

Formal Methods in Software Engineering

Theory of Computation — Spring 2025

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§1 Computability

Computable Functions

Definition 1 (Church–Turing thesis): *Computable functions* are exactly the functions that can be calculated using a mechanical (that is, automatic) calculation device given unlimited amounts of time and storage space.

“Every model of computation that has ever been imagined can compute only computable functions, and all computable functions can be computed by any of several models of computation that are apparently very different, such as Turing machines, register machines, lambda calculus and general recursive functions.”

Definition 2 (Computable function): A partial function $f : \mathbb{N}^k \hookrightarrow \mathbb{N}$ is *computable* (“can be calculated”) if there exists a computer program with the following properties:

- If $f(x)$ is defined, then the program terminates on the input x with the value $f(x)$ stored in memory.
- If $f(x)$ is undefined, then the program never terminates on the input x .

Effective Procedures

Definition 3 (Effective procedure): An *effective procedure* is a finite, deterministic, mechanical algorithm that guarantees to terminate and produce the correct answer in a finite number of steps.

An algorithm (set of instructions) is called an *effective procedure* if it:

- Consists of *exact*, finite steps.
- Always *terminates* in finite time.
- Produces the *correct* answer for given inputs.
- Requires no external assistance to execute.
- Can be performed *manually*, with pencil and paper.

Definition 4: A function is *computable* if there exists an effective procedure that computes it.

Examples of Computable Functions

Examples:

- The function $f(x) = x^2$ is computable.
- The function $f(x) = x!$ is computable.
- The function $f(n) = \text{"}n\text{-th prime number"}$ is computable.
- The function $f(n) = \text{"the } n\text{-th digit of } \pi \text{"}$ is computable.
- The Ackermann function is computable.
- The function that answers the question "Does God exist?" is computable.
- If the Collatz conjecture is true, the stopping time (number of steps to reach 1) of any n is computable.

§2 Decidability

Decidable Sets

Definition 5 (Decidable set): Given a universal set \mathcal{U} , a set $S \subseteq \mathcal{U}$ is *decidable* (or *computable*, or *recursive*) if there exists a computable function $f : \mathcal{U} \rightarrow \{0, 1\}$ such that $f(x) = 1$ iff $x \in S$.

Examples:

- The set of all WFFs is decidable.
 - ▶ *We can check if a given string is well-formed by recursively verifying the syntax rules.*
- For a given finite set Γ of WFFs, the set $\{\alpha \mid \Gamma \models \alpha\}$ of all tautological consequences of Γ is decidable.
 - ▶ *We can decide $\Gamma \models \alpha$ using a truth table algorithm by enumerating all possible interpretations (at most $2^{|\Gamma|}$) and checking if each satisfies all formulas in Γ .*
- The set of all tautologies is decidable.
 - ▶ *It is the set of all tautological consequences of the empty set.*

Undecidable Sets

Definition 6 (Undecidable set): A set S is *undecidable* if it is not decidable.

Example: The existence of *undecidable* sets of expressions can be shown as follows.

An algorithm is completely determined by its *finite* description. Thus, there are only *countably many* effective procedures. But there are uncountably many sets of expressions. (Why? The set of expressions is countably infinite. Therefore, its power set is uncountable.) Hence, there are *more* sets of expressions than there are possible effective procedures.

§3 Undecidability

Halting Problem

Definition 7 (Halting problem \boxtimes): The *halting problem* is the problem of determining, given a program and an input, whether the program will eventually halt when run with that input.

Theorem 1 (Turing): The halting problem is undecidable.

Proof sketch: Suppose there exists a procedure H that decides the halting problem. We can construct a program P that takes itself as input and runs H on it. If H says that P halts, then P enters an infinite loop. If H says that P does not halt, then P halts. This leads to a contradiction, proving that H cannot exist. \square

Halting Problem [2]

```
def halts(P, x) -> bool:
    """
    Returns True if program P halts on input x.
    Returns False if P loops forever.
    """

def self_halts(P):
    if halts(P, P):
        while True: # loop forever
    else:
        return # halt
```

Observe that `halts(self_halts, self_halts)` cannot return neither `True` nor `False`. **Contradiction!**

Thus, the halts *does not exist* (cannot be implemented), and thus the halting problem is *undecidable*.

§4 Semi-decidability

Semi-decidability

Suppose we want to determine $\Sigma \models \alpha$ where Σ is infinite. In general, it is undecidable.

However, it is possible to obtain a weaker result.

Definition 8 (Semi-decidable set): A set S is *computably enumerable* if there is an *enumeration procedure* which lists, in some order, every member of S : $s_1, s_2, s_3 \dots$

Equivalently (see [Theorem 2](#)), a set S is *semi-decidable* if there is an algorithm such that the set of inputs for which the algorithm halts is exactly S .

Note that if S is infinite, the enumeration procedure will *never* finish, but every member of S will be listed *eventually*, after some finite amount of time.

Some properties:

- Decidable sets are closed under union, intersection, Cartesian product, and complement.
- Semi-decidable sets are closed under union, intersection, and Cartesian product.

Enumerability and Semi-decidability

Theorem 2: A set S is computably enumerable iff it is semi-decidable.

Proof (\Rightarrow): If S is computably enumerable, then it is semi-decidable.

Since S is computably enumerable, we can check if $\alpha \in S$ by enumerating all members of S and checking if α is among them. If it is, we answer “yes”; otherwise, we continue enumerating. Thus, if $\alpha \in S$, the procedure produces “yes”. If $\alpha \notin S$, the procedure runs forever. □

Enumerability and Semi-decidability [2]

Proof (\Leftarrow): If S is semi-decidable, then it is computably enumerable.

Suppose we have a procedure P which, given α , terminates and produces “yes” iff $\alpha \in S$. To show that S is computably enumerable, we can proceed as follows.

1. Construct a systematic enumeration of *all* expressions (for example, by listing all strings over the alphabet in length-lexicographical order): $\beta_1, \beta_2, \beta_3, \dots$
2. Break the procedure P into a finite number of “steps” (for example, by program instructions).
3. Run the procedure on each expression in turn, for an increasing number of steps (see dovetailing):
 - Run P on β_1 for 1 step.
 - Run P on β_1 for 2 steps, then on β_2 for 2 steps.
 - ...
 - Run P on each of β_1, \dots, β_n for n steps each.
 - ...
4. If P produces “yes” for some β_i , output (yield) β_i and continue enumerating.

This procedure will eventually list all members of S , thus S is computably enumerable. □

Dual Enumerability and Decidability

Theorem 3: A set is decidable iff both it and its complement are semi-decidable.

Proof (\Rightarrow): If A is decidable, then both A and its complement \overline{A} are effectively enumerable.

Since A is decidable, there exists an effective procedure P that halts on all inputs and returns “yes” if $\alpha \in A$ and “no” otherwise.

To enumerate A :

- Systematically generate all expressions $\alpha_1, \alpha_2, \alpha_3, \dots$
- For each α_i , run P . If P outputs “yes”, yield α_i . Otherwise, continue.

Similarly, enumerate \overline{A} by yielding α_i when P outputs “no”.

Both enumerations are effective, since P always halts, so A and its complement are semi-decidable. \square

Dual Enumerability and Decidability [2]

Proof (\Leftarrow): If both A and its complement \overline{A} are effectively enumerable, then A is decidable.

Let E be an enumerator for A and \overline{E} an enumerator for \overline{A} .

To decide if $\alpha \in A$, *interleave* the execution of E and \overline{E} , that is, for $n = 1, 2, 3, \dots$

- Run E for n steps and if it produces α , *halt* and output “yes”.
- Run \overline{E} for n steps and if it produces α , *halt* and output “no”.

Since α is either in A or in \overline{A} , one of the enumerators will eventually produce α . The interleaving with increasing number of steps ensures fair scheduling without starvation.

Remark: The “dovetailing” technique (alternating between enumerators with increasing step) avoids infinite waiting while maintaining finite memory requirements. The alternative is to run both enumerators *simultaneously*, in parallel, using, for example, two computers. □

Enumerability of Tautological Consequences

Theorem 4: If Σ is an effectively enumerable set of WFFs, then the set $\{\alpha \mid \Sigma \models \alpha\}$ of tautological consequences of Σ is effectively enumerable.

Proof: Consider an enumeration of the elements of Σ : $\sigma_1, \sigma_2, \sigma_3, \dots$

By the compactness theorem, $\Sigma \models \alpha$ iff $\{\sigma_1, \dots, \sigma_n\} \models \alpha$ for some n .

Hence, it is sufficient to successively test (using truth tables)

$$\emptyset \models \alpha,$$

$$\{\sigma_1\} \models \alpha,$$

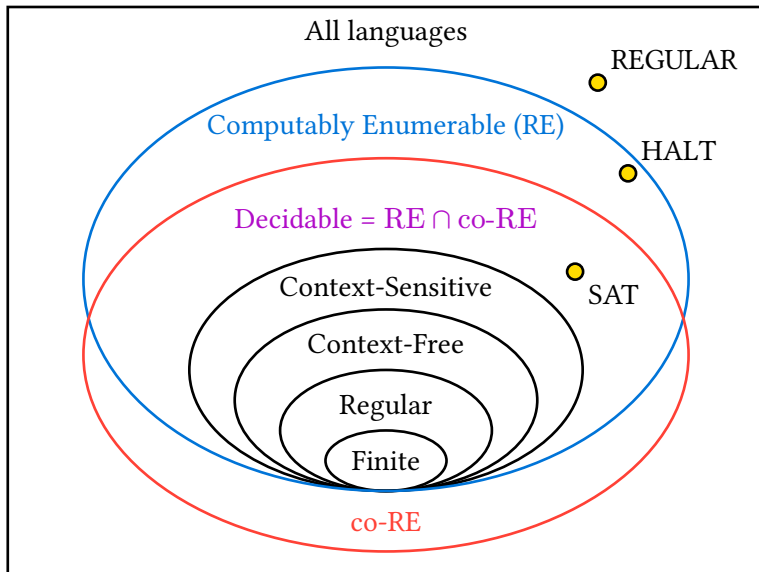
$$\{\sigma_1, \sigma_2\} \models \alpha,$$

and so on. If any of these tests succeeds (each is decidable), then $\Sigma \models \alpha$.

This demonstrates that there is an effective procedure that, given any WFF α , will output “yes” iff α is a tautological consequence of Σ . Thus, the set of tautological consequences of Σ is effectively enumerable. \square

§5 Languages

Language Classes



Language Classes [2]

$$P \subseteq NP \subseteq R \subseteq RE$$

- RE
contains languages which are *accepted* by any TM
- $R = RE \cap \text{co-RE}$
contains all languages which are *decided* by any TM
- NP
contains all languages which are *accepted* by any *polynomial-time* TM
- P
contains all languages which are *decided* by any *polynomial-time* and *deterministic* TM

§6 Complexity Zoo

Complexity Classes

TODO

See also: https://complexityzoo.net/Petting_Zoo

TODO

- ☒ Computability
- ☒ Decidability
- ☒ Undecidable sets
- ☒ Semi-decidability
- ☐ Decidable language outside of NP
- ☐ Diagram of language classes (Finite, Regular, Context-Free, Recursive (Decidable), CE(RE), co-CE)
- ☐ Complexity classes
- ☐ NP-completeness
- ☐ Polytime reductions