COL 352 Introduction to Automata and Theory of Computation

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February 20, 2023

Lecture 13: Myhill-Nerode Theorem

Recap

Define a relation $\equiv$ on the set of states:

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$$p \equiv q \iff \forall x \in \Sigma^* (\hat{\delta}(p, x) \in F \iff \hat{\delta}(q, x) \in F)$$

$\equiv$ is an equivalence relation.

$$[p] := \{q \mid q \equiv p\} \quad \text{Equivalence classes}$$

Every element $p \in Q$ is contained in exactly one equivalence class $[p]$.

$$p \equiv q \iff [p] = [q]$$

An algorithm for DFA minimization

Let M be a DFA with no inaccessible states. We will mark (unordered) pairs of states $\{p, q\}$ if we discover a reason why they are not equivalent.

1. Write down a table of pairs $\{p, q\}$, initially unmarked.
2. Mark $\{p, q\}$ if $p \in F$ and $q \notin F$, or vice-versa.
3. Repeat until no change occurs: if there exists an unmarked pair $\{p, q\}$ such that $\{\delta(p, a), \delta(q, a)\}$ is marked for some $a \in \Sigma$ then mark $\{p, q\}$.
4. When done, $p \equiv q$ iff $\{p, q\}$ is not marked.

Minimization problem

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2. For each $1 \leq i < j \leq n$

   If $(q_i \in F$ AND $q_j \notin F)$ OR $(q_i \in F$ AND $q_j \notin F)$
   $T(i, j) \leftarrow \checkmark$
3. Repeat

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   $\{$ For each $1 \leq i < j \leq n$
   If $\exists a \in \Sigma, T(\delta(q_i, a), \delta(q_j, a)) = \checkmark$
   then $T(i,j) \leftarrow \checkmark$
   $\}$

Untill T stays unchanged.

Proof of Correctness

Claim: The pair $\{p, q\}$ is not marked by the algorithm if and only if there exists $x \in \Sigma^*$ such that $\hat{\delta}(p, x) \in F$ and $\hat{\delta}(q, x) \notin F$ or vice-versa, i.e., if and only if $p \not\equiv q$.

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$$\Delta(\{p,q\},a) := \{\{p',q'\} \mid p = \delta(p',a), q = \delta(q',a)\}$$

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Question: Is the resulting automaton minimal?

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- By pigeonhole principle, there are states q_1 and q_2 of A such that they are equivalent to the same state of A'.
- Therefore, q_1 and q_2 are equivalent. But A is minimized, and no two states of A are equivalent in a minimized DFA. Contradiction!

A relation with some strange properties

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Let $R \subseteq \Sigma^*$ be a regular language and $M = (Q, \Sigma, \delta, s, F)$ be a DFA for R. Consider the relation $\equiv_M$:

$$x \equiv_M y \iff \hat{\delta}(s, x) = \hat{\delta}(s, y)$$

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Exercise: $\equiv_M$ is an equivalence relation. Note: This is different from last class! Relation $\equiv$ on the set of states:

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- **Right Congruence:** For any $x, y \in \Sigma^*$ and $a \in \Sigma$

$$x \equiv_M y \implies xa \equiv_M ya$$

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Assume $x \equiv_M y$. Then

$$\begin{aligned} \hat{\delta}(s, xa) &= \delta(\hat{\delta}(s, x), a) \\ &= \delta(\hat{\delta}(s, y), a) \qquad \text{(by assumption)} \\ &= \hat{\delta}(s, ya) \end{aligned}$$

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$$x \equiv_M y \implies (x \in R \iff y \in R)$$

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- **Finite index:** There are only finitely many equivalence classes on Σ^* under $\equiv_M$ (There is at exactly one equivalence corresponding to each state of M).

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Definition

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- Given $\equiv_M$, one can reconstruct M just using the fact that it is Myhill-Nerode. In fact,

$$
\begin{aligned}
M &\rightarrow \equiv_M \\
\equiv_M &\rightarrow M
\end{aligned}
$$

are both inverses upto isomorphism of the automata.

Myhill-Nerode theorem

Theorem (John Myhill, Anil Nerode (1958)

L is regular if and only if there exists a Myhill-Nerode relation for L.

Proof

- Suppose $\equiv$ is a Myhill-Nerode relation on Σ^*.

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  - $F = \{[x] \mid x \in L\}$
- Proof of correctness: By induction.

$\square$

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In general, $a^{p+i(q-p)]} \in L$ for every i.

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Exercise: Work out the Myhill-Nerode proof for PAL.

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Theorem

Given L, the DFA constructed from L using the Myhill-Nerode consruction has the minimum number of states possible.

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