On the Expressive Power of QLTL*

Zhilin Wu

State Key Laboratory of Computer Science, Institute of Software,
Chinese Academy of Sciences, P.O. Box 8718, Beijing, China, 100080
Graduate School of the Chinese Academy of Sciences,
19 Yuquan Street, Beijing, China
wuzl@ios.ac.cn

Abstract. LTL cannot express the whole class of ω-regular languages and several extensions have been proposed. Among them, Quantified propositional Linear Temporal Logic ($QLTL$), proposed by Sistla, extends LTL by quantifications over the atomic propositions. The expressive power of LTL and its fragments have been made relatively clear by numerous researchers. However, there are few results on the expressive power of $QLTL$ and its fragments (besides those of LTL). In this paper we get some initial results on the expressive power of $QLTL$. First, we show that both $Q(U)$ (the fragment of $QLTL$ in which "Until" is the only temporal operator used, without restriction on the use of quantifiers) and $Q(F)$ (similar to $Q(U)$, with temporal operator "Until" replaced by "Future") can express the whole class of ω-regular languages. Then we compare the expressive power of various fragments of $QLTL$ in detail and get a panorama of the expressive power of fragments of $QLTL$. Finally, we consider the quantifier hierarchy of $Q(U)$ and $Q(F)$, and show that one alternation of existential and universal quantifiers is necessary and sufficient to express the whole class of ω-regular languages.

1 Introduction

Linear Temporal Logic (LTL) was first defined by the philosopher A. Prior in 1957 [9] as a tool to reason about the temporal information. Later, in 1977, A. Pnueli introduced LTL into computer science to reason about the behaviors of reactive systems [8]. Since then, it has become one of the most popular temporal logics used in the specification and verification of reactive systems.

Expressive power is one of the main concerns of temporal logics. Perhaps because of their popularity, the expressive power of LTL and its fragments have been made relatively clear by numerous researchers. A well-known result is that an ω-regular language is LTL-definable iff it is first order definable iff it is ω-star free iff its syntactic monoid is aperiodic [5,4,14,15,7]. Since the class of ω-star-free languages is a strict subclass of the class of ω-regular languages,

* Partially supported by the National Natural Science Foundation of China under Grant No. 60223005 and the National Grand Fundamental Research 973 Program of China under Grant No. 2002cb312200.

C.B. Jones, Z. Liu, J. Woodcock (Eds.): ICTAC 2007, LNCS 4711, pp. 467–481, 2007.

some natural temporal properties such as the property that the proposition p holds at all even positions cannot be expressed in LTL [18]. Consequently several extensions of LTL have been proposed to define the whole class of ω-regular languages. Among them we mention Extended Temporal Logic (ETL) [19], linear μ-calculus (νTL)[17] and Quantified propositional Linear Temporal Logic ($QLTL$, also known as $QPTL$) [11].

$QLTL$ extends LTL by quantifications over atomic propositions. While the expressive power of LTL and its fragments have been made relatively clear, there are few results on the expressive power of $QLTL$ and its fragments (besides those of LTL). A well-known result is that ω-regular languages can be expressed by X, F operators and existential quantifiers in $QLTL$ [2,12], which, nevertheless, is almost all we know about the expressive power of $QLTL$ and its fragments besides those of LTL. We do not even know whether several natural fragments of $QLTL$, e.g. $Q(U)$ (the fragment of $QLTL$ in which "Until" is the only temporal operator used, without restriction on the use of quantifiers) and $Q(F)$ (similar to $Q(U)$, with temporal operator "Until" replaced by "Future"), are expressively equivalent to $QLTL$ or not. Consequently we believe that the expressive power of $QLTL$ could be made clearer, which is the main theme of this paper.

In this paper, we first give a positive answer to the question whether $Q(U)$ and $Q(F)$ can define the whole class of ω-regular languages. Then we compare the expressive power of various fragments of $QLTL$ in detail and get a panorama of the expressive power of fragments of $QLTL$. In particular, we show that the expressive power of $EQ(F)$(the fragments of $QLTL$ containing formulas of the form $\exists q_1 ... \exists q_k \psi$, where ψ is the LTL formula in which "Future" is the only temporal operator used) is strictly weaker than that of LTL; and the expressive power of $EQ(U)$ (the fragments of $QLTL$ containing formulas of the form $\exists q_1 ... \exists q_k \psi$, where ψ is the LTL formula in which "Until" is the only temporal operator used) is incompatible with that of LTL. Finally, we consider the quantifier hierarchy of $Q(U)$ and $Q(F)$, and show that one alternation of existential and universal quantifiers is necessary and sufficient to express the whole class of ω-regular languages.

Compared to ETL and νTL, $QLTL$ is more natural and easier to use for those people already familiar with LTL. As it was pointed out in [6,3], $QLTL$ has important applications in the verification of complex systems because quantifications have the ability to reason about refinement relations between programs.

However, the complexity of $QLTL$ is very high: $QLTL$ is not elementarily decidable [12]. So from a practical point of view, it seems that it is unnecessary to bother to clarify the expressive power of $QLTL$. Our main motivation of the exploration of the expressive power of $QLTL$ is from a theoretical point of view, that is, the analogy between $QLTL$ and $S1S$ [16], monadic second order logic over words.

The formulas of $S1S$ are constructed from atomic propositions $x = y$, $x < y$ and $P_\sigma(x)$ (P_σ is the unary relation symbol for each letter σ in the alphabet of words) by boolean combinations, first and second order quantifications. $S1S$ defines exactly the class of ω-regular languages. $QLTL$ can be seen as a variant of $S1S$ because the quantifications over atomic propositions in $QLTL$ are essentially second order quantifications over positions of the ω-words.

In $S1S$, second order quantifications are so powerful that the first order vocabulary can be suppressed into the single successor relation ("$S(x, y)$") since the linear order relation ("<") can be defined by the successor relation with the help of second order quantifications:

$$x < y \equiv \neg(x = y) \wedge \forall X((X(x) \wedge \forall z \forall z'(X(z) \wedge S(z, z') \rightarrow X(z'))) \rightarrow X(y)).$$

Then, analogously we may think that in $QLTL$ the LTL part (the first order part) can also be suppressed to the temporal operator X ("Next"), the counterpart of successor relation $S(x, y)$. However, because in $S1S$ the positions of words can be referred to directly by first order variables while in $QLTL$ they cannot, it turns out that in $QLTL$ the LTL part cannot be suppressed into the single temporal operator X (As a matter of fact, the fragment of $QLTL$ with only X operators used has the same expressive power as the fragment of LTL with only X operator used). However, we still want to know to what extent the LTL part of $QLTL$ can be suppressed. So we consider $Q(U)$ and $Q(F)$, the fragment of $QLTL$ with only U and F operator used respectively, to see whether they can still express the whole class of ω-regular languages. When we find out that they can do so, we then want to know whether they can also do so when only the existential quantifiers are available. The answer is negative, and naturally, we then consider the quantifier hierarchy of $Q(U)$ and $Q(F)$ to see how many alternations of existential and universal quantifiers are necessary and sufficient to express the whole class of ω-regular languages.

The rest of the paper is organized as follows: in Section 2, we give some notation and definitions; then in Section 3, we recall some relevant results on the expressive power of $QLTL$ and its fragments; in Section 4, we establish the main results of this paper; finally in Section 5, we give some conclusions.

2 Notation and Definitions

2.1 Syntax of QLTL

Let $\mathcal{P}$ denote the set of propositional variables $\{p_1, p_2, ...\}$. Formulas of $QLTL$ are defined by the following rules:

$$\varphi := q(q \in \mathcal{P}) \mid \varphi_1 \vee \varphi_2 \mid \neg\varphi_1 \mid X\varphi_1 \mid \varphi_1 U \varphi_2 \mid \exists q \varphi_1 (q \in \mathcal{P})$$

Let φ be a $QLTL$ formula, the subformulas of φ is denoted by $Sub(\varphi)$, and the closure of φ, denoted by $Cl(\varphi)$, is $Sub(\varphi) \cup \{\neg\psi | \psi \in Sub(\varphi)\}$.

Let φ be a $QLTL$ formula. The free-variables-set and bound-variables-set of φ, denoted by $Free(\varphi)$ and $Bound(\varphi)$ respectively, are defined similar to that of first order logic.

The set of variables occurring in a formula φ, denoted by $Var(\varphi)$, is $Free(\varphi) \cup Bound(\varphi)$.

In the remaining part of this paper, we assume that all $QLTL$ formulas φ are well-named: i.e., for all φ, $Free(\varphi) \cap Bound(\varphi) = \emptyset$, and for any $q \in Bound(\varphi)$, there is a unique quantified formula $\exists q\psi$ in $Cl(\varphi)$.

We define several abbreviations of $QLTL$ formulas as follows: $true = q \vee \neg q (q \in \mathcal{P})$, $false = \neg true$, $\varphi_1 \wedge \varphi_2 = \neg(\neg\varphi_1 \vee \neg\varphi_2)$, $\varphi_1 \rightarrow \varphi_2 = \neg\varphi_1 \vee \varphi_2$ $F\varphi_1 = trueU\varphi_1$, $G\varphi_1 = \neg F\neg\varphi_1$, $\forall q\varphi_1 = \neg\left(\exists q(\neg\varphi_1)\right)$.

Moreover, we introduce the following abbreviations. Let AP be a given nonempty finite subset of $\mathcal{P}$. Then, for $a \in 2^{AP}$,

$$\mathcal{B}(a)^{AP} = \left(\underset{p\in a}{\wedge} p\right) \wedge \left(\underset{p\in AP\backslash a}{\wedge} \neg p\right);$$

and for $A \subseteq 2^{AP}$,

$$\mathcal{B}(A)^{AP} = \bigvee_{a\in A} \mathcal{B}(a)^{AP}.$$

2.2 Semantics of QLTL

$QLTL$ formulas are interpreted as follows. Let $u \in \left(2^{\mathcal{P}}\right)^{\omega}$. Denote the suffix of u starting from the i-th position (the first position is 0) as u^i and the letter in the i-th position of u as u_i.

- $u \models q$ if $q \in u_0$.
- $u \models \varphi_1 \vee \varphi_2$ if $u \models \varphi_1$ or $u \models \varphi_2$.
- $u \models \neg\varphi_1$ if $u \not\models \varphi_1$.
- $u \models X\varphi_1$ if $u^1 \models \varphi_1$.
- $u \models \varphi_1 U \varphi_2$ if there is $i \geq 0$ such that $u^i \models \varphi_2$ and for all $0 \leq j < i$, $u^j \models \varphi_1$.
- $u \models \exists q\varphi_1$ if there is some $v \in \left(2^{\mathcal{P}}\right)^{\omega}$ such that v differs from u only in the assignments of q (namely for all $i \geq 0$ and for all $q' \in \mathcal{P}\backslash\{q\}$, $q' \in v_i$ iff $q' \in u_i$) and $v \models \varphi_1$.

Let $AP \subseteq AP' \subseteq \mathcal{P}$. If $a \in 2^{AP}$, $a' \in 2^{AP'}$, and $a' \cap AP = a$, then we say that the restriction of a' to AP is a, denoted by $a'|_{AP} = a$. If $A \subseteq 2^{AP}$, $A' \subseteq 2^{AP'}$, and $A = \{a'|_{AP} \big| \; a' \in A'\}$, then we say that the restriction of A' to AP is A, denoted by $A'|_{AP} = A$. If $u \in \left(2^{AP}\right)^{\omega}$, $u' \in \left(2^{AP'}\right)^{\omega}$ and for all $i \geq 0$, $u'_i|_{AP} = u_i$, then we say that the restriction of u' to AP is u, denoted by $u'|_{AP} = u$. Let $L \subseteq \left(2^{AP}\right)^{\omega}$ and $L' \subseteq \left(2^{AP'}\right)^{\omega}$, we say that the restriction of L' to AP is L, denoted by $L'|_{AP} = L$, if $L = \left\{u \in \left(2^{AP}\right)^{\omega} | \exists u' \in L', u'|_{AP} = u\right\}$.

Proposition 1. *Let AP be a nonempty finite subset of $\mathcal{P}$ and φ be a $QLTL$ formula such that $Free(\varphi) \subseteq AP$. Then, for any $u, v \in \left(2^{\mathcal{P}}\right)^{\omega}$ with $u|_{AP} = v|_{AP}$, we have that $u \models \varphi$ iff $v \models \varphi$.*

Let φ_1, φ_2 be two $QLTL$ formulas. φ_1 and φ_2 are said to be equivalent, denoted by $\varphi_1 \equiv \varphi_2$, if for all $u \in \left(2^{\mathcal{P}}\right)^{\omega}$, $u \models \varphi_1$ iff $u \models \varphi_2$.

Proposition 2. *Let AP be a nonempty finite subset of $\mathcal{P}$, φ_1 and φ_2 be two formulas such that $Free(\varphi_1), Free(\varphi_2) \subseteq AP$. Then $\varphi_1 \equiv \varphi_2$ iff (for all $u \in \left(2^{AP}\right)^\omega$, $u \models \varphi_1$ iff $u \models \varphi_2$).*

For a $QLTL$ formula, the bound variables are usually seen as auxiliary variables. Consequently if AP is the set of propositional variables that we are concerned about, and if we want to use $QLTL$ formula φ to define a language of $\left(2^{AP}\right)^\omega$, naturally we may require that $Free(\varphi) \subseteq AP$ and $Bound(\varphi) \cap AP = \emptyset$. So we introduce the following definition.

Definition 1 (Compatibility of AP and φ). *Let AP be a given nonempty finite subset of $\mathcal{P}$ and φ be a formula of $QLTL$. AP and φ are said to be compatible if $Free(\varphi) \subseteq AP$ and $Bound(\varphi) \cap AP = \emptyset$.*

Let AP be a nonempty finite subset of $\mathcal{P}$ and φ be a formula such that AP and φ are compatible. The language of $\left(2^{AP}\right)^\omega$ defined by φ, denoted by $\mathcal{L}(\varphi)^{AP}$, is $\left\{u \in \left(2^{AP}\right)^\omega | u \models \varphi\right\}$.

Proposition 3. *Let AP be a nonempty finite subset of $\mathcal{P}$ and $\varphi = \exists q_1 ... \exists q_k \psi$ be a formula such that AP and φ are compatible. Let $AP' = AP \cup \{q_1, ..., q_k\}$, then AP' and ψ are compatible and $\mathcal{L}(\varphi)^{AP} = \mathcal{L}(\psi)^{AP'}|_{AP}$.*

2.3 Fragments of QLTL and Expressive Power of Logics

Let $O_1, O_2, ... \in \{X, F, G, U\}$. We use $L(O_1, O_2, ...)$ to denote the fragment of $QLTL$ containing temporal operators $\{O_1, O_2, ...\}$ but containing no quantifiers, and use $Q(O_1, O_2, ...)$ to denote the fragment of $QLTL$ containing both temporal operators $\{O_1, O_2, ...\}$ and quantifiers. Moreover we denote the fragment of $QLTL$ containing exactly formulas of the form $\exists q_1 ... \exists q_k \psi$ (or $\forall q_1 ... \forall q_k \psi$), where $\psi \in L(O_1, O_2, ...)$, as $EQ(O_1, O_2, ...)$ (or $AQ(O_1, O_2, ...)$).

For instance, LTL is $L(X, U)$ and $QLTL$ is $Q(X, U)$.

Let φ be a formula in $QLTL$ and $\mathcal{SL}$ be one fragment of $QLTL$. We say that φ is expressible in $\mathcal{SL}$ iff there is a formula ψ in $\mathcal{SL}$ such that $\varphi \equiv \psi$.

Let AP be a nonempty finite subset of $\mathcal{P}$, $L \subseteq \left(2^{AP}\right)^\omega$, and $\mathcal{SL}$ be one fragment of $QLTL$ (e.g., $Q(F)$). We say that L is expressible in $\mathcal{SL}$ if there is a formula φ in $\mathcal{SL}$ such that AP and φ are compatible and $\mathcal{L}(\varphi)^{AP} = L$.

Let $\mathcal{SL}_1$ and $\mathcal{SL}_2$ be two fragments of $QLTL$. We say that $\mathcal{SL}_1$ is less expressive than $\mathcal{SL}_2$, denoted by $\mathcal{SL}_1 \leq \mathcal{SL}_2$, if for any formula $\varphi_1 \in \mathcal{SL}_1$, there exists a formula $\varphi_2 \in \mathcal{SL}_2$ such that $\varphi_1 \equiv \varphi_2$, and we say that $\mathcal{SL}_1$ and $\mathcal{SL}_2$ are expressively equivalent, denoted by $\mathcal{SL}_1 \equiv \mathcal{SL}_2$, if $\mathcal{SL}_1 \leq \mathcal{SL}_2$ and $\mathcal{SL}_2 \leq \mathcal{SL}_1$. Moreover we say that $\mathcal{SL}_1$ is strictly less expressive than $\mathcal{SL}_2$, denoted by $\mathcal{SL}_1 < \mathcal{SL}_2$, if $\mathcal{SL}_1 \leq \mathcal{SL}_2$ but not $\mathcal{SL}_2 \leq \mathcal{SL}_1$. Finally we say that the expressive power of $\mathcal{SL}_1$ and $\mathcal{SL}_2$ are incompatible, denoted by $\mathcal{SL}_1 \perp \mathcal{SL}_2$, if neither $\mathcal{SL}_1 \leq \mathcal{SL}_2$ nor $\mathcal{SL}_2 \leq \mathcal{SL}_1$, namely there are two formulas $\varphi_1 \in \mathcal{SL}_1$ and $\varphi_2 \in \mathcal{SL}_2$ such that there exists no formula in $\mathcal{SL}_2$ equivalent to φ_1 and there exists no formula in $\mathcal{SL}_1$ equivalent to φ_2.

2.4 Büchi Automaton and ω-Languages

A Büchi automaton $\mathcal{B}$ is a quintuple $(Q, \Sigma, \delta, q_0, T)$, where Q is the finite state set, Σ is the finite set of letters, $\delta \subseteq Q \times \Sigma \times Q$ is the transition relation, $q_0 \in Q$ is the initial state, and $T \subseteq Q$ is the accepting state set. Let $u \in \Sigma^\omega$, a run of $\mathcal{B}$ on u is an infinite state sequence $s_0 s_1 ... \in Q^\omega$ such that $s_0 = q_0$ and $(s_i, u_i, s_{i+1}) \in \delta$ for all $i \geq 0$. A run of $\mathcal{B}$ on u is accepting if some accepting state occurs in it infinitely often. u is accepted by $\mathcal{B}$ if $\mathcal{B}$ has an accepting run on u. The language defined by $\mathcal{B}$, denoted by $\mathcal{L}(\mathcal{B})$, is the set of ω-words accepted by $\mathcal{B}$.

An ω-language is said to be ω-regular if it can be defined by some Büchi automaton.

An ω-language $L \subseteq \Sigma^\omega$ is said to be stutter invariant if for all $u \in \Sigma^\omega$ and function $f : \mathbf{N} \to \mathbf{N} \backslash \{0\}$ ($\mathbf{N}$ is the set of natural numbers), we have that $u \in L$ iff $u^{f(0)} u^{f(1)} ... \in L$.

Let $L \subseteq \Sigma^\omega$ be ω-regular. The syntactic congruence of L, denoted by $\approx_L$, is a congruence on Σ^* defined as follows: let $u, v \in \Sigma^*$, then, $u \approx_L v$ if for all $x, y, z \in \Sigma^*$, ($xuyz^\omega \in L$ iff $xvyz^\omega \in L$) and ($x(yuz)^\omega \in L$ iff $x(yvz)^\omega \in L$). The syntactic monoid of L, denoted by $M(L)$, is the division monoid $\Sigma^* / \approx_L$.

An ω-language $L \subseteq \Sigma^\omega$ is said to be non-counting if there is $n \geq 0$ such that for all $x, y, z, u \in \Sigma^*$, ($xu^n yz^\omega \in L$ iff $xu^{n+1} yz^\omega \in L$) and ($x(yu^n z)^\omega \in L$ iff $x(yu^{n+1} z)^\omega \in L$).

A monoid M is said to be aperiodic if there is $k \geq 0$ such that for all $m \in M$, $m^k = m^{k+1}$.

Let $L \subseteq \Sigma^\omega$. It is not hard to show that $M(L)$ is aperiodic iff L is non-counting.

3 Known Results on the Expressive Power of *QLTL* and *LTL*

In the remaining part of this paper, we always assume that AP is a nonempty finite subset of $\mathcal{P}$.

Proposition 4 ([2,12]). *An ω-language is ω-regular iff it is expressible in $QLTL$.*

Corollary 1. *$Q(X, U) \equiv EQ(X, F)$.*

Proposition 5 ([1])

(i) Xp_1 is not expressible in $L(U)$;
(ii) Fp_1 is not expressible in $L(X)$;
(iii) $p_1 U p_2$ is not expressible in $L(X, F)$.

In the following we recall three propositions characterizing the expressive power of LTL(namely $L(X, U)$), $L(U)$ and $L(F)$ respectively.

In the remaining part of this subsection, we assume that $L \subseteq (2^{AP})^\omega$.

Proposition 6 (Characterization of LTL, [5,4,14,15,7]). *Suppose that L is ω-regular, then the following two conditions are equivalent:*

- *L is expressible in LTL;*
- *The syntactic monoid of L, $M(L)$, is aperiodic.*

Proposition 7 (Characterization of $L(U)$, [10]). *Let φ be a formula in $L(X,U)$ and $Free(\varphi) \subseteq AP$. Then φ is expressible in $L(U)$ iff $\mathcal{L}(\varphi)^{AP}$ is stutter invariant.*

Definition 2 (Restricted ω-regular set). *L is said to be a restricted ω-regular set if it is of the form*

$$S_1^* s_1 S_2^* s_2 ... S_{m-1}^* s_{m-1} S_m^\omega, \tag{1}$$

where $S_i \subseteq 2^{AP}$ $(1 \leq i \leq m)$, and $s_i \in S_i \backslash S_{i+1}$ $(1 \leq i < m)$.

For instance, let $AP = \{p_1\}$, then, $\left(2^{AP}\right)^\omega$ and $\left(2^{AP}\right)^* \{p_1\}\emptyset^\omega$ are both restricted ω-regular sets.

Definition 3. *Let $s_0 \in 2^{AP}$ and $S' \subseteq 2^{AP}$. We define $L_{inf(S')}^{init(s_0)}$ as follows:*

$$L_{inf(S')}^{init(s_0)} = \{u \in L | u_0 = s_0, \textit{ each element of } S' \textit{ occurs infinitely often in } u\}$$

Proposition 8 (Characterization of $L(F)$, [13]). *Let L be nonempty. Then, L is expressible in $L(F)$ iff L is a finite union of nonempty languages of the form $M_{inf(S')}^{init(s_0)}$, where $M \subseteq \left(2^{AP}\right)^\omega$ is a restricted ω-regular set, $s_0 \in 2^{AP}$ and $S' \subseteq 2^{AP}$.*

For instance, let $AP = \{p_1\}$, then, $\mathcal{L}(Fp_1)^{AP} \subseteq \left(2^{AP}\right)^\omega$ is exactly the union of languages $(L_1)_{inf(\emptyset)}^{init(\{p_1\})}$, $(L_1)_{inf(\{\{p_1\}\})}^{init(\emptyset)}$, and $(L_2)_{inf(\emptyset)}^{init(\emptyset)}$, where $L_1 = \left(2^{AP}\right)^\omega$ and $L_2 = \left(2^{AP}\right)^* \{p_1\}\emptyset^\omega$.

4 Our Results on the Expressive Power of *QLTL* and Its Fragments

According to Proposition 4, $Q(X,U)$, $Q(X,F)$, $EQ(X,U)$ and $EQ(X,F)$ are all expressively equivalent, which, nevertheless, is almost all we know about the expressive power of $QLTL$ besides those of LTL. For instance, we do not know whether several natural fragments of $QLTL$, e.g., $Q(U)$ and $Q(F)$, can define the whole class of ω-regular languages or not.

In this section, we first give a positive answer to the above question, namely, we show that $Q(U)$ and $Q(F)$ can define the whole class of ω-regular languages. Then, since $EQ(X,U)$ and $EQ(X,F)$ can also do so, analogously, we want to know whether $EQ(U)$ and $EQ(F)$ can do so or not. However, the answer is negative. As a matter of fact, we show that $EQ(F) < LTL$ and $EQ(U) \perp$

LTL. Furthermore, we compare the expressive power of $EQ(U)$ and $EQ(F)$ with that of other fragments of $QLTL$ and get a panorama of the expressive power of various fragments of $QLTL$ (Fig. 1). Since neither $EQ(U)$ nor $EQ(F)$ can express the whole class of ω-regular languages, we want to know how many alternations of existential and universal quantifiers are necessary and sufficient to do that. The answer is one, which will be shown in the end of this section.

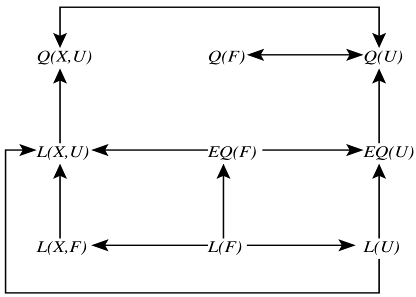

Fig. 1. Expressive power of $QLTL$ and its fragments

Remark 1 (Notation in Fig. 1). Let $\mathcal{L}_1$ and $\mathcal{L}_2$ be two nodes in Fig. 1. If $\mathcal{L}_2$ is reachable from $\mathcal{L}_1$ but not vice versa, then $\mathcal{L}_1 < \mathcal{L}_2$, e.g. $EQ(F) < EQ(U)$. If neither $\mathcal{L}_2$ is reachable from $\mathcal{L}_1$ nor $\mathcal{L}_1$ is reachable from $\mathcal{L}_2$, then $\mathcal{L}_1 \perp \mathcal{L}_2$, e.g. $EQ(F) \perp L(U)$. If $\mathcal{L}_1$ and $\mathcal{L}_2$ are reachable from each other (namely, in the same Strongly Connected Component), then $\mathcal{L}_1 \equiv \mathcal{L}_2$, e.g. $Q(U) \equiv Q(F)$. □

4.1 Expressive Power of $Q(U)$ and $Q(F)$

In the following we will show that, with the help of quantifiers, the operator X can be expressed by the operator U and the operator U can be expressed by the operator F.

Lemma 1. *Let $\varphi \in QLTL$, $q_1, q_2 \in \mathcal{P} \backslash Var(\varphi)$ and $q_1 \neq q_2$. Then*

$$X\varphi \equiv \big(\varphi \wedge \exists q_1 \left(\neg q_1 \wedge (\varphi \wedge \neg q_1)\ U\ (\varphi \wedge q_1)\right)\big) \vee \big(\neg\varphi \wedge \neg\exists q_2 \left(\neg q_2 \wedge (\neg\varphi \wedge \neg q_2)\ U\ (\neg\varphi \wedge q_2)\right)\big).$$

Lemma 2. *Let φ_1 and φ_2 be two formulas of $QLTL$ and $q \in \mathcal{P} \backslash (Var(\varphi_1) \cup Var(\varphi_2))$. Then*

$$\varphi_1 U \varphi_2 \equiv \exists q \left(F(\varphi_2 \wedge q) \wedge G(\neg q \rightarrow G\neg q) \wedge G(\varphi_1 \vee \varphi_2 \vee \neg q)\right).$$

From Lemma 1 and Lemma 2, we have the following theorem.

Theorem 1. $Q(X,U) \equiv Q(U) \equiv Q(F)$.

4.2 Expressive Power of $EQ(F)$ and $EQ(U)$

Both $EQ(X, U)$ and $EQ(X, F)$ can define the whole class of ω-regular languages (Corollary 1). Then a natural question to ask is whether this is true for $EQ(U)$ and $EQ(F)$ as well. We will give a negative answer to this question in this subsection. Moreover, in this subsection, we will compare the expressive power of $EQ(F)$ and $EQ(U)$ with that of other fragments of $QLTL$.

We first show that $EQ(F)$ cannot define the whole class of ω-regular languages. In fact we show that $EQ(F)$ is strictly less expressive than LTL.

Lemma 3. *Let $AP \subseteq AP' \subseteq \mathcal{P}$ and $L \subseteq \left(2^{AP'}\right)^{\omega}$. If L is a restricted ω-regular set, $s_0 \in 2^{AP'}$, $S' \subseteq 2^{AP'}$ and $L^{init(s_0)}_{inf(S')} \neq \emptyset$, then, $\left(L^{init(s_0)}_{inf(S')}\right)\Big|_{AP} = (L|_{AP})^{init(s_0|_{AP})}_{inf(S'|_{AP})}$.*

Lemma 4. *For any formula $\varphi = \exists q_1 ... \exists q_k \psi \in EQ(F)$, there exists some formula $\theta \in L(X, U)$ such that $\varphi \equiv \theta$.*

Proof of Lemma 4.
Suppose that $\varphi = \exists q_1 ... \exists q_k \psi \in EQ(F)$, where $\psi \in L(F)$.
Suppose that φ and AP are compatible and $AP' = AP \cup \{q_1, ..., q_k\}$.

Then, according to Proposition 3, we have that ψ and AP' are compatible, and $\mathcal{L}(\varphi)^{AP} = \mathcal{L}(\psi)^{AP'}|_{AP}$.

If $\mathcal{L}(\psi)^{AP'} = \emptyset$, then $\varphi \equiv false$. So we assume that $\mathcal{L}(\psi)^{AP'} \neq \emptyset$.

According to Proposition 8, $\mathcal{L}(\psi)^{AP'}$ is a finite union of nonempty languages of the form $L^{init(s_0)}_{inf(S')}$, where $L \subseteq \left(2^{AP'}\right)^{\omega}$ is a restricted ω-regular set, $s_0 \in 2^{AP'}$ and $S' \subseteq 2^{AP'}$.

In the remaining part of the proof of this lemma, we always suppose that L is a restricted ω-regular set, specifically, $S_1^* s_1 S_2^* s_2 ... S_{m-1}^* s_{m-1} S_m^{\omega}$, where $S_i \subseteq 2^{AP}$ $(1 \leq i \leq m)$, and $s_i \in S_i \backslash S_{i+1}$ $(1 \leq i < m)$.

From Lemma 3, we know that $\mathcal{L}(\varphi)^{AP} = \mathcal{L}(\psi)^{AP'}|_{AP}$ is a finite union of nonempty languages of the form $(L|_{AP})^{init(s_0|_{AP})}_{inf(S'|_{AP})}$.

In the following we will show that there is a formula ξ in $L(X, U)$ such that $Var(\xi) = Free(\xi) \subseteq AP$ and $\mathcal{L}(\xi)^{AP} = (L|_{AP})^{init(s_0|_{AP})}_{inf(S'|_{AP})}$. Let θ be the disjunction of all these ξ's. Then $\mathcal{L}(\varphi)^{AP} = \mathcal{L}(\theta)^{AP}$. Because $Free(\varphi) \subseteq AP$ and $Free(\theta) \subseteq AP$, according to Proposition 2, we conclude that φ and θ are equivalent.

In order to define ξ, we define a sequence of formulas η_i $(1 \leq i \leq m)$ as follows:

$$\eta_i = \begin{cases} G\left(\mathcal{B}\left(S_m|_{AP}\right)^{AP}\right) & \text{if} \quad i = m \\ \mathcal{B}\left(S_i|_{AP}\right)^{AP} \ U \ \left(\mathcal{B}(s_i|_{AP})^{AP} \wedge X\eta_{i+1}\right) & \text{if} \quad 1 \leq i < m \end{cases}$$

It is not hard to show that for all $1 \leq i \leq m$,

$$\mathcal{L}(\eta_i)^{AP} = \left(S_i|_{AP}\right)^* \left(s_i|_{AP}\right) ... \left(S_m|_{AP}\right)^{\omega}.$$

Thus, $L|_{AP} = \mathcal{L}(\eta_1)^{AP}$.

We can define ξ by the formula

$$\mathcal{B}\left(s_0|_{AP}\right)^{AP} \wedge \eta_1 \wedge \bigwedge_{a \in (S'|_{AP})} GF\left(\mathcal{B}(a)^{AP}\right).$$

$\square$

Lemma 5. *Let φ be a formula in $EQ(U)$ and AP be compatible with φ. Then for any $u \in (2^{AP})^\omega$, any function $f : \boldsymbol{N} \to \boldsymbol{N} \backslash \{0\}$, if $u \models \varphi$, then, $u_0^{f(0)} ... u_i^{f(i)} ... \models \varphi$.*

Lemma 6. *Let $AP = \{p_1\}$. Then Xp_1 is not expressible in $EQ(U)$.*

Proof of Lemma 6.
To the contrary, suppose that Xp_1 is expressible in $EQ(U)$.

We know that $\emptyset\{p_1\}^\omega \models Xp_1$, then according to Lemma 5, we have that $\emptyset^2\{p_1\}^\omega \models Xp_1$, a contradiction. $\square$

Theorem 2. *$EQ(F) < LTL$.*

Proof.
It follows directly from Lemma 4 and Lemma 6. $\square$

Theorem 3. *$EQ(F) \perp L(X, F)$.*

Proof.
From Lemma 2, we know that $p_1 U p_2$ is expressible in $EQ(F)$. While it is not expressible in $L(X, F)$ according to Proposition 5.

Xp_1 is not expressible in $EQ(F)$ according to Lemma 6.

So, $EQ(F) \perp L(X, F)$. $\square$

From Lemma 6, we already know that $EQ(U)$ cannot define the whole class of ω-regular languages. In the following, we will show that the expressive power of $EQ(U)$ and LTL are incompatible.

Lemma 7. *Let $AP = \{p_1\}$ and*

$$L = \{u \in \left(2^{AP}\right)^\omega | (\emptyset\{p_1\}) \text{ occurs an odd number of times in } u\}.$$

L is expressible in $EQ(U)$, while it is not expressible in LTL.

Remark 2. A language similar to L in Lemma 7 is used in Proposition 2 of [2]. $\square$

Theorem 4. *$EQ(U) \perp LTL$.*

Proof.
It follows from Lemma 6 and Lemma 7. $\square$

Now we compare the expressive power of $EQ(F)$ and $EQ(U)$ with that of $L(F)$ and $L(U)$.

Lemma 8. *Let* $AP = \{p_1\}$*. Then*

$$L = \{\emptyset, \{p_1\}\}^* \{p_1\}\{p_1\} \{\emptyset, \{p_1\}\}^* \emptyset^\omega \subseteq \left(2^{AP}\right)^\omega$$

is expressible in $EQ(F)$*, while it is not expressible in* $L(U)$*.*

The following theorem can be derived from Lemma 8 easily.

Theorem 5. $L(F) < EQ(F)$ *and* $L(U) < EQ(U)$*.*

But how about the expressive power of $EQ(F)$ and $L(U)$? In Lemma 8, we have shown that there is a language expressible in $EQ(F)$, but not expressible in $L(U)$. In the following we will show that there is a language expressible in $L(U)$, but not expressible in $EQ(F)$.

Lemma 9. *Let* $AP = \{p_1, p_2, p_3\}$ *and*

$$L = (\{p_1\}\{p_1\}^*\{p_2\}\{p_2\}^*\{p_3\}\{p_3\}^*)^\omega .$$

Then L *is expressible in* $L(U)$*, while it is not expressible in* $EQ(F)$*.*

Proof of Lemma 9.
We first define the formula φ in $L(U)$ such that AP and φ are compatible and $\mathcal{L}(\varphi)^{AP} = L$:

$$\begin{aligned}\varphi \equiv\ & \mathcal{B}(\{p_1\})^{AP} \wedge G\left(\mathcal{B}(\{p_1\})^{AP} \to \mathcal{B}(\{p_1\})^{AP}\ U\ \mathcal{B}(\{p_2\})^{AP}\right) \wedge \\ & G\left(\mathcal{B}(\{p_2\})^{AP} \to \mathcal{B}(\{p_2\})^{AP}\ U\ \mathcal{B}(\{p_3\})^{AP}\right) \wedge \\ & G\left(\mathcal{B}(\{p_3\})^{AP} \to \mathcal{B}(\{p_3\})^{AP}\ U\ \mathcal{B}(\{p_1\})^{AP}\right) .\end{aligned}$$

Now we show that L is not expressible in $EQ(F)$.

To the contrary, suppose that there is an $EQ(F)$ formula $\psi = \exists q_1 ... \exists q_k \xi$ such that ψ and AP are compatible and $L = \mathcal{L}(\psi)^{AP}$.

Let $AP' = AP \cup \{q_1, ..., q_k\}$. Then, according to Proposition 3, we have that ξ and AP' are compatible, $\mathcal{L}(\psi)^{AP} = \mathcal{L}(\xi)^{AP'}|_{AP}$.

According to Proposition 8, $\mathcal{L}(\xi)^{AP'}$ is a finite union of nonempty languages of the form $M^{init(s_0)}_{inf(S')}$, where M is a restricted ω-regular set, $s_0 \in 2^{AP'}$, $S' \subseteq 2^{AP'}$.

From Lemma 3, we know that $L = \mathcal{L}(\xi)^{AP'}|_{AP}$ is a finite union of nonempty languages of the form $(M|_{AP})^{init(s_0|_{AP})}_{inf(S'|_{AP})}$.

Let $u = (\{p_1\}\{p_2\}\{p_3\})^\omega \in L$. Then, $u \in (M|_{AP})^{init(s_0|_{AP})}_{inf(S'|_{AP})}$ for some restricted ω-regular set M, $s_0 \in \left(2^{AP'}\right)^\omega$ and $S' \subseteq \left(2^{AP'}\right)^\omega$.

Suppose that $M = S_1^* s_1 ... S_{m-1}^* s_{m-1} S_m^\omega$, where $S_i \subseteq 2^{AP}$ $(1 \le i \le m)$, and $s_i \in S_i \backslash S_{i+1}$ $(1 \le i < m)$. Then,

$$M|_{AP} = (S_1|_{AP})^* (s_1|_{AP}) ... (S_{m-1}|_{AP})^* (s_{m-1}|_{AP}) (S_m|_{AP})^\omega .$$

Since $\{p_1\}$, $\{p_2\}$ and $\{p_3\}$ occur infinitely often in $u \in M|_{AP}$, we have that $\{\{p_1\}, \{p_2\}, \{p_3\}\} \subseteq S_m|_{AP}$.

If $m = 1$, then $M|_{AP} = (S_m|_{AP})^\omega$. In this case, let

$$u' = \{p_1\}\{p_2\}\{p_3\}(\{p_2\}\{p_1\}\{p_3\})^\omega.$$

Evidently $u' \in M|_{AP}$. Moreover, $u_0 = u'_0$, and the elements of 2^{AP} occurring infinitely often in u and u' are the same. So, $u' \in (M|_{AP})^{init(s_0)}_{init(S')} \subseteq L$, a contradiction.

Now we assume that $m > 1$.

Since $u \in M_{AP}$, we have that $u = x(s_{m-1}|_{AP})y\left(\{p_1\}\{p_2\}\{p_3\}\right)^\omega$, where

$$x \in (S_1|_{AP})^* (s_1|_{AP}) \ldots (S_{m-1}|_{AP})^* \text{ and } y\left(\{p_1\}\{p_2\}\{p_3\}\right)^\omega \in (S_m|_{AP})^\omega.$$

Let $u' = x(s_{m-1}|_{AP})y\left(\{p_2\}\{p_1\}\{p_3\}\right)^\omega$.

Then, $u' \in (S_1|_{AP})^* (s_1|_{AP}) \ldots (s_{m-1}|_{AP}) (S_m|_{AP})^\omega$. Moreover, $u'_0 = u_0$ and the elements of 2^{AP} occurring infinitely often in u and u' are the same. So, $u' \in (M|_{AP})^{init(s_0)}_{inf(S')} \subseteq L$, a contradiction as well.

So, we conclude that L is not expressible in $EQ(F)$. □

Theorem 6. *$L(U) \perp EQ(F)$.*

Proof.
It follows from Lemma 8 and Lemma 9. □

Also we have the following theorem according to Lemma 9.

Theorem 7. *$EQ(F) < EQ(U)$.*

The expressive power of $QLTL$ and its fragments are summarized into Fig. 1.

4.3 Quantifier Hierarchy of $Q(U)$ and $Q(F)$

In Subsection 4.2, we have known that $EQ(F)$ and $EQ(U)$ can not define the whole class of ω-regular languages. It follows easily that $AQ(F)$ and $AQ(U)$ can not define the whole class of ω-regular languages as well. Moreover since $\neg X p_1 \equiv X(\neg p_1)$ is not expressible in $EQ(U)$ (similar to the proof of Lemma 6), Xp_1 is not expressible in $AQ(U)$ or in $AQ(F)$. Consequently Xp_1 is expressible in neither $EQ(U) \cup AQ(U)$ nor in $EQ(F) \cup AQ(F)$. Thus we conclude that alternations of existential and universal quantifiers are necessary to define the whole class of ω-regular languages in $Q(U)$ and $Q(F)$. A natural question then occurs: how many alternations of existential and universal quantifiers are sufficient to define the whole class of ω-regular languages? The answer is one.

Now we define the quantifier hierarchy in $Q(U)$ and $Q(F)$.

The definitions of hierarchy of Σ_k, Π_k and $\triangle_k$ in $Q(U)$ and $Q(F)$ are similar to the quantifier hierarchy of first order logic. Σ_k (Π_k resp.) contains the formulas of the prenex normal form such that there are k-blocks of quantifiers and the quantifiers in each block are of the same type (all existential or all universal); the consecutive blocks are of different types; the first block is existential (universal resp.). $\triangle_k = \Sigma_k \cap \Pi_k$, namely $\triangle_k$ contains those formulas both equivalent to some Σ_k formula and to some Π_k formula. In addition, we define $\bigtriangledown_k = \Sigma_k \cup \Pi_k$.

Lemma 10. *Σ_2^U and Σ_2^F define the whole class of ω-regular languages.*

Proof of Lemma 10.
Let $\mathcal{B} = (Q, 2^{AP}, \delta, q_0, T)$ be a Büchi automaton. Suppose that $Q = \{q_0, ..., q_n\}$, $\mathcal{L}(\mathcal{B})$ can be defined by the following formula φ.

$$\varphi := \exists q_0 ... \exists q_n \left(q_0 \wedge G\left(\bigwedge_{i \neq j} \neg(q_i \wedge q_j)\right) \wedge \right.$$
$$\left. G\left(\bigvee_{(q_i,a,q_j)\in\delta} \left(q_i \wedge \mathcal{B}(a)^{AP} \wedge Xq_j\right)\right) \wedge \left(\bigvee_{q_i \in T} GFq_i\right)\right)$$

Let $AP' = AP \cup Q$. If we can find a formula ψ in Π_1^U (Π_1^F, resp.) such that ψ and AP' are compatible and

$$\psi \equiv G\left(\bigvee_{(q_i,a,q_j)\in\delta} (q_i \wedge \mathcal{B}(a)^{AP} \wedge Xq_j)\right),$$

then, we are done.

We first show that such a ψ in Π_1^U exists.

We observe that $\bigvee_{(q_i,a,q_j)\in\delta} (q_i \wedge \mathcal{B}(a)^{AP} \wedge Xq_j)$ can be rewritten into its conjunctive normal form and the conjunctions can be moved to the outside of "G":

$$G\left(\bigvee_{(q_i,a,q_j)\in\delta} (q_i \wedge \mathcal{B}(a)^{AP} \wedge Xq_j)\right)$$

$$\equiv \bigwedge_{\substack{i_1,...,i_k \\ a_1,...,a_l \\ j_1,...,j_m}} G\left(q_{i_1} \vee ... \vee q_{i_k} \vee \mathcal{B}(a_1)^{AP} \vee ... \vee \mathcal{B}(a_l)^{AP} \vee Xq_{j_1} \vee ... \vee Xq_{j_m}\right)$$

It is sufficient to show that there is a Π_1^U formula such that the formula and AP' are compatible and the formula is equivalent to

$$G\left(q_{i_1} \vee ... \vee q_{i_k} \vee \mathcal{B}(a_1)^{AP} \vee ... \vee \mathcal{B}(a_l)^{AP} \vee Xq_{j_1} \vee ... \vee Xq_{j_m}\right). \qquad (2)$$

The negation of the formula (2) is of the form $F(\varphi_1 \wedge X\varphi_2)$, where φ_1, φ_2 are boolean combinations of propositional variables in AP'. If we can prove that for any formula of the form $F(\varphi_1 \wedge X\varphi_2)$, there is a formula ξ in Σ_1^U such that ξ and AP' are compatible, and $\xi \equiv F(\varphi_1 \wedge X\varphi_2)$, then, we are done.

Let

$$S_i = \left\{a \in 2^{AP'} \middle| a \text{ satisfies the boolean formula } \varphi_i\right\}, \text{ where } i = 1, 2.$$

Then, for any $u \in \left(2^{AP'}\right)^\omega$,

$$u \models F(\varphi_1 \wedge X\varphi_2) \text{ iff } u \models F\left(\mathcal{B}(S_1)^{AP'} \wedge X\mathcal{B}(S_2)^{AP'}\right).$$

From Proposition 2, we know that

$$F(\varphi_1 \wedge X\varphi_2) \equiv F\left(\mathcal{B}(S_1)^{AP'} \wedge X\mathcal{B}(S_2)^{AP'}\right).$$

Let $q' \in \mathcal{P}\backslash AP'$, and $AP'' = AP' \cup \{q'\}$, $S'_1 = S_1$, and $S'_2 = \{a \cup \{q'\} \big| a \in S_2\}$. We have that $S'_i|_{AP'} = S_i$ $(i = 1, 2)$ and $S'_1 \cap S'_2 = \emptyset$.

Then, Σ_1^U formula

$$\chi := \exists q' F\left(\mathcal{B}(S'_1)^{AP''} \wedge \mathcal{B}(S'_1)^{AP''} \; U \; \mathcal{B}(S'_2)^{AP''}\right)$$

satisfies that χ and AP' are compatible, and

$$\chi \equiv F\left(\mathcal{B}(S_1)^{AP'} \wedge X\mathcal{B}(S_2)^{AP'}\right) \equiv F\left(\varphi_1 \wedge X\varphi_2\right).$$

Now we show that there is also a formula $\chi' \in \Sigma_1^F$ equivalent to $F(\varphi_1 \wedge X\varphi_2)$.

According to Lemma 2, there are $q'' \in \mathcal{P}\backslash AP''$ and $\xi \in L(F)$ such that $\exists q''\xi \equiv \mathcal{B}(S'_1)^{AP''} \; U \; \mathcal{B}(S'_2)^{AP''}$.

Let

$$\chi' := \exists q' \exists q'' F\left(\mathcal{B}(S'_1)^{AP''} \wedge \xi\right).$$

Then $\chi' \in \Sigma_1^F$, χ' and AP' are compatible and

$$\chi' \equiv \chi \equiv F\left(\varphi_1 \wedge X\varphi_2\right).$$

□

The following theorem is a direct consequence of Lemma 10.

Theorem 8. *$Q(U) \equiv \Sigma_2^U \equiv \Pi_2^U \equiv \triangle_2^U \equiv \triangledown_2^U$ and $Q(F) \equiv \Sigma_2^F \equiv \Pi_2^F \equiv \triangle_2^F \equiv \triangledown_2^F$.*

5 Conclusions

In this paper, we first showed that $Q(U)$ and $Q(F)$ can define the whole class of ω-regular languages. Then we compared the expressive power of $EQ(F)$, $EQ(U)$ and other fragments of $QLTL$ in detail and got a panorama of the expressive power of fragments of $QLTL$. In particular, we showed that $EQ(F)$ is strictly less expressive than LTL and that the expressive power of $EQ(U)$ and LTL are incompatible. Furthermore, we showed that one alternation of existential and universal quantifiers is necessary and sufficient to express the whole class of ω-regular languages.

The results established in this paper can be easily adapted to the regular languages on finite words.

There are several open problems. For instance, since we discovered that neither $EQ(U)$ nor $EQ(F)$ can define the whole class of ω-regular languages, a natural problem is to find (effective) characterizations for those languages expressible in $EQ(U)$ and $EQ(F)$ respectively.

We can also consider similar problems for the other temporal operators, such as the strict "Until" and "Future" operators.

Acknowledgements. I want to thank Prof. Wenhui Zhang for his reviews on this paper and discussions with me. I also want to thank anonymous referees for their comments and suggestions.

References

1. Emerson, E.A., Halpern, J.Y.: "Sometimes" and "not never" revisited: On branching versus linear time temporal logic. Journal of the ACM 33(1), 151–178 (1986)
2. Etessami, K.: Stutter-invariant languages, ω-automata, and temporal logic. In: Halbwachs, N., Peled, D.A. (eds.) CAV 1999. LNCS, vol. 1633, pp. 236–248. Springer, Heidelberg (1999)
3. French, T., Reynolds, M.: A Sound and Complete Proof System for QPTL. Advances in Modal Logic 4, 127–147 (2003)
4. Gabbay, D.M., Pnueli, A., Shelah, S., Stavi, J.: On the Temporal Analysis of Fairness. In: POPL'80. Conference Record of the 7th ACM Symposium on Principles of Programming Languages, pp. 163–173. ACM Press, New York (1980)
5. Kamp, H.W.: Tense Logic and the Theory of Linear Order. PhD thesis, UCLA, Los Angeles, California, USA (1968)
6. Kesten, Y., Pnueli, A.: A Complete Proof Systems for QPTL. In: LICS, pp. 2-12 (1995)
7. Perrin, D.: Recent results on automata and infinite words. In: Chytil, M.P., Koubek, V. (eds.) Mathematical Foundations of Computer Science 1984. LNCS, vol. 176, pp. 134–148. Springer, Heidelberg (1984)
8. Pnueli, A.: The temporal logic of programs. In: 18th FOCS, pp. 46–51 (1977)
9. Prior, A.N.: Time and Modality. Clarendon Press, Oxford (1957)
10. Peled, D., Wilke, T.: Stutter-invariant temporal properties are expressible without the next-time operator. Information Processing Letters 63, 243–246 (1997)
11. Sistla, A.P.: Theoretical issues in the design and verification of distributed systems. PHD thesis, Harvard University (1983)
12. Sistla, A.P., Vardi, M.Y., Wolper, P.: The complementation problem for Büchi automata with applications to temporal logic. TCS 49, 217–237 (1987)
13. Sistla, A.P., Zuck, L.D.: Reasoning in a restricted temporal logic. Information and Computation 102, 167–195 (1993)
14. Thomas, W.: Star-free regular sets of ω-sequences. Inform. and Control 42, 148–156 (1979)
15. Thomas, W.: A combinatorial approach to the theory of ω-automata. Inform. and Control 48, 261–283 (1981)
16. Thomas, W.: Automata on Infinite Objects. In: Van Leeuwen, J. (ed.) Handbook of Theoretical Computer Science, pp. 133–191. Elsevier Science Publishers, Amsterdam (1990)
17. Vardi, M.Y.: A temporal fixpoint calculus. In: POPL'88. Proceedings of the 15th Annual ACM SIGACT-SIGPLAN Symposium on Principles of Programming Languages, pp. 250–259 (1988)
18. Wolper, P.: Temporal logic can be more expressive. Inform. and Control 56, 72–99 (1983)
19. Vardi, M.Y., Wolper, P.: Yet another process logic. In: Clarke, E., Kozen, D. (eds.) Logics of Programs. LNCS, vol. 164, pp. 501–512. Springer, Heidelberg (1984)