

Theory of Computer Science

C4. Reductions

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Introduction

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C4. Reductions

Introduction

What We Achieved So Far: Discussion

- ▶ We already know a concrete undecidable problem.
→ halting problem
- ▶ We will see that we can derive **further** undecidability results from the undecidability of the halting problem.
- ▶ The central notion for this is **reducing** one problem to another problem.

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Illustration

```
def is_odd(some_number):
    n = some_number + 1
    return is_even(n)
```

- ▶ Decides whether a given number is odd based on...
- ▶ an algorithm that determines whether a number is even.

Reduction: Idea (slido)

Assume that you have an algorithm that solves problem A relying on a hypothetical algorithm for problem B.

```
def is_in_A(input_A):
    input_B = <compute suitable instance based on input_A>
    return is_in_B(input_B)
```

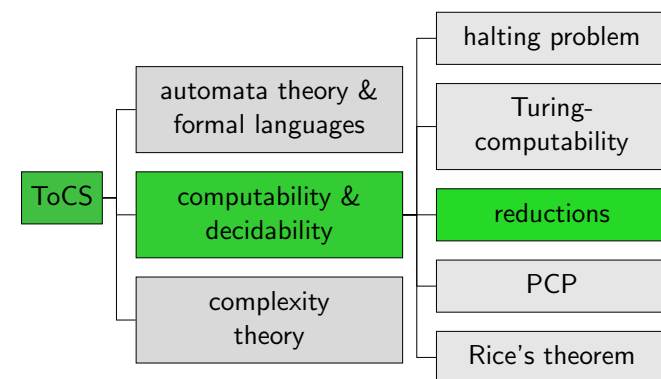
What (if anything) can you conclude

- 1 if there indeed is an algorithm for problem A?
- 2 if there indeed is an algorithm for problem B?
- 3 if problem A is undecidable?
- 4 if problem B is undecidable?



C4.2 Reduction

Content of the Course



Reduction: Definition

Definition (Reduction)

Let $A \subseteq \Sigma^*$ and $B \subseteq \Gamma^*$ be languages, and let $f : \Sigma^* \rightarrow \Gamma^*$ be a total and computable function such that for all $x \in \Sigma^*$:

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

Then we say that A can be **reduced to B** (in symbols: $A \leq B$), and f is called a **reduction from A to B** .

German: A ist auf B reduzierbar, Reduktion von A auf B

Reduction Property

Theorem (Reductions vs. Turing-recognizability/Decidability)

Let A and B be languages with $A \leq B$. Then:

- ① If B is decidable, then A is decidable.
- ② If B is Turing-recognizable, then A is Turing-recognizable.
- ③ If A is not decidable, then B is not decidable.
- ④ If A is not Turing-recognizable, then B is not Turing-recognizable.

\rightsquigarrow In the following, we use 3. to show undecidability for further problems.

Reduction Property: Proof

Proof.

for 1.: If B is decidable then there is a DTM M_B that decides B . The following algorithm decides A using reduction f from A to B .

On input x :

- ① $y := f(x)$
- ② Simulate M_B on input y . This simulation terminates.
- ③ If M_B accepted y , accept. Otherwise reject.

for 2.: identical to (1), only that M_B only recognizes B and therefore the simulation does not necessarily terminate if $y \notin B$. Since $y \notin B$ iff $x \notin A$, the procedure still recognizes A .

for 3./4.: contrapositions of 1./2. \rightsquigarrow logically equivalent □

Reductions are Preorders

Theorem (Reductions are Preorders)

The relation " \leq " is a preorder:

- ① For all languages A :
 $A \leq A$ (*reflexivity*)
- ② For all languages A, B, C :
If $A \leq B$ and $B \leq C$, then $A \leq C$ (*transitivity*)

German: schwache Halbordnung/Quasiordnung, Reflexivität, Transitivität

Reductions are Preorders: Proof

Proof.

for 1.: The function $f(x) = x$ is a reduction from A to A because it is total and computable and $x \in A$ iff $f(x) \in A$.

for 2.: \rightsquigarrow exercises □

C4.3 Halting Problem on Empty Tape

Example

As an example

- ▶ we will consider problem H_0 , a variant of the halting problem,
- ▶ ...and show that it is undecidable
- ▶ ...reducing H to H_0 .

Reminder: Halting Problem

Definition (Halting Problem)

The **halting problem** is the language

$$H = \{w\#x \in \{0, 1, \#\}^* \mid w, x \in \{0, 1\}^*, \\ M_w \text{ started on } x \text{ terminates}\}$$

Halting Problem on Empty Tape (1)

Definition (Halting Problem on the Empty Tape)

The **halting problem on the empty tape** is the language

$$H_0 = \{w \in \{0, 1\}^* \mid M_w \text{ started on } \varepsilon \text{ terminates}\}.$$

Note: H_0 is Turing-recognizable. (Why?)

German: Halteproblem auf leerem Band

Halting Problem on Empty Tape (2)

Theorem (Undecidability of Halting Problem on Empty Tape)

The halting problem on the empty tape is undecidable.

Proof.

We show $H \leq H_0$.

Consider the function $f : \{0, 1, \#\}^* \rightarrow \{0, 1\}^*$ that computes the word $f(z)$ for a given $z \in \{0, 1, \#\}^*$ as follows:

- ▶ Test if z has the form $w\#x$ with $w, x \in \{0, 1\}^*$.
- ▶ If not, return any word that is not in H_0 (e. g., encoding of a TM that instantly starts an endless loop).
- ▶ If yes, split z into w and x .
- ▶ Decode w to TM M_w .

...

Halting Problem on Empty Tape (3)

Proof (continued).

- ▶ Construct a TM $M_{\text{write } x \text{ for } \varepsilon}$ that behaves as follows:
 - ▶ If the input is empty: write x onto the tape and move the head to the first symbol of x (if $x \neq \varepsilon$); then stop
 - ▶ otherwise, stop immediately
- ▶ Construct TM M that first runs $M_{\text{write } x \text{ for } \varepsilon}$ and then M_w .
 $\rightarrow M$ started on empty tape simulates M_w on input x .
- ▶ Return the encoding of M .

f is total and (with some effort) computable. Also:

$$\begin{aligned} z \in H &\text{ iff } z = w\#x \text{ and } M_w \text{ run on } x \text{ terminates} \\ &\text{ iff } M_{f(z)} (= M) \text{ started on empty tape terminates} \\ &\text{ iff } f(z) \in H_0 \end{aligned}$$

$$\rightsquigarrow H \leq H_0 \rightsquigarrow H_0 \text{ undecidable} \quad \square$$

Summary

- ▶ **reductions:** “embedding” a problem as a special case of another problem
- ▶ important method for proving undecidability: reduce from a known undecidable problem to a new problem