Jacques Farré
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Implementation and Application of Automata

10th International Conference, CIAA 2005
Sophia Antipolis, France, June 2005
Revised Selected Papers

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Preface

The 10th International Conference on Implementation and Application of Automata (CIAA 2005) was held in the Technopole of Sophia Antipolis, France, on June 27–29, 2005.

This volume of the *Lecture Notes in Computer Science* series contains the notes of the two invited lectures, the 26 papers selected for presentation at the conference, and the abstracts of the eight posters that were displayed.

The papers and posters were selected amongst 87 submitted papers. The submissions came from countries in five continents. They show applications of automata in many fields, including mathematics, linguistics, networks, XML processing, biology and music. The elderly lady of automata is alive and kicking, ready to face the new challenges of computer science.

Based on the reviews, the Best Paper Award was given to Markus Lohrey and Sebastian Maneth for their excellent article on Tree Automata and XPath on Compressed Trees (see page 225). This award was generously sponsored by the University of California at Santa Barbara.

We wish to thank all the Program Committee members and the additional referees for their efforts in refereeing and selecting papers, and maintaining the high standard of CIAA conferences. We are grateful to all the contributors to the conference, in particular to the invited speakers, for making CIAA 2005 a scientific success.

We also thank the Computer Science Department of the École Polytechnique Universitaire of the University of Nice - Sophia Antipolis for accommodating CIAA in its buildings and providing the logistical support.

October 2005

J. Farré
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Poster Abstracts

Languages Recognizable by Quantum Finite Automata*

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Abstract. There are several nonequivalent definitions of quantum finite automata. Nearly all of them recognize only regular languages but not all regular languages. On the other hand, for all these definitions there is a result showing that there is a language l such that the size of the quantum automaton recognizing L is essentially smaller than the size of the minimal deterministic automaton recognizing L.

For most of the definitions of quantum finite automata the problem to describe the class of the languages recognizable by the quantum automata is still open. The partial results are surveyed in this paper. Moreover, for the most popular definition of the QFA, the class of languages recognizable by a QFA is not closed under union or any other binary Boolean operation where both arguments are significant.

The end of the paper is devoted to unpublished results of the description of the class of the recognizable languages in terms of the second order predicate logics. This research is influenced by the results of Büchi [1, 2], Elgot [3], Trakhtenbrot [4] (description of regular languages in terms of MSO), R.Fagin [5, 6] (description of NP in terms of ESO), von Neumann [7] (quantum logics), Barenco, Bennett et al. [8] (universal quantum gates).

1 Introduction

A quantum finite automaton (QFA) is a theoretical model for a quantum computer with a finite memory.

If we compare them with their classical (non-quantum) counterparts, QFAs have both strengths and weaknesses. The strength of QFAs is shown by the fact that quantum automata can be exponentially more space efficient than deterministic or probabilistic automata [9]. The weakness of QFAs is caused by the fact that any quantum process has to be reversible (unitary). This makes quantum automata unable to recognize some regular languages.

2 Definitions

Quantum finite automata (QFA) were introduced independently by Moore and Crutchfield [10] and Kondacs and Watrous [11]. They differ in a seemingly small

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detail. The first definition allows the measurement only at the very end of the computation process. Hence the computation is performed on the quantum information only. The second definition allows the measurement at every step of the computation. In the process of the measurement the quantum information (or rather, a part of it) is transformed into the classical information. The classical information is not processed in the subsequent steps of the computation. However, we add the classical probabilities obtained during these many measurements. There is something not 100 percent natural in this definition. We will see below that this leads to unusual properties of the quantum automata and the languages recognized by these automata.

To distinguish these quantum automata, we call them, correspondingly, MO-QFA (measure-once) and MM-QFA (measure-many).

Definition 1. *An MM-QFA is a tuple $M = (Q; \Sigma; V; q_0; Q_{acc}; Q_{rej})$ where Q is a finite set of states, Σ is an input alphabet, V is a transition function, $q_0 \in Q$ is a starting state, and $Q_{acc} \subseteq Q$ and $Q_{rej} \subseteq Q$ are sets of accepting and rejecting states ($Q_{acc} \cap Q_{rej} = \emptyset$). The states in Q_{acc} and Q_{rej}, are called* halting states *and the states in $Q_{non} = Q - (Q_{acc} \cup Q_{rej})$ are called* non halting states. *κ and \$ are symbols that do not belong to Σ. We use κ and \$ as the left and the right endmarker, respectively. The* working alphabet *of M is $\Gamma = \Sigma \cup \{\kappa; \$\}$.*

The state of M can be any superposition of states in Q (i. e., any linear combination of them with complex coefficients). We use $|q\rangle$ to denote the superposition consisting of state q only. $l_2(Q)$ denotes the linear space consisting of all superpositions, with l_2-distance on this linear space.

The transition function V is a mapping from $\Gamma \times l_2(Q)$ to $l_2(Q)$ such that, for every $a \in \Gamma$, the function $V_a : l_2(Q) \to l_2(Q)$ defined by $V_a(x) = V(a, x)$ is a unitary transformation (a linear transformation on $l_2(Q)$ that preserves l_2 norm).

The computation of a MM-QFA starts in the superposition $|q_0\rangle$. Then transformations corresponding to the left endmarker κ, the letters of the input word x and the right endmarker \$ are applied. The transformation corresponding to $a \in \Gamma$ consists of two steps.

1. First, V_a is applied. The new superposition ψ' is $V_a(\psi)$ where ψ is the superposition before this step.
2. Then, ψ' is observed with respect to $E_{acc}, E_{rej}, E_{non}$ where $E_{acc} = span\{|q\rangle : q \in Q_{acc}\}$, $E_{rej} = span\{|q\rangle : q \in Q_{rej}\}$, $E_{non} = span\{|q\rangle : q \in Q_{non}\}$. It means that if the system's state before the measurement was

$$\psi' = \sum_{q_i \in Q_{acc}} \alpha_i |q_i\rangle + \sum_{q_j \in Q_{rej}} \beta_j |q_j\rangle + \sum_{q_k \in Q_{non}} \gamma_k |q_k\rangle$$

then the measurement accepts ψ' with probability $\Sigma \alpha_i^2$, rejects with probability $\Sigma \beta_j^2$ and continues the computation (applies transformations corresponding to next letters) with probability $\Sigma \gamma_k^2$ with the system having state $\psi = \Sigma \gamma_k |q_k\rangle$.

We regard these two transformations as reading a letter a. We use V'_a to denote the transformation consisting of V_a followed by projection to E_{non}. This is the transformation mapping ψ to the non-halting part of $V_a(\psi)$. We use V'_w to denote the product of transformations $V'_w = V'_{a_n} V'_{a_{n-1}} \dots V'_{a_2} V'_{a_1}$, where a_i is the i-th letter of the word w. We also use ψ_y to denote the non-halting part of QFA's state after reading the left endmarker κ and the word $y \in \Sigma^*$. From the notation it follows that $\psi_w = V'_{\kappa w}(|q_0\rangle)$.

We will say that an automaton recognizes a language L with probability p ($p > \frac{1}{2}$) if it accepts any word $x \in L$ with probability $\geq p$ and rejects any word $x \notin L$ with probability $\geq p$.

The MO-QFA differ from MM-QFA only in the additional requirement demanding that non-zero amplitudes can be obtained by the accepting and rejecting states no earlier than on reading the end-marker of the input word.

A probability distribution $\{(p_i, \phi_i) | 1 \leq i \leq k\}$ on pure states $\{\phi_i\}_{i=1}$ with probabilities $0 \leq p_i \leq 1$ ($\sum_{i=1}^{k}(p_i) = 1$), is called a mixed state or mixture.

A quantum finite automaton with mixed states is a tuple

$$(Q, \Sigma, \phi_{init}, \{T_\delta\}, Q_a, Q_r, Q_{non}),$$

where Q is finite a set of states, Σ is an input alphabet, ϕ_{init} is a initial mixed state, $\{T_\delta\}$ is a set of quantum transformations, which consists of defined sequence of measurements and unitary transformations, $Q_a \sqsubseteq Q$, $Q_r \sqsubseteq Q$ and $Q_{non} \sqsubseteq Q$ are sets of accepting, rejecting and non-halting states.

3 MO-Quantum Finite Automata

Sometimes even MO-QFA can be size-efficient compared with the classical FA.

Theorem 1. *[9]*

1. *For every prime p the language L_p = { the length of the input word is a multiple of p } can be recognized by a MO-QFA with no more than const* $\log p$ *states.*
2. *For every p a deterministic FA recognizing L_p needs at least p states.*
3. *For every p a probabilistic FA with a bounded error recognizing L_p needs at least p states.*

4 MM-Quantum Finite Automata

4.1 First Results

The previous work on 1-way quantum finite automata (QFAs) has mainly considered 3 questions:

1. What is the class of languages recognized by QFAs?
2. What accepting probabilities can be achieved?
3. How does the size of QFAs (the number of states) compare to the size of deterministic (probabilistic) automata?

In this paper, we consider the first question. The first results in this direction were obtained by Kondacs and Watrous [11].

Theorem 2. *[11]*

1. *All languages recognized by 1-way MM-QFAs are regular.*
2. *There is a regular language that cannot be recognized by a 1-way MM-QFA with probability $\frac{1}{2}+\epsilon$ for any $\epsilon > 0$.*

Brodsky and Pippenger [12] generalized the second part of Theorem 2 by showing that any language satisfying a certain property is not recognizable by an MM-QFA.

Theorem 3. *[12] Let L be a language and M be its minimal automaton (the smallest DFA recognizing L). Assume that there is a word x such that M contains states q_1, q_2 satisfying:*

1. *$q_1 \neq q_2$,*
2. *If M starts in the state q_1 and reads x, it passes to q_2,*
3. *If M starts in the state q_2 and reads x, it passes to q_2, and*
4. *There is a word y such that if M starts in q_2 and reads y, it passes to q_1,*

then L cannot be recognized by any 1-way quantum finite automaton (Fig.1).

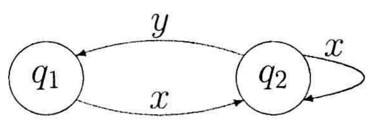

Fig. 1. Conditions of theorem 3

A language L with the minimal automaton not containing a fragment of Theorem 3 is called *satisfying the partial order condition* [13]. [12] conjectured that any language satisfying the partial order condition is recognizable by a 1-way QFA. In this paper, we disprove this conjecture.

Another direction of research is studying the accepting probabilities of QFAs.

Theorem 4. *[9] The language a^*b^* is recognizable by an MM-QFA with probability 0.68... but not with probability $7/9+\epsilon$ for any $\epsilon > 0$.*

This shows that the classes of languages recognizable with different probabilities are different. Next results in this direction were obtained by [14] where the probabilities with which the languages $a_1^* \dots a_n^*$ can be recognized are studied.

There is also a lot of results about the number of states needed for QFA to recognize different languages. In some cases, it can be exponentially less than for deterministic or even for probabilistic automata [9, 15]. In other cases, it can be exponentially bigger than for deterministic automata [16, 17].

A good survey on early results on quantum automata is Gruska [18].