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Chapter 4

How Arbitrary Are Arbitrary Public Announcements?

Chapter Summary. In this chapter we look at the *arbitrary public announcement* operator \diamond from Arbitrary Public Announcement Logic (APAL). In particular we check whether \diamond is a faithful representation of an arbitrary public announcement.

If \diamond would be a faithful representation of an arbitrary public announcement then $\diamond\varphi$ would hold whenever there is some ψ such that $\langle\psi\rangle\varphi$. In that case $\langle\psi\rangle\varphi \rightarrow \diamond\varphi$ would be valid for every ψ and φ . In this chapter I show that this is not the case: there are ψ, φ such that $\not\models \langle\psi\rangle\varphi \rightarrow \diamond\varphi$.

There are however interesting limited cases where \diamond does faithfully represent an arbitrary public announcement. If (i) we only consider finite models or (ii) we only consider finitely branching models and φ is \diamond -free then $\langle\psi\rangle\varphi \rightarrow \diamond\varphi$ is valid for all ψ .

4.1 Introduction

In epistemic logic we can reason about basic facts (represented by propositional variables) and about knowledge of different agents (represented by one operator K_a per agent). A commonly used example in epistemic logic is that of a simple card game. Suppose two agents a and b are playing a game where they each hold one card, and they know their own card but not the other's card. Then if a holds a queen (and we use the propositional variable q to represent this basic fact) the formulas (i) $K_a q$, (ii) $q \wedge \neg K_b q$ and (iii) $K_a \neg K_b q$ represent the (true) statements (i) “ a knows that she holds a queen”, (ii) “ a holds a queen but b does not know this”, and (iii) “ a knows that b does not know that she holds a queen”.

In such a basic epistemic logic we cannot express information change though. For example, we cannot reason about what would happen if a were to show her card to b in basic epistemic logic. If we want to reason about information change we need to use a *dynamic* epistemic logic. There are many different kinds of dynamic epistemic logic, see for example [van Ditmarsch et al., 2007] for an overview. One of the most

This chapter is based on the paper “How Arbitrary are Arbitrary Public Announcements” [Kuijjer, 2014a] that appeared in *Pristine Perspectives on Logic, Language and Computation*, a collection of papers that were presented at ESSLLI 2012 and ESSLLI 2013.

common ways to turn a (static) epistemic logic into a dynamic epistemic logic is to add *public announcements* [Plaza, 1989, Baltag et al., 1998] to the logic. A public announcement is a binary operator of the form $\langle \psi \rangle \varphi$. The formula $\langle \psi \rangle \varphi$ is true if φ will hold after ψ is announced *truthfully* and *publicly*.¹

Using public announcements we can reason about what would happen if a were to show her card to b ; the showing of a card can be considered an announcement of the card that a holds. The statement “after a shows her card, b knows what card a holds” is therefore represented by the (true) formula $\langle q \rangle K_b q$. One thing to note about the formula $\langle q \rangle K_b q$ is that after q is announced, agent b knows that q , so the announcing of q is a way for b to get to know q .

However, not all formulas can be learned in such a way. Consider the formula $q \wedge \neg K_b q$, representing a holding a queen and b not knowing this. This formula is a variant on a sentence that was introduced by [Moore, 1993] and [Fitch, 1963] as an example of something that can never be known by b even if it is true. Since $q \wedge \neg K_b q$ can never be known by b there is also no announcement such that b will know $q \wedge \neg K_b q$ after the announcement. So not only is it impossible for b to get to know the truth of $q \wedge \neg K_b q$ by announcing $q \wedge \neg K_b q$,² there is no formula ψ such that $\langle \psi \rangle K_b (q \wedge \neg K_b q)$.

This last property, whether for a given φ there exists a ψ such that $\langle \psi \rangle K_b \varphi$, requires us to quantify over all formulas. We can of course do this quantification meta-logically, but epistemic logic with public announcements does not allow us to perform this quantification inside the logic. This is unfortunate, as this means we cannot use public announcements to reason about whether it is possible to get to know something. A solution proposed in [van Benthem, 2004] and [Balbiani et al., 2007, 2008] is to add quantification over announced formulas to the logic. Here we follow [Balbiani et al., 2007, 2008] and use an operator \diamond to represent an *arbitrary public announcement*, with the intuitive meaning that $\diamond \varphi$ if and only if $\exists \psi : \langle \psi \rangle \varphi$.

Such arbitrary public announcements can be useful when considering problems of knowability, but also in more practical scenarios such as in cryptography where it is important to know whether it is possible to make a public statement such that agent b learns the content p of a message but another agent e does not, that is, whether $\diamond(K_b p \wedge \neg K_e p)$.

We would like to define a logic $\mathcal{L}_{\text{APAL}}$ with an operator \diamond that represents an entirely arbitrary announcement, in the sense that $\diamond \varphi$ holds if and only if there is some formula ψ of $\mathcal{L}_{\text{APAL}}$ such that $\langle \psi \rangle \varphi$ holds.³ There is a technical problem with this kind of definition, however. If we allow the announcement ψ to be *any* formula of $\mathcal{L}_{\text{APAL}}$ the evaluation of $\diamond \varphi$ would become circular. After all, in order to know whether $\diamond \varphi$ holds we would have to check whether $\langle \diamond \varphi \rangle \varphi$ holds. But in order to know whether $\langle \diamond \varphi \rangle \varphi$ holds we would among other things have to know whether $\diamond \varphi$ is a truthful announcement, so whether $\diamond \varphi$ holds.

This circularity is removed in [Balbiani et al., 2007, 2008] by restricting ψ to formulas that do not themselves contain \diamond operators. So $\diamond \varphi$ holds if and only if there is a \diamond -free formula ψ such that $\langle \psi \rangle \varphi$. Unfortunately this means that the announcements in an arbitrary public announcement operator are not in fact entirely arbitrary. But

¹Usually public announcements are defined by an operator $[\psi]$ instead of its dual $\langle \psi \rangle$ as we do here. Our reason for using $\langle \psi \rangle$ in this chapter is that it is notationally convenient to do so.

²In fact, we not only have $\neg \langle q \wedge \neg K_b q \rangle K_b (q \wedge \neg K_b q)$ but also $\neg \langle q \wedge \neg K_b q \rangle (q \wedge \neg K_b q)$. Such an update $\langle \varphi \rangle$ for which $\neg \langle \varphi \rangle \varphi$ holds is sometimes called an *unsuccessful* update, see for example [van Ditmarsch, 2000, Chapter 6] and [Gerbrandy, 1999, Chapter 7].

³So by “entirely arbitrary” we mean that the announcement could be any formula of our logic, not that it could be a formula of a different logic or, say, a cucumber.

while the definition of \diamond cannot allow completely arbitrary announcements, it might be possible to get entirely arbitrary announcements as an “emergent property”. Suppose that whenever there is a ψ containing \diamond such that $\langle\psi\rangle\varphi$ there would always also be a ψ' that is \diamond -free such that $\langle\psi'\rangle\varphi$. Then $\langle\psi\rangle\varphi$ would imply $\diamond\varphi$, even if ψ happens to contain a \diamond .

A different way of phrasing this is to ask whether $\langle\psi\rangle\varphi \rightarrow \diamond\varphi$ is valid for every ψ . It was shown in [Balbani et al., 2007] that the implication is valid if there is only a single agent. In this chapter we show that if there are multiple agents, the validity of the implication depends on the class of models we use to evaluate the logic on and on φ . If we use only finite models, then $\langle\psi\rangle\varphi \rightarrow \diamond\varphi$ is valid. If we allow finitely branching infinite models, then $\langle\psi\rangle\varphi \rightarrow \diamond\varphi$ is valid for every ψ and every \diamond -free φ . But if we allow models that are infinitely branching or if we do not restrict to \diamond -free φ , then there are φ and ψ such that $\langle\psi\rangle\varphi \rightarrow \diamond\varphi$ is not valid.

In Section 4.2, we give some definitions needed to formulate and prove the results. Then in Section 4.3, we show that for finite models $\langle\psi\rangle\varphi \rightarrow \diamond\varphi$ is valid. In Section 4.4.1, we prove that for finitely branching models $\langle\psi\rangle\varphi \rightarrow \diamond\varphi$ is valid if φ is \diamond -free. In Section 4.4.2, we construct ψ and \diamond -free φ such that $\langle\psi\rangle\varphi \rightarrow \diamond\varphi$ is not valid on infinitely branching models. Finally, in Section 4.4.3, we construct φ and ψ containing \diamond such that $\langle\psi\rangle\varphi \rightarrow \diamond\varphi$ is not valid on finitely branching models.

4.2 Definitions

Let us start by defining *arbitrary public announcement logic* $\mathcal{L}_{\text{APAL}}$ and the \diamond -free fragment *public announcement logic* \mathcal{L}_{PAL} of $\mathcal{L}_{\text{APAL}}$. Let us fix a countably infinite set \mathcal{P} of propositional variables and a finite set \mathcal{A} of agents. The language of $\mathcal{L}_{\text{APAL}}$ is then defined as follows.

Definition 4.1 (Formulas of $\mathcal{L}_{\text{APAL}}$). The *formulas* of $\mathcal{L}_{\text{APAL}}$ are given by

$$\varphi ::= p \mid \neg\varphi \mid (\varphi \vee \varphi) \mid K_a\varphi \mid \langle\varphi\rangle\varphi \mid \diamond\varphi$$

where p ranges over \mathcal{P} and a ranges over \mathcal{A} .

Definition 4.2 (Fragment \mathcal{L}_{PAL}). The logic \mathcal{L}_{PAL} is the \diamond -free fragment of $\mathcal{L}_{\text{APAL}}$.

Parentheses are omitted where this should not cause confusion and \wedge , \rightarrow , \leftrightarrow , \bigvee and \bigwedge are used in the usual way as abbreviations. Furthermore, \hat{K}_a , $[\varphi]$ and \square are used as abbreviations for $\neg K_a\neg$, $\neg\langle\varphi\rangle\neg$ and $\neg\diamond\neg$ respectively. Integer superscripts are used to indicate multiple copies of an operator, so K_a^3 stands for $K_a K_a K_a$. Finally, if B is a set of agents then K_B stands for $\bigwedge_{a \in B} K_a$ and \hat{K}_B for $\bigvee_{a \in B} K_a$. The intended reading of the non-boolean operators is as follows:

- $K_a\varphi$ is read as “agent a knows that φ ”,
- $\langle\psi\rangle\varphi$ is read as “ ψ is true and, after it is publicly announced that ψ is the case, φ holds”,
- $\diamond\varphi$ is read as “there is a \diamond -free announcement ψ such that $\langle\psi\rangle\varphi$ holds”.

Since $\mathcal{L}_{\text{APAL}}$ and \mathcal{L}_{PAL} are epistemic logics they are usually considered over the class of S5 models. We will follow this tradition, but it should be noted that none of the proofs in this chapter depend on the special properties of S5 models. So all the results presented here also hold over the class of K models.

Definition 4.3 (Models of $\mathcal{L}_{\text{APAL}}$). A *model* \mathcal{M} is a triple (W, R, v) where W is a set of worlds, $R : \mathcal{A} \rightarrow \wp(W \times W)$ assigns to each agent an equivalence relation on W and $v : \mathcal{P} \rightarrow \wp(W)$ is a valuation function that assigns an extension to each propositional variable.

A model $\mathcal{M} = (W, R, v)$ is said to be *finitely branching* if for each $w \in W$ and each $a \in \mathcal{A}$ the set $\{w' \mid (w, w') \in R(a)\}$ is finite. A model $\mathcal{M} = (W, R, v)$ is said to be *finite* if W is a finite set.

The semantics for most operators of $\mathcal{L}_{\text{APAL}}$ are as usual. For the only unusual operator \Diamond , it should be noted that it quantifies over the formulas of \mathcal{L}_{PAL} , instead of over the formulas of $\mathcal{L}_{\text{APAL}}$.

Definition 4.4 (Semantics of $\mathcal{L}_{\text{APAL}}$). Given a model $\mathcal{M} = (W, R, v)$, a world w of \mathcal{M} and φ, ψ formulas of $\mathcal{L}_{\text{APAL}}$ the *satisfaction relation* \models is given by

$$\begin{aligned} \mathcal{M}, w \models p &\iff w \in v(p) \\ \mathcal{M}, w \models \neg\varphi &\iff \mathcal{M}, w \not\models \varphi \\ \mathcal{M}, w \models \varphi \vee \psi &\iff \mathcal{M}, w \models \varphi \text{ or } \mathcal{M}, w \models \psi \\ \mathcal{M}, w \models K_a\varphi &\iff \mathcal{M}, w' \models \varphi \text{ for all } w' \in W \text{ such that } (w, w') \in R(a) \\ \mathcal{M}, w \models \langle\varphi\rangle\psi &\iff \mathcal{M}, w \models \varphi \text{ and } \mathcal{M}_\varphi, w \models \psi \\ \mathcal{M}, w \models \Diamond\varphi &\iff \text{there is an } \mathcal{L}_{\text{PAL}} \text{ formula } \psi \text{ such that } \mathcal{M}, w \models \langle\psi\rangle\varphi \end{aligned}$$

with $\mathcal{M}_\varphi = (W_\varphi, R_\varphi, v_\varphi)$ where $W_\varphi = \{w \in W \mid \mathcal{M}, w \models \varphi\}$ and R_φ and v_φ are the restrictions of R and v to W_φ .

We write $\mathcal{M} \models \varphi$ if $\mathcal{M}, w \models \varphi$ for every $w \in W$ and $\models \varphi$ if $\mathcal{M} \models \varphi$ for every model \mathcal{M} . Furthermore, we write $\models_{\text{br}} \varphi$ if $\mathcal{M} \models \varphi$ for every finitely branching model \mathcal{M} and $\models_{\text{fin}} \varphi$ if $\mathcal{M} \models \varphi$ for every finite model \mathcal{M} .

4.3 APAL on Finite Models

With the definitions out of the way, we can show that $\models_{\text{fin}} \langle\psi\rangle\varphi \rightarrow \Diamond\varphi$ for all $\mathcal{L}_{\text{APAL}}$ formulas ψ . This is not a very surprising result; in a finite model we can replace any \Diamond operator by the announcement of a disjunction of \mathcal{L}_{PAL} formulas, one for each world where the \Diamond is replaced by the ‘‘chosen announcement’’ for that world.

Lemma 4.1. *Let $\mathcal{M} = (W, R, v)$ be a finite model and φ an $\mathcal{L}_{\text{APAL}}$ formula. Then there is an \mathcal{L}_{PAL} formula ψ such that $\mathcal{M} \models \varphi \leftrightarrow \psi$.*

Proof. By induction on the construction of φ . The lemma trivially holds if φ is atomic. Suppose then as induction hypothesis that φ is not atomic, and that the lemma holds for all finite models and all subformulas of φ . The formula φ is not atomic, so it is of one of the following forms:

1. $\varphi = \neg\varphi'$,
2. $\varphi = \varphi' \vee \varphi''$,
3. $\varphi = K_a\varphi'$,
4. $\varphi = \langle\varphi''\rangle\varphi'$ or
5. $\varphi = \Diamond\varphi'$.

By the induction hypothesis, there is an \mathcal{L}_{PAL} formula ψ' such that $\mathcal{M} \models \varphi' \leftrightarrow \psi'$ and, if applicable, an \mathcal{L}_{PAL} formula ψ'' such that $\mathcal{M} \models \varphi'' \leftrightarrow \psi''$. So if we take ψ to be $\neg\psi'$, $\psi' \vee \psi''$ or $K_a\psi'$, then we have $\mathcal{M} \models \varphi \leftrightarrow \psi$ in the first, second or third case, respectively.

Let us then consider fourth case. By the induction hypothesis there are \mathcal{L}_{PAL} formulas ψ'' such that $\mathcal{M} \models \varphi'' \leftrightarrow \psi''$ and ψ' such that $\mathcal{M}_{\varphi''} \models \varphi' \leftrightarrow \psi'$. This implies that $\mathcal{M} \models \varphi \leftrightarrow \langle \psi'' \rangle \psi'$.

Let us then consider the fifth case, $\varphi = \diamond\varphi'$. Let W' be the extension of φ , so $W' := \{w \in W \mid \mathcal{M}, w \models \diamond\varphi'\}$. For each $w_i \in W'$ we have $\mathcal{M}, w_i \models \diamond\varphi'$, so there is an \mathcal{L}_{PAL} formula φ''_i such that $\mathcal{M}, w_i \models \langle \varphi''_i \rangle \varphi'$. By the induction hypothesis there is an \mathcal{L}_{PAL} formula ψ'_i such that $\mathcal{M}_{\varphi''_i} \models \psi'_i \leftrightarrow \varphi'$. We therefore have $\mathcal{M} \models \langle \varphi''_i \rangle \psi'_i \leftrightarrow \langle \varphi''_i \rangle \varphi'$.

Now let $\psi := \bigvee_{w_i \in W'} \langle \varphi''_i \rangle \psi'_i$. This is an \mathcal{L}_{PAL} formula, since all its subformulas are \mathcal{L}_{PAL} formulas and W' is a finite set. Furthermore, for each $w_i \in W'$ we have $\mathcal{M}, w_i \models \psi$.

Suppose now towards a contradiction that for some $w' \in W \setminus W'$ we have $\mathcal{M}, w' \models \psi$. Then one of the disjuncts of ψ holds in w' , so for some $w_i \in W'$ we have $\mathcal{M}, w' \models \langle \varphi''_i \rangle \psi'_i$. Then we also have $\mathcal{M}, w' \models \langle \varphi''_i \rangle \varphi'$, since $\mathcal{M} \models \langle \varphi''_i \rangle \psi'_i \leftrightarrow \langle \varphi''_i \rangle \varphi'$. But φ''_i is an \mathcal{L}_{PAL} formula so this implies that $\mathcal{M}, w' \models \diamond\varphi'$. This contradicts w' being an element of $W \setminus W'$, so we must have $\mathcal{M}, w' \not\models \psi$.

This shows that $\mathcal{M} \models \varphi \leftrightarrow \psi$, which completes the induction step and thereby the proof. \square

It now follows immediately that $\models_{\text{fin}} \langle \psi \rangle \varphi \rightarrow \diamond\varphi$.

Theorem 4.1. *For every $\mathcal{L}_{\text{APAL}}$ formulas φ and χ we have $\models_{\text{fin}} \langle \varphi \rangle \chi \rightarrow \diamond\chi$.*

Proof. Fix any $\mathcal{L}_{\text{APAL}}$ formulas φ and χ , and any finite model \mathcal{M} . Then by Lemma 4.1 there is an \mathcal{L}_{PAL} formula ψ such that $\mathcal{M} \models \varphi \leftrightarrow \psi$. This implies that $\mathcal{M} \models \langle \varphi \rangle \chi \leftrightarrow \langle \psi \rangle \chi$. But ψ is an \mathcal{L}_{PAL} formula so $\models \langle \psi \rangle \chi \rightarrow \diamond\chi$ and therefore $\mathcal{M} \models \langle \varphi \rangle \chi \rightarrow \diamond\chi$. Since this is true for any finite model \mathcal{M} , this implies that $\models_{\text{fin}} \langle \varphi \rangle \chi \rightarrow \diamond\chi$. \square

4.4 APAL on Infinite Models

On infinite models we cannot use the method that worked for finite models, since $\bigvee_{w_i \in W'} \langle \varphi''_i \rangle \psi'_i$ is in general not a formula on infinite models because W' may be infinite. Here we show that no other method can work; there are infinite models \mathcal{M} , worlds w of \mathcal{M} and $\mathcal{L}_{\text{APAL}}$ formulas φ and ψ such that $\mathcal{M}, w \models \langle \psi \rangle \varphi \wedge \neg\diamond\varphi$.

Like the result for the finite case this should not surprise us. What is somewhat surprising, however, is that the result extends to finitely branching models; there are φ and ψ such that $\not\models_{\text{br}} \langle \psi \rangle \varphi \rightarrow \diamond\varphi$. To see why it is unexpected that $\not\models_{\text{br}} \langle \psi \rangle \varphi \rightarrow \diamond\varphi$ consider the following. Fix any finitely branching model \mathcal{M} and any world w of \mathcal{M} . We cannot guarantee the existence of an \mathcal{L}_{PAL} formula ψ' such that $\mathcal{M} \models \psi \leftrightarrow \psi'$, but since \mathcal{M} is finitely branching we can for any $n \in \mathbb{N}$ guarantee the existence of an \mathcal{L}_{PAL} formula ψ'' such that $\mathcal{M}, w' \models \psi \leftrightarrow \psi''$ for every world w' that is reachable within n steps from w .

The language of $\mathcal{L}_{\text{APAL}}$ does not contain common knowledge, so it would at first glance seem like such a ψ'' that is equivalent to ψ up to a given distance might be sufficient to make φ have the same value after both announcements. If φ does not contain any \diamond operators then this does indeed work, for any $\mathcal{L}_{\text{APAL}}$ formula ψ and any

\mathcal{L}_{PAL} formula φ we have $\models_{\text{br}} \langle \psi \rangle \varphi \rightarrow \diamond \varphi$. But a \diamond operator (or more precisely: a \square operator) can make a formula depend on worlds that are arbitrarily far away in such a way that in certain models no finite approximation ψ'' of ψ will suffice.

Let us first show that for \diamond -free φ we have $\models_{\text{br}} \langle \psi \rangle \varphi \rightarrow \diamond \varphi$, then that there are ψ and \diamond -free φ such that $\not\models \langle \psi \rangle \varphi \rightarrow \diamond \varphi$ and finally that for some φ that do contain \diamond we have $\not\models_{\text{br}} \langle \psi \rangle \varphi \rightarrow \diamond \varphi$. This order of proofs is chosen for reasons of clarity of exposition; the proof that $\not\models_{\text{br}} \langle \psi \rangle \varphi \rightarrow \diamond \varphi$ uses more complicated variants of some of the same techniques that are used in the proof of $\not\models \langle \psi \rangle \varphi \rightarrow \diamond \varphi$.

4.4.1 Validity of $\langle \psi \rangle \varphi \rightarrow \diamond \varphi$ for \diamond -free φ

Before proving that $\models_{\text{br}} \langle \psi \rangle \varphi \rightarrow \diamond \varphi$, we need one auxiliary lemma.

Lemma 4.2. *Let \mathcal{M} be any finitely branching model and w_1, w_2 two worlds of \mathcal{M} . Then there is an $\mathcal{L}_{\text{APAL}}$ formula that distinguishes between \mathcal{M}, w_1 and \mathcal{M}, w_2 if and only if there is an \mathcal{L}_{PAL} formula that distinguishes between them.*

Proof. If there is an \mathcal{L}_{PAL} formula ψ' that distinguishes between two worlds, then there is also an $\mathcal{L}_{\text{APAL}}$ formula ψ that distinguishes between the two worlds, namely $\psi = \psi'$. Left to show is that if $\mathcal{L}_{\text{APAL}}$ can distinguish between two worlds then so can \mathcal{L}_{PAL} .

The formulas of $\mathcal{L}_{\text{APAL}}$ are invariant under bisimulation (see [Balbiani et al., 2008]), so if an $\mathcal{L}_{\text{APAL}}$ formula distinguishes between \mathcal{M}, w_1 and \mathcal{M}, w_2 , then \mathcal{M}, w_1 and \mathcal{M}, w_2 are not bisimilar. On finitely branching models, worlds are bisimilar if and only if they are indistinguishable by basic modal logic (see for example [van Ditmarsch et al., 2007, p. 219]). So since \mathcal{M}, w_1 and \mathcal{M}, w_2 are not bisimilar, they can be distinguished by an \mathcal{L}_{PAL} formula. \square

Lemma 4.2 also holds for models that are not finitely branching, but that requires a more complicated proof and we only need the result for finitely branching models.⁴

Lemma 4.3. *Let ψ be any $\mathcal{L}_{\text{APAL}}$ formula and let φ be any \mathcal{L}_{PAL} formula. Then $\models_{\text{br}} \langle \psi \rangle \varphi \rightarrow \diamond \varphi$.*

Proof. Fix any finitely branching model \mathcal{M} and any world w of \mathcal{M} . It was shown in [Plaza, 1989] that every \mathcal{L}_{PAL} formula is equivalent to an \mathcal{L}_{PAL} formula that does not contain any public announcements. Let φ' be the announcement-free formula equivalent to φ , and let n be the maximum nesting depth of K operators in φ' . Then the truth of φ' —and therefore also φ —on \mathcal{M}, w does not depend on changes to worlds that are not reachable from w in at most n steps.

Let W' be the set of worlds that are reachable from w in at most n steps, and let $W_1 := \{w' \in W' \mid \mathcal{M}, w' \models \psi\}$ and $W_2 := W' \setminus W_1$. Then for each $w_i \in W_1$ and $w_j \in W_2$ the formula ψ distinguishes \mathcal{M}, w_i from \mathcal{M}, w_j , so by Lemma 4.2 there is also an \mathcal{L}_{PAL} formula that distinguishes the two worlds. Let $\psi'_{i,j}$ be this distinguishing \mathcal{L}_{PAL} formula and assume without loss of generality that $\mathcal{M}, w_i \models \psi'_{i,j}$ and $\mathcal{M}, w_j \not\models \psi'_{i,j}$.

For $w_i \in W_1$ let $\psi'_i := \bigwedge_{w_j \in W_2} \psi'_{i,j}$. Then $\mathcal{M}, w_i \models \psi'_i$ and $\mathcal{M}, w_j \not\models \psi'_i$ for each $w_j \in W_2$. Finally, let $\psi' := \bigvee_{w_i \in W_1} \psi'_i$. This ψ' satisfies $\mathcal{M}, w_i \models \psi'$ for each $w_i \in W_1$ and $\mathcal{M}, w_j \not\models \psi'$ for each $w_j \in W_2$.

⁴For an idea of why Lemma 4.2 also holds for infinitely branching models, consider the case where $\mathcal{M}, w \models \diamond \varphi$ and $\mathcal{M}, w' \not\models \diamond \varphi$. Then there is a ψ such that $\mathcal{M}, w \models \langle \psi \rangle \varphi$ and in particular $\mathcal{M}, w' \not\models \langle \psi \rangle \varphi$, so the formula $\langle \psi \rangle \varphi$ distinguishes the two worlds as well. This can be extended to any formula containing a \diamond operator.

As such, the models \mathcal{M}_ψ and $\mathcal{M}_{\psi'}$ only differ in worlds that are not reachable from w within n steps, so $\mathcal{M}, w \models \langle \psi \rangle \varphi \leftrightarrow \langle \psi' \rangle \varphi$. Because ψ' is an \mathcal{L}_{PAL} formula, this implies that $\mathcal{M}, w \models \langle \psi \rangle \varphi \rightarrow \diamond \varphi$. The model \mathcal{M} and world w were chosen as any finitely branching model and any world of that model, so we have $\models_{\text{br}} \langle \psi \rangle \varphi \rightarrow \diamond \varphi$. \square

4.4.2 Invalidity of $\langle \psi \rangle \varphi \rightarrow \diamond \varphi$ on Infinitely Branching Models

If we do not restrict ourselves to finite or finitely branching models, there are φ and ψ such that $\langle \psi \rangle \varphi \rightarrow \diamond \varphi$ is not valid. Let

$$\begin{aligned}\varphi_1 &:= \hat{K}_c p \wedge K_c(r \rightarrow \hat{K}_d \neg r) \wedge K_c((p \wedge \neg r) \rightarrow \hat{K}_e r), \\ \varphi_2 &:= K_c(\neg q \rightarrow (\hat{K}_f(\neg \hat{K}_c q \wedge K_a p) \wedge \hat{K}_f \neg K_a p)), \\ \varphi &:= \varphi_1 \wedge \varphi_2 \\ \psi &:= p \vee q \vee K_a \neg \diamond (\hat{K}_b K_a p \wedge \hat{K}_b \neg K_a p).\end{aligned}$$

Furthermore, let \mathcal{M} be the model shown in Figure 4.1 and let \mathcal{M}_n for $n \in \mathbb{N}$ be the submodels indicated in Figure 4.1.

We want to show that $\mathcal{M}, w \not\models \langle \psi \rangle \varphi \rightarrow \diamond \varphi$. This requires us to show that $\mathcal{M}, w \models \langle \psi \rangle \varphi$ and that $\mathcal{M}, w \not\models \diamond \varphi$. In order to prove that $\mathcal{M}, w \not\models \diamond \varphi$, we have to demonstrate that if $\mathcal{M}, w \models \langle \psi' \rangle \varphi$, then ψ' contains a \diamond operator. The subformula φ_1 is constructed in such a way that if $\mathcal{M}, w \models \langle \psi' \rangle \varphi$ then the update $\langle \psi' \rangle$ retains an infinite number of worlds. The subformula φ_2 guarantees that if $\mathcal{M}, w \models \langle \psi' \rangle \varphi$ and $\langle \psi' \rangle$ retains an infinite number of worlds, then ψ' must perform an infinite number of different updates, which cannot be done without a \diamond operator. But before looking at the details of the proof that $\mathcal{M}, w \not\models \diamond \varphi$, let us start by proving the simpler part of the statement, namely that $\mathcal{M}, w \models \langle \psi \rangle \varphi$.

Lemma 4.4. *We have $\mathcal{M}, w \models \langle \psi \rangle \varphi$.*

Proof. To show is that $\mathcal{M}_\psi \models \varphi$, so let us look at which worlds are retained by $\langle \psi \rangle$. The disjuncts p and q of ψ guarantee that any world in the leftmost three columns is retained.

The worlds in the fourth column from the left satisfy neither p nor q though, so they are retained only if they satisfy $K_a \neg \diamond (\hat{K}_b K_a p \wedge \hat{K}_b \neg K_a p)$. These worlds themselves always satisfy $\neg \diamond (\hat{K}_b K_a p \wedge \hat{K}_b \neg K_a p)$; there is no update that would let them satisfy $\hat{K}_b K_a p$ because every b -reachable world satisfies $\neg p$.

So the worlds in the fourth column are retained if and only if the p world to the left of them (which they are a -connected with) satisfies $\neg \diamond (\hat{K}_b K_a p \wedge \hat{K}_b \neg K_a p)$.

Now we reach the difference between the rows of a submodel \mathcal{M}_n . Consider the p world in the bottom row of \mathcal{M}_n for any n . The only world b -reachable from this world is itself, so there is no update that can make the world satisfy $\hat{K}_b K_a p \wedge \hat{K}_b \neg K_a p$. So the p world in the bottom row satisfies $\neg \diamond (\hat{K}_b K_a p \wedge \hat{K}_b \neg K_a p)$.

Now consider one of the p worlds in the top two rows of \mathcal{M}_n . These two worlds can be distinguished from each other because their “tails” are of different lengths. This allows us to create an update χ_n that removes the $\neg p$ world adjacent to the top p world but not the one adjacent to the second row p world. The formula $\chi_n := \neg p \rightarrow \hat{K}_{\{a,b\}}^{n-1} K_{\{a,b\}}^{n-1} \neg p$ for example does this.

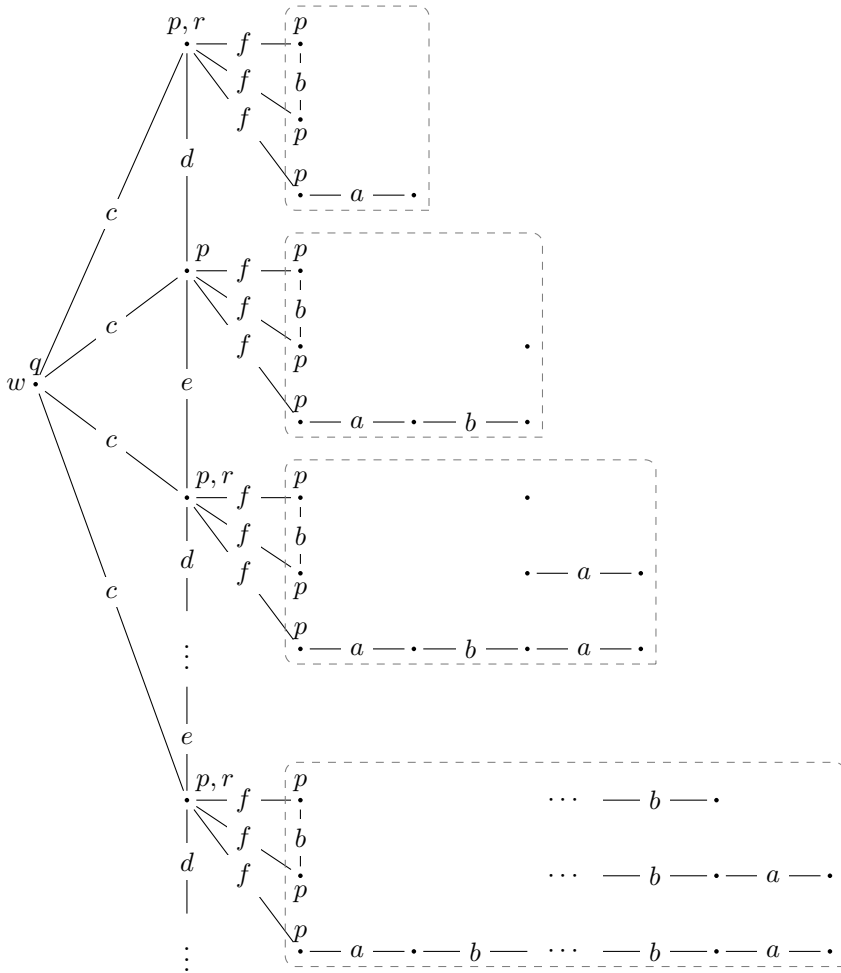


Figure 4.2: The model \mathcal{M}_ψ . Some accessibility arrows are not drawn.

The specific formula χ_n that works for a submodel \mathcal{M}_n depends on n , but in every case it is a PAL formula, so for every n the top two p worlds of \mathcal{M}_n satisfy $\diamond(\hat{K}_b K_{ap} \wedge \hat{K}_b \neg K_{ap})$.

This means that the worlds in the fourth column are retained by $\langle \psi \rangle$ if and only if they are in the third row of any submodel \mathcal{M}_n . The model \mathcal{M}_ψ is therefore as shown in Figure 4.2. It is straightforward to verify that w satisfies φ in that model. \square

Now to show that there is no PAL formula ψ' that satisfies $\mathcal{M}, w \models \langle \psi' \rangle \varphi$. Recall that the two parts of $\varphi = \varphi_1 \wedge \varphi_2$ have different purposes. The part φ_1 is designed in such a way that if $\mathcal{M}, w \models \langle \psi' \rangle \varphi$, then the update $\langle \psi' \rangle$ retains an infinite number of worlds. The part φ_2 is designed in such a way that different updates have to be performed in all but finitely many of the infinite number of worlds that $\langle \psi' \rangle$ retains. But that cannot be done without a \diamond operator.

Lemma 4.5. *For every \mathcal{L}_{PAL} formula ψ' , we have $\mathcal{M}, w \not\models \langle \psi' \rangle \varphi$.*

Proof. Suppose towards a contradiction that there is an \mathcal{L}_{PAL} formula ψ' such that $\mathcal{M}, w \models \langle \psi' \rangle \varphi$. Then we have $\mathcal{M}, w \models \langle \psi' \rangle \varphi_1$ and $\mathcal{M}, w \models \langle \psi' \rangle \varphi_2$.

Consider $\mathcal{M}, w \models \langle \psi' \rangle \varphi_1$. The conjunct \hat{K}_{cp} guarantees that $\langle \psi' \rangle$ retains at least one of the p worlds that are accessible from w , so at least one of the worlds in the second column.

The worlds in the second column alternate between r and $\neg r$, and the arrows between those worlds alternate between d and e . As a result, the conjunct $K_c(r \rightarrow \hat{K}_d \neg r)$ implies that if ψ' retains an r world in the second column, then it also retains the $\neg r$ world below it. Likewise, the conjunct $K_c((p \wedge \neg r) \rightarrow \hat{K}_e r)$ implies that if ψ' retains a $\neg r$ world in the second column, then it also retains the r world below it.

So the three conjuncts of φ_1 together imply that ψ' retains at least one of the worlds in the second column as well as all worlds below it.

Consider then $\mathcal{M}, w \models \langle \psi' \rangle \varphi_2$. The formula φ_2 says something about all c -reachable worlds that do not satisfy q , so all worlds in the second column (that are retained by $\langle \psi' \rangle$). Of these worlds it says that they can reach two worlds by using f , one world satisfying $\neg \hat{K}_{cq} \wedge K_{ap}$ and one satisfying $\neg K_{ap}$.

The worlds in the first two columns all satisfy \hat{K}_{cq} and K_{ap} , so these two f -reachable worlds must be in the third column. If the n -th world of the second column is retained by $\langle \psi' \rangle$ there must therefore be two p worlds retained in \mathcal{M}_n . Furthermore, one of those worlds in \mathcal{M}_n must be adjacent to a $\neg p$ world that is retained while the other must not be adjacent to a retained $\neg p$ world.

One of the $\neg p$ worlds in the second column of \mathcal{M}_n (so the fourth column of \mathcal{M}) must be retained and one must not be retained, so in particular ψ' must distinguish between two of those worlds. But the only way to distinguish between those worlds is to use the fact that one “tail” is shorter than the others, and doing this requires a formula with K -depth at least $2n - 2$.

The K -depth of ψ' is fixed and finite, so there is some $N \in \mathbb{N}$ such that for every $n \geq N$ the formula ψ' cannot distinguish between the worlds in the second column of \mathcal{M}_n . Putting all of the above together, we get that ψ' :

- must retain all worlds in the second column below a certain point,
- must distinguish between two worlds in the second column of \mathcal{M}_n if the n -th world of the second column is retained and

- cannot distinguish between the worlds in the second column of \mathcal{M}_n for all n greater than some number N .

This is a contradiction, so our initial assumption that such a ψ' exists must be false, which proves the lemma. \square

The theorem now follows easily.

Theorem 4.2. *There are an \mathcal{L}_{PAL} formula φ and an $\mathcal{L}_{\text{APAL}}$ formula ψ such that $\not\models \langle \psi \rangle \varphi \rightarrow \diamond \varphi$.*

Proof. Let \mathcal{M} , w , φ and ψ be as defined above. Then $\mathcal{M}, w \models \langle \psi \rangle \varphi$ by Lemma 4.4. Furthermore, by Lemma 4.5 we know that $\mathcal{M}, w \not\models \langle \psi' \rangle \varphi$ for every \mathcal{L}_{PAL} formula ψ' so we have $\mathcal{M}, w \not\models \diamond \varphi$. This implies that $\mathcal{M}, w \not\models \langle \psi \rangle \varphi \rightarrow \diamond \varphi$ and so that $\not\models \langle \psi \rangle \varphi \rightarrow \diamond \varphi$. \square

4.4.3 Invalidity of $\langle \psi \rangle \varphi \rightarrow \diamond \varphi$ on Finitely Branching Models

Now to show that $\not\models_{\text{br}} \langle \psi \rangle \varphi \rightarrow \diamond \varphi$. The method used to show this is very similar to the method used to show that $\not\models \langle \psi \rangle \varphi \rightarrow \diamond \varphi$. We use φ to force ψ to retain an infinite number of worlds in a pointed model (\mathcal{N}, w) . Additionally we force ψ to distinguish between infinitely many pairs of worlds, and we let the difference between the two worlds in a pair get further and further away.

Unfortunately, forcing ψ to retain an infinite number of worlds is much more complicated in a finitely branching frame, so we need more complex formulas and models. Let \mathcal{N} be the model shown in Figure 4.3 and let

$$\begin{aligned} \psi &:= (\neg p \wedge \hat{K}_b(p \wedge \hat{K}_a(q \vee r))) \rightarrow \diamond(\hat{K}_a K_b p \wedge \hat{K}_a(p \wedge \neg K_b p)), \\ \varphi_1 &:= (q \vee r) \rightarrow (\hat{K}_a K_b p \wedge \hat{K}_a(p \wedge \neg K_b p)), \\ \varphi_2 &:= (q \rightarrow \neg \hat{K}_c \hat{K}_a \hat{K}_b \hat{K}_c r) \wedge (r \rightarrow \neg \hat{K}_c \hat{K}_a \hat{K}_b \hat{K}_c q), \\ \varphi &:= \langle \varphi_1 \rangle (\hat{K}_a \hat{K}_b \hat{K}_c q \wedge \hat{K}_a \hat{K}_b \hat{K}_c r \wedge \langle \varphi_2 \rangle) \square \neg (\hat{K}_a K_b p \wedge \hat{K}_a(p \wedge \neg K_b p)). \end{aligned}$$

Note the recurring a -triangles with two p worlds in the model and the recurring subformula $\hat{K}_a K_b p \wedge \hat{K}_a(p \wedge \neg K_b p)$. These subformulas have the property that they hold in the $\neg p$ world of such a triangle if and only if for one of the p worlds in the triangle a b -reachable $\neg p$ world is retained but for the other it is not.

Lemma 4.6. *We have $\mathcal{N}, w \models \langle \psi \rangle \varphi$.*

Proof. Let us consider the update $\langle \psi \rangle$. It places the condition on $\neg p \wedge \hat{K}_b(p \wedge \hat{K}_a(q \vee r))$ worlds that they must satisfy $\diamond(\hat{K}_a K_b p \wedge \hat{K}_a(p \wedge \neg K_b p))$. The $\neg p \wedge \hat{K}_b(p \wedge \hat{K}_a(q \vee r))$ worlds are exactly those that are in the third line from the bottom in \mathcal{N}_n^x submodels. Furthermore, of the two such worlds in a submodel \mathcal{N}_n^x the left one satisfies $\diamond(\hat{K}_a K_b p \wedge \hat{K}_a(p \wedge \neg K_b p))$, and the right one does not.⁵ The updated submodel $\mathcal{N}_n^x \psi$ is therefore as shown in Figure 4.5. (The worlds of \mathcal{N} that are not in one of the submodels \mathcal{N}_n^x are all retained by the update so nothing changes there.)

⁵Announcements that make $\hat{K}_a K_b p \wedge \hat{K}_a(p \wedge \neg K_b p)$ true in the leftmost world in the third row do so by removing one of the $\neg p$ worlds in the fifth row but not the other. This can be done because there are formulas that differentiate between a “tail” of $2n$ worlds and a “tail” of $2n - 1$ worlds, as in the infinitely branching case.

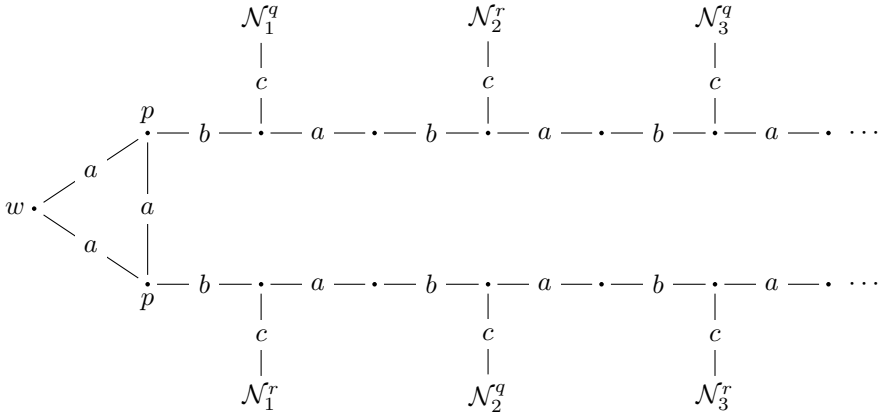


Figure 4.3: The model \mathcal{N} . Reflexive arrows are not drawn. The submodels \mathcal{N}_n^x for $n \in \mathbb{N}$, $x \in \{q, r\}$ are shown in Figure 4.4.

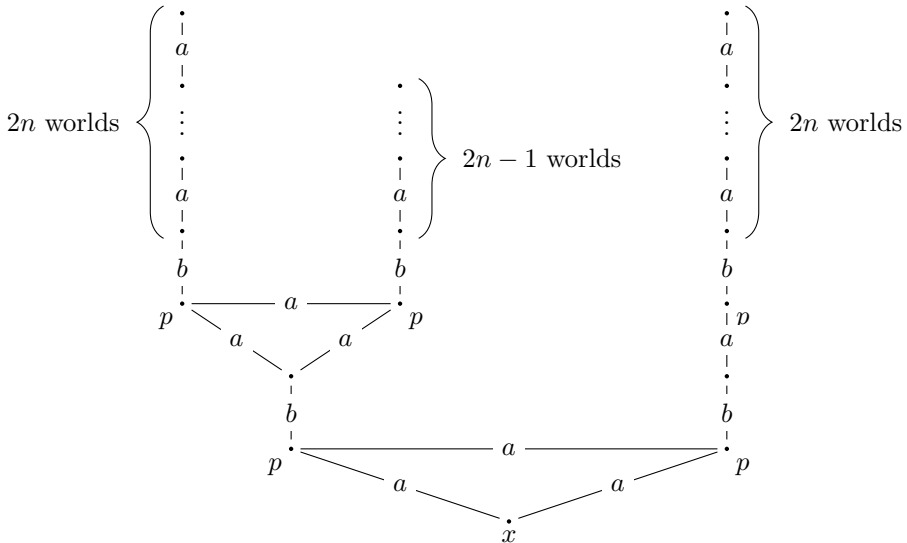


Figure 4.4: The submodel \mathcal{N}_n^x for $x \in \{q, r\}$ and $n \in \mathbb{N}_{>0}$. The origin world that connects it to \mathcal{N} is the world satisfying x .

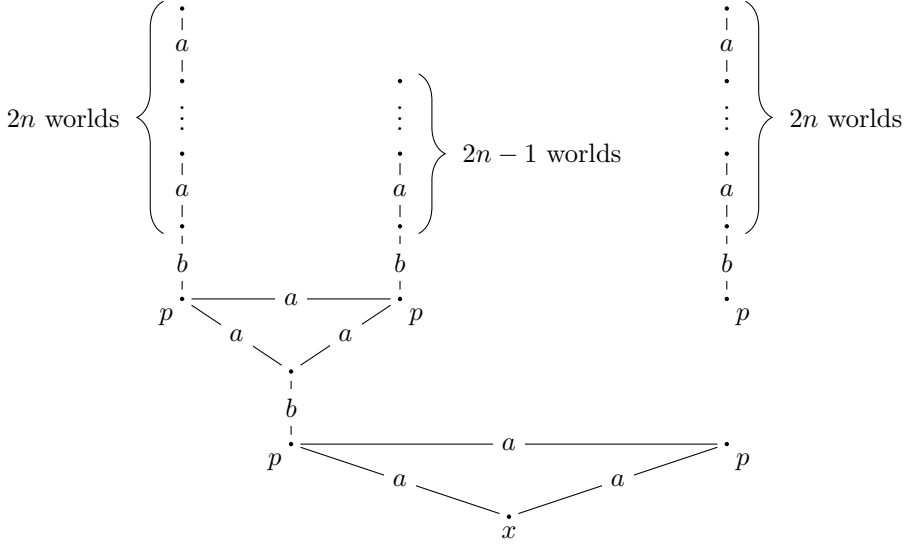


Figure 4.5: The submodel \mathcal{N}_n^x for $x \in \{q, r\}$ and $n \in \mathbb{N}_{>0}$.

After the update $\langle \psi \rangle$, the formula $\hat{K}_a K_b p \wedge \hat{K}_a (p \wedge \neg K_b p)$ therefore holds in the origin world of each submodel \mathcal{N}_n^x . Since q and r only hold in the origin worlds of these submodels the update $\langle \varphi_1 \rangle = \langle (q \vee r) \rightarrow (\hat{K}_a K_b p \wedge \hat{K}_a (p \wedge \neg K_b p)) \rangle$ does nothing if executed immediately after $\langle \psi \rangle$. We therefore have $\mathcal{N}, w \models \langle \psi \rangle \langle \varphi_1 \rangle (\hat{K}_a \hat{K}_b \hat{K}_c q \wedge \hat{K}_a \hat{K}_b \hat{K}_c r)$.

Finally consider the third update $\langle \varphi_2 \rangle$. It places conditions on $q \vee r$ worlds; q worlds must satisfy $\neg \hat{K}_c \hat{K}_a \hat{K}_b \hat{K}_c r$ and r worlds must satisfy $\neg \hat{K}_c \hat{K}_a \hat{K}_b \hat{K}_c q$. After the other updates, there are no q or r worlds that satisfy this condition.

As such the result of applying the three updates $\langle \psi \rangle \langle \varphi_1 \rangle \langle \varphi_2 \rangle$ removes the origin worlds of all \mathcal{N}_n^x submodels. In the resulting model the two p worlds that are a -reachable from w are indistinguishable, so we have $\mathcal{N}, w \models \langle \psi \rangle \langle \varphi_1 \rangle \langle \varphi_2 \rangle \Box \neg (\hat{K}_a K_b p \wedge \hat{K}_a (p \wedge \neg K_b p))$. Together with the previous result $\mathcal{N}, w \models \langle \psi \rangle \langle \varphi_1 \rangle (\hat{K}_a \hat{K}_b \hat{K}_c q \wedge \hat{K}_a \hat{K}_b \hat{K}_c r)$, this shows that $\mathcal{N}, w \models \langle \psi \rangle \varphi$. \square

Lemma 4.7. *For every \mathcal{L}_{PAL} formula ψ' we have $\mathcal{N}, w \not\models \langle \psi' \rangle \varphi$.*

Proof. Suppose towards a contradiction that there is an \mathcal{L}_{PAL} formula ψ' such that $\mathcal{N}, w \models \langle \psi' \rangle \varphi$. Then after the updates $\langle \psi' \rangle \langle \varphi_1 \rangle$, the formula $\hat{K}_a \hat{K}_b \hat{K}_c q \wedge \hat{K}_a \hat{K}_b \hat{K}_c r$ must hold in w . The origin worlds of \mathcal{N}_1^q and \mathcal{N}_1^r and the paths to those worlds must therefore be retained by $\langle \psi' \rangle \langle \varphi_1 \rangle$.

But after those two updates it must also hold in w that $\langle \varphi_2 \rangle \Box \neg (\hat{K}_a K_b p \wedge \hat{K}_a (p \wedge \neg K_b p))$, so after the update $\langle \varphi_2 \rangle$ the two worlds that are b -accessible from the p worlds that are a -accessible from w (so the two $\neg p$ worlds immediately to the right of the two p worlds) must be indistinguishable. In particular this means that neither the origin world of \mathcal{N}_1^q nor that of \mathcal{N}_1^r may be reachable after the update $\langle \varphi_2 \rangle$, because otherwise $\hat{K}_c q$ or $\hat{K}_c r$ would distinguish the worlds.

Since the update $\langle \varphi_2 \rangle$ only removes $q \vee r$ worlds this implies that the origin worlds of \mathcal{N}_1^q and \mathcal{N}_1^r must satisfy $\neg \varphi_2$ after the first two updates. But then $\hat{K}_c \hat{K}_a \hat{K}_b \hat{K}_c r$ must hold in the origin of \mathcal{N}_1^q and $\hat{K}_c \hat{K}_a \hat{K}_b \hat{K}_c q$ in the origin of \mathcal{N}_1^r .

But then the origins of \mathcal{N}_2^q and \mathcal{N}_2^r must be reachable after the first two updates. But these two origin worlds must also be removed by $\langle \varphi_2 \rangle$, because otherwise $\hat{K}_a \hat{K}_b \hat{K}_c q$ would distinguish the two worlds that must be indistinguishable. But then the origins of \mathcal{N}_3^q and \mathcal{N}_3^r must be retained. Repeating the argument shows that if the origins of \mathcal{N}_n^q and \mathcal{N}_n^r remain reachable, then so do those of \mathcal{N}_{n+1}^q and \mathcal{N}_{n+1}^r . Therefore, the updates $\langle \psi' \rangle \langle \varphi_1 \rangle$ must leave the origin of every \mathcal{N}_n^x submodel reachable.

But then consider the update $\langle \varphi_1 \rangle$. This update retains the origin of a \mathcal{N}_n^x submodel if and only if it satisfies $\hat{K}_a K_b p \wedge \hat{K}_a (p \wedge \neg K_b p)$. This implies that for each $n \in \mathbb{N}$ and $x \in \{q, r\}$ the update $\langle \psi' \rangle$ must retain one of the worlds on the third row of the submodel but not the other. However, in \mathcal{N}_n^x these worlds are indistinguishable up to depth $2n$, so an \mathcal{L}_{PAL} formula must contain at least $2n + 1$ iterations of a K -operator to distinguish them. There is therefore no single formula in \mathcal{L}_{PAL} that distinguishes the two worlds for every submodel. This contradicts the assumption that such a ψ' exists. \square

The theorem now follows easily.

Theorem 4.3. *There are $\mathcal{L}_{\text{APAL}}$ formulas φ, ψ such that $\not\models_{\text{br}} \langle \psi \rangle \varphi \rightarrow \Diamond \varphi$.*

Proof. For the $\mathcal{L}_{\text{APAL}}$ formulas φ, ψ , finitely branching model \mathcal{N} and world w of \mathcal{N} as defined above we have $\mathcal{N}, w \models \langle \psi \rangle \varphi$ by Lemma 4.6 and $\mathcal{N}, w \not\models \langle \psi' \rangle \varphi$ for every \mathcal{L}_{PAL} formula ψ' by Lemma 4.7. This implies that $\mathcal{N}, w \not\models \langle \psi \rangle \varphi \rightarrow \Diamond \varphi$ so $\not\models_{\text{br}} \langle \psi \rangle \varphi \rightarrow \Diamond \varphi$. \square

4.5 Conclusion and further research

We showed that for any $\mathcal{L}_{\text{APAL}}$ formula φ and ψ we have $\models_{\text{fin}} \langle \psi \rangle \varphi \rightarrow \Diamond \varphi$ and that for any \mathcal{L}_{PAL} formula φ and any $\mathcal{L}_{\text{APAL}}$ formula ψ we also have $\models_{\text{br}} \langle \psi \rangle \varphi \rightarrow \Diamond \varphi$. Additionally, we showed that there are $\mathcal{L}_{\text{APAL}}$ formulas φ and ψ such that $\not\models_{\text{br}} \langle \psi \rangle \varphi \rightarrow \Diamond \varphi$ and that there are an \mathcal{L}_{PAL} formula φ and an $\mathcal{L}_{\text{APAL}}$ formula ψ such that $\not\models \langle \psi \rangle \varphi \rightarrow \Diamond \varphi$.

The operator \Diamond therefore only represents a truly arbitrary public announcement on finite models. There are scenarios that can be modeled in finite models and where arbitrary public announcements are useful, such as the cryptography example mentioned in the introduction. The message p for which we want to know whether $\Diamond(K_b p \wedge \neg K_e p)$ is generally taken from a finite set of possible messages which allows for a finite model to be used.

However, not all interesting scenarios allow for finite modeling, so it seems like an interesting topic for further research whether semantics for a different arbitrary public announcement operator \blacklozenge can be found such that for any $\mathcal{L}_{\text{PAL}+\blacklozenge}$ formulas φ, ψ we have $\models \langle \psi \rangle \varphi \rightarrow \blacklozenge \varphi$. One possibility that might work is an infinite hierarchy of \Diamond_i operators, where each \Diamond_i quantifies over all formulas that use only \Diamond_j with $j < i$. I conjecture that if we then define $\blacklozenge \varphi$ as $\bigvee_{i \in \mathbb{N}} \Diamond_i \varphi$, we have $\models \langle \psi \rangle \varphi \rightarrow \blacklozenge \varphi$.

Another interesting subject for further research would be to take the same questions we asked about $\mathcal{L}_{\text{APAL}}$ and apply them to different “arbitrary updates”, such as Arbitrary Updates of Objective Belief [Seban, 2011], Arbitrary Action Models [Hales, 2013] or Arbitrary Arrow Updates [van Ditmarsch et al., 2014b]. We already know that Arbitrary Action Models are (trivially) completely arbitrary because [Hales, 2013] showed that they do not add expressivity. But it would be interesting to determine

whether the other two operators are truly arbitrary and, if they are not, whether we can find a truly arbitrary variant.

