CS 121 Section 8

Harvard University

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Overview

This week we will focus on reviewing the core concepts involved with undecidability, reducibility, Rice's theorem, incompleteness of mathematics, and so on.

1 Concept Review

1.1 Undecidability

By a cardinality argument, we know that almost all languages are undecidable. This argument, however, does not give us an explicit construction. The following theorem does just that.

Theorem 1.1. *The language $\{\langle M, w\rangle : M$ accepts the input $w\}$ is not decidable.*

Proof. Assume $\{\langle M, w\rangle : M$ accepts the input $w\}$ is decidable, then the language $D = \{\langle M\rangle : M$ accepts $\langle M\rangle\}$ is decidable, hence $\overline{D} = \{\langle M\rangle : M$ does not accepts $\langle M\rangle\}$ is decidable. Suppose $\overline{D}$ is decidable by M_1, then $\langle M_1\rangle \in \overline{D}$ iff M_1 accepts $\langle M_1\rangle$ iff $\langle M_1\rangle \in D$, which is a contradiction. (This is the standard diagonalization argument.) □

1.2 Reducibility

Definition 1.1. *A function $f : \Sigma_1^* \to \Sigma_2^*$ is computable if there is a Turing machine such that for every input $w \in \Sigma_1^*$, M halts with just $f(w)$ on its tape.*

Definition 1.2. *A reduction of $L_1 \subseteq \Sigma_1^*$ to $L_2 \subseteq \Sigma_2^*$ is a computable function $f : \Sigma_1^* \to \Sigma_2^*$ such that, for any $w \in \Sigma^*$, $w \in L_1$ if and only if $f(w) \in L_2$, and we write $L_1 \leq_m L_2$.*

Intuitively, L_1 reduces to L_2 means that L_1 is not harder than L_2. More formally, we can express this intution in the following lemma.

Lemma 1.1. *If $L_1 \leq_m L_2$ and L_1 is undecidable, then so it L_2.*

1.3 Rice's theorem

Theorem 1.2 (Rice's theorem)**.** *Let $\mathcal{P}$ be any subset of the class of r.e. languages such that $\mathcal{P}$ and its complement are both nonempty. Then the language $L_{\mathcal{P}} = \{\langle M\rangle : L(M) \in \mathcal{P}\}$ is undecidable.*

Intuitively, Rice's theorem states that Turing machines can not test whether another Turing machine satisfies a (nontrivial) property. For example, let $\mathcal{P}$ be the subset of the recursively enumerable languages which contains the string a. Then Rice's theorem claims that there is no Turing machine which can decide whether a Turing machine accepts a.

2 Exercises

Exercise 2.1. *Reductions can be tricky to get the hang of, and you want to avoid "going the wrong way" with them. In which of these scenarios does $L_1 \leq_m L_2$ provide useful information (and in those cases, what may we conclude)?*

(a) L_1's decidability is unknown and L_2 is undecidable

(b) L_1's decidability is unknown and L_2 is decidable

(c) L_1 is undecidable and L_2's decidability is unknown

(d) L_1 is decidable and L_2's decidability is unknown

Exercise 2.2. *Argue that $\leq_m$ is a transitive relation.*

Exercise 2.3. *Determine, with proof, whether the following languages are decidable.*

(a) $L = \{\langle M, x\rangle :$ At some point it its computation on x, M re-enters its start state$\}$

(b) $L = \{\langle x, y\rangle : f(x) = y\}$ where f is a fixed computable function.

(c) $\mathrm{CF}_{TM} = \{\langle M\rangle : L(M)$ is context-free$\}$

Exercise 2.4. *Show $\{G : G$ is a CFG generating $x\} \leq_M \{G : G$ is a CFG generating $xy\}$.*