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Enqvist, S.; Venema, Y.

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Disjunctive Bases: Normal Forms for Modal Logics*

Sebastian Enqvist[1] and Yde Venema[2]

1 **Department of Philosophy, Stockholm University, Sweden**
thesebastianenqvist@gmail.se

2 **Institute for Logic, Language and Computation, Universiteit van Amsterdam, Netherlands**
y.venema@uva.nl

Abstract

We present the concept of a disjunctive basis as a generic framework for normal forms in modal logic based on coalgebra. Disjunctive bases were defined in previous work on completeness for modal fixpoint logics, where they played a central role in the proof of a generic completeness theorem for coalgebraic mu-calculi. Believing the concept has a much wider significance, here we investigate it more thoroughly in its own right. We show that the presence of a disjunctive basis at the "one-step" level entails a number of good properties for a coalgebraic mu-calculus, in particular, a simulation theorem showing that every alternating automaton can be transformed into an equivalent nondeterministic one. Based on this, we prove a Lyndon theorem for the full fixpoint logic, its fixpoint-free fragment and its one-step fragment, and a Uniform Interpolation result, for both the full mu-calculus and its fixpoint-free fragment.

We also raise the questions, when a disjunctive basis exists, and how disjunctive bases are related to Moss' coalgebraic "nabla" modalities. Nabla formulas provide disjunctive bases for many coalgebraic modal logics, but there are cases where disjunctive bases give useful normal forms even when nabla formulas fail to do so, our prime example being graded modal logic.

Finally, we consider the problem of giving a category-theoretic formulation of disjunctive bases, and provide a partial solution.

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1 Introduction

The topic of this paper connects modal μ-calculi, coalgebra and automata. The connection between the modal μ-calculus, as introduced by Kozen [13], and automata running on infinite objects, is standard [9]. Many of the most fundamental results about the modal μ-calculus have been proved by making use of this connection, including completeness of Kozen's axiom system [23], and model theoretic results like expressive completeness [12], uniform interpolation and a Lyndon theorem [3].

* For a full version of this paper, containing proofs of all statements, see [6], http://www.illc.uva.nl/Research/Publications/Reports/PP-2017-05.text.pdf.

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The standard modal μ-calculus was generalized to a generic, coalgebraic modal μ-calculi [21], of which the modal basis was provided by Moss' original coalgebraic modality [17], now known as the *nabla* modality. From a meta-logical perspective, Moss' nabla logics and their fixpoint extensions are wonderfully well-behaved. For example, a generic completeness theorem for nabla logics by a uniform system of axioms was established [14], and this was recently extended to the fixpoint extension of the finitary Moss logic [4]. Most importantly, the automata corresponding to the fixpoint extension of Moss' finitary nabla logic always enjoy a *simulation theorem*, allowing arbitrary coalgebraic automata to be simulated by *non-deterministic* ones; this goes back to the work of Janin & Walukiewicz on μ-automata [11]. The simulation theorem provides a very strong normal form for these logics, and plays an important role in the proofs of several results for coalgebraic fixpoint logics.

The downside of this approach is that the nabla modality is rather non-standard, and understanding what concrete formulas actually say is not always easy. For this reason, another approach to coalgebraic modal logic has become popular, based on so called *predicate liftings*. This approach, going back to the work of Pattinson [19], provides a much more familiar syntax in concrete applications, but can still be elegantly formulated at the level of generality and abstraction that makes the coalgebraic approach to modal logic attractive in the first place. (For a comparison between the two approaches, see [15].) Coalgebraic μ-calculi have also been developed as extensions of the predicate liftings based languages [2], and the resulting logics are very well behaved: for example, good complexity results were obtained in op. cit. Again, the connection between formulas and automata can be formulated in this setting [7], but a central piece is now missing: so far, no simulation theorem has been established for logics based on predicate liftings. In fact, it is not trivial even to define what a non-deterministic automaton *is* in this setting.

This problem turned up in recent work [5], by ourselves together with Seifan, where we extended our earlier completeness result for Moss-style fixpoint logics [4] to the predicate liftings setting. Our solution was to introduce the concept of a *disjunctive basis*, which formalizes in a compact way the minimal requirements that a collection of predicate liftings Λ must meet in order for the class of corresponding Λ-automata to admit a simulation theorem. Our aim in the present paper is to follow up on this conceptual contribution, which we believe is of much wider significance besides providing a tool to prove completeness results.

Exemplifying this, we shall explore some of the applications of our coalgebraic simulation theorem. Some of these transfer known results for nabla based fixpoint logics to the predicate liftings setting; for example, we show that a linear-size model property holds for our non-deterministic automata (or "disjunctive" automata as we will call them), following [21]. We also show that uniform interpolation results hold for coalgebraic fixpoint logics in the presence of a disjunctive basis, which was proved for the Moss-style languages in [16]. Finally, we prove a Lyndon theorem for coalgebraic fixpoint logics, generalizing a result for the standard modal μ-calculus proved in [3]: a formula is monotone in one of its variables if and only if it is equivalent to one in which the variable appears positively. We also prove an explicitly *one-step* version of this last result, which we believe has some practical interest for modal fixpoint logics: It is used to show that, given an expressively complete set of monotone predicate liftings, its associated μ-calculus has the same expressive power as the full μ-calculus based on the collection of all monotone predicate liftings.

Next to proving these results, we compare the notion of a disjunctive basis to the nabla based approach to coalgebraic fixpoint logics. The connection will be highlighted in Section 7 where we discuss disjunctive predicate liftings via the Yoneda lemma: here the Barr lifting of the ambient functor (on which the semantics of nabla modalities are based) comes into the picture naturally. This is not to say that disjunctive bases are just "nablas in disguise": it is a fundamental concept, and in some cases it is the *right* concept as *opposed* to nabla formulas. As a clear example of this, we consider *graded modal logic*, which adds counting modalities to modal logic. While we will see that this language has a disjunctive basis, at the same time we will prove that no such basis can be based on the nabla modalities.

2 Preliminaries

We assume that the reader is familiar with coalgebra, coalgebraic modal logic and the basic theory of automata operating on infinite objects. The aim of this section is to fix some definitions and notations.

First of all, throughout this paper we will use the letter T to denote an arbitrary *set functor*, that is, a covariant endofunctor on the category Set having sets as objects and functions as arrows. For notational convenience we sometimes assume that T preserves inclusions; our arguments can easily be adapted to the more general case. Functors of coalgebraic interest include the identity functor Id, the *powerset functor* P, the monotone neighborhood functor M and the (finitary) bag functor B (where $\mathsf{B}S$ is the collection of *weight functions* $\sigma : S \to \omega$ with finite support). We also need the contravariant powerset functor $\breve{\mathsf{P}}$.

A T-*coalgebra* is a pair $\mathbb{S} = (S, \sigma)$ where S is a set of objects called *states* or *points* and $\sigma : S \to \mathsf{T}S$ is the *transition* or *coalgebra map* of $\mathbb{S}$. A *pointed* T-coalgebra is a pair $(\mathbb{S}, s)$ consisting of a T-coalgebra and a state $s \in S$. We call a function $f : S' \to S$ a *coalgebra homomorphism* from (S', σ') to (S, σ) if $\sigma \circ f = \mathsf{T}f \circ \sigma'$, and write $(\mathbb{S}', s') \rightrightarrows (\mathbb{S}, s)$ if there is such a coalgebra morphism mapping s' to s.

With $\mathtt{X}$ a set of proposition letters, a T-*model over* $\mathtt{X}$ is a pair $(\mathbb{S}, V)$ consisting of a T-coalgebra $\mathbb{S} = (S, \sigma)$ and a $\mathtt{X}$-*valuation* V on S, that is, a function $V : \mathtt{X} \to \mathsf{P}S$. The *marking* associated with V is the transpose map $V^\flat : S \to \mathsf{P}\mathtt{X}$ given by $V^\flat(s) := \{p \in \mathtt{X} \mid s \in V(p)\}$. Thus the pair $(\mathbb{S}, V)$ induces a $\mathsf{T}_\mathtt{X}$-coalgebra $(S, (V^\flat, \sigma))$, where $\mathsf{T}_\mathtt{X}$ is the set functor $\mathsf{P}\mathtt{X} \times \mathsf{T}$.

We will mainly follow the approach in coalgebraic modal logic where modalities are associated (or even identified) with finitary predicate liftings. A *predicate lifting* of arity n is a natural transformation $\lambda : \breve{\mathsf{P}}^n \Rightarrow \breve{\mathsf{P}}\mathsf{T}$. Such a predicate lifting is *monotone* if for every set S, the map $\lambda_S : (\mathsf{P}S)^n \to \mathsf{P}\mathsf{T}S$ preserves the subset order in each coordinate. The induced predicate lifting $\lambda^\partial : \mathsf{P}^n \Rightarrow \mathsf{P}\mathsf{T}$, given by $\lambda^\partial_S(X_1, \ldots, X_n) := \mathsf{T}S \setminus \lambda_S(S \setminus X_1, \ldots, S \setminus X_1)$, is called the *(Boolean) dual* of λ. A *monotone modal signature*, or briefly: *signature* for T is a set Λ of monotone predicate liftings for T, which is closed under taking boolean duals.

Given a signature Λ, the formulas of the *coalgebraic μ-calculus* $\mu\mathtt{ML}_\Lambda$ are given by the following grammar:

$$\varphi ::= p \mid \bot \mid \neg\varphi \mid \varphi_0 \vee \varphi_1 \mid \heartsuit_\lambda(\varphi_1, \ldots, \varphi_n) \mid \mu x.\varphi'$$

where p and x are propositional variables, $\lambda \in \Lambda$ has arity n, and the application of the fixpoint operator μx is under the proviso that all occurrences of x in φ' are positive (i.e., under an even number of negations). We let $\mathtt{ML}_\Lambda$ and $\mu\mathtt{ML}_\Lambda(\mathtt{X})$ denote, respectively, the fixpoint-free fragment of $\mu\mathtt{ML}_\Lambda$ and the set of $\mu\mathtt{ML}_\Lambda$-formulas taking free variables from $\mathtt{X}$.

Formulas of such coalgebraic μ-calculi are interpreted in coalgebraic models, as follows. Let $\mathbb{S} = (S, \sigma, V)$ be a T-model over a set $\mathtt{X}$ of proposition letters. By induction on the complexity of formulas, we define a *meaning function* $[\![\cdot]\!]^\mathbb{S} : \mu\mathtt{ML}_\Lambda(\mathtt{X}) \to \mathsf{P}S$, together with an associated *satisfaction relation* $\Vdash \subseteq S \times \mu\mathtt{ML}_\Lambda(\mathtt{X})$ given by $\mathbb{S}, s \Vdash \varphi$ iff $s \in [\![\varphi]\!]^\mathbb{S}$. All clauses of this definition are standard; for instance, the one for the modality $\heartsuit_\lambda$ is given by

$$\mathbb{S}, s \Vdash \heartsuit_\lambda(\varphi_1, \ldots, \varphi_n) \text{ if } \sigma(s) \in \lambda_S([\![\varphi_1]\!]^\mathbb{S}, \ldots, [\![\varphi_n]\!]^\mathbb{S}). \tag{1}$$

For the least fixpoint operator we apply the standard description of least fixpoints of monotone maps from the Knaster-Tarski theorem and take

$$[\![\mu x.\varphi]\!]^{\mathbb{S}} := \bigcap \big\{U \in \mathsf{P}S \mid [\![\varphi]\!]^{(S,\sigma,V[x\mapsto U])} \subseteq U\big\},$$

where $V[x \mapsto U]$ is given by $V[x \mapsto U](x) := U$ while $V[x \mapsto U](p) := V(p)$ for $p \neq x$. A formula φ is said to be *monotone* in a variable p if, for every T-model $\mathbb{S} = (S, \sigma, V)$ and all sets $Z_1 \subseteq Z_2 \subseteq S$, we have $[\![\varphi]\!]^{(S,\sigma,V[p\mapsto Z_1])} \subseteq [\![\varphi]\!]^{(S,\sigma,V[p\mapsto Z_2])}$.

Well-known examples of coalgebraic modalities include the next-time operator $\bigcirc$ of linear time temporal logic, the standard Kripkean modalities $\Box$ and $\Diamond$, the more general modalities of monotone modal logic, and the *counting modalities* $\Diamond^k$ and $\Box^k$ of graded modal logic, which can be interpreted over B-coalgebras using the predicate liftings $\underline{k}$ and $\overline{k}$ given by

$$\begin{array}{rl} \underline{k}_S: & U \mapsto \big\{\sigma \in \mathsf{B}S \mid \sum_{u\in U} \sigma(u) \geq k\big\} \\ \overline{k}_S: & U \mapsto \{\sigma \in \mathsf{B}S \mid \sum_{u\notin U} \sigma(u) < k\big\}. \end{array}$$

A pivotal role in our approach is filled by the one-step versions of coalgebraic logics. Given a signature Λ and a set A of variables, we define the set $\mathtt{Bool}(A)$ of *boolean formulas* over A and the set $\mathtt{1ML}_\Lambda(A)$ of *one-step* Λ*-formulas* over A, by the following grammars:

$$\begin{array}{rcl} \mathtt{Bool}(A) \ni \pi & ::= & a \mid \bot \mid \top \mid \pi \vee \pi \mid \pi \wedge \pi \mid \neg\pi \\ \mathtt{1ML}_\Lambda(A) \ni \alpha & ::= & \heartsuit_\lambda \overline{\pi} \mid \bot \mid \top \mid \alpha \vee \alpha \mid \alpha \wedge \alpha \mid \neg\alpha \end{array}$$

where $a \in A$ and $\pi = (\pi_1, \ldots, \pi_n)$ for some $\lambda \in \Lambda$ of arity n. We will denote the positive (negation-free) fragments of $\mathtt{Bool}(A)$ and $\mathtt{1ML}_\Lambda(A)$ as, respectively, $\mathtt{Latt}(A)$ and $\mathtt{1ML}^+_\Lambda(A)$.

We shall often make use of substitutions: given a finite set A, let $\vee_A : \mathsf{P}A \to \mathtt{Bool}(A)$ be the map sending B to $\bigvee B$, and let $\wedge_A : \mathsf{P}A \to \mathtt{Bool}(A)$ be the map sending B to $\bigwedge B$, and given sets A, B let $\wedge_{A,B} : A \times B \to \mathtt{Bool}(A \cup B)$ be defined by mapping (a, b) to $a \wedge b$.

A monotone modal signature Λ for T is *expressively complete* if, for every n-place predicate lifting λ and variables $a_1, \ldots, a_n$ there is a formula $\alpha \in \mathtt{1ML}_\Lambda(\{a_1, \ldots, a_n\})$ which is equivalent to $\heartsuit_\lambda \overline{a}$. We will also be interested in the following strengthening of expressive completeness: we say that Λ is *Lyndon complete* if, for every *monotone* n-place predicate lifting λ and variables $a_1, \ldots, a_n$, there is a *positive* formula $\alpha \in \mathtt{1ML}^+_\Lambda(\{a_1, \ldots, a_n\})$ equivalent to $\heartsuit_\lambda \overline{a}$.

One-step formulas are naturally interpreted in the following structures. A *one-step* T*-frame* is a pair (S, σ) with $\sigma \in \mathsf{T}S$, i.e., an object in the category $\mathcal{E}(\mathsf{T})$ of elements of T. Similarly a *one-step* T*-model* over a set A of variables is a triple (S, σ, m) such that (S, σ) is a one-step T-frame and $m : S \to \mathsf{P}A$ is an A-marking on S. *Morphisms* of one-step frames and of one-step models are defined in the obvious way.

Given a one-step model (S, σ, m), we define the 0*-step interpretation* $[\![\pi]\!]^0_m \subseteq S$ of $\pi \in \mathtt{Bool}(A)$ by the obvious induction: $[\![a]\!]^0_m := \{v \in S \mid a \in m(v)\}$, $[\![\top]\!]^0_m := S$, $[\![\bot]\!]^0_m := \varnothing$, and the standard clauses for $\wedge, \vee$ and $\neg$. Similarly, the *one-step interpretation* $[\![\alpha]\!]^1_m$ of $\alpha \in \mathtt{1ML}_\Lambda(A)$ is defined as a subset of $\mathsf{T}S$, with $[\![\heartsuit_\lambda(\pi_1, \ldots, \pi_n)]\!]^1_m := \lambda_S([\![\pi_1]\!]^0_m, \ldots, [\![\pi_n]\!]^0_m)$, and standard clauses for $\bot, \top, \wedge, \vee$ and $\neg$. Given a one-step modal (S, σ, m), we write $S, \sigma, m \Vdash^1 \alpha$ for $\sigma \in [\![\alpha]\!]^1_m$. Notions like one-step satisfiability, validity and equivalence are defined in the obvious way.

A Λ*-automaton* over a set $\mathtt{X}$ of proposition letters, or more broadly, a *coalgebra automaton*, is a quadruple $\mathbb{A} = (A, \Theta, \Omega, a_I)$ where A is a finite set of *states*, with *initial state* $a_I \in A$, $\Theta : A \times \mathsf{P}\mathtt{X} \to \mathtt{1ML}^+_\Lambda(A)$ is the *transition map* and $\Omega : A \to \omega$ is the *priority map* of $\mathbb{A}$. Its semantics is given in terms of a two-player infinite parity game: With $\mathbb{S} = (S, \sigma, V)$ a T-model over a set $\mathtt{Y} \supseteq \mathtt{X}$, the *acceptance game* $\mathcal{A}(\mathbb{A}, \mathbb{S})$ is the parity game given by the table below.

Position	Player	Admissible moves	Priority
$(a, s) \in A \times S$	$\exists$	$\{m : S \to \mathsf{P}A \mid (S, \sigma(s), m) \Vdash^1 \Theta(a, \mathtt{X} \cap V^\flat(s))\}$	$\Omega(a)$
$m : S \to \mathsf{P}A$	$\forall$	$\{(b, t) \mid b \in m(t)\}$	0

We say that $\mathbb{A}$ *accepts* the pointed T-model $(\mathbb{S}, s)$, notation: $\mathbb{S}, s \Vdash \mathbb{A}$, if (a_I, s) is a winning position for $\exists$ in the acceptance game $\mathcal{A}(\mathbb{A}, \mathbb{S})$.

▶ **Fact 1.** *There are effective constructions transforming a formula in $\mu\mathtt{ML}_\Lambda(\mathtt{X})$ into an equivalent Λ-automaton over $\mathtt{X}$, and vice versa.*

3 Disjunctive formulas and disjunctive bases

In this section, we present the main conceptual contribution of the paper, and define disjunctive bases. We then immediately consider a number of examples.

▶ **Definition 2.** A one-step formula $\alpha \in \mathtt{1ML}^+_\Lambda(A)$ is called *disjunctive* if for every one-step model (S, σ, m) such that $S, \sigma, m \Vdash^1 \alpha$ there is a one-step frame morphism $f : (S', \sigma') \to (S, \sigma)$ and a marking $m' : S' \to \mathsf{P}A$ such that:
1. $S', \sigma', m' \Vdash^1 \alpha$;
2. $m'(s') \subseteq m(f(s'))$, for all $s' \in S'$;
3. $|m'(s')| \leq 1$, for all $s' \in S'$.

▶ **Definition 3.** Let $\mathtt{D}$ be an assignment of a set of positive one-step formulas $\mathtt{D}(A) \subseteq \mathtt{1ML}^+_\Lambda(A)$ for all sets of variables A. Then $\mathtt{D}$ is called a *disjunctive basis* for Λ if each formula in $\mathtt{D}(A)$ is disjunctive, and the following conditions hold:
1. $\mathtt{D}(A)$ is closed under finite disjunctions (in particular, it contains $\top = \bigvee \varnothing$).
2. $\mathtt{D}$ is *distributive over* Λ: for every one-step formula of the form $\heartsuit_\lambda \overline{\pi}$ there is a formula $\delta \in \mathtt{D}(\mathsf{P}(A))$ such that $\heartsuit_\lambda \overline{\pi} \equiv^1 \delta[\bigwedge_A]$.
3. $\mathtt{D}$ *admits a binary distributive law*: for any two formulas $\alpha \in \mathtt{D}(A)$ and $\beta \in \mathtt{D}(B)$, there is a formula $\gamma \in \mathtt{D}(A \times B)$ such that $\alpha \wedge \beta \equiv^1 \gamma[\wedge_{A,B}]$.

Disjunctive bases for weak pullback preserving functors. It is not hard to prove that disjunctive formulas generalize the Moss modalities, which are tightly connected to weak pullback preservation of the coalgebraic type functor. (Due to space limitations we refer to [14] for the details on the syntax and semantics of the Moss modalities.) In many interesting cases this suffices to find a disjunctive basis.

▶ **Proposition 4.** *Let Λ be a signature for a weak-pullback preserving functor T. If Λ is Lyndon complete, then the collection of all (finite or infinite) disjunctions of nabla formulas provides a disjunctive basis for Λ.*

For a proof of this proposition, which is a fairly straightforward exercise in coalgebraic logic, we refer the reader to [6].

Graded modal logic. Our main motivating example to introduce disjunctive bases is graded modal logic. The bag functor does preserve weak pullbacks, and so its Moss modalities are disjunctive, and the set of all monotone liftings for B does admit a disjunctive basis as an instance of Proposition 4. Note, however, that this proposition does not apply to graded modal logic, since the signature Σ_B is not expressively complete; this was essentially shown in [18]. It was observed already in [1] that very simple formulas in the one-step language $\mathtt{1ML}_{\Sigma_\mathsf{B}}$ are impossible to express in the (finitary) Moss language; consequently, the Moss modalities for the bag functor are not suitable to provide disjunctive normal forms for graded modal logic. Still, the signature Σ_{B} does have a disjunctive basis.

We say that a one-step model for the finite bag functor is *Kripkean* if all states have multiplicity 1. Note that a Kripkean one-step model (S, σ, m) can also be seen as a structure (in the sense of standard first-order model theory) for a first-order signature consisting of a monadic predicate for each $a \in A$: Simply consider the pair (S, V_m), where $V_m : A \to \mathsf{P}S$ is the interpretation given by putting $V_m(a) := \{s \in S \mid a \in m(s)\}$. We consider special basic formulas of monadic first-order logic of the form:

$$\gamma(\overline{a}, B) := \exists \overline{x}(\mathsf{diff}(\overline{x}) \wedge \bigwedge_{i \in I} a_i(x_i) \wedge \forall y(\mathsf{diff}(\overline{x}, y) \to \bigvee_{b \in B} b(y)))$$

It is not hard to see that any Kripkean one-step B-model (S, σ, m) satisfies:

$$S, \sigma, m \Vdash^1 \gamma(\overline{a}, B) \text{ implies } S, \sigma, m' \Vdash^1 \gamma(\overline{a}, B) \text{ for some } m' \subseteq m \text{ with } \mathsf{Ran}(m') \subseteq \mathsf{P}_{\leq 1}A. \quad (2)$$

We can turn the formula $\gamma(\overline{a}, B)$ into a modality $\nabla(\overline{a};B)$ that can be interpreted in *all* one-step B-models, using the observation that every one-step B-frame (S, σ) has a unique Kripkean cover $(\widetilde{S}, \widetilde{\sigma})$ defined by putting $\widetilde{S} := \bigcup\{s \times \sigma(s) \mid s \in S\}$, and $\widetilde{\sigma}(s, i) := 1$ for all $s \in S$ and $i \in \sigma(s)$ (where we view each finite ordinal as the set of all smaller ordinals). Then we can define, for an arbitrary one-step B-model (S, σ)

$$S, \sigma, m \Vdash^1 \nabla(\overline{a};B) \text{ if } \widetilde{S}, \widetilde{\sigma}, m \circ \pi_S \Vdash^1 \gamma(\overline{a}, B), \quad (3)$$

where π_S is the projection map $\pi_S : \widetilde{S} \to S$. It is then an immediate consequence of (2) that $\nabla(\overline{a};B)$ is a disjunctive formula.

Given a set A we define $\mathtt{D}_{\mathsf{B}}(A)$ as the set of all formulas $\nabla(\overline{a};B)$ with $a \in A$ and $B \subseteq A$.

▶ **Theorem 5.** *The collection $\mathtt{D}_{\mathsf{B}}$ provides a disjunctive basis for the signature Σ_{B}.*

As far as we know, this result is new. The hardest part in proving it is actually not to show that the language $\mathtt{D}_{\mathsf{B}}$ is distributive over Σ_{B} or that it admits a distributive law (these are easy exercises that we leave to the reader), but to show that formulas in $\mathtt{D}_{\mathsf{B}}(A)$ can be expressed as one-step formulas in $\mathtt{1ML}^+_{\Sigma_{\mathsf{B}}}(A)$. The reason that this is not so easy is subtle; by contrast, it is fairly straightforward to show that formulas in $\mathtt{D}_{\mathsf{B}}(A)$ can be expressed in $\mathtt{1ML}_{\Sigma_{\mathsf{B}}}(A)$, using Ehrenfeucht-Fraïssé games, see e.g. Fontaine & Place [8]. However, a proper disjunctive basis as we have defined it has to consist of *positive* formulas, and this will be crucial for applications to modal fixpoint logics[1].

▶ **Proposition 6.** *Every formula $\nabla(\overline{a};B) \in \mathtt{D}_{\mathsf{B}}$ is one-step equivalent to a formula in $\mathtt{1ML}_{\Sigma_{\mathsf{B}}}(A)$.*

Our main tool in proving this proposition will be Hall's Marriage Theorem, which can be formulated as follows. A *matching* of a bi-partite graph $\mathbb{G} = (V_1, V_2, E)$ is a subset M of E such that no two edges in M share any common vertex. M is said to *cover* V_1 if $\mathsf{Dom}M = V_1$.

▶ **Fact 7** (Hall's Marriage Theorem). *Let $\mathbb{G}$ be a finite bi-partite graph, $\mathbb{G} = (V_1, V_2, E)$. Then $\mathbb{G}$ has a matching that covers V_1 iff, for all $U \subseteq V_1$, $|U| \leq |E[U]|$, where $E[U]$ is the set of vertices in V_2 that are adjacent to some element of U.*

[1] The same subtlety appears in Janin & Lenzi [10], where the translation of the language $\mathtt{D}_{\mathsf{B}}$ into $\mathtt{1ML}^+_{\Sigma_{\mathsf{B}}}$ is required to prove that the graded μ-calculus is equivalent, over trees, to monadic second-order logic. Proposition 6 in fact fills a minor gap in this proof.

Proof of Proposition 6. We will show this for the simple case where B is a singleton $\{b\}$. The general case is an immediate consequence of this (consider the substitution $B \mapsto \bigvee B$).

Where $\overline{a} = (a_1, \ldots, a_n)$, define $I := \{1, \ldots, n\}$. For each subset $J \subseteq I$, let χ_J be the formula

$$\chi_J := \Diamond^{|J|} \bigvee_{i \in J} a_i \wedge \Box^{n+1-|J|}(\bigvee_{i \in J} a_i \vee b),$$

and let γ be the conjunction $\gamma := \bigwedge\{\chi_J \mid J \subseteq I\}$. What the formula χ_J says about a Kripkean (finite) one-step model is that at least $|J|$ elements satisfy the disjunction of the set $\{a_i \mid i \in J\}$, while all but at most $n - |J|$ elements satisfy the disjunction of the set $\{a_i \mid i \in J\} \cup \{b\}$. Abbreviating $\nabla(\overline{a};b) := \nabla(\overline{a};\{b\})$, we claim that $\gamma \equiv^1 \nabla(\overline{a};b)$, and to prove this it suffices to consider Kripkean one-step models.

It is straightforward to verify that the formula γ is a semantic one-step consequence of $\nabla(\overline{a};b)$. For the converse, consider a Kripkean one-step model (S, σ, m) in which γ is true. Let K be an index set of size $|S| - n$, and disjoint from I. Clearly then, $|I \cup K| = |I| + |K| = |S|$. Furthermore, let $a_k := b$, for all $k \in K$.

We define a bipartite graph $\mathbb{G} := (V_1, V_2, E)$ by setting $V_1 := I \cup K$, $V_2 := S$, and $E := \{(j, s) \in (I \cup K) \times S \mid a_j \in m(s)\}$. By Hall's Theorem the graph $\mathbb{G}$ has a matching M that covers V_1 (a full proof of this is given in [6]). Since the size of the set V_1 is the same as that of V_2, any matching M of $\mathbb{G}$ that covers V_1 is (the graph of) a bijection between these two sets. Furthermore, it easily follows that such an M restricts to a bijection between I and a subset $\{s_1, ..., s_n\}$ of S such that $a_i \in m(s_i)$ for each $i \in I$, and that $b \in m(t)$ for each $t \notin \{s_1, ..., s_n\}$. Hence $\nabla(\overline{a};b)$ is true in (S, σ, m), as required. ◀

This concludes the proof of Theorem 5.

An example without weak pullback preservation. There are also functors that do not preserve weak pullbacks, but do have a disjunctive basis. As an example of this, consider the subfunctor $\mathsf{P}^{2/3}$ of P^3 given by: $\mathsf{P}_{2/3}S = \{(Z_0, Z_1, Z_2) \mid Z_0 \cap Z_1 \neq \varnothing \text{ or } Z_1 \cap Z_2 \neq \varnothing\}$. While it is easy to show that this functor does not preserve weak pullbacks, the signature Σ_{P^3} (regarded as a set of liftings for $\mathsf{P}_{2/3}$ rather than P^3) still admits a disjunctive basis.

A non-example. Finally, we mention an example of a signature that does not admit any disjunctive basis: the signature Σ consisting of the box- and diamond liftings for M does not have a disjunctive basis. The full proof of this can be found in [6].

4 Disjunctive automata and simulation

We now introduce disjunctive automata, which serve as a coalgebraic generalization of non-deterministic automata for the modal μ-calculus.

▶ **Definition 8.** A Λ-automaton $\mathbb{A} = (A, \Theta, \Omega, a_I)$ is said to be *disjunctive* (relative to a disjunctive basis $\mathtt{D}$) if $\Theta(c, a) \in \mathtt{D}(A)$, for all colors $c \in \mathsf{P}\mathtt{X}$ and all states $a \in A$.

▶ **Definition 9.** Let $\mathbb{A} = (A, \Theta, \Omega, a_I)$ be a Λ-automaton and let $(\mathbb{S}, s_I)$ be a pointed T-model. A strategy f for $\exists$ in $\mathcal{A}(\mathbb{A}, \mathbb{S})@(a_I, s_I)$ is *separating* if for every s in $\mathbb{S}$ there is at most one state a in $\mathbb{A}$ such that the position (a, s) is *f-reachable* (i.e., occurs in some f-guided match). We say that $\mathbb{A}$ *strongly accepts* $(\mathbb{S}, s_I)$, notation: $\mathbb{S}, s_I \Vdash_s \mathbb{A}$ if $\exists$ has a separating winning strategy in the game $\mathcal{A}(\mathbb{A}, \mathbb{S})@(a_I, s_I)$.

Disjunctive automata are very well behaved. For instance, the following result, which can be proved using essentially the same argument as in [21], states a *linear-size* model property.

▶ **Theorem 10.** *Let $\mathbb{A} = (A, \Theta, a_I, \Omega)$ be a disjunctive automaton for a set functor T. If $\mathbb{A}$ accepts some pointed T-model, then it accepts one of which the carrier S satisfies $S \subseteq A$.*

The main property of disjunctive automata, which we will use throughout the remainder of this paper, is the following.

▶ **Proposition 11.** *Let $\mathbb{A}$ be a disjunctive Λ-automaton. Then any pointed T-model which is accepted by $\mathbb{A}$ has a pre-image model which is strongly accepted by $\mathbb{A}$.*

Proof. Let $\mathbb{S} = (S, \sigma, V)$ be a pointed T-model, let $s_I \in S$, and let f be a winning strategy for $\exists$ in the acceptance game $\mathcal{A} := \mathcal{A}(\mathbb{A}, \mathbb{S})@(a_I, s_I)$; without loss of generality we may assume that f is positional. We will construct (i) a pointed T-model (X, ξ, W, x_I), (ii) a tree (X, R) which is rooted at x_I (in the sense that for every $t \in X$ there is a unique R-path from x_I to x) and supports (X, ξ) (in the sense that $\xi(x) \in \mathsf{T}R(x)$, for every $x \in X$), (iii) a morphism $h : (X, \xi, W) \to (S, \sigma, V)$ such that $h(x_I) = s_I$. In addition (X, ξ, W, x_I) will be strongly accepted by $\mathbb{A}$.

In more detail, we will construct all of the above step by step, and by a simultaneous induction we will associate, with each $t \in X$ of depth k, a (partial) f-guided match Σ_t of length $2k + 1$; we will denote the final position of Σ_t as (a_t, s_t), and will define $h(t) := s_t$.

For the base step of the construction we take some fresh object x_I, we define Σ_{x_I} to be the match consisting of the single position (a_I, s_I), and set $h(x_I) := s_I$.

Inductively assume that we are dealing with a node $t \in X$ of depth k, and that Σ_t, a_t and s_t are as described above. Since Σ_t is an f-guided match and f is a winning strategy in $\mathcal{A}$, the pair (a_t, s_t) is a winning position for $\exists$ in $\mathcal{A}$. In particular, the marking $m_t : S \to \mathsf{P}A$ prescribed by f at this position satisfies

$$S, \sigma(s_t), m_t \Vdash^1 \Theta(V^\flat(s_t), a_t).$$

Now by disjunctiveness of the automaton $\mathbb{A}$ there is a set $R(t)$ (that we may take to consist of fresh objects), an object $\xi(t) \in \mathsf{T}R(t)$, an A-marking $m'_t : R(t) \to \mathsf{P}A$ and a map $h_t : R(t) \to S$, such that[2] $|m(u)| = 1$ and $m'_t(u) \subseteq m_t(h_t(u))$ for all $u \in R(t)$, $(\mathsf{T}h_t)\xi(t) = \sigma(s_t)$ and

$$R(t), \xi(t), m'_t \Vdash^1 \Theta(V^\flat(s_t), a_t).$$

Let a_u be the unique object such that $m'_t(u) = \{a_u\}$, define $s_u := h_t(u)$, and put $\Sigma_u := \Sigma_t \cdot m_t \cdot (a_u, s_u)$.

With (X, R, x_I) the tree constructed in this way, and observing that $\xi(t) \in R(t) \subseteq X$, we let ξ be the coalgebra map on X. Taking $h : X \to S$ to be the union $(x_I, s_I) \cup \{h_t \mid t \in X\}$, we can easily verify that h is a surjective coalgebra morphism. Finally, we define the valuation $W : \mathtt{X} \to \mathsf{P}X$ by putting $W(p) := \{x \in X \mid hx \in V(p)\}$.

It remains to show that $\mathbb{A}$ strongly accepts the pointed T-model $(\mathbb{X}, x_I)$, with $\mathbb{X} = (X, \xi, W)$; for this purpose consider the following (positional) strategy f' for $\exists$ in $\mathcal{A}(\mathbb{A}, \mathbb{X})$. At a position $(a, t) \in A \times X$ such that $a \neq a_t$ $\exists$ moves randomly (we may show that such a position will not occur); on the other hand, at a position of the form (a_t, t), the move

[2] To simplify our construction, we strengthen clause (3) in Definition 2. This is not without loss of generality, but we may take care of the general case using a routine extension of the present proof.

suggested by the strategy f' is the marking m'_t. Then it is obvious that f' is a separating strategy; to see that f' is winning from starting position (a_I, x_I), consider an infinite match Σ of $\mathcal{A}(\mathbb{A}, \mathbb{X})@(a_I, x_I)$ (finite matches are left to the reader). It is not hard to see that Σ must be of the form $\Sigma = (a_0, x_0)m'_{x_0}(a_1, x_1)m'_{x_1} \cdots$, where $\Sigma^- = (a_0, h(s_0))m_{x_0}(a_1, h(s_1))m_{x_1} \cdots$ is an f-guided match of $\mathcal{A}$. From this observation it is immediate that Σ is won by $\exists$. ◀

We now come to our main application of disjunctive bases, and fill in the main missing piece in the theory of coalgebraic automata based on predicate liftings: a simulation theorem.

▶ **Theorem 12** (Simulation). *Let Λ be a monotone modal signature for the set functor* T *and assume that Λ has a disjunctive basis. Then there is an effective construction transforming an arbitrary Λ-automaton $\mathbb{A}$ into an equivalent disjunctive Λ-automaton* $\mathsf{sim}(\mathbb{A})$*.*

Proof. Assume that $\mathtt{D}$ is a disjunctive basis for Λ, and let $\mathbb{A} = (A, \Theta, \Omega, a_I)$ be a Λ-automaton. Our definition of $\mathsf{sim}(\mathbb{A})$ is rather standard [22], so we will confine ourselves to the definitions. The construction takes place in two steps, a 'pre-simulation' step that produces a disjunctive automaton $\mathsf{pre}(\mathbb{A})$ with a non-parity acceptance condition, and a second 'synchronization' step that turns this nonstandard disjunctive automaton into a standard one.

We define the pre-simulation automaton of $\mathbb{A}$ as the structure $\mathsf{pre}(\mathbb{A}) := (A^\sharp, \Theta^\sharp, NBT_{\mathbb{A}}, R_I)$, where the carrier of the pre-simulation $\mathsf{pre}(\mathbb{A})$ of $\mathbb{A}$ is the collection $A^\sharp$ of *binary* relations over A, and the initial state R_I is the singleton pair $\{(a_I, a_I)\}$. For its transition function, first define the map $\Theta^\star : A \times \mathtt{PX} \to \mathtt{1ML}^+_\Lambda(A \times A)$ by putting, for $a \in A$ and $c \in \mathtt{PX}$:

$$\Theta^\star(a, c) := \Theta(a, c)[\theta_a],$$

where $\theta_a : A \to \mathtt{Latt}(A \times A)$ is the *tagging* substitution given by $\theta_a : b \mapsto (a, b)$. Now, given a state $R \in A^\sharp$ and color $c \in \mathtt{PX}$, take $\Theta^\sharp(R, c)$ to be an arbitrary but fixed formula in $\mathtt{D}(A^\sharp)$ such that

$$\Theta^\sharp(R, c)[\wedge_{A\times A}] \equiv \bigwedge_{a \in \mathsf{Ran} R} \Theta^\star(a, c).$$

Clearly such a formula exists by our assumption on $\mathtt{D}$ being a disjunctive basis for Λ.

Turning to the *acceptance condition*, define a *trace* on an $A^\sharp$-stream $\rho = (R_n)_{0 \le n < \omega}$ to be an A-stream $\alpha = (a_n)_{0 \le n < \omega}$ with $R_i a_i a_{i+1}$ for all $i \le 0$. Calling such a trace α *bad* if $\max\{\Omega(a) \mid a \text{ occurs infinitely often in } \alpha\}$ is odd, we obtain the acceptance condition of the automaton $\mathsf{pre}(\mathbb{A})$ as the set $NBT_{\mathbb{A}} \subseteq (A^\sharp)^\omega$ of $A^\sharp$-streams that contain no bad trace.

Finally we produce the simulation of $\mathbb{A}$ by forming a certain kind of product of $\mathsf{pre}(\mathbb{A})$ with $\mathbb{Z}$, where $\mathbb{Z} = (Z, \delta, \Omega', z_I)$ is some deterministic parity stream automaton recognizing the ω-regular language $NBT_{\mathbb{A}}$. More precisely, we define $\mathsf{sim}(\mathbb{A}) := (A^\sharp \times Z, \Theta'', \Omega'', (R_I, z_I))$ where:

- $\Theta''(R, z) := \Theta^\sharp(R)[(Q, \delta(R, z)/Q \mid Q \in A^\sharp]$ and
- $\Omega''(R, z) := \Omega'(z)$.

The equivalence of $\mathbb{A}$ and $\mathsf{sim}(\mathbb{A})$ can be proved by relatively standard means [22]. ◀

5 Lyndon theorems

Lyndon's classical theorem in model theory provides a syntactic characterization of a semantic property, showing that a formula is *monotone* in a predicate P if and only if it is equivalent to a formula in which P occurs only *positively*. A version of this result for the modal μ-calculus was proved by d'Agostino and Hollenberg in [3]. Here, we show that their result holds for any μ-calculus based on a signature that admits a disjunctive basis.

We first turn to the one-step version of the Lyndon Theorem, for which we need the following definition; we also recall the substitutions $\wedge_A$ and $\vee_A$ defined in section 2.

▶ **Definition 13.** A *propositional A-type* is a subset of A. For $B \subseteq A$ and $a \in A$, the formulas τ_B and τ_B^{a+} are defined by:

$$\begin{array}{lll} \tau_B & := & \bigwedge B \wedge \bigwedge\{\neg a \mid a \in A \setminus B\} \\ \tau_B^{a+} & := & \bigwedge B \wedge \bigwedge\{\neg b \mid b \in A \setminus (B \cup \{a\})\} \end{array}$$

We let τ and τ^{a+} denote the maps $B \mapsto \tau_B$ and $B \mapsto \tau_B^{a+}$, respectively.

▶ **Proposition 14.** *Suppose Λ admits a disjunctive basis. Then for any formula α in $\mathtt{1ML}_\Lambda(A)$ there is a one-step equivalent formula of the form $\delta[\vee_{\mathsf{P}A}][\tau]$ for some $\delta \in \mathtt{D}(\mathsf{P}A)$.*

Proof. Let's first check that everything is correctly typed: note that we have $\vee_{\mathsf{P}A} : \mathsf{P}A \to \mathtt{Bool}(\mathsf{P}A)$ and so $\delta[\vee_{\mathsf{P}A}] \in \mathtt{1ML}_\Lambda(\mathsf{P}A)$, and $\tau_{\mathsf{P}A} : \mathsf{P}A \to \mathtt{Bool}(A)$. So $\delta[\vee_{\mathsf{P}A}][\tau] \in \mathtt{1ML}_\Lambda(A)$, as required.

For the normal form proof, first note that we can use boolean duals of the modal operators to push negations down to the zero-step level. Putting the resulting formula in disjunctive normal form, we obtain a disjunction of formulas of the form $\heartsuit_{\lambda_1}\pi_1 \wedge ... \wedge \heartsuit_{\lambda_k}\pi_k$, where $\pi_1, ..., \pi_k \in \mathtt{Bool}(A)$. Repeatedly applying the distributivity of $\mathtt{D}$ over Λ and the distributive law for $\mathtt{D}$, we can rewrite each such disjunct as a formula of the form $\delta[\sigma]$ where $\delta \in \mathtt{D}(\{1, ..., k\})$ and $\sigma : \{1, ..., k\} \to \mathtt{Bool}(A)$ is defined by setting $i \mapsto \pi_i$. Now, just apply propositional logic to rewrite each formula π_i as a disjunction of formulas in $\tau[\mathsf{P}A]$, and we are done. ◀

▶ **Theorem 15** (One-step Lyndon theorem)**.** *Let Λ be a monotone modal signature for the set functor T and assume that Λ has a disjunctive basis. Any $\alpha \in \mathtt{1ML}_\Lambda(A)$, monotone in the variable $a \in A$, is one-step equivalent to some formula in $\mathtt{1ML}_\Lambda(A)$, which is positive in a.*

Proof. By Proposition 14, we can assume that α is of the form $\delta[\vee_{\mathsf{P}A}][\tau]$ for some $\delta \in \mathtt{D}(\mathsf{P}A)$. Clearly it suffices to show that :

$$\delta[\vee_{\mathsf{P}A}][\tau] \equiv^1 \delta[\vee_{\mathsf{P}A}][\tau^{a+}]$$

One direction, from left to right, is easy since $\delta[\vee_{\mathsf{P}A}]$ is a monotone formula in $\mathtt{1ML}_\Lambda(\mathsf{P}A)$, and $[\![\tau_B]\!]^0_m \subseteq [\![\tau_B^{a+}]\!]^0_m$ for each $B \subseteq A$ and each marking $m : X \to \mathsf{P}A$.

For the converse direction, suppose $X, \xi, m \Vdash^1 \delta[\vee_{\mathsf{P}A}][\tau^{a+}]$. We define a $\mathsf{P}A$-marking $m_0 : X \to \mathsf{PP}A$ by setting $m_0(u) := \{B \subseteq A \mid B \preceq_a m(u)\}$, where the relation $\preceq_a$ over $\mathsf{P}A$ is defined by $B \preceq_a B'$ iff $B \setminus \{a\} = B' \setminus \{a\}$, and $a \notin B$ or $a \in B'$. We claim that $X, \xi, m_0 \Vdash^1 \delta[\vee_{\mathsf{P}A}]$. Since $\delta[\vee_{\mathsf{P}A}]$ is a monotone formula, it suffices to check that $[\![\tau_B^{a+}]\!]^0_m \subseteq [\![B]\!]^0_{m_0}$ for each $B \subseteq A$. This follows by just unfolding definitions.

Since δ was disjunctive, so is $\delta[\vee_{\mathsf{P}A}]$, as an easy argument will reveal. So we now find a one-step frame morphism $f : (X', \xi') \to (X, \xi)$, together with a marking $m' : X' \to \mathsf{PP}A$ such that $|m'(u)| \leq 1$ and $m'(u) \subseteq m_0(f(u))$ for all $u \in X'$, and such that $X', \xi', m' \Vdash^1 \delta[\vee_{\mathsf{P}A}]$. We define a new A-marking $m'' : X' \to \mathsf{P}A$ on X' by setting $m''(u) = B$, if $m'(u) = \{B\}$, and $m''(u) = m(f(u))$ if $m'(u) = \emptyset$. Note that, for each $B \subseteq A$, we have $[\![B]\!]^0_{m'} \subseteq [\![\tau_B]\!]^0_{m''}$, so by monotonicity of $\delta[\vee_{\mathsf{P}A}]$ we get $X', \xi', m'' \Vdash^1 \delta[\vee_{\mathsf{P}A}][\tau]$.

If we compare the markings m'' and $m \circ f$, we see that $m''(u) \preceq_a m(f(u))$ for all $u \in X'$. If $m'(u) = \emptyset$, then in fact $m''(u) = m(f(u))$ by definition of m''. If $m'(u) = \{B\}$, then $m''(u) = B \in m'(u) \subseteq m_0(f(u))$, hence $B \preceq_a m(f(u))$ by definition of m_0. Since $\delta[\vee_{\mathsf{P}A}][\tau]$

was monotone with respect to the variable a it follows that $X', \xi', m \circ f \Vdash^1 \delta[\bigvee_{\mathsf{P}A}][\tau]$ and so $X, \xi, m \Vdash^1 \delta[\bigvee_{\mathsf{P}A}][\tau]$ by naturality, thus completing the proof of the theorem. ◀

A useful corollary to this theorem is the following.

▶ **Corollary 16.** *Suppose Λ is an expressively complete set of monotone predicate liftings for T. If Λ admits a disjunctive basis, then Λ is Lyndon complete and hence $\mu\mathtt{ML}_\Lambda \equiv \mu\mathtt{ML}_\mathsf{T}$.*

At first glance this proposition (of which a full proof can be found in [6]) may seem trivial, but it is important to see that it is not: given a formula φ of $\mu\mathtt{ML}_\mathsf{T}$, a naive definition of an equivalent formula in $\mu\mathtt{ML}_\Lambda$ would be to apply expressive completeness to simply replace each subformula of the form $\heartsuit_\lambda(\psi_1, ..., \psi_n)$ with an equivalent one-step formula α over $\{\psi_1, ..., \psi_n\}$, using only predicate liftings in Λ. But if this subformula contains bound fixpoint variables, these must still appear positively in α in order for the translation to even produce a grammatically correct formula! We need the stronger condition of *Lyndon completeness* for Λ. We do not know whether expressive completeness entails Lyndon completeness in general, but in the presence of a disjunctive basis, it does: this is a consequence of Theorem 15.

We now turn to our Lyndon Theorems for the full coalgebraic modal (fixpoint) languages. Let $(\mu\mathtt{ML}_\Lambda)^M_p$ and $(\mathtt{ML}_\Lambda)^M_p$ denote the fragments of respectively $\mu\mathtt{ML}$ and $\mathtt{ML}_\Lambda$, consisting of the formulas that are positive in the proposition letter p.

▶ **Theorem 17** (Lyndon Theorem)**.** *There is an effective translation $(\cdot)^M_p : \mu\mathtt{ML}_\Lambda \to (\mu\mathtt{ML}_\Lambda)^M_p$, which restricts to a map $(\cdot)^M_p : \mathtt{ML}_\Lambda \to (\mathtt{ML}_\Lambda)^M_p$, and satisfies that*

$\xi \in \mu\mathtt{ML}$ is monotone in p iff $\xi \equiv \xi^M_p$.

Proof. Due to space limitations, we have to confine ourselves to a sketch. By the equivalence between formulas and Λ-automata and the Simulation Theorem, it suffices to prove the analogous statement for disjunctive coalgebra automata. Given a disjunctive Λ-automaton $\mathbb{A} = (A, \Theta, \Omega, a_I)$, we define $\mathbb{A}^M_p$ to be the automaton $(A, \Theta^M_p, \Omega, a_I)$, where

$$\Theta^M_p(c, a) := \begin{cases} \Theta(c, a) & \text{if } p \in c \\ \top & \text{if } p \notin c. \end{cases}$$

Clearly $\mathbb{A}^M_p$ is a disjunctive automaton as well, and it is routine to show that $\mathbb{A}^M_p$ is equivalent to a formula in $\mu\mathtt{ML}_\Lambda$ that is positive in the variable p. Our main claim is then that $\mathbb{A}$ is monotone in p iff $\mathbb{A} \equiv \mathbb{A}^M_p$. Some more details of this proof can be found in the appendix. ◀

▶ Remark. Observe that as a corollary of Theorem 17 and the decidability of the satisfiability problem of $\mu\mathtt{ML}_\Lambda$ [2], it is decidable whether a given formula $\xi \in \mu\mathtt{ML}$ is monotone in p.

6 Uniform Interpolation

Uniform interpolation is a very strong form of the interpolation theorem, first proved for the modal μ-calculus in [3]. It was later generalized to coalgebraic modal logics in [16]. However, the proof crucially relies on non-deterministic automata, and for that reason the generalization in [16] is stated for nabla-based languages. With a simulation theorem for predicate liftings based automata in place, we can prove the uniform interpolation theorem for a large class of μ-calculi based on predicate liftings. Given a set $\mathtt{X}$ of proposition letters and a single proposition letter p, it may be convenient to denote the set $\mathtt{X} \cup \{p\}$ as $\mathtt{X}p$.

▶ **Definition 18.** Given a formula $\varphi \in \mu\mathtt{ML}_\Lambda$, we let $\mathtt{X}_\varphi$ denote the set of proposition letters occurring in φ.

A logic $\mathcal{L}$ with semantic consequence relation $\models$ is said to have the property of *uniform interpolation* if, for any formula $\varphi \in \mathcal{L}$ and any set $\mathtt{X} \subseteq \mathtt{X}_\varphi$ of proposition letters, there is a formula $\varphi_\mathtt{X} \in \mathcal{L}(\mathtt{X})$, effectively constructible from φ, such that

$$\varphi \models \psi \text{ iff } \varphi_\mathtt{X} \models \psi, \tag{4}$$

for every formula $\psi \in \mathcal{L}$ such that $\mathtt{X}_\varphi \cap \mathtt{X}_\psi \subseteq \mathtt{X}$.

To see why this property is called uniform *interpolation*, it is not hard to prove that, if $\varphi \models \psi$, with $\mathtt{X}_\varphi \cap \mathtt{X}_\psi \subseteq \mathtt{X}$, then the formula $\varphi_\mathtt{X}$ is indeed an interpolant in the sense that $\varphi \models \varphi_\mathtt{X} \models \psi$ and $\mathtt{X}_{\varphi_\mathtt{X}} \subseteq \mathtt{X}_\varphi \cap \mathtt{X}_\psi$.

▶ **Theorem 19** (Uniform Interpolation). *Let Λ be a monotone modal signature for the set functor T and assume that Λ has a disjunctive basis. Then both logics $\mathtt{ML}_\Lambda$ and $\mu\mathtt{ML}_\Lambda$ enjoy the property of uniform interpolation.*

Following D'Agostino & Hollenberg [3], we prove Theorem 19 by automata-theoretic means. The key proposition in our proof is Proposition 21 below, which refers to the following construction on disjunctive automata.

▶ **Definition 20.** Let $\mathtt{X}$ be a set of proposition letters not containing the letter p. Given a disjunctive $(\Lambda, \mathtt{X}p)$-automaton $\mathbb{A} = (A, \Theta, \Omega, a_I)$, we define the map $\Theta^{\exists p} : A \times \mathsf{P}\mathtt{X} \to \mathtt{D}(A)$ by

$$\Theta^{\exists p}(c, a) := \Theta(c, a) \vee \Theta(c \cup \{p\}, a),$$

and we let $\mathbb{A}^{\exists p}$ denote the $(\Lambda, \mathtt{X})$-automaton $(A, \Theta^{\exists p}, \Omega, a_I)$.

▶ **Proposition 21.** *Let $\mathtt{X} \subseteq \mathtt{Y}$ be sets of proposition letters, both not containing the letter p. Then for any disjunctive $(\Lambda, \mathtt{X}p)$-automaton $\mathbb{A}$ and any pointed T-model $(\mathbb{S}, s_I)$ over $\mathtt{Y}$:*

$$\mathbb{S}, s_I \Vdash \mathbb{A}^{\exists p} \textit{ iff } \mathbb{S}', s'_I \Vdash_s \mathbb{A} \textit{ for some } \mathtt{Y}p\textit{-model } (S', s'_I) \textit{ such that } \mathbb{S}'{\restriction}_\mathtt{Y}, s'_I \mathrel{\underline{\rightrightarrows}} \mathbb{S}, s_I. \tag{5}$$

Proof. We only prove the direction from left to right, leaving the other (easier) direction as an exercise to the reader. For notational convenience we assume that $\mathtt{X} = \mathtt{Y}$.

By Proposition 11 it suffices to assume that $(\mathbb{S}, s_I)$ is *strongly* accepted by $\mathbb{A}^{\exists p}$ and find a subset U of S for which we can prove that $\mathbb{S}[p \mapsto U], s_I \Vdash_s \mathbb{A}$. So let f be a separating winning strategy for $\exists$ in $\mathcal{A}(\mathbb{A}^{\exists p}, \mathbb{S})@(a_I, s_I)$ witnessing that $\mathbb{S}, s_I \Vdash_s \mathbb{A}^{\exists p}$. Call a point $s \in S$ *f-accessible* if there is a state $a \in A$ such that the position (a, s) is f-reachable; since this state is unique by the assumption of strong acceptance we may denote it as a_s. Clearly any position of the form (a_s, s) is winning for $\exists$, and hence by legitimacy of f it holds in particular that

$$S, \sigma(s), m_s \Vdash^1 \Theta^{\exists p}(V^\flat(s), a_s),$$

where $m_s : S \to \mathsf{P}A$ denotes the marking selected by f at position (a_s, s). Recalling that $\Theta^{\exists p}(V^\flat(s), a_s) = \Theta(V^\flat(s), a_s) \vee \Theta(V^\flat(s) \cup \{p\}, a_s)$, we define

$$U := \{s \in S \mid s \text{ is } f\text{-accessible and } S, \sigma(s), m_s \nVdash^1 \Theta(V^\flat(s), a_s)\}.$$

By this we ensure that, for all f-accessible points s:

$$s \notin U \text{ implies } S, \sigma(s), m_s \Vdash^1 \Theta(V^\flat(s), a_s) \tag{6}$$

$$\text{while } s \in U \text{ implies } S, \sigma(s), m_s \Vdash^1 \Theta(V^\flat(s) \cup \{p\}, a_s) \tag{7}$$

Now consider the valuation $V_U := V[p \mapsto U]$, and observe that by this definition we have $V_U^\flat(s) = V^\flat(s)$ if $s \notin U$ while $V_U^\flat(s) = V^\flat(s) \cup \{p\}$ if $s \in U$. Combining this with (6) and (7) we find that

$$S, \sigma(s), m_s \Vdash^1 \Theta(V_U^\flat, a_s)$$

whenever s is f-accessible. In other words, f provides a legitimate move m_s in $\mathcal{A}(\mathbb{A}, \mathbb{S})@(a_s, s)$ at any position of the form (a_s, s). From this it is straightforward to derive that f itself is a (separating) winning strategy for $\exists$ in $\mathcal{A}(\mathbb{A}, \mathbb{S}[p \mapsto U])@(a_I, s_I)$, and so we obtain that $\mathbb{S}[p \mapsto U], s_I \Vdash_s \mathbb{A}$ as required. ◀

The remaining part of the argument follows by a fairly standard argument going back to D'Agostino & Hollenberg [3] (see also Marti et alii [16]), with a twist provided by the fact that the 'bisimulation quantifier' here refers to pre-images rather than to bisimilar models.

▶ **Proposition 22.** *Given any proposition letter p, there is a map $\exists p$ on $\mu\mathtt{ML}_\Lambda$, restricting to $\mathtt{ML}_\Lambda$, such that $\mathtt{X}_{\exists p.\varphi} = \mathtt{X}_\varphi \setminus \{p\}$ and, for every pointed $(\mathbb{S}, s_I)$ over a set $\mathtt{Y} \supseteq \mathtt{X}_\varphi$ with $p \notin \mathtt{Y}$:*

$$\mathbb{S}, s_I \Vdash \exists p.\varphi \textit{ iff } \mathbb{S}', s'_I \Vdash \varphi \textit{ for some } \mathtt{Y}p\textit{-model } (S', s'_I) \textit{ such that } \mathbb{S}'{\restriction_{\mathtt{Y}}}, s'_I \rightrightarrows \mathbb{S}, s_I. \qquad (8)$$

Proof. Straightforward by the equivalence between formulas and Λ-automata, the Simulation Theorem, and Proposition 21. ◀

Proof of Theorem 19. With $p_1, \ldots, p_n$ enumerating the proposition letters in $\mathtt{X}_\varphi \setminus \mathtt{X}$, set

$$\varphi_{\mathtt{X}} := \exists p_1 \exists p_2 \cdots \exists p_n.\varphi.$$

Then a relatively routine exercise shows that $\varphi \models \psi$ iff $\varphi_{\mathtt{Y}} \models \psi$, for all formulas $\psi \in \mu\mathtt{ML}_\Lambda$ such that $\mathtt{X}_\varphi \cap \mathtt{X}_\psi \subseteq \mathtt{X}$. Finally, it is not difficult to verify that $\varphi_{\mathtt{Y}}$ is fixpoint-free if φ is so; that is, the uniform interpolants of a formula in $\mathtt{ML}_\Lambda$ also belong to $\mathtt{ML}_\Lambda$. ◀

7 Yoneda representation of disjunctive liftings

It is a well known fact in coalgebraic modal logic that predicate liftings have a neat representation via an application of the Yoneda lemma. This was explored by Schröder in [20], where it was used among other things to prove a characterization theorem for the monotone predicate liftings. Here, we apply the same idea to disjunctive liftings. We shall be working with a slightly generalized notion of predicate lifting here, taking a predicate lifting over a finite set of variables A to be a natural transformation $\lambda : \breve{\mathsf{P}}^A \to \breve{\mathsf{P}} \circ \mathsf{T}$. Clearly, one-step formulas in $1\mathtt{ML}_\Lambda(A)$ can then be viewed as predicate liftings over A.

▶ **Definition 23.** Let $\lambda : \breve{\mathsf{P}}^A \to \breve{\mathsf{P}} \circ \mathsf{T}$ be a predicate lifting over variables $A = \{a_1, ..., a_n\}$. The *Yoneda representation* $y(\lambda)$ of λ is the subset

$$\lambda_{\mathsf{P}A}(\mathsf{true}_{a_1}, ..., \mathsf{true}_{a_n}) \in \mathsf{PTP}A$$

where $\mathsf{true}_{a_i} = \{B \subseteq A \mid a_i \in B\}$. We shall write simply $\lambda \subseteq \mathsf{TP}A$ instead of $y(\lambda)$.

▶ **Definition 24.** Given a set A, let $A^\top$ be the set $A \cup \{\top\}$. Let $\epsilon_A \subseteq A^\top \times \mathsf{P}A$ be the relation defined by $a\epsilon_A B$ iff $a \in B$, and $\top\epsilon_A B$ for all $B \subseteq A$. Let $\eta_A : A^\top \to \mathsf{P}A$ be defined by $\eta_A(a) = \{a\}$, and $\eta_A(\top) = \varnothing$.

In the remainder of this section we assume familiarity with the Barr relation lifting $\overline{\mathsf{T}}$ associated with a functor T; see [14] for the definition and some basic properties.

▶ **Definition 25.** A predicate lifting $\lambda \subseteq \mathsf{TP}A$ is said to be *divisible* if, for all $\alpha \in \lambda$ there is some $\beta \in \mathsf{T}A^\top$ such that $(\beta, \alpha) \in \overline{\mathsf{T}}(\epsilon_A)$ and $\mathsf{T}\eta_A(\beta) \in \lambda$.

▶ **Proposition 26.** *Any disjunctive lifting over A is divisible, and if T preserves weak pullbacks the disjunctive liftings over A are precisely the divisible ones.*

Proof. Suppose $\lambda \subseteq \mathsf{TP}A$ is disjunctive, and pick $\alpha \in \lambda$. Then $\mathsf{P}A, \alpha, \mathsf{id}_{\mathsf{P}A} \Vdash^1 \lambda$, so since λ is disjunctive there are some one-step model (X, ξ, m) and map $f : X \to \mathsf{P}A$ with $m : X \to \mathsf{P}A$, $m(u) \subseteq f(u)$ for all $u \in X$, $\mathsf{T}f(\xi) = \alpha$, and $|m(u)| \leq 1$ for all $u \in X$. We define a map $g : X \to A^\top$ by setting $g : u \mapsto \top$ if $m(u) = \varnothing$, $g : u \mapsto a$ if $m(u) = \{a\}$. We tuple the maps f, g to get a map $\langle f, g\rangle : X \to A^\top \times \mathsf{P}A$. In fact, since $m(u) \subseteq f(u)$ for all $u \in X$, we have $\langle f, g\rangle : X \to \epsilon_A$. Let $\pi_1 : \epsilon_A \to A^\top$ and $\pi_2 : \epsilon_A \to \mathsf{P}A$ be the projection maps. We have the following diagram, in which the two triangles and the outer edges commute (i.e., $m = \eta_A \circ g$).

$$\begin{tikzcd}
 & \mathsf{P}A \\
X \arrow[ur, bend left, "m"] \arrow[ur, "f"'] \arrow[r, "\langle f,g\rangle"'] \arrow[dr, "g"'] & \epsilon_A \arrow[u, "\pi_2"'] \arrow[d, "\pi_1"] \\
 & A^\top \arrow[uu, bend right=60, "\eta_A"']
\end{tikzcd}$$

Now apply T to this diagram and define $\beta \in \mathsf{T}A^\top$ to be $\mathsf{T}(\pi_1 \circ \langle f, g\rangle)(\xi) = \mathsf{T}g(\xi)$. First, we have $(\beta, \alpha) \in \overline{\mathsf{T}}(\epsilon_A)$, witnessed by $\mathsf{T}(\langle f, g\rangle)(\xi) \in \mathsf{T}\epsilon_A$. We claim that $\mathsf{T}\eta_A(\beta) \in \lambda$. But since $X, \xi, m \Vdash^1 \lambda$ and $m = \eta_A \circ g$, naturality of λ applied to the map $g : X \to A^\top$, gives $A^\top, \beta, \eta_A \Vdash^1 \lambda$. Another naturality argument, applied to $\eta_A : (A^\top, \beta, \eta_A) \to (\mathsf{P}A, \mathsf{T}\eta_A(\beta), \mathsf{id}_{\mathsf{P}A})$ gives $\mathsf{P}A, \mathsf{T}\eta_A(\beta), \mathsf{id}_{\mathsf{P}A} \Vdash^1 \lambda$, i.e., $\mathsf{T}\eta_A(\beta) \in \lambda$.

For the converse direction, under the assumption that T preserves weak pullbacks, suppose that λ is divisible, and suppose $X, \xi, m \Vdash^1 \lambda$. We get $\mathsf{T}m(\xi) \in \lambda$ and so we find some $\beta \in \mathsf{T}A^\top$ with $\beta(\overline{\mathsf{T}}\epsilon_A)\mathsf{T}m(\xi)$ and $\mathsf{T}\eta_A(\beta) \in \lambda$. Pick some $\beta' \in \mathsf{T}\epsilon_A$ with $\mathsf{T}\pi_2(\beta') = \mathsf{T}m(\xi)$ and $\mathsf{T}\pi_1(\beta') = \beta$. Let R, g_1, g_2 be the pullback of the diagram $X \to \mathsf{P}A \leftarrow \epsilon_A$, shown in the diagram.

$$\begin{tikzcd}
X \arrow[r, "m"] & \mathsf{P}A \\
R \arrow[u, "g_1"] \arrow[r, "g_2"'] & \epsilon_A \arrow[u, "\pi_2"'] \arrow[d, "\pi_1"] \\
 & A^\top \arrow[uu, bend right=60, "\eta_A"']
\end{tikzcd}$$

By weak pullback preservation there is $\rho \in \mathsf{T}R$ with $\mathsf{T}g_1(\rho) = \xi$ and $\mathsf{T}g_2(\rho) = \beta'$. The map $g_1 : (R, \rho) \to (X, \xi)$ is thus a cover, and we have a marking m' on R defined by $\eta_A \circ \pi_1 \circ g_2$ (follow the bottom-right path in the previous diagram). It is now routine to check that $R, \rho, m' \Vdash^1 \lambda$, and $|m'(u)| \leq 1$ and $m'(u) \subseteq m(g_1(u))$ for all $u \in R$, so we are done. ◀

For the moment, we leave the question open, whether a similar characterization of disjunctive predicate liftings can be proved without weak pullback preservation. We also leave it as an open problem to characterize the functors that admit a disjunctive basis.

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