

## Week9 monday

Recall definition:  $A$  is **mapping reducible to**  $B$  means there is a computable function  $f : \Sigma^* \rightarrow \Sigma^*$  such that for all strings  $x$  in  $\Sigma^*$ ,

$$x \in A \quad \text{if and only if} \quad f(x) \in B.$$

Notation: when  $A$  is mapping reducible to  $B$ , we write  $A \leq_m B$ .

**Theorem** (Sipser 5.23): If  $A \leq_m B$  and  $A$  is undecidable, then  $B$  is undecidable.

### Halting problem

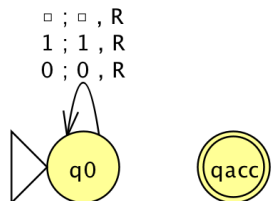
$$HALT_{TM} = \{ \langle M, w \rangle \mid M \text{ is a Turing machine, } w \text{ is a string, and } M \text{ halts on } w \}$$

We will define a computable function that witnesses the mapping reduction  $A_{TM} \leq_m HALT_{TM}$ .

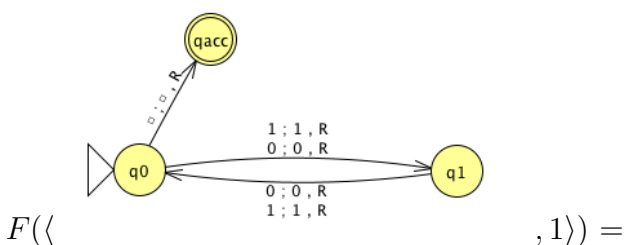
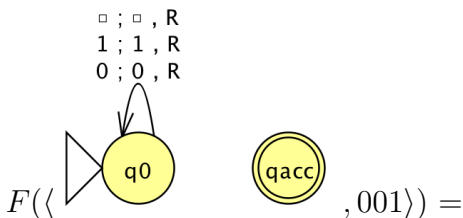
Using Theorem 5.23, we can then conclude that  $HALT_{TM}$  is undecidable.

Define  $F : \Sigma^* \rightarrow \Sigma^*$  by

$$F(x) = \begin{cases} const_{out} & \text{if } x \neq \langle M, w \rangle \text{ for any Turing machine } M \text{ and string } w \text{ over the alphabet of } M \\ \langle M', w \rangle & \text{if } x = \langle M, w \rangle \text{ for some Turing machine } M \text{ and string } w \text{ over the alphabet of } M. \end{cases}$$



where  $const_{out} = \langle \text{start state}, \varepsilon \rangle$  and  $M'$  is a Turing machine that computes like  $M$  except, if the computation ever were to go to a reject state,  $M'$  loops instead.



To use this function to prove that  $A_{TM} \leq_m HALT_{TM}$ , we need two claims:

Claim (1):  $F$  is computable

Claim (2): for every  $x$ ,  $x \in A_{TM}$  iff  $F(x) \in HALT_{TM}$ .

True or False:  $\overline{A_{TM}} \leq_m \overline{HALT_{TM}}$

True or False:  $HALT_{TM} \leq_m A_{TM}$ .

## Week9 wednesday

Recall:  $A$  is **mapping reducible to**  $B$ , written  $A \leq_m B$ , means there is a computable function  $f : \Sigma^* \rightarrow \Sigma^*$  such that *for all* strings  $x$  in  $\Sigma^*$ ,

$$x \in A \quad \text{if and only if} \quad f(x) \in B.$$

**Theorem** (Sipser 5.28): If  $A \leq_m B$  and  $B$  is recognizable, then  $A$  is recognizable.

**Proof:**

**Corollary:** If  $A \leq_m B$  and  $A$  is unrecognizable, then  $B$  is unrecognizable.

*Strategy:*

- (i) To prove that a recognizable language  $R$  is undecidable, prove that  $A_{TM} \leq_m R$ .
- (ii) To prove that a co-recognizable language  $U$  is undecidable, prove that  $\overline{A_{TM}} \leq_m U$ , i.e. that  $A_{TM} \leq_m \overline{U}$ .

$$E_{TM} = \{\langle M \rangle \mid M \text{ is a Turing machine and } L(M) = \emptyset\}$$

Example string in  $E_{TM}$  is \_\_\_\_\_ . Example string not in  $E_{TM}$  is \_\_\_\_\_ .

$E_{TM}$  is decidable / undecidable and recognizable / unrecognizable .

$\overline{E_{TM}}$  is decidable / undecidable and recognizable / unrecognizable .

**Claim:** \_\_\_\_\_  $\leq_m \overline{E_{TM}}$ .

**Proof:** Need computable function  $F : \Sigma^* \rightarrow \Sigma^*$  such that  $x \in A_{TM}$  iff  $F(x) \notin E_{TM}$ . Define

$F =$  “ On input  $x$ ,

1. Type-check whether  $x = \langle M, w \rangle$  for some TM  $M$  and string  $w$ . If so, move to step 2; if not, output
2. Construct the following machine  $M'_x$ :

3. Output  $\langle M'_x \rangle$ .”

Verifying correctness:

Input string	Output string
$\langle M, w \rangle$ where $w \in L(M)$	
$\langle M, w \rangle$ where $w \notin L(M)$	
$x$ not encoding any pair of TM and string	

$$EQ_{TM} = \{\langle M, M' \rangle \mid M \text{ and } M' \text{ are both Turing machines and } L(M) = L(M')\}$$

Example string in  $EQ_{TM}$  is \_\_\_\_\_ . Example string not in  $EQ_{TM}$  is \_\_\_\_\_ .

$EQ_{TM}$  is decidable / undecidable and recognizable / unrecognizable .

$\overline{EQ_{TM}}$  is decidable / undecidable and recognizable / unrecognizable .

To prove, show that \_\_\_\_\_  $\leq_m EQ_{TM}$  and that \_\_\_\_\_  $\leq_m \overline{EQ_{TM}}$ .

Verifying correctness:

Input string	Output string
$\langle M, w \rangle$ where $M$ halts on $w$	
$\langle M, w \rangle$ where $M$ loops on $w$	
$x$ not encoding any pair of TM and string	

## Week9 friday

In practice, computers (and Turing machines) don't have infinite tape, and we can't afford to wait unboundedly long for an answer. "Decidable" isn't good enough - we want "Efficiently decidable".

For a given algorithm working on a given input, how long do we need to wait for an answer? How does the running time depend on the input in the worst-case? average-case? We expect to have to spend more time on computations with larger inputs.

A language is **recognizable** if \_\_\_\_\_

A language is **decidable** if \_\_\_\_\_

A language is **efficiently decidable** if \_\_\_\_\_

A function is **computable** if \_\_\_\_\_

A function is **efficiently computable** if \_\_\_\_\_

Definition (Sipser 7.1): For  $M$  a deterministic decider, its **running time** is the function  $f : \mathbb{N} \rightarrow \mathbb{N}$  given by

$$f(n) = \max \text{ number of steps } M \text{ takes before halting, over all inputs of length } n$$

Definition (Sipser 7.7): For each function  $t(n)$ , the **time complexity class**  $TIME(t(n))$ , is defined by

$$TIME(t(n)) = \{L \mid L \text{ is decidable by a Turing machine with running time in } O(t(n))\}$$

An example of an element of  $TIME(1)$  is

An example of an element of  $TIME(n)$  is

Note:  $TIME(1) \subseteq TIME(n) \subseteq TIME(n^2)$

Definition (Sipser 7.12) :  $P$  is the class of languages that are decidable in polynomial time on a deterministic 1-tape Turing machine

$$P = \bigcup_k TIME(n^k)$$

*Compare to exponential time: brute-force search.*

Theorem (Sipser 7.8): Let  $t(n)$  be a function with  $t(n) \geq n$ . Then every  $t(n)$  time deterministic multitape Turing machine has an equivalent  $O(t^2(n))$  time deterministic 1-tape Turing machine.

Definition (Sipser 7.9): For  $N$  a nondeterministic decider. The **running time** of  $N$  is the function  $f : \mathbb{N} \rightarrow \mathbb{N}$  given by

$$f(n) = \max \text{ number of steps } N \text{ takes on any branch before halting, over all inputs of length } n$$

Definition (Sipser 7.21): For each function  $t(n)$ , the **nondeterministic time complexity class**  $NTIME(t(n))$ , is defined by

$$NTIME(t(n)) = \{L \mid L \text{ is decidable by a nondeterministic Turing machine with running time in } O(t(n))\}$$

$$NP = \bigcup_k NTIME(n^k)$$

**True or False:**  $TIME(n^2) \subseteq NTIME(n^2)$

**True or False:**  $NTIME(n^2) \subseteq DTIME(n^2)$

### Examples in $P$

*Can't use nondeterminism; Can use multiple tapes; Often need to be "more clever" than naïve / brute force approach*

$$PATH = \{\langle G, s, t \rangle \mid G \text{ is digraph with } n \text{ nodes there is path from } s \text{ to } t\}$$

Use breadth first search to show in  $P$

$$RELPRIME = \{\langle x, y \rangle \mid x \text{ and } y \text{ are relatively prime integers}\}$$

Use Euclidean Algorithm to show in  $P$

$$L(G) = \{w \mid w \text{ is generated by } G\}$$

(where  $G$  is a context-free grammar). Use dynamic programming to show in  $P$ .

### Examples in $NP$

*"Verifiable" i.e. NP, Can be decided by a nondeterministic TM in polynomial time, best known deterministic solution may be brute-force, solution can be verified by a deterministic TM in polynomial time.*

$HAMPATH = \{\langle G, s, t \rangle \mid G \text{ is digraph with } n \text{ nodes, there is path from } s \text{ to } t \text{ that goes through every node exactly once}\}$

$VERTEX - COVER = \{\langle G, k \rangle \mid G \text{ is an undirected graph with } n \text{ nodes that has a } k\text{-node vertex cover}\}$

$CLIQUE = \{\langle G, k \rangle \mid G \text{ is an undirected graph with } n \text{ nodes that has a } k\text{-clique}\}$

$SAT = \{\langle X \rangle \mid X \text{ is a satisfiable Boolean formula with } n \text{ variables}\}$



## Week8 monday

**Theorem:**  $A_{TM}$  is not Turing-decidable.

**Proof:** Suppose **towards a contradiction** that there is a Turing machine that decides  $A_{TM}$ . We call this presumed machine  $M_{ATM}$ .

By assumption, for every Turing machine  $M$  and every string  $w$

- If  $w \in L(M)$ , then the computation of  $M_{ATM}$  on  $\langle M, w \rangle$  \_\_\_\_\_
- If  $w \notin L(M)$ , then the computation of  $M_{ATM}$  on  $\langle M, w \rangle$  \_\_\_\_\_

Define a **new** Turing machine using the high-level description:

$D =$  “ On input  $\langle M \rangle$ , where  $M$  is a Turing machine:

1. Run  $M_{ATM}$  on  $\langle M, \langle M \rangle \rangle$ .
2. If  $M_{ATM}$  accepts, reject; if  $M_{ATM}$  rejects, accept.”

Is  $D$  a Turing machine?

Is  $D$  a decider?

What is the result of the computation of  $D$  on  $\langle D \rangle$ ?

**Theorem** (Sipser Theorem 4.22): A language is Turing-decidable if and only if both it and its complement are Turing-recognizable.

**Proof, first direction:** Suppose language  $L$  is Turing-decidable. WTS that both it and its complement are Turing-recognizable.

**Proof, second direction:** Suppose language  $L$  is Turing-recognizable, and so is its complement. WTS that  $L$  is Turing-decidable.

Give an example of a **decidable** set:

Give an example of a **recognizable undecidable** set:

Give an example of an **unrecognizable** set:

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

Definition: A language  $L$  over an alphabet  $\Sigma$  is called **co-recognizable** if its complement, defined as  $\Sigma^* \setminus L = \{x \in \Sigma^* \mid x \notin L\}$ , is Turing-recognizable.

Notation: The complement of a set  $X$  is denoted with a superscript  $c$ ,  $X^c$ , or an overline,  $\overline{X}$ .

## Week8 wednesday

### Mapping reduction

Motivation: Proving that  $A_{TM}$  is undecidable was hard. How can we leverage that work? Can we relate the decidability / undecidability of one problem to another?

If problem  $X$  is **no harder than** problem  $Y$   
... and if  $Y$  is easy,  
... then  $X$  must be easy too.

If problem  $X$  is **no harder than** problem  $Y$   
... and if  $X$  is hard,  
... then  $Y$  must be hard too.

“Problem  $X$  is no harder than problem  $Y$ ” means “Can answer questions about membership in  $X$  by converting them to questions about membership in  $Y$ ”.

Definition:  $A$  is **mapping reducible to**  $B$  means there is a computable function  $f : \Sigma^* \rightarrow \Sigma^*$  such that for all strings  $x$  in  $\Sigma^*$ ,

$$x \in A \quad \text{if and only if} \quad f(x) \in B.$$

Notation: when  $A$  is mapping reducible to  $B$ , we write  $A \leq_m B$ .

*Intuition:*  $A \leq_m B$  means  $A$  is no harder than  $B$ , i.e. that the level of difficulty of  $A$  is less than or equal the level of difficulty of  $B$ .

## Computable functions

Definition: A function  $f : \Sigma^* \rightarrow \Sigma^*$  is a **computable function** means there is some Turing machine such that, for each  $x$ , on input  $x$  the Turing machine halts with exactly  $f(x)$  followed by all blanks on the tape

*Examples of computable functions:*

The function that maps a string to a string which is one character longer and whose value, when interpreted as a fixed-width binary representation of a nonnegative integer is twice the value of the input string (when interpreted as a fixed-width binary representation of a non-negative integer)

$$f_1 : \Sigma^* \rightarrow \Sigma^* \quad f_1(x) = x0$$

To prove  $f_1$  is computable function, we define a Turing machine computing it.

*High-level description*

“On input  $w$

1. Append 0 to  $w$ .
2. Halt.”

*Implementation-level description*

“On input  $w$

1. Sweep read-write head to the right until find first blank cell.
2. Write 0.
3. Halt.”

*Formal definition* ( $\{q_0, q_{acc}, q_{rej}\}, \{0, 1\}, \{0, 1, \_ \}, \delta, q_0, q_{acc}, q_{rej}$ ) where  $\delta$  is specified by the state diagram:

The function that maps a string to the result of repeating the string twice.

$$f_2 : \Sigma^* \rightarrow \Sigma^* \quad f_2(x) = xx$$

The function that maps strings that are not the codes of Turing machines to the empty string and that maps strings that code Turing machines to the code of the related Turing machine that acts like the Turing machine coded by the input, except that if this Turing machine coded by the input tries to reject, the new machine will go into a loop.

$$f_3 : \Sigma^* \rightarrow \Sigma^* \quad f_3(x) = \begin{cases} \varepsilon & \text{if } x \text{ is not the code of a TM} \\ \langle\langle Q \cup \{q_{trap}\}, \Sigma, \Gamma, \delta', q_0, q_{acc}, q_{rej} \rangle\rangle & \text{if } x = \langle\langle Q, \Sigma, \Gamma, \delta, q_0, q_{acc}, q_{rej} \rangle\rangle \end{cases}$$

where  $q_{trap} \notin Q$  and

$$\delta'((q, x)) = \begin{cases} (r, y, d) & \text{if } q \in Q, x \in \Gamma, \delta((q, x)) = (r, y, d), \text{ and } r \neq q_{rej} \\ (q_{trap}, \sqcup, R) & \text{otherwise} \end{cases}$$

The function that maps strings that are not the codes of CFGs to the empty string and that maps strings that code CFGs to the code of a PDA that recognizes the language generated by the CFG.

*Other examples?*

## Week8 friday

Recall definition:  $A$  is **mapping reducible to**  $B$  means there is a computable function  $f : \Sigma^* \rightarrow \Sigma^*$  such that *for all* strings  $x$  in  $\Sigma^*$ ,

$$x \in A \quad \text{if and only if} \quad f(x) \in B.$$

Notation: when  $A$  is mapping reducible to  $B$ , we write  $A \leq_m B$ .

*Intuition:*  $A \leq_m B$  means  $A$  is no harder than  $B$ , i.e. that the level of difficulty of  $A$  is less than or equal the level of difficulty of  $B$ .

*Example:*  $A_{TM} \leq_m A_{TM}$

*Example:*  $A_{DFA} \leq_m \{ww \mid w \in \{0,1\}^*\}$

*Example:*  $\{0^i 1^j \mid i \geq 0, j \geq 0\} \leq_m A_{TM}$

**Theorem** (Sipser 5.22): If  $A \leq_m B$  and  $B$  is decidable, then  $A$  is decidable.

**Theorem** (Sipser 5.23): If  $A \leq_m B$  and  $A$  is undecidable, then  $B$  is undecidable.

## Halting problem

$$HALT_{TM} = \{ \langle M, w \rangle \mid M \text{ is a Turing machine, } w \text{ is a string, and } M \text{ halts on } w \}$$

Define  $F : \Sigma^* \rightarrow \Sigma^*$  by

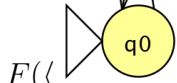
$$F(x) = \begin{cases} const_{out} & \text{if } x \neq \langle M, w \rangle \text{ for any Turing machine } M \text{ and string } w \text{ over the alphabet of } M \\ \langle M', w \rangle & \text{if } x = \langle M, w \rangle \text{ for some Turing machine } M \text{ and string } w \text{ over the alphabet of } M. \end{cases}$$

□ ; □ , R  
1 ; 1 , R  
0 ; 0 , R

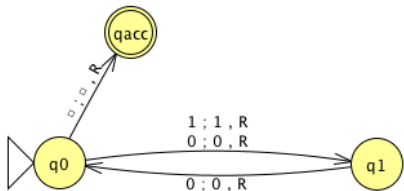


where  $const_{out} = \langle \text{start symbol}, \varepsilon \rangle$  and  $M'$  is a Turing machine that computes like  $M$  except, if the computation ever were to go to a reject state,  $M'$  loops instead.

□ ; □ , R  
1 ; 1 , R  
0 ; 0 , R



$$F(\langle \text{start symbol}, 001 \rangle) =$$



$$F(\langle \text{start symbol}, 1 \rangle) =$$

To use this function to prove that  $A_{TM} \leq_m HALT_{TM}$ , we need two claims:

Claim (1):  $F$  is computable

Claim (2): for every  $x$ ,  $x \in A_{TM}$  iff  $F(x) \in HALT_{TM}$ .

## Week6 monday

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

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

- 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

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

To define a Turing machine, we could give a

- **Formal definition**, namely 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.

Conventions for drawing state diagrams of Turing machines: (1) omit the reject state from the diagram (unless it's the start state), (2) any missing transitions in the state diagram have value  $(q_{reject}, \sqcup, R)$ .





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




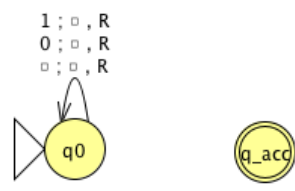
A Turing machine  $M$  **recognizes** a language  $L$  if means

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>Implementation level description:</p> <p>Example of string accepted: Example of string rejected:</p> <p>Decider? Yes / No</p>	 <p>Implementation level description:</p> <p>Example of string accepted: Example of string rejected:</p> <p>Decider? Yes / No</p>
 <p>Implementation level description:</p> <p>Example of string accepted: Example of string rejected:</p> <p>Decider? Yes / No</p>	 <p>Implementation level description:</p> <p>Example of string accepted: Example of string rejected:</p> <p>Decider? Yes / No</p>

## Week6 wednesday

Two models of computation are called **equally expressive** when every language recognizable with the first model is recognizable with the second, and vice versa.

True / False: NFAs and PDAs are equally expressive.

True / False: Regular expressions and CFGs are equally expressive.

*Some examples of models that are **equally expressive** with deterministic Turing machines:*

**May-stay machines** The May-stay machine model is the same as the usual Turing machine model, except that on each transition, the tape head may move L, move R, or Stay.

Formally:  $(Q, \Sigma, \Gamma, \delta, q_0, q_{accept}, q_{reject})$  where

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

**Claim:** Turing machines and May-stay machines are equally expressive. *To prove ...*

To translate a standard TM to a may-stay machine:

To translate one of the may-stay machines to standard TM: any time TM would Stay, move right then left.

Formally: suppose  $M_S = (Q, \Sigma, \Gamma, \delta, q_0, q_{acc}, q_{rej})$  has  $\delta : Q \times \Gamma \rightarrow Q \times \Gamma \times \{L, R, S\}$ . Define the Turing-machine

$$M_{new} = ( \quad )$$

**Multitape Turing machine** A multitape Turing machine with  $k$  tapes can be formally represented as  $(Q, \Sigma, \Gamma, \delta, q_0, q_{acc}, q_{rej})$  where  $Q$  is the finite set of states,  $\Sigma$  is the input alphabet with  $\sqcup \notin \Sigma$ ,  $\Gamma$  is the tape alphabet with  $\Sigma \subsetneq \Gamma$ ,  $\delta : Q \times \Gamma^k \rightarrow Q \times \Gamma^k \times \{L, R\}^k$  (where  $k$  is the number of tapes)

If  $M$  is a standard TM, it is a 1-tape machine.

To translate a  $k$ -tape machine to a standard TM: Use a new symbol to separate the contents of each tape and keep track of location of head with special version of each tape symbol. Sipser Theorem 3.13

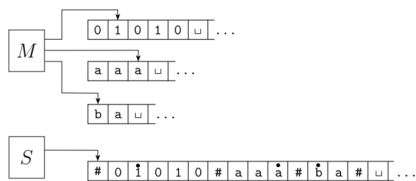


FIGURE 3.14 Representing three tapes with one

*Extra practice:* **Wikipedia Turing machine** Define a machine  $(Q, \Gamma, b, \Sigma, q_0, F, \delta)$  where  $Q$  is the finite set of states,  $\Gamma$  is the tape alphabet,  $b \in \Gamma$  is the blank symbol,  $\Sigma \subsetneq \Gamma$  is the input alphabet,  $q_0 \in Q$  is the start state,  $F \subseteq Q$  is the set of accept states,  $\delta : (Q \setminus F) \times \Gamma \rightarrow Q \times \Gamma \times \{L, R\}$  is a partial transition function. If computation enters a state in  $F$ , it accepts. If computation enters a configuration where  $\delta$  is not defined, it rejects. Hopcroft and Ullman, cited by Wikipedia



## Week6 friday

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.

**Theorem 3.21** A language is Turing-recognizable iff some enumerator enumerates it.

**Proof:**

Assume  $L$  is enumerated by some enumerator,  $E$ , so  $L = L(E)$ . We’ll use  $E$  in a subroutine within a high-level description of a new Turing machine that we will build to recognize  $L$ .

**Goal:** build Turing machine  $M_E$  with  $L(M_E) = L(E)$ .

Define  $M_E$  as follows:  $M_E =$  “On input  $w$ ,

1. Run  $E$ . For each string  $x$  printed by  $E$ .
2. Check if  $x = w$ . If so, accept (and halt); otherwise, continue.”

Assume  $L$  is Turing-recognizable and there is a Turing machine  $M$  with  $L = L(M)$ . We’ll use  $M$  in a subroutine within a high-level description of an enumerator that we will build to enumerate  $L$ .

**Goal:** build enumerator  $E_M$  with  $L(E_M) = L(M)$ .

**Idea:** check each string in turn to see if it is in  $L$ .

*How?* Run computation of  $M$  on each string. *But:* need to be careful about computations that don’t halt.

*Recall* String order for  $\Sigma = \{0, 1\}$ :  $s_1 = \varepsilon$ ,  $s_2 = 0$ ,  $s_3 = 1$ ,  $s_4 = 00$ ,  $s_5 = 01$ ,  $s_6 = 10$ ,  $s_7 = 11$ ,  $s_8 = 000$ , ...

Define  $E_M$  as follows:  $E_M =$  “ignore any input. Repeat the following for  $i = 1, 2, 3, \dots$

1. Run the computations of  $M$  on  $s_1, s_2, \dots, s_i$  for (at most)  $i$  steps each
2. For each of these  $i$  computations that accept during the (at most)  $i$  steps, print out the accepted string.”

## Nondeterministic Turing machine

At any point in the computation, the nondeterministic machine may proceed according to several possibilities:  $(Q, \Sigma, \Gamma, \delta, q_0, q_{acc}, q_{rej})$  where

$$\delta : Q \times \Gamma \rightarrow \mathcal{P}(Q \times \Gamma \times \{L, R\})$$

The computation of a nondeterministic Turing machine is a tree with branching when the next step of the computation has multiple possibilities. A nondeterministic Turing machine accepts a string exactly when some branch of the computation tree enters the accept state.

Given a nondeterministic machine, we can use a 3-tape Turing machine to simulate it by doing a breadth-first search of computation tree: one tape is “read-only” input tape, one tape simulates the tape of the nondeterministic computation, and one tape tracks nondeterministic branching. Sipser page 178

Two models of computation are called **equally expressive** when every language recognizable with the first model is recognizable with the second, and vice versa.

**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.

**Claim:** If two languages (over a fixed alphabet  $\Sigma$ ) are Turing-recognizable, then their union is as well.

**Proof using Turing machines:**

**Proof using nondeterministic Turing machines:**

**Proof using enumerators:**

## Week7 monday

	Suppose $M$ is a TM that recognizes $L$	Suppose $D$ is a TM that decides $L$	Suppose $E$ is an enumerator that enumerates $L$
If string $w$ is in $L$ then ...			
If string $w$ is not in $L$ then ...			

### Describing Turing machines (Sipser p. 185)

The Church-Turing thesis posits that each algorithm can be implemented by some Turing machine

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. This string may be the encoding of some object or list of objects.

**Notation:**  $\langle O \rangle$  is the string that encodes the object  $O$ .  $\langle O_1, \dots, O_n \rangle$  is the string that encodes the list of objects  $O_1, \dots, O_n$ .

**Assumption:** There are Turing machines that can be called as subroutines to decode the string representations of common objects and interact with these objects as intended (data structures).





A **computational problem** is decidable iff language encoding its positive problem instances is decidable.

The computational problem “Does a specific DFA accept a given string?” is encoded by the language

$$\begin{aligned} & \{\text{representations of DFAs } M \text{ and strings } w \text{ such that } w \in L(M)\} \\ = & \{\langle M, w \rangle \mid M \text{ is a DFA, } w \text{ is a string, } w \in L(M)\} \end{aligned}$$

The computational problem “Is the language generated by a CFG empty?” is encoded by the language

$$\begin{aligned} & \{\text{representations of CFGs } G \text{ such that } L(G) = \emptyset\} \\ = & \{\langle G \rangle \mid G \text{ is a CFG, } L(G) = \emptyset\} \end{aligned}$$

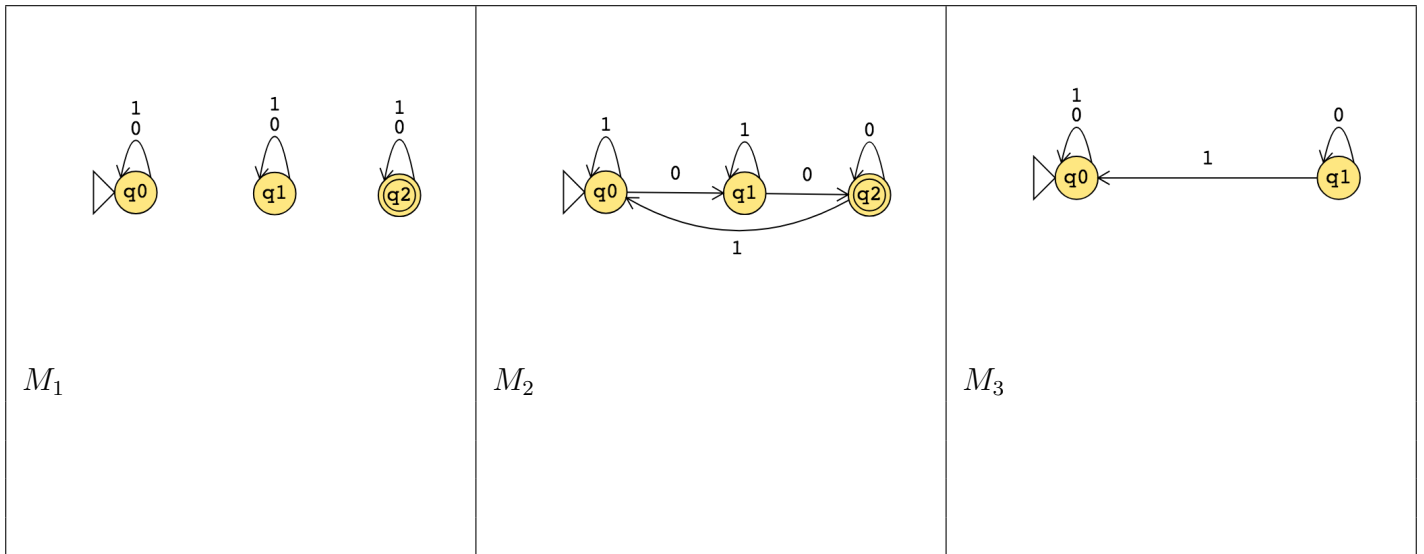
The computational problem “Is the given Turing machine a decider?” is encoded by the language

$$\begin{aligned} & \{\text{representations of TMs } M \text{ such that } M \text{ halts on every input}\} \\ = & \{\langle M \rangle \mid M \text{ is a TM and for each string } w, M \text{ halts on } w\} \end{aligned}$$

*Note: writing down the language encoding a computational problem is only the first step in determining if it's recognizable, decidable, or ...*

**Some classes of computational problems help us understand the differences between the machine models we've been studying:**

Acceptance problem		
... for DFA	$A_{DFA}$	$\{\langle B, w \rangle \mid B \text{ is a DFA that accepts input string } w\}$
... for NFA	$A_{NFA}$	$\{\langle B, w \rangle \mid B \text{ is a NFA that accepts input string } w\}$
... for regular expressions	$A_{REX}$	$\{\langle R, w \rangle \mid R \text{ is a regular expression that generates input string } w\}$
... for CFG	$A_{CFG}$	$\{\langle G, w \rangle \mid G \text{ is a context-free grammar that generates input string } w\}$
... for PDA	$A_{PDA}$	$\{\langle B, w \rangle \mid B \text{ is a PDA that accepts input string } w\}$
Language emptiness testing		
... for DFA	$E_{DFA}$	$\{\langle A \rangle \mid A \text{ is a DFA and } L(A) = \emptyset\}$
... for NFA	$E_{NFA}$	$\{\langle A \rangle \mid A \text{ is a NFA and } L(A) = \emptyset\}$
... for regular expressions	$E_{REX}$	$\{\langle R \rangle \mid R \text{ is a regular expression and } L(R) = \emptyset\}$
... for CFG	$E_{CFG}$	$\{\langle G \rangle \mid G \text{ is a context-free grammar and } L(G) = \emptyset\}$
... for PDA	$E_{PDA}$	$\{\langle A \rangle \mid A \text{ is a PDA and } L(A) = \emptyset\}$
Language equality testing		
... for DFA	$EQ_{DFA}$	$\{\langle A, B \rangle \mid A \text{ and } B \text{ are DFAs and } L(A) = L(B)\}$
... for NFA	$EQ_{NFA}$	$\{\langle A, B \rangle \mid A \text{ and } B \text{ are NFAs and } L(A) = L(B)\}$
... for regular expressions	$EQ_{REX}$	$\{\langle R, R' \rangle \mid R \text{ and } R' \text{ are regular expressions and } L(R) = L(R')\}$
... for CFG	$EQ_{CFG}$	$\{\langle G, G' \rangle \mid G \text{ and } G' \text{ are CFGs and } L(G) = L(G')\}$
... for PDA	$EQ_{PDA}$	$\{\langle A, B \rangle \mid A \text{ and } B \text{ are PDAs and } L(A) = L(B)\}$
Sipser Section 4.1		



Example strings in  $A_{DFA}$

Example strings in  $E_{DFA}$

Example strings in  $EQ_{DFA}$

Food for thought: which of the following computational problems are decidable:  $A_{DFA}$ ?,  $E_{DFA}$ ?,  $EQ_{DFA}$ ?

## Week7 wednesday

Deciding a computational problem means building / defining a Turing machine that recognizes the language encoding the computational problem, and that is a decider.

<b>Acceptance problem</b> for ... $A...$ $\{\langle B, w \rangle \mid B \text{ is a } \dots \text{ that accepts input string } w\}$
<b>Language emptiness testing</b> for ... $E...$ $\{\langle A \rangle \mid A \text{ is a } \dots \text{ and } L(A) = \emptyset\}$
<b>Language equality testing</b> for ... $EQ...$ $\{\langle A, B \rangle \mid A \text{ and } B \text{ are } \dots \text{ and } L(A) = L(B)\}$
Sipser Section 4.1

$M_1 =$  “On input  $\langle M, w \rangle$ , where  $M$  is a DFA and  $w$  is a string:

0. Type check encoding to check input is correct type.
1. Simulate  $M$  on input  $w$  (by keeping track of states in  $M$ , transition function of  $M$ , etc.)
2. If the simulations ends in an accept state of  $M$ , accept. If it ends in a non-accept state of  $M$ , reject. ”

What is  $L(M_1)$ ?

Is  $L(M_1)$  a decider?

$M_2 =$  “On input  $\langle M, w \rangle$  where  $M$  is a DFA and  $w$  is a string,

1. Run  $M$  on input  $w$ .
2. If  $M$  accepts, accept; if  $M$  rejects, reject.”

What is  $L(M_2)$ ?

Is  $M_2$  a decider?

$A_{REX} =$

$A_{NFA} =$

True / False:  $A_{REX} = A_{NFA} = A_{DFA}$

True / False:  $A_{REX} \cap A_{NFA} = \emptyset$ ,  $A_{REX} \cap A_{DFA} = \emptyset$ ,  $A_{DFA} \cap A_{NFA} = \emptyset$

A Turing machine that decides  $A_{NFA}$  is:

A Turing machine that decides  $A_{REX}$  is:

$M_3 =$  “On input  $\langle M \rangle$  where  $M$  is a DFA,

1. For integer  $i = 1, 2, \dots$
2. Let  $s_i$  be the  $i$ th string over the alphabet of  $M$  (ordered in string order).
3. Run  $M$  on input  $s_i$ .
4. If  $M$  accepts, \_\_\_\_\_ . If  $M$  rejects, increment  $i$  and keep going.”

Choose the correct option to help fill in the blank so that  $M_3$  recognizes  $E_{DFA}$

- A. accepts
- B. rejects
- C. loop for ever
- D. We can't fill in the blank in any way to make this work
- E. None of the above

$M_4 =$  “ On input  $\langle M \rangle$  where  $M$  is a DFA,

1. Mark the start state of  $M$ .
2. Repeat until no new states get marked:
3. Loop over the states of  $M$ .
4. Mark any unmarked state that has an incoming edge from a marked state.
5. If no accept state of  $A$  is marked, \_\_\_\_\_; otherwise, \_\_\_\_\_”.

To build a Turing machine that decides  $EQ_{DFA}$ , notice that

$$L_1 = L_2 \quad \text{iff} \quad ( (L_1 \cap \overline{L_2}) \cup (L_2 \cap \overline{L_1}) ) = \emptyset$$

*There are no elements that are in one set and not the other*

$M_{EQDFA} =$

**Summary:** We can use the decision procedures (Turing machines) of decidable problems as subroutines in other algorithms. For example, we have subroutines for deciding each of  $A_{DFA}$ ,  $E_{DFA}$ ,  $EQ_{DFA}$ . We can also use algorithms for known constructions as subroutines in other algorithms. For example, we have subroutines for: counting the number of states in a state diagram, counting the number of characters in an alphabet, converting DFA to a DFA recognizing the complement of the original language or a DFA recognizing the Kleene star of the original language, constructing a DFA or NFA from two DFA or NFA so that we have a machine recognizing the language of the union (or intersection, concatenation) of the languages of the original machines; converting regular expressions to equivalent DFA; converting DFA to equivalent regular expressions, etc.

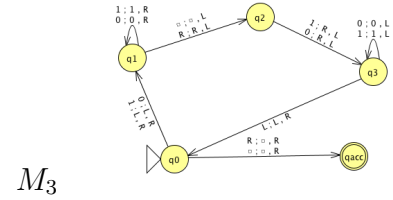
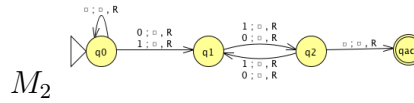
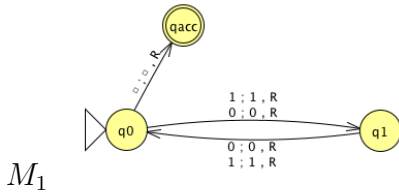
## Week7 friday

### Acceptance problem

... for DFA	$A_{DFA}$	$\{\langle B, w \rangle \mid B \text{ is a DFA that accepts input string } w\}$
... for NFA	$A_{NFA}$	$\{\langle B, w \rangle \mid B \text{ is a NFA that accepts input string } w\}$
... for regular expressions	$A_{REX}$	$\{\langle R, w \rangle \mid R \text{ is a regular expression that generates input string } w\}$
... for CFG	$A_{CFG}$	$\{\langle G, w \rangle \mid G \text{ is a context-free grammar that generates input string } w\}$
... for PDA	$A_{PDA}$	$\{\langle B, w \rangle \mid B \text{ is a PDA that accepts input string } w\}$

**Acceptance problem**for Turing machines  $A_{TM} \{ \langle M, w \rangle \mid M \text{ is a Turing machine that accepts input string } w \}$ **Language emptiness testing**for Turing machines  $E_{TM} \{ \langle M \rangle \mid M \text{ is a Turing machine and } L(M) = \emptyset \}$ **Language equality testing**for Turing machines  $EQ_{TM} \{ \langle M_1, M_2 \rangle \mid M_1 \text{ and } M_2 \text{ are Turing machines and } L(M_1) = L(M_2) \}$ 

Sipser Section 4.1

Example strings in  $A_{TM}$ Example strings in  $E_{TM}$ Example strings in  $EQ_{TM}$



**Theorem:**  $A_{TM}$  is Turing-recognizable.

**Strategy:** To prove this theorem, we need to define a Turing machine  $R_{ATM}$  such that  $L(R_{ATM}) = A_{TM}$ .

Define  $R_{ATM} =$  “

Proof of correctness:

We will show that  $A_{TM}$  is undecidable. *First, let's explore what that means.*

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 undecidable language is also unrecognizable.

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

To prove that a computational problem is **decidable**, we find/ build a Turing machine that recognizes the language encoding the computational problem, and that is a decider.

How do we prove a specific problem is **not decidable**?

How would we even find such a computational problem?

*Counting arguments for the existence of an undecidable language:*

- The set of all Turing machines is countably infinite.
- Each Turing-recognizable language is associated with a Turing machine in a one-to-one relationship, so there can be no more Turing-recognizable languages than there are Turing machines.
- Since there are infinitely many Turing-recognizable languages (think of the singleton sets), there are countably infinitely many Turing-recognizable languages.
- Such the set of Turing-decidable languages is an infinite subset of the set of Turing-recognizable languages, the set of Turing-decidable languages is also countably infinite.

Since there are uncountably many languages (because  $\mathcal{P}(\Sigma^*)$  is uncountable), there are uncountably many unrecognizable languages and there are uncountably many undecidable languages.

Thus, there's at least one undecidable language!

**What's a specific example of a language that is unrecognizable or undecidable?**

To prove that a language is undecidable, we need to prove that there is no Turing machine that decides it.

**Key idea:** proof by contradiction relying on self-referential disagreement.

## Week10 wednesday

Recall: For  $M$  a deterministic decider, its **running time** is the function  $f : \mathbb{N} \rightarrow \mathbb{N}$  given by

$$f(n) = \text{max number of steps } M \text{ takes before halting, over all inputs of length } n$$

For each function  $t(n)$ , the **time complexity class**  $TIME(t(n))$ , is defined by

$$TIME(t(n)) = \{L \mid L \text{ is decidable by a Turing machine with running time in } O(t(n))\}$$

$P$  is the class of languages that are decidable in polynomial time on a deterministic 1-tape Turing machine

$$P = \bigcup_k TIME(n^k)$$

Definition (Sipser 7.9): For  $N$  a nondeterministic decider. The **running time** of  $N$  is the function  $f : \mathbb{N} \rightarrow \mathbb{N}$  given by

$$f(n) = \text{max number of steps } N \text{ takes on any branch before halting, over all inputs of length } n$$

Definition (Sipser 7.21): For each function  $t(n)$ , the **nondeterministic time complexity class**  $NTIME(t(n))$ , is defined by

$$NTIME(t(n)) = \{L \mid L \text{ is decidable by a nondeterministic Turing machine with running time in } O(t(n))\}$$

$$NP = \bigcup_k NTIME(n^k)$$

**True or False:**  $TIME(n^2) \subseteq NTIME(n^2)$

**True or False:**  $NTIME(n^2) \subseteq DTIME(n^2)$

**Every problem in NP is decidable with an exponential-time algorithm**

Nondeterministic approach: guess a possible solution, verify that it works.

Brute-force (worst-case exponential time) approach: iterate over all possible solutions, for each one, check if it works.

## Examples in $P$

*Can't use nondeterminism; Can use multiple tapes; Often need to be "more clever" than naïve / brute force approach*

$$PATH = \{\langle G, s, t \rangle \mid G \text{ is digraph with } n \text{ nodes there is path from } s \text{ to } t\}$$

Use breadth first search to show in  $P$

$$RELPRIME = \{\langle x, y \rangle \mid x \text{ and } y \text{ are relatively prime integers}\}$$

Use Euclidean Algorithm to show in  $P$

$$L(G) = \{w \mid w \text{ is generated by } G\}$$

(where  $G$  is a context-free grammar). Use dynamic programming to show in  $P$ .

## Examples in $NP$

*"Verifiable" i.e. NP, Can be decided by a nondeterministic TM in polynomial time, best known deterministic solution may be brute-force, solution can be verified by a deterministic TM in polynomial time.*

$$HAMPATH = \{\langle G, s, t \rangle \mid G \text{ is digraph with } n \text{ nodes,} \\ \text{there is path from } s \text{ to } t \text{ that goes through every node exactly once}\}$$

$$VERTEX - COVER = \{\langle G, k \rangle \mid G \text{ is an undirected graph with } n \text{ nodes that has a } k\text{-node vertex cover}\}$$

$$CLIQUE = \{\langle G, k \rangle \mid G \text{ is an undirected graph with } n \text{ nodes that has a } k\text{-clique}\}$$

$$SAT = \{\langle X \rangle \mid X \text{ is a satisfiable Boolean formula with } n \text{ variables}\}$$

Problems in $P$	Problems in $NP$
(Membership in any) regular language	Any problem in $P$
(Membership in any) context-free language	
$A_{DFA}$	$SAT$
$E_{DFA}$	$CLIQUE$
$EQ_{DFA}$	$VERTEX - COVER$
$PATH$	$HAMPATH$
$RELPRIME$	...
...	

Million-dollar question: Is  $P = NP$ ?

One approach to trying to answer it is to look for *hardest* problems in  $NP$  and then (1) if we can show that there are efficient algorithms for them, then we can get efficient algorithms for all problems in  $NP$  so  $P = NP$ , or (2) these problems might be good candidates for showing that there are problems in  $NP$  for which there are no efficient algorithms.

Definition (Sipser 7.29) Language  $A$  is **polynomial-time mapping reducible** to language  $B$ , written  $A \leq_P B$ , means there is a polynomial-time computable function  $f : \Sigma^* \rightarrow \Sigma^*$  such that for every  $x \in \Sigma^*$

$$x \in A \quad \text{iff} \quad f(x) \in B.$$

The function  $f$  is called the polynomial time reduction of  $A$  to  $B$ .

**Theorem** (Sipser 7.31): If  $A \leq_P B$  and  $B \in P$  then  $A \in P$ .

Proof:

Definition (Sipser 7.34; based in Stephen Cook and Leonid Levin's work in the 1970s): A language  $B$  is **NP-complete** means (1)  $B$  is in NP **and** (2) every language  $A$  in  $NP$  is polynomial time reducible to  $B$ .

**Theorem** (Sipser 7.35): If  $B$  is NP-complete and  $B \in P$  then  $P = NP$ .

Proof:

**3SAT:** A literal is a Boolean variable (e.g.  $x$ ) or a negated Boolean variable (e.g.  $\bar{x}$ ). A Boolean formula is a **3cnf-formula** if it is a Boolean formula in conjunctive normal form (a conjunction of disjunctive clauses of literals) and each clause has three literals.

$$3SAT = \{\langle \phi \rangle \mid \phi \text{ is a satisfiable 3cnf-formula}\}$$

Example strings in  $3SAT$

Example strings not in  $3SAT$

**Cook-Levin Theorem:**  $3SAT$  is  $NP$ -complete.

Are there other  $NP$ -complete problems? To prove that  $X$  is  $NP$ -complete

- *From scratch:* prove  $X$  is in  $NP$  and that all  $NP$  problems are polynomial-time reducible to  $X$ .
- *Using reduction:* prove  $X$  is in  $NP$  and that a known-to-be  $NP$ -complete problem is polynomial-time reducible to  $X$ .

**CLIQUE:** A  $k$ -**clique** in an undirected graph is a maximally connected subgraph with  $k$  nodes.

$$CLIQUE = \{\langle G, k \rangle \mid G \text{ is an undirected graph with a } k\text{-clique}\}$$

Example strings in  $CLIQUE$

Example strings not in  $CLIQUE$

Theorem (Sipser 7.32):

$$3SAT \leq_P CLIQUE$$

Given a Boolean formula in conjunctive normal form with  $k$  clauses and three literals per clause, we will map it to a graph so that the graph has a clique if the original formula is satisfiable and the graph does not have a clique if the original formula is not satisfiable.

The graph has  $3k$  vertices (one for each literal in each clause) and an edge between all vertices except

- vertices for two literals in the same clause
- vertices for literals that are negations of one another

Example:  $(x \vee \bar{y} \vee \bar{z}) \wedge (\bar{x} \vee y \vee z) \wedge (x \vee y \vee z)$

# Week10 friday

Model of Computation	Class of Languages
<p><b>Deterministic finite automata:</b> formal definition, how to design for a given language, how to describe language of a machine? <b>Nondeterministic finite automata:</b> formal definition, how to design for a given language, how to describe language of a machine? <b>Regular expressions:</b> formal definition, how to design for a given language, how to describe language of expression? <i>Also:</i> converting between different models.</p>	<p><b>Class of regular languages:</b> what are the closure properties of this class? which languages are not in the class? using <b>pumping lemma</b> to prove nonregularity.</p>
<p><b>Push-down automata:</b> formal definition, how to design for a given language, how to describe language of a machine? <b>Context-free grammars:</b> formal definition, how to design for a given language, how to describe language of a grammar?</p>	<p><b>Class of context-free languages:</b> what are the closure properties of this class? which languages are not in the class?</p>
<p>Turing machines that always halt in polynomial time</p> <p>Nondeterministic Turing machines that always halt in polynomial time</p>	<p><math>P</math></p> <p><math>NP</math></p>
<p><b>Deciders</b> (Turing machines that always halt): formal definition, how to design for a given language, how to describe language of a machine?</p>	<p><b>Class of decidable languages:</b> what are the closure properties of this class? which languages are not in the class? using diagonalization and mapping reduction to show undecidability</p>
<p><b>Turing machines</b> formal definition, how to design for a given language, how to describe language of a machine?</p>	<p><b>Class of recognizable languages:</b> what are the closure properties of this class? which languages are not in the class? using closure and mapping reduction to show unrecognizability</p>

## Given a language, prove it is regular

*Strategy 1:* construct DFA recognizing the language and prove it works.

*Strategy 2:* construct NFA recognizing the language and prove it works.

*Strategy 3:* construct regular expression recognizing the language and prove it works.

*“Prove it works” means ...*

**Example:**  $L = \{w \in \{0, 1\}^* \mid w \text{ has odd number of 1s or starts with } 0\}$

Using NFA

Using regular expressions



**Example:** Select all and only the options that result in a true statement: “To show a language  $A$  is not regular, we can...”

- a. Show  $A$  is finite
- b. Show there is a CFG generating  $A$
- c. Show  $A$  has no pumping length
- d. Show  $A$  is undecidable

**Example:** What is the language generated by the CFG with rules

$$S \rightarrow aSb \mid bY \mid Ya$$

$$Y \rightarrow bY \mid Ya \mid \varepsilon$$

**Example:** Prove that the language  $T = \{\langle M \rangle \mid M \text{ is a Turing machine and } L(M) \text{ is infinite}\}$  is undecidable.

**Example:** Prove that the class of decidable languages is closed under concatenation.