

Büchi's Logical Characterisation of Regular Languages

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Outline

- 1 First-Order Logic of $(\mathbb{N}, <)$
- 2 The logic $\text{MSO}(A)$
- 3 Proof of Büchi's theorem

Background

- Büchi's motivation: Decision procedure for deciding truth of first-order logic statements about natural numbers and their ordering. Eg.

$$\forall x \exists y (x < y).$$

- Used finite-state automata to give decision procedure.
- By-product: a logical characterisation of regular languages.

Theorem (Büchi 1960)

L is regular iff L can be described in Monadic-Second Order Logic.

First-Order logic of $(\mathbb{N}, <)$.

- Interpreted over $\mathbb{N} = \{0, 1, 2, 3, \dots\}$.
- What you can say:

$$x < y, \quad \exists x \varphi, \quad \forall x \varphi, \quad \neg, \wedge, \vee.$$

- Examples:
 - ① $\forall x \exists y (x < y)$.

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- Question: Is there an **algorithm** to decide if a given $\text{FO}(\mathbb{N}, <)$ sentence is true or not?

Monadic Second-Order logic over alphabet A : $\text{MSO}(A)$

- Interpreted over a string $w \in A^*$.

$$\begin{array}{cccccccc}
 w & = & a & a & b & a & b & a & b & a & b \\
 & & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8
 \end{array}$$

- Domain is set of positions in w : $\{0, 1, 2, \dots, |w| - 1\}$.
- “ $<$ ” is interpreted as usual $<$ over numbers.
- What we can say in the logic:
 - $Q_a(x)$: “Position x is labelled a ”.
 - $x < y$: “Position x is strictly less than position y ”.
 - $\exists x \varphi$: “There exists a position x ...”
 - $\forall x \varphi$: “For all positions x ...”
 - $\exists X \varphi$: “There exists a **set of positions** X ...”
 - $\forall X \varphi$: “For all **sets of positions** X ...”
 - $x \in X$: “Position x belongs to the set of positions X ”.

Example $\text{MSO}(\{a, b\})$ formulas

What language do the sentences below define?

- ① $\exists x(\neg \exists y(y < x) \wedge Q_a(x))$.
- ② $\exists y(\neg \exists x(y < x) \wedge Q_b(y))$.
- ③ $\exists x \exists y \exists z(\text{succ}(x, y) \wedge \text{succ}(y, z) \wedge \text{last}(z) \wedge (Q_b(x)))$.

Give sentences that describe the following languages:

- ① Every a is immediately followed by a b .
- ② Strings of odd length.

MSO sentence for strings of odd length

Language $L \subseteq \{a, b\}^*$ of strings of odd length.

	<i>a</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>
X_e	1	0	1	0	1	0	1	0	1
X_o	0	1	0	1	0	1	0	1	0

$$\begin{aligned} \exists X_e \exists X_o (&\exists x (x \in X_e) \wedge (\forall x ((x \in X_e \implies \neg x \in X_o) \wedge (x \in X_o \implies \neg x \in X_e)) \wedge \\ &(x \in X_e \vee x \in X_o) \wedge \\ &(\text{zero}(x) \implies x \in X_e) \wedge \\ &(\forall y ((x \in X_e \wedge \text{succ}(x, y)) \implies y \in X_o)) \wedge \\ &(\forall y ((x \in X_o \wedge \text{succ}(x, y)) \implies y \in X_e)) \wedge \\ &(\text{last}(x) \implies x \in X_e))). \end{aligned}$$

First-Order Logic

- A First-Order Logic usually has a **signature** comprising the constants, and function/relation symbols. Eg. $(0, <, +)$.
- **Terms** are expressions built out of the constants and variables and function symbols. Eg. $0, x + y, (x + y) + 0$. They are interpreted as elements of the domain of interpretation.
- **Atomic formulas** are obtained using the relation symbols on terms of the logic. Eg. $x < y, x = 0 + y, x + y < 0$.
- **Formulas** are obtained from atomic formulas using boolean operators, and existential quantification $(\exists x)$ and universal quantification $(\forall x)$. Eg. $\neg(x < y), (x < 0) \wedge (x = y), \exists x(\forall y(x < y) \wedge (z < x))$.

First-Order Logic

- Given a “structure” (i.e. a domain, a concrete interpretation for each constant and function/relation symbol) and an assignment for variables to values in the domain) to interpret the formulas in, each formula is either true or false.
- A formula is called a **sentence** if it has no free (unquantified) variables.

Second-Order Logic

- In **Second-Order** logic, one allows quantification over relations over the domain (not just elements of the domain). Eg:

$$\exists R^{(2)}(R^{(2)}(x, y) \implies x < y).$$

- In **Monadic** second-order logic, one allows quantification over monadic relations (i.e. relations of arity one, or subsets of the domain). Eg:

$$\exists X(x \in X \implies 0 < x).$$

Formal Semantics of MSO

- An interpretation for the logic will be a pair $(w, \mathbb{I})$ where $w \in \mathcal{A}^*$ and $\mathbb{I}$ is an assignment of individual variables to a position in w , and set variables to a set of positions of w .

$$\mathbb{I} : \text{Var} \rightarrow \text{pos}(w) \cup 2^{\text{pos}(w)}.$$

- $\mathbb{I}[i/x]$ denotes the assignment which maps x to i and agrees with $\mathbb{I}$ on all other individual and set variables.
- Similarly for $\mathbb{I}[S/X]$.

Formal Semantics of MSO

The satisfaction relation $w, \mathbb{I} \models \varphi$ is given by:

$w, \mathbb{I} \models Q_a(x)$	iff	$w(\mathbb{I}(x)) = a$
$w, \mathbb{I} \models x < y$	iff	$\mathbb{I}(x) < \mathbb{I}(y)$
$w, \mathbb{I} \models x \in X$	iff	$\mathbb{I}(x) \in \mathbb{I}(X)$
$w, \mathbb{I} \models \neg \varphi$	iff	$w, \mathbb{I} \not\models \varphi$
$w, \mathbb{I} \models \varphi \vee \varphi'$	iff	$w, \mathbb{I} \models \varphi$ or $w, \mathbb{I} \models \varphi'$
$w, \mathbb{I} \models \exists x \varphi$	iff	exists $i \in \text{pos}(w)$ s.t. $w, \mathbb{I}[i/x] \models \varphi$
$w, \mathbb{I} \models \exists X \varphi$	iff	exists $S \subseteq \text{pos}(w)$ s.t. $w, \mathbb{I}[S/X] \models \varphi$

MSO sentences

- A **sentence** is a formula with no free variables.
- For example $\exists X(y \in X \implies 0 < y)$ is not a sentence since y occurs free.
- $\exists X(0 \in X \implies \exists y(0 < y \wedge y \in X))$ is a sentence.
- If φ is a sentence, then we don't need an interpretation for variables to say if φ is true or false of a given word w :

$$w \models \varphi.$$

- For a sentence φ , we can define the language of words that satisfy φ :

$$L(\varphi) = \{w \in A^* \mid w \models \varphi\}.$$

Languages definable by MSO

- We say that a language $L \subseteq A^*$ is **definable** in $\text{MSO}(A)$ if there is a sentence φ in $\text{MSO}(A)$ such that $L(\varphi) = L$.

Theorem (Büchi 1960)

$L \subseteq A^$ is regular iff L is definable in $\text{MSO}(A)$.*

From automata to MSO sentence

- Let $L \subseteq A^*$ be regular. Let $\mathcal{A} = (Q, s, \delta, F)$ be a DFA for L .
- To show L is definable in $\text{MSO}(A)$.
- Idea: Construct a sentence $\varphi_{\mathcal{A}}$ describing an **accepting run** of $\mathcal{A}$ on a given word.

That is: $\varphi_{\mathcal{A}}$ is true over a given word w precisely when $\mathcal{A}$ has an accepting run on w .

Let $Q = \{q_1, \dots, q_n\}$, with $q_1 = s$.

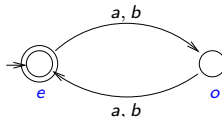
Define $\varphi_{\mathcal{A}}$ as

$$\begin{aligned} \exists X_1 \cdots \exists X_n (\forall x (& (\bigwedge_{i \neq j} (x \in X_i \implies \neg x \in X_j) \wedge \bigvee_i x \in X_i) \wedge \\ & (\text{zero}(x) \implies x \in X_1) \wedge \\ & (\bigwedge_{a \in A, i, j \in \{1, \dots, n\}, \delta(q_i, a) = q_j} ((x \in X_i \wedge Q_a(x) \wedge \neg \text{last}(x)) \implies \\ & \qquad \qquad \qquad \exists y (\text{succ}(x, y) \wedge y \in X_j))) \wedge \\ & (\text{last}(x) \implies \bigvee_{a \in A, \delta(q_i, a) \in F} (Q_a(x) \wedge x \in X_i))). \end{aligned}$$

Example

Consider language $L \subseteq \{a, b\}^*$ of strings of even length.

DFA $\mathcal{A}$ for L :



	a	a	b	a	b	a	b	a	b
X_e	1	0	1	0	1	0	1	0	1
X_o	0	1	0	1	0	1	0	1	0

$\varphi_{\mathcal{A}}$:

$$\begin{aligned}
 \exists X_e \exists X_o (\forall x (& (x \in X_e \implies \neg x \in X_o) \wedge (x \in X_o \implies \neg x \in X_e) \wedge \\
 & (x \in X_e \vee x \in X_o) \wedge \\
 & (zero(x) \implies x \in X_e) \wedge \\
 & ((x \in X_e \wedge Q_a(x) \wedge \neg last(x)) \implies \exists y (succ(x, y) \wedge y \in X_o)) \wedge \\
 & ((x \in X_e \wedge Q_b(x) \wedge \neg last(x)) \implies \exists y (succ(x, y) \wedge y \in X_e)) \wedge \\
 & ((x \in X_o \wedge Q_a(x) \wedge \neg last(x)) \implies \exists y (succ(x, y) \wedge y \in X_e)) \wedge \\
 & ((x \in X_o \wedge Q_b(x) \wedge \neg last(x)) \implies \exists y (succ(x, y) \wedge y \in X_o)) \wedge \\
 & (last(x) \implies ((Q_a(x) \wedge x \in X_o) \vee (Q_b(x) \wedge x \in X_e))))).
 \end{aligned}$$

From MSO sentence to automaton

- Idea: Inductively describe the language of **extended models** of a given MSO formula φ by an automaton $\mathcal{A}_\varphi$.
- Extended models wrt set of first-order and second-order variables $T = \{x_1, \dots, x_m, X_1, \dots, X_n\}$: $(w, \mathbb{I})$
- Can be represented as a word over $A \times \{0, 1\}^{m+n}$.

	<i>a</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>
x_1	0	1	0	0	0	0	0	0	0
x_2	0	0	0	0	1	0	0	0	0
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- For example above extended word satisfies the formula

$$Q_a(x_1) \wedge (x_2 \in X_1).$$

Inductive construction of $\mathcal{A}_\varphi^T$.

- If φ is a formula whose free variables are in T , then we have the notion of whether $w' \models \varphi$ based on whether the $(w, \mathbb{I})$ encoded by w' satisfies φ or not.
- Let the set of valid extended words wrt T be $\text{valid}^T(A)$.
- We can define an automaton $\mathcal{A}_{\text{val}}^T$ which accepts this set.
- Claim: with every formula φ in $\text{MSO}(A)$, and any finite set of variables T containing at least the free variables of φ , we can construct an automaton $\mathcal{A}_\varphi^T$ which accepts the language $L^T(\varphi)$.
- Proof: by induction on structure of φ .

$$Q_a(x), x < y, x \in Y, \neg\varphi, \varphi \vee \psi, \exists x\varphi, \exists X\varphi.$$

Back to First-Order logic of $(\mathbb{N}, <)$.

- Interpreted over $\mathbb{N} = \{0, 1, 2, 3, \dots\}$.
- What you can say:

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Büchi's decision procedure for $\text{MSO}(\mathbb{N}, <)$

- Büchi considered finite automata over **infinite** strings (so called ω -automata).
- An infinite word is accepted if there is a run of the automaton on it that visits a final state infinitely often.
- Büchi showed that ω -automata have similar properties to classical automata: are closed under boolean operations, projection, and can be effectively checked for emptiness.
- MSO characterisation works similarly for ω -automata as well.
- Given a sentence φ in $\text{MSO}(\mathbb{N}, <)$ we can now view it as an $\text{MSO}(\{a\})$ sentence.
- Construct an ω -automaton $\mathcal{A}_\varphi$ that accepts precisely the words that satisfy φ .
- Check if $L(\mathcal{A}_\varphi)$ is non-empty.
- If non-empty say “Yes, φ is true”, else say “No, it is not true.”

Summary

- We saw another characterisation of the class of regular languages, this time via logic:

Theorem (Büchi 1960)

$L \subseteq A^*$ is regular iff L is definable in $\text{MSO}(A)$.

- We saw an application of automata theory to solve a decision procedure in logic:

Theorem (Büchi 1960)

The Monadic Second-Order (MSO) logic of $(\mathbb{N}, <)$ is decidable.