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Mu-calculus path checking

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Abstract

We investigate the path model checking problem for the μ -calculus. Surprisingly, restricting to deterministic structures does not allow for more efficient model checking algorithm, as we prove that it can encode any instance of the standard model checking problem for the μ -calculus.

1 Introduction

Model checking is a fundamental problem, originally motivated by concerns with the automatic verification of systems, but now more broadly associated with several different fields ranging from Bio-Informatics to Databases to Automated Deduction. In verification settings, model checking problems usually ask whether S , a given model of a system, satisfies ϕ , a given formal property, denoted “ $S \models \phi$ ”. In [8] we introduced the *path model checking* problem (see also Open Problem 4.1 in [4]). This problem is unusual since it is a *restriction* of the classical model checking problem, not an extension as is usually considered. The restriction is that one only considers models having the form of a *finite path* (or a finite loop, or more generally an ultimately periodic infinite path). These are models *without choice*, or *without nondeterminism*. Checking finite paths or loops occurs naturally in many applications: run-time verification [5], analysis of machine-generated scenarios or debugger traces [1], analysis of log files [11], Monte Carlo methods for verification [6], etc.

In [8] we consider path model checking for several temporal logics. Our findings can be summarized as follows:

- checking a deterministic path is usually much easier than checking a nondeterministic structure,
- checking a finite path and checking a loop are usually equivalent (inter-reducible).

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In this note, we consider path model checking for the modal μ -calculus. It is known that checking whether a Kripke structure S satisfies a μ -calculus formula (called the *branching-time*, or B_μ , model-checking problem) is **PTIME**-hard, and is in $\mathbf{UP} \cap \mathbf{coUP}$ [7]. Additionally, checking whether all paths of S satisfy a μ -calculus formula (called the *linear-time*, or L_μ , model-checking problem) is **PSPACE**-complete [12].

For path model checking, our findings are surprising:

- (1) General B_μ model checking reduces to path model checking. Hence B_μ model checking does not become easier when it is restricted to structures without choice. This does not fit the pattern observed in [8] for other logics like CTL or CTL*.
- (2) The above reduction uses loops. We were not able to reduce checking of finite loops to checking of finite paths. Again this does not fit the pattern observed in [8] for other logics.

The paper contains some additional results, e.g., that model checking of finite paths is **PTIME**-complete (hence the above discrepancies would disappear if it turns out that μ -calculus model checking is in **PTIME**, a conjecture believed true by several researchers), or relating loops and finite paths in a μ -calculus extended with backwards (sometimes called “past-time”) modalities.

2 Preliminaries

We refer to [3]. μ -calculus formulae are given by the following grammar:

$$B_\mu \ni \varphi, \psi ::= p \mid \neg p \mid Z \mid \varphi \wedge \psi \mid \varphi \vee \psi \mid \diamond \varphi \mid \square \varphi \mid \mu Z. \varphi \mid \nu Z. \varphi$$

where p ranges over a set AP of *atomic propositions*, and Z over a set \mathcal{V} of *variable names*. Our definition only allows negations on propositions, but negation of arbitrary formulae can be defined in the standard way, and similarly for classical shorthands such as \Rightarrow , etc. We define the CTL-modalities **EF** and **AG** with: $\mathbf{EF}\varphi \stackrel{\text{def}}{=} \mu Z.(\varphi \vee \diamond Z)$ and $\mathbf{AG}\varphi \stackrel{\text{def}}{=} \nu Z.(\varphi \wedge \square Z)$ where Z is any variable not free in φ .

Formulae in B_μ are interpreted over finite Kripke structures (KS), *i.e.*, labeled finite-state systems of the general form $K = (Q, R, l)$ where $R \subseteq Q \times Q$ is the set of transitions and $l : Q \rightarrow 2^{\text{AP}}$ is the state labeling. As usual, and when R is understood, we write $x \rightarrow y$ rather than $(x, y) \in R$, and we say y is a *successor* of x . Given $S \subseteq Q$, we write $\text{Pre}(S)$ for the set $\{x \in Q \mid \exists y \in S. x \rightarrow y\}$, and \overline{S} for $Q \setminus S$. Then $x \in \overline{\text{Pre}(\overline{S})}$ iff all the successors of x (if any) are in S .

Formally, for a KS $K = (Q, R, l)$ and a context $v : \mathcal{V} \rightarrow 2^Q$, the set $\llbracket \varphi \rrbracket_v^K$ of states

where φ holds is defined inductively:

$$\begin{aligned}
\llbracket p \rrbracket_v^K &\stackrel{\text{def}}{=} \{x \in Q \mid p \in l(x)\} & \llbracket \neg p \rrbracket_v^K &\stackrel{\text{def}}{=} \{x \in Q \mid p \notin l(x)\} \\
\llbracket \varphi \vee \psi \rrbracket_v^K &\stackrel{\text{def}}{=} \llbracket \varphi \rrbracket_v^K \cup \llbracket \psi \rrbracket_v^K & \llbracket \varphi \wedge \psi \rrbracket_v^K &\stackrel{\text{def}}{=} \llbracket \varphi \rrbracket_v^K \cap \llbracket \psi \rrbracket_v^K \\
\llbracket Z \rrbracket_v^K &\stackrel{\text{def}}{=} v(Z) \\
\llbracket \diamond \varphi \rrbracket_v^K &\stackrel{\text{def}}{=} \text{Pre}(\llbracket \varphi \rrbracket_v^K) & \llbracket \square \varphi \rrbracket_v^K &\stackrel{\text{def}}{=} \overline{\text{Pre}(\llbracket \varphi \rrbracket_v^K)} \\
\llbracket \mu Z. \varphi \rrbracket_v^K &\stackrel{\text{def}}{=} \bigcap \{U \subseteq Q \mid \llbracket \varphi \rrbracket_{v[Z \mapsto U]}^K \subseteq U\} \\
\llbracket \nu Z. \varphi \rrbracket_v^K &\stackrel{\text{def}}{=} \bigcup \{U \subseteq Q \mid U \subseteq \llbracket \varphi \rrbracket_{v[Z \mapsto U]}^K\}
\end{aligned}$$

We sometimes omit the “ K ” and “ v ” subscripts when no ambiguity arises (or for closed formulae where “ v ” is irrelevant) and write $x \models_v^K \varphi$ when $x \in \llbracket \varphi \rrbracket_v^K$. The above definition entails the following standard *fixed-point equalities*:

$$\llbracket \mu Z. \varphi \rrbracket_v = \llbracket \varphi \rrbracket_{v[Z \mapsto \llbracket \mu Z. \varphi \rrbracket_v]} \quad \llbracket \nu Z. \varphi \rrbracket_v = \llbracket \varphi \rrbracket_{v[Z \mapsto \llbracket \nu Z. \varphi \rrbracket_v]}$$

For $\alpha \in \mathbb{N}$, the *approximant* $\llbracket \mu Z^\alpha. \varphi \rrbracket_v^K$ is defined inductively by

$$\llbracket \mu Z^0. \varphi \rrbracket_v \stackrel{\text{def}}{=} \emptyset \quad \text{and} \quad \llbracket \mu Z^{\alpha+1}. \varphi \rrbracket_v \stackrel{\text{def}}{=} \llbracket \varphi \rrbracket_{v[Z \mapsto \llbracket \mu Z^\alpha. \varphi \rrbracket_v]}$$

Set $\llbracket \nu Z^\alpha. \varphi \rrbracket_v$ is defined dually. It is well known that, since K is finite, the sequences $(\llbracket \mu Z^\alpha. \varphi \rrbracket_v)_{\alpha \in \mathbb{N}}$ and $(\llbracket \nu Z^\alpha. \varphi \rrbracket_v)_{\alpha \in \mathbb{N}}$ eventually reach $\llbracket \mu Z. \varphi \rrbracket_v$ and $\llbracket \nu Z. \varphi \rrbracket_v$ resp.

A KS is *deterministic* if every state has at most one successor. For such KS’s, $\diamond \varphi$ and $\square \varphi$ have very close meanings: $\diamond \varphi$ means that φ holds in the successor state, while $\square \varphi$ means that, *if* there is a successor state, *then* φ holds in that state. We consider below deterministic KS’s having the form of a finite *path* (isomorphic to an initial segment of \mathbb{N} , with a last state having no successors), or a finite *loop* (where there is a single strongly connected component). On loops, the meanings of $\diamond \varphi$ and $\square \varphi$ coincide exactly.

3 Main result

Theorem 3.1 *B_μ model checking logspace-reduces to model checking of loops.*

Hence μ -calculus model checking of loops and general B_μ model checking are equivalent (inter-reducible). Considering deterministic KS’s does not simplify the problem:

Corollary 3.2 *B_μ model checking of loops is PTIME-hard, and in $\text{UP} \cap \text{coUP}$.*

The rest of this section describes our reduction. We transform an instance “ $x \models_v^K \varphi$?” into an equivalent “ $x' \models_v^L \tilde{\varphi}$?” where L is a loop. We observe that $|L| = O(|K|)$,

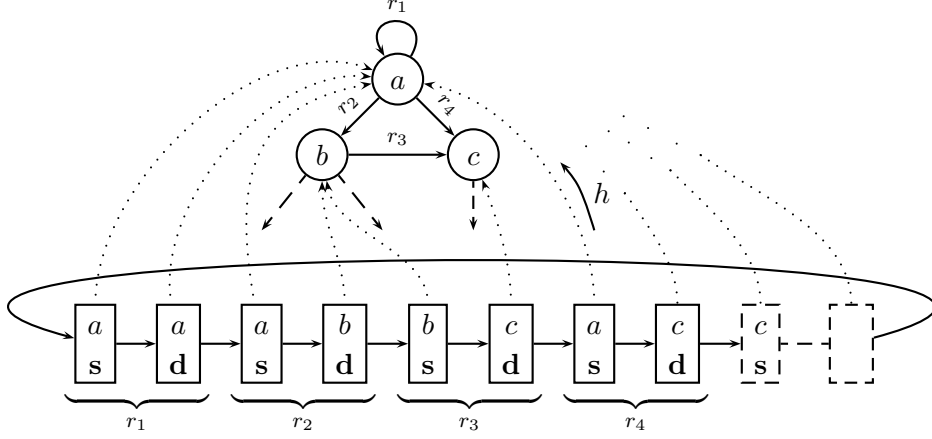


Fig. 1. From non-deterministic to deterministic Kripke structure

and $|\tilde{\varphi}| = O(|K| \cdot |\varphi|)$. Furthermore, the transformation from φ to $\tilde{\varphi}$ does not increase the alternation depth (Prop. 3.8).

Let $K = (Q, R, l)$ be a KS. For this reduction we assume that AP and Q coincide, and that l is the identity.¹ L has labels from $\text{AP}' \stackrel{\text{def}}{=} \text{AP} \cup \{\mathbf{s}, \mathbf{d}\}$ where \mathbf{s} (for *source*) and \mathbf{d} (for *destination*) are two new atomic propositions. Assume $R = \{r_1, \dots, r_n\}$ contains n transitions: then $L = (Q', R', l')$ has $Q' \stackrel{\text{def}}{=} \{s_1, d_1, s_2, d_2, \dots, s_n, d_n\}$. R' has transitions $s_i \rightarrow d_i$ and $d_i \rightarrow s_{(i \bmod n) + 1}$ for $1 \leq i \leq n$, arranging Q' into a loop. Finally, the labeling l' is defined as follows: if $r_i = (x, y)$ then $l'(s_i) = \{x, \mathbf{s}\}$ and $l'(d_i) = \{y, \mathbf{d}\}$.

In summary, L lists the transitions of K . The states of L maps to original states via the mapping $h: Q' \rightarrow Q$ given by $h(x') = x \Leftrightarrow x \in l'(x')$. Fig. 1 illustrates this construction on a schematic example.

In the sequel we use $h(x')$ either as a state or as an element of AP' , depending on the context. For any $S \subseteq Q$, $h(x') \in S$ iff $x' \in h^{-1}(S)$.

Lemma 3.3 *Let $S \subseteq Q$. Then $\text{Pre}_K(S) = h(\llbracket \mathbf{s} \rrbracket^L \cap \text{Pre}_L(h^{-1}(S)))$.*

PROOF. Assume $x \in \text{Pre}_K(S)$ because of a transition r_i of the form $x \rightarrow y$ with $y \in S$. In L , $s_i \rightarrow d_i$ has $d_i \in h^{-1}(y) \subseteq h^{-1}(S)$ and $s_i \in \llbracket \mathbf{s} \rrbracket^L$. Hence $x = h(s_i) \in h(\llbracket \mathbf{s} \rrbracket^L \cap \text{Pre}_L(h^{-1}(S)))$. Conversely, if $x \in h(\llbracket \mathbf{s} \rrbracket^L \cap \text{Pre}_L(h^{-1}(S)))$, then $x = h(s_i)$ for some i such that $h(d_i) \in S$. Therefore r_i shows that $x \in \text{Pre}_K(S)$. \square

Now, define $\Theta(Z) \stackrel{\text{def}}{=} \bigvee_{x \in Q} [x \wedge \mathbf{EF}(x \wedge Z)]$ and $\Xi(Z) \stackrel{\text{def}}{=} \bigwedge_{x \in Q} [x \Rightarrow \mathbf{AG}(x \Rightarrow Z)]$.

Lemma 3.4 *For all v , $\llbracket \Theta(Z) \rrbracket_v^L = h^{-1}(h(\llbracket Z \rrbracket_v^L))$ and $\llbracket \Xi(Z) \rrbracket_v^L = \overline{h^{-1}(h(\overline{\llbracket Z \rrbracket_v^L}))}$.*

¹ This assumption is no loss of generality. Any general KS can be relabeled in such a way. This requires replacing any proposition used in the original labeling with a disjunction of (the propositions denoting) the states where it holds. This transformation is logspace.

PROOF. $\llbracket \Theta(Z) \rrbracket_v$ is $\bigcup_{x \in Q} \llbracket x \wedge \mathbf{EF}(x \wedge Z) \rrbracket_v$. Since L is strongly connected, this is $\{x' \mid \exists y' \in \llbracket Z \rrbracket_v, h(x') = h(y')\}$ by definition of l' . We end up with $h^{-1}(h(\llbracket Z \rrbracket_v))$. The second result follows by duality. \square

Lemma 3.5 *Assume Y and Z are distinct variables. Then for all v , we have*

$$\begin{aligned} \llbracket \mu Z.(Y \vee \Theta(Z)) \rrbracket_v^L &= \Theta(Y) = h^{-1}\left(h\left(\llbracket Y \rrbracket_v^L\right)\right) \\ \llbracket \nu Z.(Y \wedge \Xi(Z)) \rrbracket_v^L &= \Xi(Y) = \overline{h^{-1}\left(h\left(\overline{\llbracket Y \rrbracket_v^L}\right)\right)}. \end{aligned}$$

PROOF. We only prove the first result, the second one being dual.

(\subseteq): Write U for $h^{-1}(h(\llbracket Y \rrbracket_v))$. Then $\llbracket Y \vee \Theta(Z) \rrbracket_{v[Z \mapsto U]} = \llbracket Y \rrbracket_v \cup \llbracket \Theta(Z) \rrbracket_{v[Z \mapsto U]} = \llbracket Y \rrbracket_v \cup h^{-1}(h(U))$ (by Lemma 3.4) $= U$. Hence U is a fixed point and $\llbracket \mu Z.(Y \vee \Theta(Z)) \rrbracket_v \subseteq U$.

(\supseteq): Write S for $\llbracket \mu Z.(Y \vee \Theta(Z)) \rrbracket_v$. From the fixed-point property, we have $S = \llbracket Y \vee \Theta(Z) \rrbracket_{v[Z \mapsto S]} = \llbracket Y \rrbracket_v \cup \llbracket \Theta(S) \rrbracket_v = \llbracket Y \rrbracket_v \cup h^{-1}(h(S))$ (by Lemma 3.4). Hence $S \supseteq h^{-1}(h(\llbracket Y \rrbracket_v))$. \square

Thus $\Theta(\psi)$ and $\mu Z.(\psi \vee \Theta(Z))$ are equivalent on L (when Z does not occur free in ψ). The important difference between them is size: $|\Theta(\psi)|$ is in $O(|Q| \cdot |\psi|)$ while $|\mu Z.(\psi \vee \Theta(Z))|$ is in $O(|Q| + |\psi|)$.

We now translate each formula φ into a $\tilde{\varphi}$ in such a way that if φ holds in $x \in Q$, then $\tilde{\varphi}$ holds in all $x' \in h^{-1}(x)$. Formally, $\tilde{\varphi}$ is defined inductively by:

$$\begin{array}{lll} \tilde{p} \stackrel{\text{def}}{=} p & \tilde{\neg p} \stackrel{\text{def}}{=} \neg p & \tilde{Z} \stackrel{\text{def}}{=} Z \\ \widetilde{\varphi \vee \psi} \stackrel{\text{def}}{=} \tilde{\varphi} \vee \tilde{\psi} & \widetilde{\diamond \varphi} \stackrel{\text{def}}{=} \mu Z [(\mathbf{s} \wedge \diamond \tilde{\varphi}) \vee \Theta(Z)] & \widetilde{\mu Z.\varphi} \stackrel{\text{def}}{=} \mu Z.\tilde{\varphi} \\ \widetilde{\varphi \wedge \psi} \stackrel{\text{def}}{=} \tilde{\varphi} \wedge \tilde{\psi} & \widetilde{\square \varphi} \stackrel{\text{def}}{=} \nu Z. [(\mathbf{s} \Rightarrow \square \tilde{\varphi}) \wedge \Xi(Z)] & \widetilde{\nu Z.\varphi} \stackrel{\text{def}}{=} \nu Z.\tilde{\varphi} \end{array}$$

Lemma 3.6 *For any formula φ involving atomic propositions in AP, and any context $v: \mathcal{V} \rightarrow 2^Q$, and writing v' for $h^{-1} \circ v$:*

$$h^{-1}\left(\llbracket \varphi \rrbracket_v^K\right) = \llbracket \tilde{\varphi} \rrbracket_{v'}^L \quad (1)$$

In other words, $x' \in \llbracket \tilde{\varphi} \rrbracket_{v'}^L$ iff $h(x') \in \llbracket \varphi \rrbracket_v^K$.

PROOF. By induction on the structure of φ .

Case $\varphi = p \in \text{AP}$: Since $\text{AP} = Q$, and by definition of l' , $h^{-1}(\llbracket p \rrbracket^K) = \llbracket p \rrbracket^L$.

Case $\varphi = Z \in \mathcal{V}$: $h^{-1}(\llbracket Z \rrbracket_v) = h^{-1} \circ v(Z) = \llbracket Z \rrbracket_{v'}$ by definition of v' .

Case $\varphi = \mu Z.\psi$: It is sufficient to show that, for all integers α , $h^{-1}(\llbracket \mu Z^\alpha.\psi \rrbracket_v) = \llbracket \mu Z^\alpha.\tilde{\psi} \rrbracket_{v'}$. We proceed by induction on α . The base case where $\alpha = 0$ holds trivially, and the inductive step relies on $h^{-1}(\llbracket \mu Z^{\alpha+1}.\psi \rrbracket_v) = h^{-1}(\llbracket \psi \rrbracket_{v[Z \mapsto \llbracket \mu Z^\alpha.\psi \rrbracket_v]}) = \llbracket \tilde{\psi} \rrbracket_{h^{-1} \circ v[Z \mapsto \llbracket \mu Z^\alpha.\psi \rrbracket_v]}$ by ind. hyp. (Lemma 3.6 on ψ). This is $\llbracket \tilde{\psi} \rrbracket_{v'[Z \mapsto h^{-1}(\llbracket \mu Z^\alpha.\psi \rrbracket_v)]} = \llbracket \tilde{\psi} \rrbracket_{v'[Z \mapsto \llbracket \mu Z^\alpha.\tilde{\psi} \rrbracket_{v'}]}$ (by ind. hyp. on α), hence equals $\llbracket \mu Z^{\alpha+1}.\tilde{\psi} \rrbracket_{v'}$.

Case $\varphi = \diamond\psi$: $h^{-1}(\llbracket \diamond\psi \rrbracket_v) = h^{-1}(\text{Pre}(\llbracket \psi \rrbracket_v)) = h^{-1}(h(\llbracket \mathbf{s} \rrbracket \cap \text{Pre}(h^{-1}(\llbracket \psi \rrbracket_v))))$ (Lemma 3.3) $= h^{-1}(h(\llbracket \mathbf{s} \rrbracket \cap \text{Pre}(\llbracket \tilde{\psi} \rrbracket_{v'})))$ by ind. hyp. This is $h^{-1}(h(\llbracket \mathbf{s} \rrbracket \wedge \diamond\tilde{\psi} \rrbracket_{v'}))$, or $\llbracket \diamond\tilde{\psi} \rrbracket_{v'}$ (Lemma 3.5).

Remaining cases: The case where φ is some $\varphi_1 \wedge \varphi_2$ is obvious and the remaining cases are obtained by duality. \square

Corollary 3.7 For $x' \in h^{-1}(x)$ and φ a closed formula, $x \models_K \varphi$ iff $x' \models_L \tilde{\varphi}$.

PROOF. Lemma 3.6 provides the “ \Rightarrow ” direction, and the “ \Leftarrow ” direction too once we observe that $h \circ h^{-1} = \text{Id}_Q$. \square

Regarding alternation depth, we refer to [10,2]. A μ -calculus formula is in Σ_0 ($= \Pi_0$) iff it contains not fixpoint operation. Then, for $n \in \mathbb{N}$, Σ_{n+1} is defined as the smallest class of formulae that contains $\Sigma_n \cup \Pi_n$ and is closed under conjunctions and disjunctions, \diamond - and \square -modalities, least fixed points $\mu Z.\varphi$ with $\varphi \in \Sigma_{n+1}$, and substitution of $\varphi' \in \Sigma_{n+1}$ for a free variable of a formula $\varphi \in \Sigma_{n+1}$, provided that no free variable of φ' is captured by φ . Π_{n+1} is defined dually.

Proposition 3.8 If $\varphi \in \Sigma_n$ (or dually, Π_n), then $\tilde{\varphi}$ is in $\Sigma_{\max(n,2)}$ (resp. $\Pi_{\max(n,2)}$).

PROOF. By induction on the structure of φ . The only difficult cases are \diamond - and \square -formulae. If $\varphi = \diamond\psi$, with $\psi \in \Sigma_n$, the induction hypothesis yields that $\tilde{\psi} \in \Sigma_{\max(n,1)}$. Then $\tilde{\varphi}$ is obtained from $\mu Z.[(\mathbf{s} \wedge \diamond W) \vee \Theta(Z)]$, a Σ_1 -formula, by substituting $\tilde{\psi}$ for W . If $\varphi = \square\psi$, we substitute in a Π_1 (hence Σ_2) formula. \square

4 Finite paths and acyclic structures

It is well-known that, for acyclic KS's, B_μ model checking can be done in polynomial-time (hence is **PTIME**-complete), see, *e.g.*, [9]. Thus model checking finite paths is in polynomial-time and it is not surprising that we could not reduce model checking of loops to model checking of paths: with Theorem 3.1, this would have solved the general B_μ model-checking problem.

However, even if finite paths seem easier than finite loops, they are not easier than arbitrary acyclic KS's as we now show.

Theorem 4.1 *B_μ model checking of finite paths is **PTIME**-complete.*

For this result, it turns out that the reduction from the previous section adapts very easily. If we omit the step $d_n \rightarrow s_1$ that closed the loop, we obtain a finite path where, assuming that the transitions $R = \{r_1, \dots, r_n\}$ of the acyclic K are given in some topological order, for every vertex of K , the *destination* copies (if any) occur before the *source* copies. That way, we get:

Lemma 4.2 *Given $x', y' \in Q'$ s.t. $h(x') = h(y')$ and x' occurs before y' , for any formula $\varphi \in B_\mu$ and any context $v: \mathcal{V} \rightarrow 2^Q$, writing $v' = h^{-1} \circ v$, we have: if $y' \in \llbracket \tilde{\varphi} \rrbracket_{v'}^{K'}$, then $x' \in \llbracket \tilde{\varphi} \rrbracket_{v'}^{K'}$.*

That result can easily be shown by induction. We then obtain weaker versions of Lemmas 3.4, 3.5 and 3.6:

Lemma 4.3 *Assuming Y and Z are distinct variables, for any context v' , we have*

$$h \left(\llbracket \Theta(Y) \rrbracket_{v'}^{K'} \right) = h \left(\llbracket Y \rrbracket_{v'}^{K'} \right) = h \left(\llbracket \mu Z.(Y \vee \Theta(Z)) \rrbracket_{v'}^{K'} \right)$$

Lemma 4.4 *For any formula φ of B_μ involving atomic propositions in AP, context $v: \mathcal{V} \rightarrow 2^Q$, and writing v' for $h^{-1} \circ v$:*

$$\llbracket \varphi \rrbracket_v^K = h \left(\llbracket \tilde{\varphi} \rrbracket_{v'}^{K'} \cap \llbracket \mathbf{s} \rrbracket \right) \quad h^{-1} \left(\llbracket \varphi \rrbracket_v^K \right) \cap \llbracket \mathbf{d} \rrbracket = \llbracket \tilde{\varphi} \rrbracket_{v'}^{K'} \cap \llbracket \mathbf{d} \rrbracket$$

Now, clearly, a state in K satisfies formula φ iff its first *source* copy in L satisfies $\tilde{\varphi}$.

5 Paths, loops, and backwards modalities

Model checking of loops reduces to finite paths when one considers $2B_\mu$, or “2-way B_μ ”, the extension of B_μ with backwards modalities \diamond^{-1} and \square^{-1} . One lets $x \in \llbracket \diamond^{-1}\varphi \rrbracket$ iff there is some $y \in \llbracket \varphi \rrbracket$ with $y \rightarrow x$, and dually for \square^{-1} [13].

Theorem 5.1 *The following three problems are logspace inter-reducible:*

- (a) B_μ model checking of loops,
- (b) $2B_\mu$ model checking of loops,
- (c) $2B_\mu$ model checking of finite paths.

Corollary 5.2 *These three problems are equivalent to B_μ model checking on arbitrary KS's. They are thus **PTIME**-hard, and in $\mathbf{UP} \cap \mathbf{coUP}$.*

PROOF. (of Theorem 5.1) Since (a) is a special case of (b), we only need two reductions.

(b reduces to c) Let L be a loop $x_1 \rightarrow x_2 \rightarrow \dots \rightarrow x_n (\rightarrow x_1)$. With L , the reduction associates a finite path F of the form $x_0 \rightarrow x_1 \rightarrow x_2 \rightarrow \dots \rightarrow x_n \rightarrow x_{n+1}$. The labeling of F is inherited from L (and irrelevant for x_0 and x_{n+1}). The reduction translates a formula φ to a φ' such that $\llbracket \varphi' \rrbracket^F \setminus \{x_0, x_{n+1}\} = \llbracket \varphi \rrbracket^L$. The translation is obtained with

$$\begin{aligned} (\diamond\psi)' &\stackrel{\text{def}}{=} \mu Z. \left((\diamond\psi' \wedge \diamond\diamond\top) \vee (\diamond^{-1})^n Z \right) \\ (\diamond^{-1}\psi)' &\stackrel{\text{def}}{=} \mu Z. \left((\diamond^{-1}\psi' \wedge \diamond^{-1}\diamond^{-1}\top) \vee (\diamond)^n Z \right) \end{aligned}$$

One adds dual clauses for $(\square\psi)'$ and $(\square^{-1}\psi)'$, and obvious clauses, like $(\mu Z.\psi)'$ $\stackrel{\text{def}}{=} \mu Z.(\psi')$, for the other constructs. Then $|\varphi'|$ is in $O(|\varphi| \cdot |L|)$.

(c reduces to a) Let F be a finite path $x_1 \rightarrow x_2 \rightarrow \dots \rightarrow x_n$. A loop L is obtained from F by adding a transition $x_n \rightarrow x_1$ and labeling x_1 with a new additional proposition \mathbf{i} . The reduction then translates a formula φ to a φ' without backwards modalities, and such that $\llbracket \varphi' \rrbracket^L = \llbracket \varphi \rrbracket^F$. We use

$$(\diamond\psi)' \stackrel{\text{def}}{=} \diamond(\psi' \wedge \neg\mathbf{i}) \quad \text{and} \quad (\diamond^{-1}\psi)' \stackrel{\text{def}}{=} \neg\mathbf{i} \wedge \diamond^{n-1}\psi'$$

and obvious remaining clauses. Again, $|\varphi'|$ is in $O(|\varphi| \cdot |L|)$. \square

6 Conclusion

We proved that μ -calculus model checking is not easier when restricting to deterministic Kripke structures having the form of a single loop. On the other hand, we could not reduce model checking of finite loops to model checking of finite paths, a **P**TIME-complete problem. These results help understand what makes μ -calculus model checking difficult.

It comes as a surprise that none of these two results fits the pattern we exhibited for several other logics [8], where checking nondeterministic KS's is harder than checking deterministic loops, and where finite loops are no harder than finite paths. A possible explanation for the first discrepancy is the expressive power of the μ -calculus, that allows the reduction we developed in Section 3. The second discrepancy is harder to justify, but would disappear if μ -calculus model checking were proved to be in **P**TIME.

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