations of Turing machines informally.
    - \* **Motivate the definition of a Turing machine**
    - \* **Trace the computation of a Turing machine on given input**
    - \* **Describe the language recognized by a Turing machine**
    - \* **Determine if a Turing machine is a decider**
    - \* **Given an implementation-level description of a Turing machine**
    - \* **Use high-level descriptions to define and trace Turing machines**
    - \* **Apply dovetailing in high-level definitions of machines**
  - Give examples of sets that are recognizable and decidable (and prove that they are).
    - \* **State the definition of the class of recognizable languages**
    - \* **State the definition of the class of decidable languages**
    - \* **State the definition of the class of co-recognizable languages**
- Know, select and apply appropriate computing knowledge and problem-solving techniques. Reason about computation and systems.
- Describe and prove closure properties of classes of languages under certain operations.
  - **Apply a general construction to create a new Turing machine from an example one.**
  - **Formalize a general construction from an informal description of it.**
  - **Use general constructions to prove closure properties of the class of decidable languages.**
  - **Use general constructions to prove closure properties of the class of recognizable languages.**

### TODO:

This week: Test 1 Attempt 1 in CBTF.

Review Quiz 5 on PrairieLearn (<http://us.prairielearn.com>), due 2/12/2025

Mid quarter feedback survey on Canvas.

# Monday: Descriptions of Turing machines

We are ready to introduce a formal model that will capture a notion of general purpose computation.

- *Similar to DFA, NFA, PDA*: input will be an arbitrary string over a fixed alphabet.
- *Different from NFA, PDA*: machine is deterministic.
- *Different from DFA, NFA, PDA*: read-write head can move both to the left and to the right, and can extend to the right past the original input.
- *Similar to DFA, NFA, PDA*: transition function drives computation one step at a time by moving within a finite set of states, always starting at designated start state.
- *Different from DFA, NFA, PDA*: the special states for rejecting and accepting take effect immediately.

(See more details: Sipser p. 166)

Formally: a Turing machine is  $M = (Q, \Sigma, \Gamma, \delta, q_0, q_{accept}, q_{reject})$  where  $\delta$  is the **transition function**

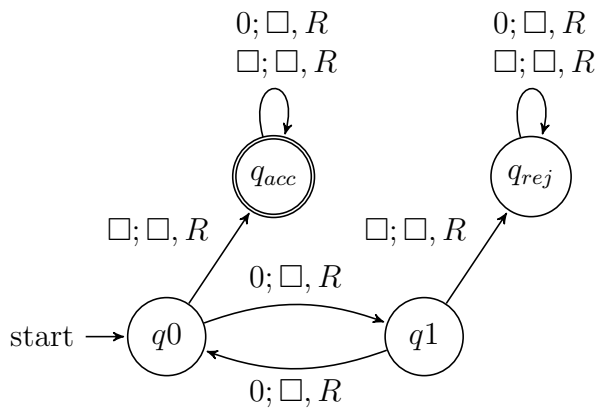
$$\delta : Q \times \Gamma \rightarrow Q \times \Gamma \times \{L, R\}$$

The **computation** of  $M$  on a string  $w$  over  $\Sigma$  is:

- Read/write head starts at leftmost position on tape.
- Input string is written on  $|w|$ -many leftmost cells of tape, rest of the tape cells have the blank symbol. **Tape alphabet** is  $\Gamma$  with  $\sqcup \in \Gamma$  and  $\Sigma \subseteq \Gamma$ . The blank symbol  $\sqcup \notin \Sigma$ .
- Given current state of machine and current symbol being read at the tape head, the machine transitions to next state, writes a symbol to the current position of the tape head (overwriting existing symbol), and moves the tape head L or R (if possible).
- Computation ends **if and when** machine enters either the accept or the reject state. This is called **halting**. Note:  $q_{accept} \neq q_{reject}$ .

The **language recognized by the Turing machine**  $M$ , is  $L(M) = \{w \in \Sigma^* \mid w \text{ is accepted by } M\}$ , which is defined as

$$\{w \in \Sigma^* \mid \text{computation of } M \text{ on } w \text{ halts after entering the accept state}\}$$



Formal definition:

Sample computation:

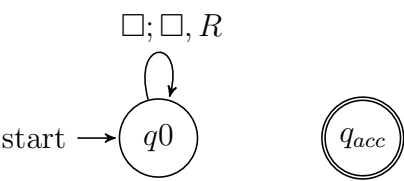
$q0 \downarrow$						
0	0	0	□	□	□	□

The language recognized by this machine is ...

**Describing Turing machines** (Sipser p. 185) To define a Turing machine, we could give a

- **Formal definition:** the 7-tuple of parameters including set of states, input alphabet, tape alphabet, transition function, start state, accept state, and reject state; or,
- **Implementation-level definition:** English prose that describes the Turing machine head movements relative to contents of tape, and conditions for accepting / rejecting based on those contents.
- **High-level description:** description of algorithm (precise sequence of instructions), without implementation details of machine. As part of this description, can “call” and run another TM as a subroutine.

Fix  $\Sigma = \{0, 1\}$ ,  $\Gamma = \{0, 1, \sqcup\}$  for the Turing machines with the following state diagrams:



Example of string accepted:

Example of string rejected:

Implementation-level description

High-level description

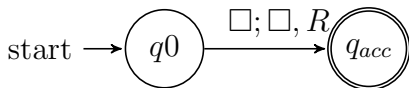


Example of string accepted:

Example of string rejected:

Implementation-level description

High-level description

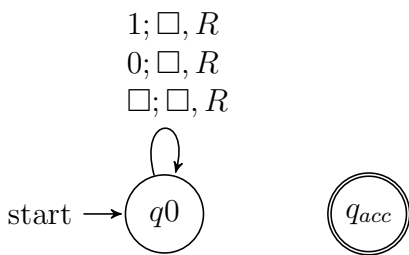


Example of string accepted:

Example of string rejected:

Implementation-level description

High-level description



Example of string accepted:

Example of string rejected:

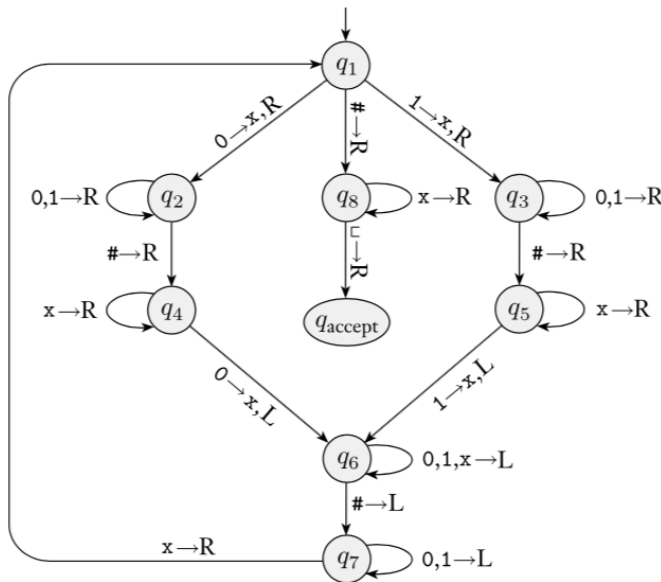
Implementation-level description

High-level description

## Wednesday: Recognizable and decidable languages

*Sipser Figure 3.10*

**Conventions in state diagram of TM:**  $b \rightarrow R$  label means  $b \rightarrow b, R$  and all arrows missing from diagram represent transitions with output  $(q_{reject}, \sqcup, R)$



Computation on input string 01#01

[illegible]

Implementation level description of this machine:

Zig-zag across tape to corresponding positions on either side of  $\#$  to check whether the characters in these positions agree. If they do not, or if there is no  $\#$ , reject. If they do, cross them off.

Once all symbols to the left of the # are crossed off, check for any un-crossed-off symbols to the right of #; if there are any, reject; if there aren't, accept.

The language recognized by this machine is

$$\{w\#w \mid w \in \{0,1\}^*\}$$

High-level description of this machine is

*Extra practice*

Computation on input string 01#1

[illegible]

*Recall:* High-level descriptions of Turing machine algorithms are written as indented text within quotation marks. Stages of the algorithm are typically numbered consecutively. The first line specifies the input to the machine, which must be a string.

A language  $L$  is **recognized by** a Turing machine  $M$  means

A Turing machine  $M$  **recognizes** a language  $L$  means

A Turing machine  $M$  is a **decider** means

A language  $L$  is **decided by** a Turing machine  $M$  means

A Turing machine  $M$  **decides** a language  $L$  means

Fix  $\Sigma = \{0, 1\}$ ,  $\Gamma = \{0, 1, \sqcup\}$  for the Turing machines with the following state diagrams:

<p>A state diagram for a Turing machine. It has two states: <math>q_0</math> and <math>q_{acc}</math>. <math>q_0</math> is the start state, indicated by an arrow labeled "start". <math>q_{acc}</math> is an accepting state, indicated by a double circle. There is a self-loop on <math>q_0</math> labeled with the transition <math>\square; \square, R</math>. Below the diagram, the text "Decider? Yes / No" is written.</p>	<p>A state diagram for a Turing machine. It has two states: <math>q_{rej}</math> and <math>q_{acc}</math>. <math>q_{rej}</math> is the start state, indicated by an arrow labeled "start". <math>q_{acc}</math> is an accepting state, indicated by a double circle. Below the diagram, the text "Decider? Yes / No" is written.</p>
<p>A state diagram for a Turing machine. It has two states: <math>q_0</math> and <math>q_{acc}</math>. <math>q_0</math> is the start state, indicated by an arrow labeled "start". <math>q_{acc}</math> is an accepting state, indicated by a double circle. There is a transition from <math>q_0</math> to <math>q_{acc}</math> labeled with the transition <math>\square; \square, R</math>. Below the diagram, the text "Decider? Yes / No" is written.</p>	<p>A state diagram for a Turing machine. It has two states: <math>q_0</math> and <math>q_{acc}</math>. <math>q_0</math> is the start state, indicated by an arrow labeled "start". <math>q_{acc}</math> is an accepting state, indicated by a double circle. There is a self-loop on <math>q_0</math> with three transitions labeled <math>0; \square, R</math>, <math>1; \square, R</math>, and <math>\square; \square, R</math>. Below the diagram, the text "Decider? Yes / No" is written.</p>



## Friday: Closure for the classes of recognizable and decidable languages

A **Turing-recognizable** language is a set of strings that is the language recognized by some Turing machine. We also say that such languages are recognizable.

A **Turing-decidable** language is a set of strings that is the language recognized by some decider. We also say that such languages are decidable.

An **unrecognizable** language is a language that is not Turing-recognizable.

An **undecidable** language is a language that is not Turing-decidable.

**True or False:** Any decidable language is also recognizable.

**True or False:** Any recognizable language is also decidable.

**True or False:** Any undecidable language is also unrecognizable.

**True or False:** Any unrecognizable language is also undecidable.

**True or False:** The class of Turing-decidable languages is closed under complementation.

Using formal definition:

Using high-level description:

**Church-Turing Thesis** (Sipser p. 183): The informal notion of algorithm is formalized completely and correctly by the formal definition of a Turing machine. In other words: all reasonably expressive models of computation are equally expressive with the standard Turing machine.