

Theory of Computer Science

B11. Type-1 and Type-0 Languages: Closure & Decidability

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April 12, 2021

Turing Machines vs. Grammars

Turing Machines

We have seen several variants of Turing machines:

- Deterministic TM with head movements left or right
- Deterministic TM with head movements left, right or neutral
- Multitape Turing machines
- Nondeterministic Turing machines

All variants recognize the same languages.

Turing Machines

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All variants recognize the same languages.

We mentioned earlier that we can relate Turing machines to the Type-1 and Type-0 languages.

Reminder: Context-sensitive Grammar

Type-1 languages are also called **context-sensitive** languages.

Definition (Context-sensitive Grammar)

A **context-sensitive grammar** is a 4-tuple $\langle V, \Sigma, R, S \rangle$ with

- V finite set of variables (nonterminal symbols)
- Σ finite alphabet of terminal symbols with $V \cap \Sigma = \emptyset$
- $R \subseteq (V \cup \Sigma)^* V (V \cup \Sigma)^* \times (V \cup \Sigma)^* \times (V \cup \Sigma)^*$ finite set of rules, where all rules are of the form $\alpha B \gamma \rightarrow \alpha \beta \gamma$ with $B \in V$ and $\alpha, \gamma \in (V \cup \Sigma)^*$ and $\beta \in (V \cup \Sigma)^+$.
Exception: $S \rightarrow \varepsilon$ is allowed if S never occurs on the right-hand side of a rule.
- $S \in V$ start variable.

One Automata Model for Two Grammar Types?

Don't we need
different automata models for
context-sensitive and Type-0
languages?



Linear Bounded Automata: Idea

- **Linear bounded automata** are NTMs that may only use the **part of the tape occupied by the input word**.
- one way of formalizing this: NTMs where blank symbol may never be replaced by a different symbol

Linear Bounded Turing Machines: Definition

Definition (Linear Bounded Automata)

An NTM $M = \langle Q, \Sigma, \Gamma, \delta, q_0, q_{\text{accept}}, q_{\text{reject}} \rangle$
is called a **linear bounded automaton (LBA)**
if for all $q \in Q \setminus \{q_{\text{accept}}, q_{\text{reject}}\}$ and all transition rules
 $\langle q', c, y \rangle \in \delta(q, \square)$ we have $c = \square$.

German: linear beschränkte Turingmaschine

LBAs Recognize Type-1 Languages

Theorem

The languages that can be recognized by linear bounded automata are exactly the context-sensitive (type-1) languages.

Without proof.

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Without proof.

proof sketch for grammar \Rightarrow NTM direction:

- computation of the NTM follows the production of the word in the grammar **in opposite order**
- accept when only the start symbol (and blanks) are left on the tape
- because the language is context-sensitive, we never need additional space on the tape (empty word needs special treatment)

NTMs Recognize Type-0 Languages

Theorem

The languages that can be recognized by nondeterministic Turing machines are exactly the type-0 languages.

Without proof.

NTMs Recognize Type-0 Languages

Theorem

The languages that can be recognized by nondeterministic Turing machines are exactly the type-0 languages.

Without proof.

proof sketch for grammar \Rightarrow NTM direction:

- analogous to previous proof
- for grammar rules $w_1 \rightarrow w_2$ with $|w_1| > |w_2|$, we must “insert” symbols into the existing tape content; this is a bit tedious, but not very difficult

What about the Deterministic Variants?

We know that DTMs and NTMs recognize the same languages.
Hence:

Corollary

*The **Turing-recognizable** languages are exactly the **Type-0** languages.*

What about the Deterministic Variants?

We know that DTM_s and NTM_s recognize the same languages.
Hence:

Corollary

*The **Turing-recognizable** languages are exactly the **Type-0** languages.*

Note: It is an open problem whether **deterministic** LBAs can recognize exactly the type-1 languages.

Questions



Closure Properties and Decidability

Closure Properties

	Intersection	Union	Complement	Concatenation	Star
Type 3	Yes	Yes	Yes	Yes	Yes
Type 2	No	Yes	No	Yes	Yes
Type 1	Yes ⁽²⁾	Yes ⁽¹⁾	Yes ⁽²⁾	Yes ⁽¹⁾	Yes ⁽¹⁾
Type 0	Yes ⁽²⁾	Yes ⁽¹⁾	No ⁽³⁾	Yes ⁽¹⁾	Yes ⁽¹⁾

Proofs?

- (1) proof via grammars, similar to context-free cases
- (2) without proof
- (3) proof in later chapters (part C)

Decidability

	Word problem	Emptiness problem	Equivalence problem	Intersection problem
Type 3	Yes	Yes	Yes	Yes
Type 2	Yes	Yes	No	No
Type 1	Yes ⁽¹⁾	No ⁽³⁾	No ⁽²⁾	No ⁽²⁾
Type 0	No ⁽⁴⁾	No ⁽⁴⁾	No ⁽⁴⁾	No ⁽⁴⁾

Proofs?

- (1) same argument we used for context-free languages
- (2) because already undecidable for context-free languages
- (3) without proof
- (4) proofs in later chapters (part C)

Questions



Summary

Summary

- Turing machines recognize exactly the **type-0** languages.
- Linear bounded automata recognize exactly the **context-sensitive** languages.
- The context-sensitive and type-0 languages are **closed** under **almost all** usual operations.
 - exception: type-0 not closed under **complement**
- For context-sensitive and type-0 languages **almost no problem is decidable**.
 - exception: word problem for **context-sensitive** lang. decidable

What's Next?

contents of this course:

- A. **background** ✓
 - ▷ mathematical foundations and proof techniques
- B. **automata theory and formal languages** ✓
 - ▷ What is a computation?
- C. **Turing computability**
 - ▷ What can be computed at all?
- D. **complexity theory**
 - ▷ What can be computed efficiently?
- E. **more computability theory**
 - ▷ Other models of computability