

CS 228 : Logic in Computer Science

Krishna. S

Recap

- ▶ $DFA = NFA = \epsilon\text{-NFA} = \text{regular languages}$
- ▶ Closure properties of regular languages

Agenda

- ▶ FO-definable \Rightarrow regular
- ▶ Given an FO formula φ , construct a DFA A_φ such that $L(\varphi) = L(A_\varphi)$
- ▶ If $L(A_\varphi) = \emptyset$, then φ is unsatisfiable
- ▶ If $L(A_\varphi) \neq \emptyset$, then φ is satisfiable

FO to Regular Languages

- ▶ Every FO sentence φ over words can be converted into a DFA A_φ such that $L(\varphi) = L(A_\varphi)$.
- ▶ Start with atomic formulae, construct DFA for each of them.
- ▶ Conjunctions, disjunctions, negation of formulae easily handled via union, intersection and complementation of of respective DFA
- ▶ Handling quantifiers?

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- ▶ Think of this as $\begin{array}{c} baab \\ 0010 \end{array}$ or $\begin{array}{c} baab \\ 0100 \end{array}$

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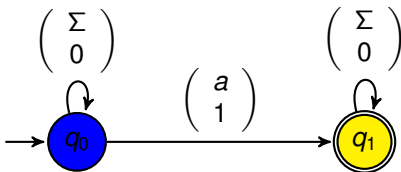
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- ▶ Think of an extended alphabet $\Sigma' = \Sigma \times \{0, 1\}$, and construct an automaton over Σ' .
- ▶ Deterministic, not complete.



Atomic Formulae to DFA : $S(x, y)$

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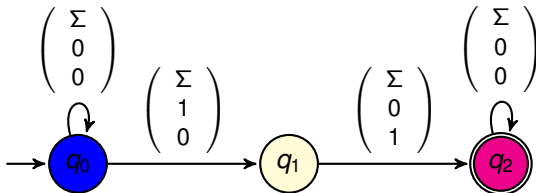
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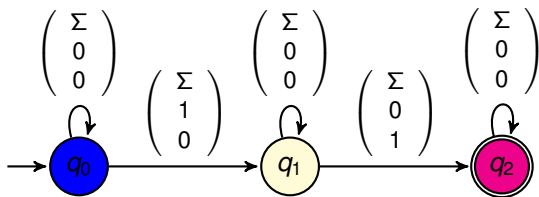
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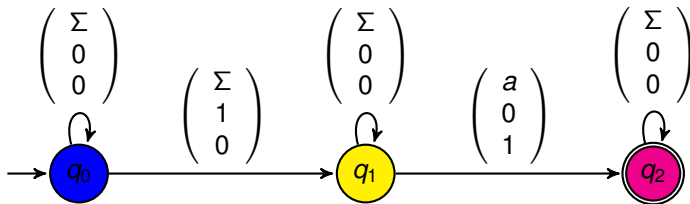
Atomic Formulae to DFA : $x < y$

- ▶ bab satisfies $x < y$ with assignment $x = 0$ or $y = 1$ or $x = 1, y = 2$ or $x = 0, y = 2$.



Simple Formulae to DFA

- ▶ $x < y \wedge Q_a(y)$
- ▶ $\Sigma' = \Sigma \times \{0, 1\} \times \{0, 1\}$
- ▶ Obtain intersection of DFA for $x < y$ and $Q_a(y)$



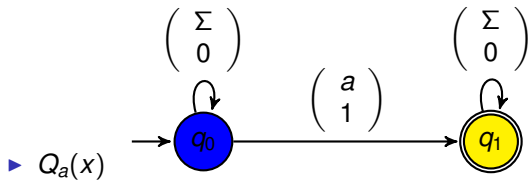
Formulae to DFA

- ▶ Given $\varphi(x_1, \dots, x_n)$, a FO formula over Σ , consider the extended alphabet

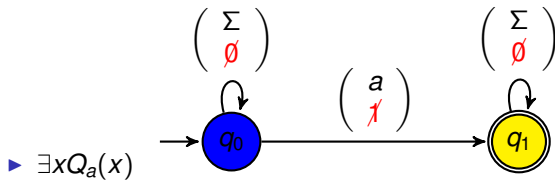
$$\Sigma' = \Sigma \times \{0, 1\}^n$$

- ▶ Assign values to x_i at every position as seen in the cases of atomic formulae
- ▶ Keep in mind that every x_i can be assigned 1 at a unique position

Quantifiers

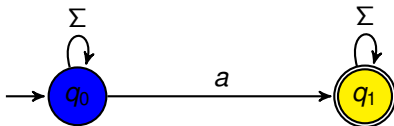


Handling Quantifiers



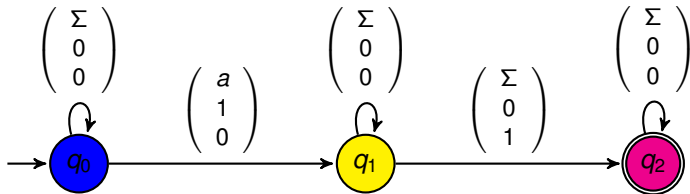
Handling Quantifiers

► $\exists x Q_a(x)$



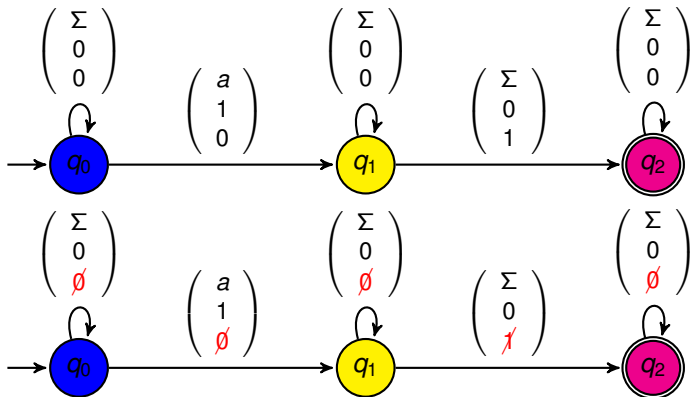
Handling Quantifiers

- $Q_a(x) \wedge \exists y(x < y)$



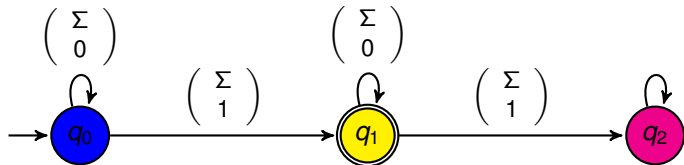
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Handling Quantifiers: $\forall x(x \neq x)$

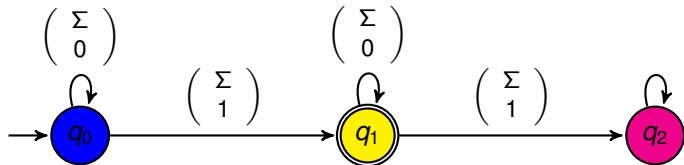
► $(x = x)$



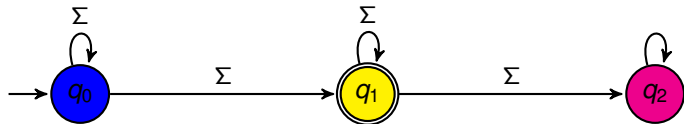
► $\exists x(x = x)$

Handling Quantifiers: $\forall x(x \neq x)$

- ▶ $(x = x)$



- ▶ $\exists x(x = x)$



- ▶ $\neg \exists x(x = x)$

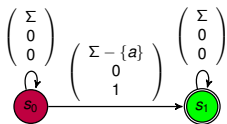
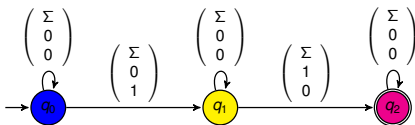
Handling Quantifiers : Summary

Quantifier Lemma

Let $L \subseteq (\Sigma \times \{0, 1\}^n)^*$ be defined by $\varphi(x_1, \dots, x_n)$. Let $f : (\Sigma \times \{0, 1\}^n)^* \rightarrow (\Sigma \times \{0, 1\}^{n-1})^*$ be the projection $f(a, c_1, \dots, c_n) = (a, c_1, \dots, c_{n-1})$. Then $\exists x_n \varphi(x_1, \dots, x_{n-1})$ defines $f(L)$.

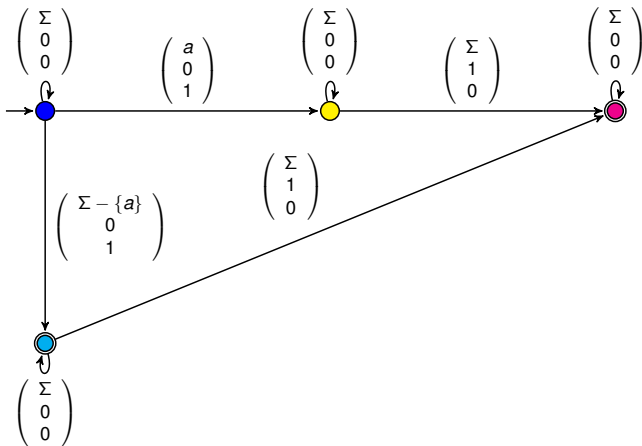
Handling Quantifiers

- ▶ $\exists y \forall x [x \leq y \wedge Q_a(y)] = \exists y [\neg \exists x [x > y \vee \neg Q_a(y)]]$
- ▶ $[x > y \vee \neg Q_a(y)]$



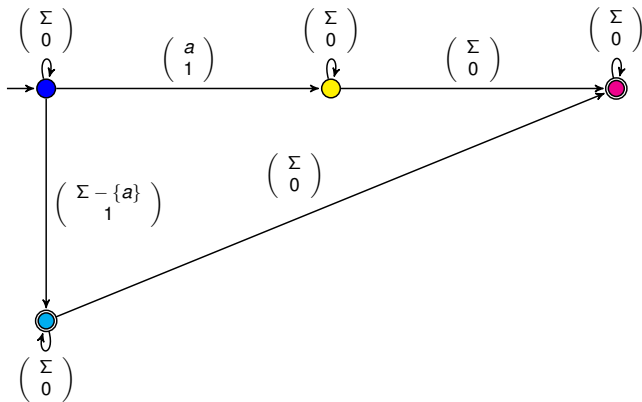
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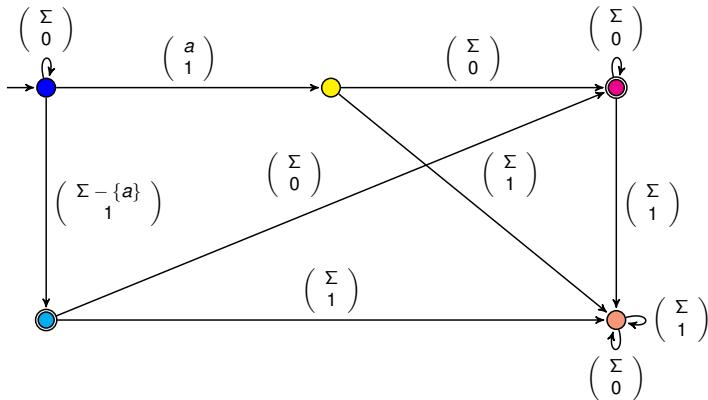
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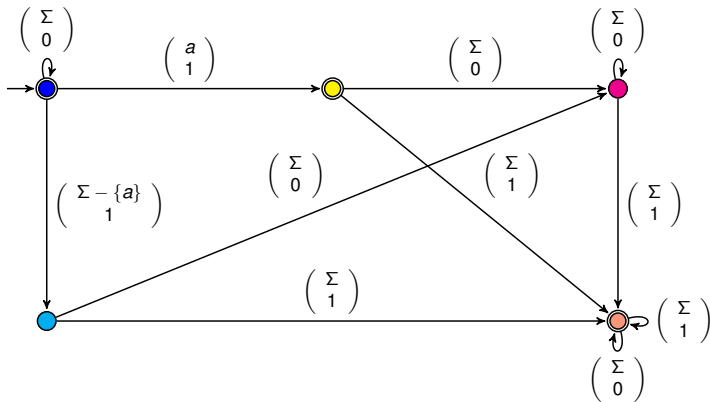
Handling Quantifiers

- ▶ $\neg \exists x[x > y \vee \neg Q_a(y)]$
- ▶ Deterministic Automaton corresponding to $\exists x[x > y \vee \neg Q_a(y)]$



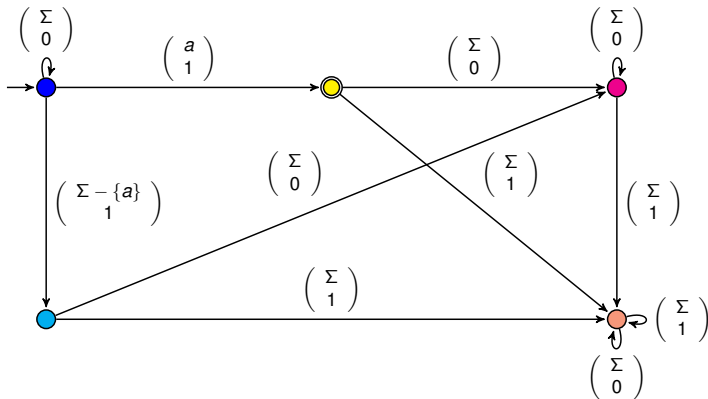
Handling Quantifiers

- Incorrect deterministic Automaton corresponding to $\neg \exists x [x > y \vee \neg Q_a(y)]$



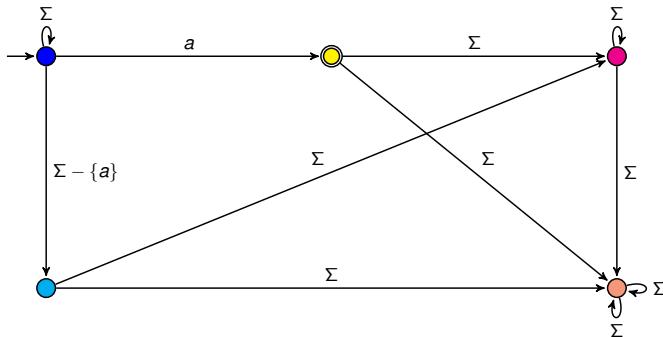
Handling Quantifiers

- ▶ $\neg \exists x [x > y \vee \neg Q_a(y)]$
- ▶ Deterministic Automaton corresponding to $\neg \exists x [x > y \vee \neg Q_a(y)]$
- ▶ Intersect with $\begin{pmatrix} \Sigma \\ 0 \end{pmatrix}^* \begin{pmatrix} \Sigma \\ 1 \end{pmatrix} \begin{pmatrix} \Sigma \\ 0 \end{pmatrix}^*$



Handling Quantifiers

► $\exists y \neg \exists x [x > y \vee \neg Q_a(y)] = \exists y \forall x [x \leq y \wedge Q_a(y)]$



Points to Remember

- ▶ Given $\varphi(x_1, \dots, x_n)$, construct automaton for atomic FO formulae over the extended alphabet $\Sigma \times \{0, 1\}^n$
- ▶ Intersect with the regular language where every x_i is assigned 1 exactly at one position
- ▶ Given a sentence $Q_{x_1} \dots Q_{x_n} \varphi$, first construct the automaton for the formula $\varphi(x_1, \dots, x_n)$
- ▶ Replace \forall in terms of \exists

Points to Remember

- ▶ Given the automaton for $\varphi(x_1, \dots, x_n)$, the automaton for $\exists x_i \varphi(x_1, \dots, x_n)$ is obtained by **projecting out** the row of x_i
- ▶ This may result in an NFA
- ▶ Determinize it and complement it to get a DFA for $\neg \exists x_i \varphi(x_1, \dots, x_{i-1}, x_{i+1}, \dots, x_n)$
- ▶ Intersect with the regular language where each of $x_1, \dots, x_{i-1}, x_{i+1}, \dots, x_n$ are assigned 1 exactly at one position

The Computational Effort

Given NFAs A_1, A_2 each with at most n states,

- ▶ The union has at most $2n + 1$ states
- ▶ Intersection has at most n^2 states
- ▶ The complement has at most 2^n states
- ▶ The projection has at most n states

The Computational Effort

- ▶ $\psi = Q_1 \dots Q_n \varphi$. If $Q_i = \exists$ for all i , then size of A_ψ is same the size of A_φ .
- ▶ When $Q_1 = \exists, Q_2 = \forall, \dots$: each \forall quantifier can create a 2^n blowup in automaton size
- ▶ Size of automaton is

$$2^{2^{2^{2^{2^n}}}}$$

where the tower height k is the quantifier alternation size.

- ▶ This number is indeed a lower bound!

$n + 1$ to 2^n

- ▶ $\Sigma = \{0, 1\}$, languages where the n th bit from the right is a 1.
- ▶ NFA has $n + 1$ states.
- ▶ Size of corresponding DFA?

The Automaton-Logic Connection

Given any FO sentence φ , one can construct a DFA A_φ such that $L(\varphi) = L(A_\varphi)$.