

# Theoretical Computer Science II (ACS II)

## 9. Time complexity

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January 30th, 2012

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growth

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# A scenario

## Example scenario

- You are a programmer working for a logistics company.
- Your boss asks you to implement a program that optimizes the travel route of your company's delivery truck:
  - The truck is initially located in your company's depot.
  - There are 50 locations the truck must visit on its route.
  - You know the travel distances between all locations (including the depot).
  - Your job is to write a program that determines a route from the depot via all locations back to the depot that **minimizes total travel distance**.

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# A scenario (ctd.)

## Example scenario (ctd.)

- You try solving the problem for weeks, but don't manage to come up with a program. All your attempts either
  - cannot guarantee optimality or
  - don't terminate within reasonable time (say, a month of computation).
- What do you tell your boss?

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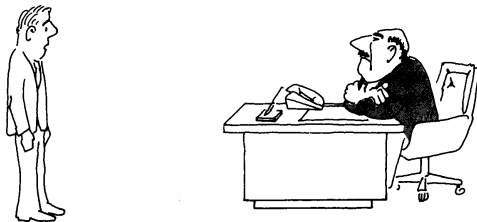
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# What you don't want to say



**“I can't find an efficient algorithm,  
I guess I'm just too dumb.”**

source: M. Garey & D. Johnson, Computers and Intractability, Freeman 1979, p. 2

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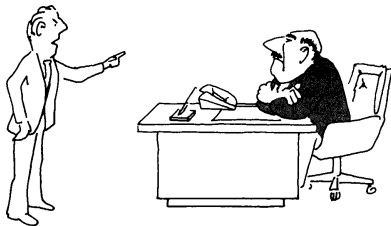
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# What you would ideally like to say



**“I can’t find an efficient algorithm,  
because no such algorithm is possible!”**

source: M. Garey & D. Johnson, Computers and Intractability, Freeman 1979, p. 2

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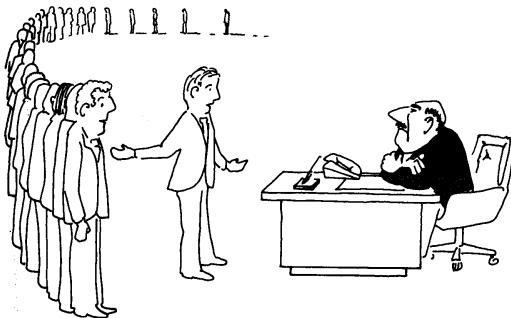
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# What complexity theory allows you to say



**“I can’t find an efficient algorithm,  
but neither can all these famous people.”**

source: M. Garey & D. Johnson, Computers and Intractability, Freeman 1979, p. 3

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# Why complexity theory?

## Complexity theory

**Complexity theory** tells us which problems can be solved **quickly** (“easy problems”) and which ones cannot (“hard problems”).

- This is useful because **different algorithmic techniques** are required for problems for easy and hard problems.
- Moreover, if we can prove a problem to be hard, we should not **waste our time** looking for “easy” algorithms.

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# Why reductions?

## Reductions

One important part of complexity theory are **reductions** that show how a new problem  $P$  can be expressed in terms of a known problem  $Q$

- This is useful for **theoretical analyses** of  $P$  because it allows us to apply our knowledge about  $Q$ .
- It is also often useful for **practical algorithms** because we can use the best known algorithm for  $Q$  and apply it to  $P$ .

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# Complexity pop quiz

- The following slide contains a selection of **graph problems**.
- In all cases, the input is a **directed, weighted graph**  $G = \langle V, A, w \rangle$  with positive edge weights.
- **How hard** do you think these graph problems are?
- Sort from **easiest** (requires least time to solve) to **hardest** (requires most time to solve).
- **No justifications needed**, just follow your intuition!

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# Some graph problems

- 1 Find a **cycle-free path** from  $u \in V$  to  $v \in V$  with **minimum cost**.
- 2 Find a **cycle-free path** from  $u \in V$  to  $v \in V$  with **maximum cost**.
- 3 Determine if  $G$  is **strongly connected** (paths exist from everywhere to everywhere).
- 4 Determine if  $G$  is **weakly connected** (paths exist from everywhere to everywhere, ignoring arc directions).
- 5 Find a **directed cycle**.
- 6 Find a **directed cycle involving all vertices**.
- 7 Find a **directed cycle involving a given vertex  $u$** .
- 8 Find a path **visiting all vertices** without repeating a vertex.
- 9 Find a path **using all arcs** without repeating an arc.

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# Overview of this chapter

## Chapter overview:

- **Refresher:** asymptotic growth (“big- $O$  notation”)
- models of computation
- P and NP
- polynomial reductions
- NP-hardness and NP-completeness
- some NP-complete problems

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# Asymptotic growth: motivation

- Often, we are interested in how an algorithm behaves **on large inputs**, as these tend to be most critical in practice.
- For example, consider the following problem:

## Duplicate elimination

**Input:** a sequence of words  $s_1, \dots, s_n$  over some alphabet

**Output:** the same words, in any order, without duplicates

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# Asymptotic growth: motivation

- Often, we are interested in how an algorithm behaves **on large inputs**, as these tend to be most critical in practice.
- For example, consider the following problem:

## Duplicate elimination

**Input:** a sequence of words  $s_1, \dots, s_n$  over some alphabet

**Output:** the same words, in any order, without duplicates

- Here are three algorithms for the problem:
  - A1 The naive algorithm with two nested for loops.
  - A2 Sort input; traverse sorted list and skip duplicates.
  - A3 Hash & report new entries upon insertion.
- Which one is fastest? Let's compare!

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# Runtimes for duplicate elimination algorithms

Assume that on an input with  $n$  words, the algorithms require the following amount of time (in  $\mu\text{s}$ ):

$$\text{A1 } f_1(n) = 0.1n^2$$

$$\text{A2 } f_2(n) = 10n \log n + 0.1n$$

$$\text{A3 } f_3(n) = 30n$$

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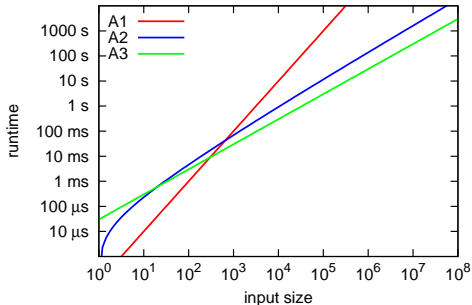
# Runtimes for duplicate elimination algorithms

Assume that on an input with  $n$  words, the algorithms require the following amount of time (in  $\mu\text{s}$ ):

A1  $f_1(n) = 0.1n^2$

A2  $f_2(n) = 10n \log n + 0.1n$

A3  $f_3(n) = 30n$



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# Runtime growth in the limit

- For **very small** inputs, **A1** is faster than **A2**, which is faster than **A3**.
- However, for **very large** inputs, the ordering is opposite.
- **Big-O notation** captures this by considering how runtime **grows in the limit** of large input sizes.
- It also ignores **constant factors**, since for large enough inputs, these do not matter compared to differences in growth rate.

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# Big-O: Definition

## Definition ( $O(g)$ )

Let  $g : \mathbb{N}_0 \rightarrow \mathbb{R}$  be a function mapping from the natural numbers to the real numbers.

$O(g)$  is the set of all functions  $f : \mathbb{N}_0 \rightarrow \mathbb{R}$  such that for some  $c \in \mathbb{R}^+$  and  $M \in \mathbb{N}_0$ , we have  $f(n) \leq c \cdot g(n)$  for all  $n \geq M$ .

**In words:** from a certain point onwards,  $f$  is bounded by  $g$  multiplied with some constant.

**Intuition:** If  $f \in O(g)$ , then  $f$  does not grow faster than  $g$  (maybe apart from constant factors that we do not care about).

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# Big-O: Notational conventions

“ $f$  is  $O(g)$ :”

- Formally,  $O(g)$  is a **set of functions**, so to express that function  $f$  belongs to this class, we should write  $f \in O(g)$ .
- However, it is **much more common** to write  $f = O(g)$  instead of  $f \in O(g)$ .
- In this context, “=” is pronounced “**is**”, not “**equals**”:  
“ **$f$  is  $O$  of  $g$ .**”
- Note that this is not the usual meaning for “=”.
- For example, it is not symmetric: we write  $f = O(g)$ , but **not**  $O(g) = f$ .

Further abbreviations:

- Notation like  $f = O(g)$  where  $g(n) = n^2$  is often abbreviated to  $f = O(n^2)$ .
- Similarly, if for example  $f(n) = n \log n$ , we can further abbreviate this to  $n \log n \in O(n^2)$ .

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# Big-O example (1)

## Big-O example

Let  $f(n) = 3n^2 + 14n + 7$ .

We show that  $f = O(n^2)$ .

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# Big-O example (2)

## Big-O example

Let  $f(n) = 3n^2 + 14n + 7$ .

We show that  $f = O(n^3)$ .

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# Big-O example (3)

## Big-O example

Let  $f(n) = n^{100}$ .

We show that  $f = O(2^n)$ .

(We may use that  $\log_2(x) \leq \sqrt{x}$  for all  $x \geq 25$ .)

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# Big-O for the duplicate elimination example

- In the duplicate elimination example, using big-O notation we can show that
    - $f_1 = O(n^2)$
    - $f_2 = O(n \log n)$
    - $f_3 = O(n)$
- which emphasizes the essential aspects of the different runtime growths for the algorithms.
- Moreover, big-O notation allows us to **order** the runtimes:
    - $f_3 = O(f_1)$ , but not  $f_1 = O(f_3)$
    - $f_2 = O(f_1)$ , but not  $f_1 = O(f_2)$
    - $f_3 = O(f_2)$ , but not  $f_2 = O(f_3)$

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# What is runtime complexity?

- **Runtime complexity** is a measure that tells us **how much time** we need to solve a problem.
- How do we **define** this appropriately?

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Summary

# What is runtime complexity?

- **Runtime complexity** is a measure that tells us **how much time** we need to solve a problem.
- How do we **define** this appropriately?

Examples of different statements about runtime:

- “Running `sort /usr/share/dict/words` on computer `alfons` requires 0.242 seconds.”
- “On an input file of size 1 MB, `sort` requires at most 1 second on a modern computer.”
- “Quicksort is faster than Insertion sort.”
- “Insertion sort is slow.”

These are very different statements, each with different **advantages** and **disadvantages**.

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# Precise statements vs. general statements

## Example statement about runtime

“Running `sort /usr/share/dict/words` on computer `alfons` requires 0.242 seconds.”

Advantage: very **precise**

Disadvantage: not **general**

- **input-specific:**  
What if we want to sort other files?
- **machine-specific:**  
What if we run the program on another machine?
- even **situation-specific:**  
If we run the program again tomorrow,  
will we get the same result?

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# General statements about runtime

In this course, we want to make **general** statements about runtime. This is accomplished in three ways:

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# General statements about runtime

In this course, we want to make **general** statements about runtime. This is accomplished in three ways:

- 1 Rather than consider runtime for **a particular input**, we consider general classes of inputs:
  - **Example:** **worst-case** runtime to sort any input of size  $n$
  - **Example:** **average-case** runtime to sort any input of size  $n$

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# General statements about runtime

In this course, we want to make **general** statements about runtime. This is accomplished in three ways:

- 2 Rather than consider **runtime on a particular machine**, we consider **more abstract** cost measures:
  - **Example:** count executed x86 **machine code instructions**
  - **Example:** count executed **Java bytecode instructions**
  - **Example:** for sort algorithms, count **number of comparisons**

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# General statements about runtime

In this course, we want to make **general** statements about runtime. This is accomplished in three ways:

- ③ Rather than consider **all implementation details**, we ignore “unimportant” aspects:
  - **Example**: rather than saying that we need  $4n - \lceil 1.2 \log n \rceil + 10$  instructions, we say that we need **a linear number** ( $O(n)$ ) of instructions.

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# Which computational model do we use?

We know many models of computation:

- programs in some programming language
  - for example Java, C++, Scheme, ...
- Turing machines
  - Variants: single-tape or multi-tape
  - Variants: deterministic or nondeterministic
- push-down automata
- finite automata
  - variants: deterministic or nondeterministic

Here, we use **Turing machines** because they are the most powerful of our formal computation models.

(Programming languages are equally powerful, but not formal enough, and also too complicated.)

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# Are Turing machines an adequate model?

- According to the Church-Turing thesis, everything that can be computed can be computed by a Turing machine.
- However, many operations that are easy on an actual computer require a lot of time on a Turing machine.
- ↪ Runtime on a Turing machine is not necessarily indicative of runtime on an actual machine!
- The main problem of Turing machines is that they do not allow **random access**.
- Alternative formal models of computation exist:
  - **Examples:** lambda calculus, register machines, random access machines (RAMs)
- Some of these are closer to how today's computers actually work (in particular, RAMs).

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# Turing machines are an adequate enough model

- So Turing machines are not the most accurate model for an actual computer.
- **However**, everything that can be done in a “more realistic model” in  $n$  computation steps can be done on a TM with **at most polynomial overhead** (e. g., in  $n^2$  steps).
- For the big topic of this part of the course, the **P vs. NP** question, we **do not care** about polynomial overhead.
- Hence, **for this purpose** TMs are an adequate model, and they have the advantage of being easy to analyze.
- Hence, we use TMs in the following.

For **more fine-grained questions** (e. g., linear vs. quadratic algorithms), one should use a different computation model.

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# Which flavour of Turing machines do we use?

There are many variants of Turing machines:

- **deterministic** or **nondeterministic**
- **one tape** or **multiple tapes**
- **one-way** or **two-way** infinite tapes
- **tape alphabet size:** 2, 3, 4, ...

Which one do we use?

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# Deterministic or nondeterministic Turing machines?

- We earlier proved that deterministic TMs (DTMs) and nondeterministic ones (NTMs) have the **same power**.
- However, there we **did not care about speed**.
- The DTM simulation of an NTM we presented can cause an **exponential slowdown**.
- Are NTMs more powerful than DTMs if we care about speed, but don't care about polynomial overhead?

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# Deterministic or nondeterministic Turing machines?

- We earlier proved that deterministic TMs (DTMs) and nondeterministic ones (NTMs) have the **same power**.
- However, there we **did not care about speed**.
- The DTM simulation of an NTM we presented can cause an **exponential slowdown**.
- Are NTMs more powerful than DTMs if we care about speed, but don't care about polynomial overhead?
- Actually, that is **the big question**:  
it is one of the most famous open problems in mathematics and computer science.
- To get to the core of this question, we will consider **both** kinds of TM separately.

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# What about the other variations?

We do **not** have to consider other TM variations separately:

- **Multi-tape** TMs can be simulated on single-tape TMs with quadratic overhead.
- TMs with **two-way infinite** tapes can be simulated on TMs with one-way infinite tapes with constant-factor overhead, and vice versa.
- TMs with **tape alphabets** of any size  $K$  can be simulated on TMs with tape alphabet  $\{0, 1, \square\}$  with constant-factor overhead  $\lceil \log_2 K \rceil$ .

$\rightsquigarrow$  Whenever we want a simple model, we can limit ourselves to single-tape one-way infinite TMs with  $\Sigma = \{0, 1\}$  and  $\Gamma = \Sigma \cup \{\square\}$ .

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# Nondeterministic Turing machines

## Definition (nondeterministic Turing machine)

A **nondeterministic Turing machine (NTM)** is a 6-tuple  $\langle \Sigma, \square, Q, q_0, q_{\text{acc}}, \delta \rangle$ , where

- $\Sigma$  is the finite, non-empty **input alphabet** (often  $\{0, 1\}$ )
- $\square \notin \Sigma$  is the **blank symbol**
  - $\Sigma_{\square} := \Sigma \cup \{\square\}$  is the **tape alphabet**
- $Q$  is the finite set of **states**
- $q_0 \in Q$  is the **initial state**,  $q_{\text{acc}} \in Q$  the **accepting state**
  - $Q' := Q \setminus \{q_{\text{acc}}\}$  is the set of **nonterminal** states
- $\delta \subseteq (Q' \times \Sigma_{\square}) \times (Q \times \Sigma_{\square} \times \{-1, +1\})$   
is the **transition relation**

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# Deterministic Turing machines

## Definition (deterministic Turing machine)

An NTM  $\langle \Sigma, \square, Q, q_0, q_{\text{acc}}, \delta \rangle$  is called **deterministic** (a **DTM**) if for all  $q \in Q$ ,  $a \in \Sigma \cup \square$  there is exactly one triple  $\langle q', a', \Delta \rangle$  with  $\langle \langle q, a \rangle, \langle q', a', \Delta \rangle \in \delta$ .

We then denote this triple with  $\delta(q, a)$ .

**Note:** In this definition, a DTM is a special case of an NTM, so if we define something for all NTMs, it is automatically defined for DTMs.

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# Turing machine configurations

## Definition (configuration)

Let  $M = \langle \Sigma, \square, Q, q_0, q_{\text{acc}}, \delta \rangle$  be an NTM.

A **configuration** of  $M$  is a triple  $\langle w, q, x \rangle \in \Sigma_{\square}^* \times Q \times \Sigma_{\square}^+$ .

- $w$ : tape contents before tape head
- $q$ : current state
- $x$ : tape contents after and including tape head

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# Turing machine transitions

## Definition (yields relation)

Let  $M = \langle \Sigma, \square, Q, q_0, q_{\text{acc}}, \delta \rangle$  be an NTM.

A configuration  $c$  of  $M$  **yields** a configuration  $c'$  of  $M$ , in symbols  $c \vdash c'$ , as defined by the following rules,

where  $a, a', b \in \Sigma_{\square}$ ,  $w, x \in \Sigma_{\square}^*$ ,  $q, q' \in Q$  and  $\langle \langle q, a \rangle, \langle q', a', \Delta \rangle \rangle \in \delta$ :

$$\begin{array}{ll} \langle w, q, ax \rangle \vdash \langle wa', q', x \rangle & \text{if } \Delta = +1, |x| \geq 1 \\ \langle w, q, a \rangle \vdash \langle wa', q', \square \rangle & \text{if } \Delta = +1 \\ \langle wb, q, ax \rangle \vdash \langle w, q', ba'x \rangle & \text{if } \Delta = -1 \\ \langle \epsilon, q, ax \rangle \vdash \langle \epsilon, q', \square a'x \rangle & \text{if } \Delta = -1 \end{array}$$

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# Acceptance of configurations

## Definition (acceptance of configurations within time $n$ )

Let  $c$  be a configuration of an NTM  $M$ .

**Acceptance within time  $n$**  is inductively defined as follows:

- If  $c = \langle w, q_{\text{acc}}, x \rangle$  where  $q_{\text{acc}}$  is the accepting state of  $M$ , then  $M$  **accepts  $c$  within time  $n$**  for all  $n \in \mathbb{N}_0$ .
- If  $c \vdash c'$  and  $M$  accepts  $c'$  within time  $n - 1$ , then  $M$  **accepts  $c$  within time  $n$** .

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# Acceptance of words and languages

## Definition (acceptance of words within time $n$ )

Let  $M = \langle \Sigma, \square, Q, q_0, q_{\text{acc}}, \delta \rangle$  be an NTM.

$M$  **accepts the word  $w \in \Sigma^*$  within time  $n \in \mathbb{N}_0$**

iff  $M$  accepts  $\langle \epsilon, q_0, w \rangle$  within time  $n$ .

- Special case:  $M$  accepts  $\epsilon$  within time  $n \in \mathbb{N}_0$   
iff  $M$  accepts  $\langle \epsilon, q_0, \square \rangle$  within time  $n$ .

## Definition (acceptance of languages within time $f$ )

Let  $M$  be an NTM with input alphabet  $\Sigma$ .

Let  $f : \mathbb{N}_0 \rightarrow \mathbb{N}_0$ .

$M$  **accepts the language  $L \subseteq \Sigma^*$  within time  $f$**

iff  $M$  accepts each word  $w \in L$  within time at most  $f(|w|)$ ,  
and  $M$  does not accept any word  $w \notin L$ .

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# P and NP

## Definition (P and NP)

**P** is the set of all languages  $L$  for which there exists a **DTM**  $M$  and a **polynomial**  $p$  such that  $M$  accepts  $L$  within time  $p$ .

**NP** is the set of all languages  $L$  for which there exists an **NTM**  $M$  and a **polynomial**  $p$  such that  $M$  accepts  $L$  within time  $p$ .

## Notes:

- Sets of languages like P and NP that are defined in terms of resource bounds for TMs are called **complexity classes**.
- We know that  $P \subseteq NP$ . (**Why?**)
- Whether the converse holds is an open problem: this is the famous **P vs. NP** question.

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# General algorithmic problems vs. decision problems

- An important aspect of complexity theory is to **compare the difficulty** of solving different algorithmic problems.
  - **Examples:** sorting, finding shortest paths, finding cycles in graphs including all vertices, ...
- **Solutions** to algorithmic problems take different forms.
  - **Examples:** a sorted sequence, a path, a cycle, ...
- To simplify the study, it is common in complexity theory to limit attention to **decision problems**, i. e., problems where the “solution” is an answer of the form **Yes** or **No**.
  - **Examples:** Is this sequence sorted?  
Is there a path from  $u$  to  $v$  of cost at most  $K$ ?  
Is there a cycle in this graph that includes all vertices?
- If we pick the decision problems properly, we can usually show that if the decision problem is easy to solve, then the corresponding algorithmic problem is also easy to solve.

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# Decision problems: example

## Using decision problems to solve more general problems

[O] Shortest path **optimization** problem:

- **Input:** Directed, weighted graph  $G = \langle V, A, w \rangle$  with positive edge weights  $w : A \rightarrow \mathbb{N}_1$ , vertices  $u \in V, v \in V$ .
- **Output:** A shortest (= minimum-cost) path from  $u$  to  $v$

[D] Shortest path **decision** problem:

- **Input:** Directed, weighted graph  $G = \langle V, A, w \rangle$  with positive edge weights  $w : A \rightarrow \mathbb{N}_1$ , vertices  $u \in V, v \in V$ , **cost bound**  $K \in \mathbb{N}_0$ .
- **Question:** Is there a path from  $u$  to  $v$  with cost  $\leq K$ ?

- If we can solve [O] in polynomial time, we can solve [D] in polynomial time

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# Decision problems: example

## Using decision problems to solve more general problems

[O] Shortest path **optimization** problem:

- **Input:** Directed, weighted graph  $G = \langle V, A, w \rangle$  with positive edge weights  $w : A \rightarrow \mathbb{N}_1$ , vertices  $u \in V, v \in V$ .
- **Output:** A shortest (= minimum-cost) path from  $u$  to  $v$

[D] Shortest path **decision** problem:

- **Input:** Directed, weighted graph  $G = \langle V, A, w \rangle$  with positive edge weights  $w : A \rightarrow \mathbb{N}_1$ , vertices  $u \in V, v \in V$ , **cost bound**  $K \in \mathbb{N}_0$ .
- **Question:** Is there a path from  $u$  to  $v$  with cost  $\leq K$ ?

- If we can solve [O] in polynomial time, we can solve [D] in polynomial time **and vice versa**.

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# Decision problems as languages

Decision problems can be represented as languages:

- For every decision problem, if we want to pose it to a computer (or other computational device), we must express the input as a word over some alphabet  $\Sigma$ .
- The **language** defined by the decision problem then contains a word  $w \in \Sigma^*$  iff
  - $w$  is a well-formed input for the decision problem, and
  - the correct answer for input  $w$  is **Yes**.

**Example** (shortest path decision problem):  $w \in \text{SP}$  iff

- the input properly describes  $G, u, v, K$  such that  $G$  is a graph, arc weights are positive, etc.
- that graph  $G$  has a path of cost at most  $K$  from  $u$  to  $v$

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# Decision problems as languages (ctd.)

- Since decision problems can be represented as languages, we do not distinguish between “languages” and (decision) “problems” from now on.
- For example, we can say that  $P$  is the set of all **decision problems** that can be solved in polynomial time by a DTM.
- Similarly,  $NP$  is the set of all decision problems that can be solved in polynomial time by an NTM.
  - From the definition of NTM acceptance, “solved” means
    - If  $w$  is a **Yes** instance, then the NTM has **some** polynomial-time accepting computation for  $w$
    - If  $w$  is a **No** instance (or not a well-formed input), then the NTM never accepts it.

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# Example: HAMILTONIANCYCLE $\in$ NP

## HAMILTONIANCYCLE $\in$ NP

The HAMILTONIANCYCLE problem is defined as follows:

**Given:** An undirected graph  $G = \langle V, E \rangle$

**Question:** Does  $G$  contain a Hamiltonian cycle?

A Hamiltonian cycle is a path  $\pi = \langle v_0, v_1, \dots, v_n \rangle$  such that

- $\pi$  is a path: for all  $i \in \{0, \dots, n-1\}$ ,  $\{v_i, v_{i+1}\} \in E$
- $\pi$  is a cycle:  $v_0 = v_n$
- $\pi$  is simple:  $v_i \neq v_j$  for all  $i, j \in \{1, \dots, n\}$  with  $i \neq j$
- $\pi$  is Hamiltonian: for all  $v \in V$ , there exists  $i \in \{1, \dots, n\}$  such that  $v = v_i$

We show that HAMILTONIANCYCLE  $\in$  NP.

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# Guess and check

- The (nondeterministic) Hamiltonian Cycle algorithm illustrates a general design principle for NTMs: **guess and check**.
- NTMs can solve decision problems in polynomial time by
  - nondeterministically **guessing** a “solution” (also called “witness” or “proof”) for the instance
  - deterministically **verifying** that the guessed witness indeed describes a proper solution, and accepting iff it does
- It is possible to prove that **all** decision problems in NP can be solved by an NTM using such a guess-and-check approach.

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# Polynomial reductions: idea

- **Reductions** are a very common and powerful idea in mathematics and computer science.
- The idea is to solve a new problem by **reducing** (mapping) it to one for which already now how to solve it.
- **Polynomial reductions** (also called **Karp reductions**) are an example of this in the context of decision problems.

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# Polynomial reductions

## Definition (Polynomial reductions/Karp reductions)

Let  $A \subseteq \Sigma^*$  and  $B \subseteq \Sigma^*$  be decision problems for alphabet  $\Sigma$ . We say that  $A$  is **polynomially reducible to  $B$** , written  $A \leq_p B$ , if there exists a DTM  $M$  with the following properties:

- $M$  is **polynomial-time**
  - i. e., there is a polynomial  $p$  such that  $M$  stops within time  $p(|w|)$  on any input  $w \in \Sigma^*$ .
- $M$  **reduces  $A$  to  $B$** 
  - i. e., for all  $w \in \Sigma^*$ : ( $w \in A$  iff  $f_M(w) \in B$ ),
  - where  $f_M : \Sigma^* \rightarrow \Sigma^*$  is the function computed by  $M$ , i. e., when  $M$  is run on input  $w \in \Sigma^*$ , then  $f_M(w)$  is the tape content of  $M$  after stopping, ignoring blanks

$M$  is called a **polynomial reduction** from  $A$  to  $B$ .

Polynomial reductions are also called **Karp reductions**.

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# Polynomial reduction: example

## HAMILTONIANCYCLE $\leq_p$ TSP

The TSP (Travelling Salesperson) problem is defined as follows:

**Given:** A finite nonempty set of locations  $L$ , a symmetric travel cost function  $cost : L \times L \rightarrow \mathbb{N}_0$ , a cost bound  $K \in \mathbb{N}_0$

**Question:** Is there a tour of total cost at most  $K$ , i. e., a permutation  $\langle l_1, \dots, l_n \rangle$  of the locations such that  $\sum_{i=1}^{n-1} cost(l_i, l_{i+1}) + cost(l_n, l_1) \leq K$ ?

We show that HAMILTONIANCYCLE  $\leq_p$  TSP.

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# Properties of polynomial reductions

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## Theorem (properties of polynomial reductions)

Let  $A, B, C$  be decision problems over alphabet  $\Sigma$ .

- 1 If  $A \leq_p B$  and  $B \in P$ , then  $A \in P$ .
- 2 If  $A \leq_p B$  and  $B \in NP$ , then  $A \in NP$ .
- 3 If  $A \leq_p B$  and  $A \notin P$ , then  $B \notin P$ .
- 4 If  $A \leq_p B$  and  $A \notin NP$ , then  $B \notin NP$ .
- 5 If  $A \leq_p B$  and  $B \leq_p C$ , then  $A \leq_p C$ .

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# NP-hardness and NP-completeness

## Definition (NP-hard, NP-complete)

Let  $B$  be a decision problem.

$B$  is called **NP-hard** if  $A \leq_p B$  for **all** problems  $A \in \text{NP}$ .

$B$  is called **NP-complete** if  $B \in \text{NP}$  and  $B$  is NP-hard.

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# NP-hardness and NP-completeness

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Let  $B$  be a decision problem.

$B$  is called **NP-hard** if  $A \leq_p B$  for **all** problems  $A \in \text{NP}$ .

$B$  is called **NP-complete** if  $B \in \text{NP}$  and  $B$  is NP-hard.

- NP-hard problems are “at least as hard” as all problems in NP.
- NP-complete problems are “the hardest” problems in NP.
- Do NP-complete problems exist?
- If  $A \in P$  for **any** NP-complete problem  $A$ , then  $P = \text{NP}$ .  
Why?

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# SAT is NP-complete

## Definition (SAT)

The **SAT** (satisfiability) problem is defined as follows:

Given: A propositional logic formula  $\varphi$

Question: Is  $\varphi$  satisfiable?

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# SAT is NP-complete

## Definition (SAT)

The **SAT** (satisfiability) problem is defined as follows:

Given: A propositional logic formula  $\varphi$

Question: Is  $\varphi$  satisfiable?

## Theorem (Cook, 1971)

*SAT is NP-complete.*

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# SAT is NP-complete

## Definition (SAT)

The **SAT** (satisfiability) problem is defined as follows:

Given: A propositional logic formula  $\varphi$

Question: Is  $\varphi$  satisfiable?

## Theorem (Cook, 1971)

*SAT is NP-complete.*

## Proof.

SAT  $\in$  NP: Guess and check.

SAT is NP-hard: This is more involved...

(Continued on next slide.)

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# NP-hardness proof for SAT

## Proof (ctd.)

We must show that  $A \leq_p \text{SAT}$  for all  $A \in \text{NP}$ .

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# NP-hardness proof for SAT

## Proof (ctd.)

We must show that  $A \leq_p \text{SAT}$  for all  $A \in \text{NP}$ .

Let  $A \in \text{NP}$ . This means that there exists a polynomial  $p$  and an NTM  $M$  s.t.  $M$  accepts  $A$  within time  $p$ .

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We must show that  $A \leq_p \text{SAT}$  for all  $A \in \text{NP}$ .

Let  $A \in \text{NP}$ . This means that there exists a polynomial  $p$  and an NTM  $M$  s.t.  $M$  accepts  $A$  within time  $p$ .

Let  $w \in \Sigma^*$  be the input for  $A$ .

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# NP-hardness proof for SAT

## Proof (ctd.)

We must show that  $A \leq_p \text{SAT}$  for all  $A \in \text{NP}$ .

Let  $A \in \text{NP}$ . This means that there exists a polynomial  $p$  and an NTM  $M$  s.t.  $M$  accepts  $A$  within time  $p$ .

Let  $w \in \Sigma^*$  be the input for  $A$ .

We must, in polynomial time, construct a propositional logic formula  $f(w)$  s.t.  $w \in A$  iff  $f(w) \in \text{SAT}$  (i. e., is satisfiable).

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# NP-hardness proof for SAT

## Proof (ctd.)

We must show that  $A \leq_p \text{SAT}$  for all  $A \in \text{NP}$ .

Let  $A \in \text{NP}$ . This means that there exists a polynomial  $p$  and an NTM  $M$  s.t.  $M$  accepts  $A$  within time  $p$ .

Let  $w \in \Sigma^*$  be the input for  $A$ .

We must, in polynomial time, construct a propositional logic formula  $f(w)$  s.t.  $w \in A$  iff  $f(w) \in \text{SAT}$  (i. e., is satisfiable).

**Idea:** Construct a logical formula that **encodes the possible configurations** that  $M$  can reach from input  $w$  and which is **satisfiable iff an accepting configuration is reached**.

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# NP-hardness proof for SAT (ctd.)

## Proof (ctd.)

Let  $M = \langle \Sigma, \square, Q, q_0, q_{acc}, \delta \rangle$  be the NTM for  $A$ . We assume (w.l.o.g.) that it never moves to the left of the initial position.

Let  $w = w_1 \dots w_n \in \Sigma^*$  be the input for  $M$ .

Let  $p$  be the run-time bounding polynomial for  $M$ .

Let  $N = p(n) + 1$  (w.l.o.g.  $N \geq n$ ).

- ↪ During any computation that takes time  $p(n)$ ,  $M$  can only visit the first  $N$  tape cells.
- ↪ We can encode any configuration of  $M$  that can possibly be part of an accepting configuration by denoting:
  - what the current **state** of  $M$  is
  - which of the tape cells  $\{1, \dots, N\}$  is the current location of the **tape head**
  - which of the symbols in  $\Sigma_{\square}$  is contained in each of the tape cells  $\{1, \dots, N\}$

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# NP-hardness proof for SAT (ctd.)

## Proof (ctd.)

Use these propositional variables in formula  $f(w)$ :

- $state_{t,q}$  ( $t \in \{0, \dots, N\}$ ,  $q \in Q$ )  
     $\rightsquigarrow$  encode Turing Machine state in  $t$ -th configuration
- $head_{t,i}$  ( $t \in \{0, \dots, N\}$ ,  $i \in \{1, \dots, N\}$ )  
     $\rightsquigarrow$  encode tape head location in  $t$ -th configuration
- $content_{t,i,a}$  ( $t \in \{0, \dots, N\}$ ,  $i \in \{1, \dots, N\}$ ,  $a \in \Sigma_{\square}$ )  
     $\rightsquigarrow$  encode tape contents in  $t$ -th configuration

Construct  $f(w)$  in such a way that every satisfying assignment

- describes a **sequence of configurations** of the TM
- that **starts from the initial configuration**
- and **reaches an accepting configuration**
- and **follows the transition rules** in  $\delta$

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# NP-hardness proof for SAT (ctd.)

## Proof (ctd.)

*oneof*  $X := (\bigvee_{x \in X} x) \wedge \neg(\bigvee_{x \in X} \bigvee_{y \in X \setminus \{x\}} (x \wedge y))$

1. Describe a sequence of configurations of the TM:

$$\begin{aligned} \text{Valid} := & \bigwedge_{t=0}^N (\text{oneof} \{ \text{state}_{t,q} \mid q \in Q \} \wedge \\ & \text{oneof} \{ \text{head}_{t,i} \mid i \in \{1, \dots, N\} \} \wedge \\ & \bigwedge_{i=1}^N \text{oneof} \{ \text{content}_{t,i,a} \mid a \in \Sigma_{\square} \} ) \end{aligned}$$

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# NP-hardness proof for SAT (ctd.)

## Proof (ctd.)

2. Start from the initial configuration:

$$\text{Init} := \text{state}_{0,q_0} \wedge \text{head}_{0,1} \wedge \bigwedge_{i=1}^n \text{content}_{0,i,w_i} \wedge \bigwedge_{i=n+1}^N \text{content}_{0,i,\square}$$

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# NP-hardness proof for SAT (ctd.)

## Proof (ctd.)

3. Reach an accepting configuration:

$$\text{Accept} := \bigvee_{t=0}^N \text{state}_{t,q_{\text{acc}}}$$

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# NP-hardness proof for SAT (ctd.)

## Proof (ctd.)

4. Follow the transition rules in  $\delta$ :

$$\begin{aligned} Trans := & \bigwedge_{t=0}^{N-1} ((state_{t,q_{acc}} \rightarrow Noop_t) \wedge \\ & (\neg state_{t,q_{acc}} \rightarrow \bigvee_{R \in \delta} \bigvee_{i=1}^N Rule_{t,i,R})) \end{aligned}$$

where ...

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# NP-hardness proof for SAT (ctd.)

## Proof (ctd.)

4. Follow the transition rules in  $\delta$  (ctd.):

$$\begin{aligned} \text{Noop}_t := & \bigwedge_{q \in Q} (\text{state}_{t,q} \rightarrow \text{state}_{t+1,q}) \wedge \\ & \bigwedge_{i=1}^N (\text{head}_{t,i} \rightarrow \text{head}_{t+1,i}) \wedge \\ & \bigwedge_{i=1}^N \bigwedge_{a \in \Sigma_{\square}} (\text{content}_{t,i,a} \rightarrow \text{content}_{t+1,i,a}) \end{aligned}$$

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# NP-hardness proof for SAT (ctd.)

## Proof (ctd.)

4. Follow the transition rules in  $\delta$  (ctd.):

$$\begin{aligned} \text{Rule}_{t,i,\langle\langle q,a\rangle,\langle q',a',\Delta\rangle\rangle} := & \\ & (\text{state}_{t,q} \wedge \text{state}_{t+1,q'}) \wedge \\ & (\text{head}_{t,i} \wedge \text{head}_{t+1,i+\Delta}) \wedge \\ & (\text{content}_{t,i,a} \wedge \text{content}_{t+1,i,a'}) \wedge \\ & \bigwedge_{j \in \{1, \dots, N\} \setminus \{i\}} \bigwedge_{a \in \Sigma_{\square}} (\text{content}_{t,j,a} \rightarrow \text{content}_{t+1,j,a}) \end{aligned}$$

(Replace by  $\perp$  if  $i + \Delta = 0$  or  $i + \Delta = N + 1$ : these correspond to situations where  $M$  leaves the “allowed” part of the tape.)

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# NP-hardness proof for SAT (ctd.)

## Proof (ctd.)

Putting it all together:

Define  $f(w) := \text{Valid} \wedge \text{Init} \wedge \text{Accept} \wedge \text{Trans}$ .

- $f(w)$  can be computed in polynomial time in  $|w|$ .
- $w \in A$  iff  $M$  accepts  $w$  within time  $p(|w|)$   
iff  $f(w)$  is satisfiable  
iff  $f(w) \in \text{SAT}$

$\rightsquigarrow A \leq_p \text{SAT}$

Since  $A \in \text{NP}$  was chosen arbitrarily, we can conclude that SAT is NP-hard and hence NP-complete. □

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# More NP-complete problems

- The proof of NP-hardness of SAT was rather involved.
- However, now that we have it, we can prove other problems NP-hard **much more easily**.
- Simply prove  $A \leq_p B$  for some known NP-hard problem  $A$  (such as SAT). This immediately proves that  $B$  is NP-hard. **Why?**
- A huge number of problems are known to be NP-complete.
- Garey & Johnson's textbook "Computers and Intractability — A Guide to the Theory of NP-Completeness" (1979) lists several hundred such problems, with references to proofs.

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# 3SAT is NP-complete

## Definition (3SAT)

The **3SAT** problem is defined as follows:

Given: A propositional logic formula  $\varphi$  in **CNF** with  
**at most three literals** per clause.

Question: Is  $\varphi$  satisfiable?

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Given: A propositional logic formula  $\varphi$  in **CNF** with  
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Question: Is  $\varphi$  satisfiable?

## Theorem

**3SAT is NP-complete.**

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# 3SAT is NP-complete

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Given: A propositional logic formula  $\varphi$  in **CNF** with  
**at most three literals** per clause.

Question: Is  $\varphi$  satisfiable?

## Theorem

*3SAT is NP-complete.*

## Proof.

3SAT  $\in$  NP: Guess and check.

3SAT is NP-hard: SAT  $\leq_p$  3SAT ( $\rightsquigarrow$  whiteboard) □

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Summary

# CLIQUE is NP-complete

## Definition (CLIQUE)

The **CLIQUE** problem is defined as follows:

**Given:** An undirected graph  $G = \langle V, E \rangle$  and a number  $K \in \mathbb{N}_0$

**Question:** Does  $G$  contain a **clique** of size at least  $K$ ,  
i. e., a vertex set  $C \subseteq V$  with  $|C| \geq K$   
such that  $\langle u, v \rangle \in E$  for all  $u, v \in C$  with  $u \neq v$ ?

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## Theorem

**CLIQUE** is NP-complete.

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such that  $\langle u, v \rangle \in E$  for all  $u, v \in C$  with  $u \neq v$ ?

## Theorem

**CLIQUE** is NP-complete.

## Proof.

**CLIQUE**  $\in$  NP: Guess and check.

**CLIQUE** is NP-hard:  $3\text{SAT} \leq_p \text{CLIQUE}$  ( $\rightsquigarrow$  whiteboard)



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# INDSET is NP-complete

## Definition (INDSET)

The **INDSET** problem is defined as follows:

**Given:** An undirected graph  $G = \langle V, E \rangle$  and a number  $K \in \mathbb{N}_0$

**Question:** Does  $G$  contain an **independent set** of size at least  $K$ , i. e., a vertex set  $I \subseteq V$  with  $|I| \geq K$  such that for all  $u, v \in I$ ,  $\langle u, v \rangle \notin E$ ?

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## Theorem

**INDSET is NP-complete.**

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# INDSET is NP-complete

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## Theorem

INDSET is NP-complete.

## Proof.

INDSET  $\in$  NP: Guess and check.

INDSET is NP-hard: CLIQUE  $\leq_p$  INDSET ( $\rightsquigarrow$  exercises)  $\square$

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# VERTEXCOVER is NP-complete

## Definition (VERTEXCOVER)

The **VERTEXCOVER** problem is defined as follows:

**Given:** An undirected graph  $G = \langle V, E \rangle$  and a number  $K \in \mathbb{N}_0$

**Question:** Does  $G$  contain a **vertex cover** of size at most  $K$ ,  
i. e., a vertex set  $C \subseteq V$  with  $|C| \leq K$   
s. t. for all  $\langle u, v \rangle \in E$ , we have  $u \in C$  or  $v \in C$ ?

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s. t. for all  $\langle u, v \rangle \in E$ , we have  $u \in C$  or  $v \in C$ ?

## Theorem

**VERTEXCOVER** is NP-complete.

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# VERTEXCOVER is NP-complete

## Definition (VERTEXCOVER)

The **VERTEXCOVER** problem is defined as follows:

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i. e., a vertex set  $C \subseteq V$  with  $|C| \leq K$   
s. t. for all  $\langle u, v \rangle \in E$ , we have  $u \in C$  or  $v \in C$ ?

## Theorem

VERTEXCOVER is NP-complete.

## Proof.

VERTEXCOVER  $\in$  NP: Guess and check.

VERTEXCOVER is NP-hard:  $\text{INDSET} \leq_p \text{VERTEXCOVER}$

( $\rightsquigarrow$  exercises)



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# DIRHAMILTONIANCYCLE is NP-complete

## Definition (DIRHAMILTONIANCYCLE)

The **DIRHAMILTONIANCYCLE** problem is defined as follows:

**Given:** A directed graph  $G = \langle V, A \rangle$

**Question:** Does  $G$  contain a **directed Hamiltonian cycle**  
(i. e., a cyclic path visiting each vertex exactly once)?

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## Theorem

DIRHAMILTONIANCYCLE *is NP-complete.*

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# DIRHAMILTONIANCYCLE is NP-complete

## Definition (DIRHAMILTONIANCYCLE)

The **DIRHAMILTONIANCYCLE** problem is defined as follows:

Given: A directed graph  $G = \langle V, A \rangle$

Question: Does  $G$  contain a **directed Hamiltonian cycle**  
(i. e., a cyclic path visiting each vertex exactly once)?

## Theorem

DIRHAMILTONIANCYCLE is NP-complete.

## Proof sketch.

DIRHAMILTONIANCYCLE  $\in$  NP: Guess and check.

DIRHAMILTONIANCYCLE is NP-hard:

3SAT  $\leq_p$  DIRHAMILTONIANCYCLE ( $\rightsquigarrow$  next slides)

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# DIRHAMILTONIANCYCLE is NP-complete (ctd.)

## Proof sketch (ctd.)

$3SAT \leq_p \text{DIRHAMILTONIANCYCLE}$ :

- A 3SAT instance  $\varphi$  is given.
- W.l.o.g. each clause has exactly three literals, and there are no repetitions within a clause.
- Let  $v_1, \dots, v_n$  be the propositional variables in  $\varphi$ .
- Let  $c_1, \dots, c_m$  be the clauses of  $\varphi$ , where each  $c_i$  is of the form  $l_{i1} \vee l_{i2} \vee l_{i3}$ .
- The reduction generates a graph  $f(\varphi)$  with  $6m + n$  vertices, described in the following.

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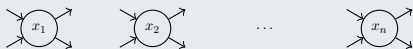
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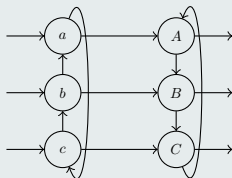
# DIRHAMILTONIANCYCLE is NP-complete (ctd.)

## Proof sketch (ctd.)

- Introduce vertex  $x_i$  with indegree 2 and outdegree 2 for each variable  $v_i$ :



- Introduce subgraph  $C_j$  with six vertices for each clause  $c_j$ :



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# DIRHAMILTONIANCYCLE is NP-complete (ctd.)

## Proof sketch (ctd.)

Let  $\pi$  be a directed Hamiltonian cycle of the overall graph.

- Whenever  $\pi$  traverses  $C_j$ , it must leave it at the corresponding “exit” for the given “entrance” (i. e.,  $a \rightarrow A$ ,  $b \rightarrow B$ ,  $c \rightarrow C$ ).  
Otherwise  $\pi$  cannot be a Hamiltonian cycle.
- The following are all valid possibilities for Hamiltonian cycles in graphs containing  $C_j$ :
  - $\pi$  crosses  $C_j$  once, entering at any entrance
  - $\pi$  crosses  $C_j$  twice, entering at any two different entrances
  - $\pi$  crosses  $C_j$  three times, entering once at each entrance

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# DIRHAMILTONIANCYCLE is NP-complete (ctd.)

## Proof sketch (ctd.)

Connect the “open ends” of the graph as follows:

- Identify the entrances and exits of the  $C_j$  graphs with the three literals of clause  $c_j$ .
- One exit of  $x_i$  is **positive**, one **negative**.
- For the **positive** exit, determine the clauses in which the positive literal  $v_i$  occurs
  - Connect the positive  $x_i$  exit to the  $v_i$  entrance of the  $C_j$  graph for the first such clause.
  - Connect the  $v_i$  exit of that graph to the  $x_i$  entrance of the second such clause, and so on.
  - Connect the  $v_i$  exit of the last such clause to the positive entrance of  $x_{i+1}$  (or  $x_1$  if  $n = 1$ ).
- Similarly for the **negative** exit of  $x_i$  and literal  $\neg v_i$ .

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# DIRHAMILTONIANCYCLE is NP-complete (ctd.)

## Proof sketch (ctd.)

This is a reduction (which is clearly polynomial):

- ( $\Rightarrow$ ):
  - Given a satisfying truth assignment  $\alpha(v_i)$ , we can construct a Hamiltonian cycle by leaving  $x_i$  through the positive exit if  $\alpha(v_i) = \mathbf{T}$ ; the negative exit if  $\alpha(v_i) = \mathbf{F}$ .
  - We can then visit all  $C_j$  graphs for clauses made true by that literal.
  - Overall, we visit each  $C_j$  graph 1–3 times.
- ( $\Leftarrow$ ):
  - A Hamiltonian cycle visits each vertex  $x_i$  and leaves it through the positive or negative exit.
  - Set  $v_i$  to true or false according to which exit is chosen.
  - This gives a satisfying truth assignment.



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# HAMILTONIANCYCLE is NP-complete

## Theorem

HAMILTONIANCYCLE *is NP-complete.*

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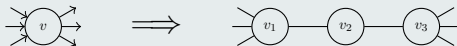
# HAMILTONIANCYCLE is NP-complete

## Theorem

HAMILTONIANCYCLE is NP-complete.

## Proof sketch.

- HAMILTONIANCYCLE  $\in$  NP : Guess and check.
- HAMILTONIANCYCLE is NP-hard:  
DIRHAMILTONIANCYCLE  $\leq_p$  HAMILTONIANCYCLE
- Basic gadget of the reduction:



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# TSP is NP-complete

## Theorem

TSP *is NP-complete.*

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# TSP is NP-complete

## Theorem

TSP is NP-complete.

## Proof.

- TSP  $\in$  NP : Guess and check.
- TSP is NP-hard:  
HAMILTONIANCYCLE  $\leq_p$  TSP was already shown earlier.



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# And many, many more. . .

More NP-complete problems:

- **SUBSETSUM**: Given natural numbers  $a_1, \dots, a_n$  and a target  $K$ , is there a subsequence with sum exactly  $K$ ?
- **BINPACKING**: Given objects of size  $a_1, \dots, a_n$ , can the objects fit into  $K$  bins with capacity  $B$  each?
- **MINESWEEPERCONSISTENCY**: In a given Minesweeper position, is a given cell safe?
- **GENERALIZEDFREECELL**: Does a given generalized FreeCell deal (i. e., one that may have more than 52 cards) have a solution?
- . . .

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# Summary

- Complexity theory is about **proving** which problems are “easy” to solve and which ones are “hard”.
- Two important classes of problems are
  - **P** (problems that can be solved in **polynomial time** by a regular computing mechanism) and
  - **NP** (problems that can be solved in polynomial time using **nondeterminism**).
- We know  $P \subseteq NP$ , but we do not know whether  $P = NP$ .
- Many practically relevant problems are **NP-complete**, i. e., as hard as any other problem in NP.
- If there exists an efficient algorithm for **one** NP-complete problem, then there exists an efficient algorithm for **all** problems in NP.

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