

Theory of Computer Science

D2. Recursive Enumerability and Decidability

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April 22, 2020

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D2.1 Introduction

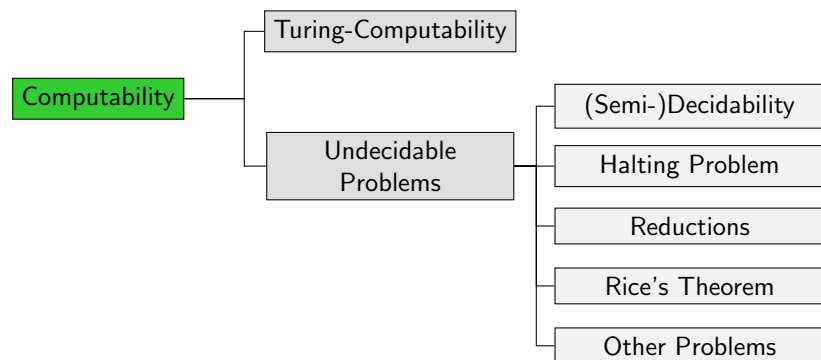
D2.2 Encoding/Decoding Functions

D2.3 Recursive Enumerability

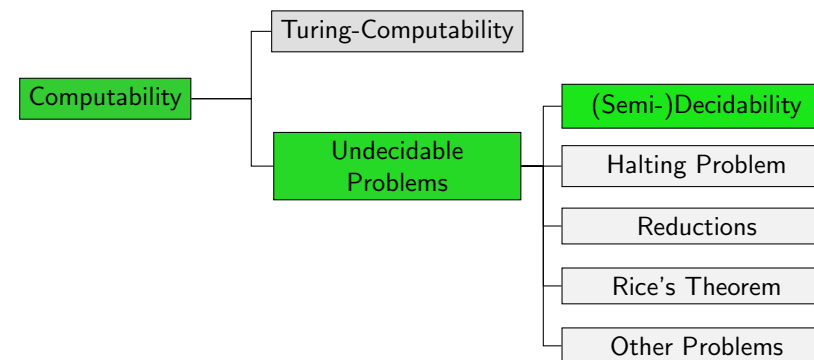
D2.4 Semi-Decidability

D2.5 Decidability

Overview: Computability Theory



Overview: Computability Theory



D2.1 Introduction

Computable Functions

For a higher level of abstraction, we consider the Church-Turing thesis to be correct (we will further back this up in part F).

- ▶ Instead of saying Turing-computable, we just say **computable**.
- ▶ Instead of presenting TMs we use **pseudo-code**.
- ▶ Instead of only considering computable functions over words ($\Sigma^* \rightarrow_p \Sigma^*$) or numbers ($\mathbb{N}_0^k \rightarrow_p \mathbb{N}_0$), we permit **arbitrary domains and codomains** (e.g., $\Sigma^* \rightarrow_p \{0, 1\}$, $\mathbb{N}_0 \rightarrow \Sigma^*$), ignoring details of encoding.

Computability vs. Decidability

- ▶ last chapter: **computability** of **functions**
- ▶ now: analogous concept for **languages**

Why languages?

- ▶ Only yes/no questions (“Is $w \in L$?”) instead of general function computation (“What is $f(w)$?”) makes it **easier** to investigate questions.
- ▶ Results are **directly transferable** to the more general problem of computing arbitrary functions. (\rightsquigarrow “playing 20 questions”)

How do we proceed?

- ▶ We first get to know computable functions for encoding pairs of numbers as numbers (later used for dovetailing).
- ▶ Then we consider two new concepts
 - ▶ **recursive enumerability** and
 - ▶ **semi-decidability**
 and relate them to each other and earlier concepts.
- ▶ Afterwards, we require termination of algorithms \rightsquigarrow **decidability**

D2.2 Encoding/Decoding Functions

Encoding and Decoding: Binary Encode

Consider the function $encode : \mathbb{N}_0^2 \rightarrow \mathbb{N}_0$ with:

$$encode(x, y) := \binom{x + y + 1}{2} + x$$

- ▶ $encode$ is known as the **Cantor pairing function** (German: Cantorsche Paarungsfunktion)
- ▶ $encode$ is computable
- ▶ $encode$ is **bijective**

	$x = 0$	$x = 1$	$x = 2$	$x = 3$	$x = 4$
$y = 0$	0	2	5	9	14
$y = 1$	1	4	8	13	19
$y = 2$	3	7	12	18	25
$y = 3$	6	11	17	24	32
$y = 4$	10	16	23	31	40

Encoding and Decoding: Binary Decode

Consider the **inverse functions**

$decode_1 : \mathbb{N}_0 \rightarrow \mathbb{N}_0$ and $decode_2 : \mathbb{N}_0 \rightarrow \mathbb{N}_0$ of $encode$:

$$decode_1(encode(x, y)) = x$$

$$decode_2(encode(x, y)) = y$$

- ▶ $decode_1$ and $decode_2$ are computable

D2.3 Recursive Enumerability

Recursive Enumerability: Definition

Definition (Recursively Enumerable)

A language $L \subseteq \Sigma^*$ is called **recursively enumerable** if $L = \emptyset$ or if there is a total and computable function $f : \mathbb{N}_0 \rightarrow \Sigma^*$ such that

$$L = \{f(0), f(1), f(2) \dots\}.$$

We then say that f (recursively) **enumerates** L .

Note: f does not have to be injective!

German: rekursiv aufzählbar, f zählt L (rekursiv) auf
 \rightsquigarrow do not confuse with “abzählbar” (countable)

Recursive Enumerability: Examples (1)

- ▶ $\Sigma = \{a, b\}$, $f(x) = a^x$ enumerates $\{\varepsilon, a, aa, \dots\}$.
- ▶ $\Sigma = \{a, b, \dots, z\}$, $f(x) = \begin{cases} \text{hund} & \text{if } x \bmod 3 = 0 \\ \text{katze} & \text{if } x \bmod 3 = 1 \\ \text{superpapagei} & \text{if } x \bmod 3 = 2 \end{cases}$
 enumerates $\{\text{hund}, \text{katze}, \text{superpapagei}\}$.
- ▶ $\Sigma = \{0, \dots, 9\}$, $f(x) = \begin{cases} 2^x - 1 \text{ (as digits)} & \text{if } 2^x - 1 \text{ prime} \\ 3 & \text{otherwise} \end{cases}$
 enumerates Mersenne primes.

Recursive Enumerability: Examples (2)

For every alphabet Σ , the language Σ^* can be recursively enumerated with a function $f_{\Sigma^*} : \mathbb{N}_0 \rightarrow \Sigma^*$. (How?)

D2.4 Semi-Decidability

Semi-Decidability

Definition (Semi-Decidable)

A language $L \subseteq \Sigma^*$ is called **semi-decidable** if the following function $\chi'_L : \Sigma^* \rightarrow_p \{0, 1\}$ is computable.

Here, for all $w \in \Sigma^*$:

$$\chi'_L(w) = \begin{cases} 1 & \text{if } w \in L \\ \text{undefined} & \text{if } w \notin L \end{cases}$$

German: semi-entscheidbar

Type-0 Languages vs. Semi-Decidability

- ▶ Consider a DTM M that **accepts** a language L .
- ▶ On input w
 - ▶ M stops after a finite number of steps in an end state if $w \in L$.
 - ▶ For $w \notin L$, the computation does not terminate.
- ▶ We can easily create a DTM M' from M that **computes** χ'_L . (How?)
- ▶ Vice versa, given a DTM that **computes** χ'_L for some language L , we can derive a DTM that **accepts** L .

Theorem (Semi-Decidable = Type 0)

A language L is **of type 0** iff L is **semi-decidable**.

Recursive Enumerability and Semi-Decidability (1)

Theorem (Recursively Enumerable = Semi-Decidable)

A language L is **recursively enumerable** iff L is **semi-decidable**.

Proof.

Special case $L = \emptyset$ is not a problem. (Why?)

Thus, let $L \neq \emptyset$ be a language over the alphabet Σ .

(\Rightarrow): L is recursively enumerable.

Let f be a function that enumerates L .

Then this is a semi-decision procedure for L , given input w :

FOR $n := 0, 1, 2, 3, \dots$ DO

 IF $f(n) = w$ THEN

 RETURN 1

 END

DONE

...

Recursive Enumerability and Semi-Decidability (2)

Proof (continued).

(\Leftarrow): L is semi-decidable with semi-decision procedure M .

Choose $\tilde{w} \in L$ arbitrarily. (We have $L \neq \emptyset$.)

Define:

$$f(n) = \begin{cases} f_{\Sigma^*}(x) & \text{if } n \text{ is the encoding of pair } \langle x, y \rangle \\ & \text{and } M \text{ executed on } f_{\Sigma^*}(x) \text{ stops in } y \text{ steps} \\ \tilde{w} & \text{otherwise} \end{cases}$$

f is **total** and **computable** and has **codomain** L .

Therefore f enumerates L . □

f uses idea of **dovetailing**: interleaving unboundedly many computations by starting new computations dynamically forever

Characterizations of Semi-Decidability

Theorem

Let L be a language. The following statements are equivalent:

- ① L is semi-decidable.
- ② L is recursively enumerable.
- ③ L is of type 0.
- ④ $L = \mathcal{L}(M)$ for some Turing machine M
- ⑤ χ'_L is (Turing-) computable.
- ⑥ L is the domain of a computable function.
- ⑦ L is the codomain of a computable function.

Characterizations of Semi-Decidability: Proof (1)

Proof.

- (1) \Leftrightarrow (5): definition of semi-decidability
 (1) \Leftrightarrow (2): earlier theorem in this chapter
 (4) \Leftrightarrow (5): earlier theorem in this chapter
 (3) \Leftrightarrow (4): from Chapter C8
 (5) \Rightarrow (6): χ'_L is computable with domain L
 (6) \Rightarrow (5): to compute χ'_L , compute a function with domain L , then return 1
 (2) \Rightarrow (7): use a function enumerating L (special case $L = \emptyset$) ...

Characterizations of Semi-Decidability: Proof (2)

Proof (continued).

(7) \Rightarrow (2): If $L = \emptyset$, obvious.

Otherwise, choose $\tilde{w} \in L$ arbitrarily, and let M be an algorithm computing $g : \Sigma^* \rightarrow_p \Sigma^*$ with codomain L .

To compute a function f enumerating L , use the same dovetailing idea as in our earlier proof:

$$f(n) = \begin{cases} g(f_{\Sigma^*}(x)) & \text{if } n \text{ is the encoding of pair } \langle x, y \rangle \\ & \text{and } M \text{ executed on } f_{\Sigma^*}(x) \text{ stops in } y \text{ steps} \\ \tilde{w} & \text{otherwise} \end{cases}$$

□

D2.5 Decidability

Semi-Decidability

Definition (Semi-Decidable)

A language $L \subseteq \Sigma^*$ is called **semi-decidable** if $\chi'_L : \Sigma^* \rightarrow_p \{0, 1\}$ is computable.

Here, for all $w \in \Sigma^*$:

$$\chi'_L(w) = \begin{cases} 1 & \text{if } w \in L \\ \text{undefined} & \text{if } w \notin L \end{cases}$$

For $w \notin L$, the computation does not (have to) terminate.

Decidability

Definition (Decidable)

A language $L \subseteq \Sigma^*$ is called **decidable** if $\chi_L : \Sigma^* \rightarrow \{0, 1\}$, the **characteristic function of L** , is computable.

Here, for all $w \in \Sigma^*$:

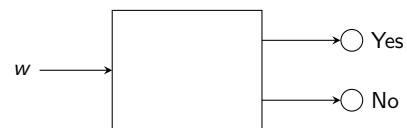
$$\chi_L(w) := \begin{cases} 1 & \text{if } w \in L \\ 0 & \text{if } w \notin L \end{cases}$$

German: entscheidbar, charakteristische Funktion

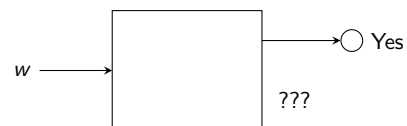
Decidability and Semi-Decidability: Intuition

Are these two definitions meaningfully different? Yes!

decidability:



semi-decidability:



Example: Diophantine equations

Connection Decidability/Semi-Decidability (1)

Theorem (Decidable vs. Semi-Decidable)

A language L is decidable iff both L and \bar{L} are semi-decidable.

Proof.

(\Rightarrow) : obvious (Why?)

...

Connection Decidability/Semi-Decidability (2)

Proof (continued).

(\Leftarrow): Let M_L be a semi-deciding algorithm for L , and let $M_{\bar{L}}$ be a semi-deciding algorithm for \bar{L} .

The following algorithm then is a decision procedure for L , i.e., computes $\chi_L(w)$ for a given input word w :

```

FOR  $s := 1, 2, 3, \dots$  DO
  IF  $M_L$  stops on  $w$  in  $s$  steps with output 1 THEN
    RETURN 1
  END
  IF  $M_{\bar{L}}$  stops on  $w$  in  $s$  steps with output 1 THEN
    RETURN 0
  END
DONE

```

□

Example: Decidable \neq Known Algorithm

Computability of χ_L does not mean we know **how** to compute it:

- ▶ $L = \{n \in \mathbb{N} \mid \text{there are } n \text{ consecutive 7s in the decimal representation of } \pi\}$.
- ▶ L is decidable.
- ▶ There are either 7-sequences of arbitrary length in π (case 1) or there is a maximal number n_0 of consecutive 7s (case 2).
 - ▶ Case 1: $\chi_L(n) = 1$ for all n
 - ▶ Case 2: $\chi_L(n) = 1$ if $n \leq n_0$, otherwise it is 0
- ▶ In both cases, the functions are computable.
- ▶ We just do not know what is the correct function.

Summary

- ▶ **decidability** of **problems** (= languages) corresponds to **computability** of “yes/no” functions
- ▶ **semi-decidability**:
 - ▶ recognizing “yes” instances in finite time
 - ▶ no answer for “no” instances
- ▶ **decidability** of $L =$ **semi-decidability** of L and \bar{L}
- ▶ semi-decidability = **recursive enumerability**
- ▶ relationship to type-0 languages