

Automata and Fixed Point Logic: a Coalgebraic Perspective

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Abstract

This paper generalizes existing connections between automata and logic to a coalgebraic level.

Let $F : \mathbf{Set} \rightarrow \mathbf{Set}$ be a standard functor that preserves weak pullbacks. We introduce various notions of F -automata, devices that operate on pointed F -coalgebras. The criterion under which such an automaton accepts or rejects a pointed coalgebra is formulated in terms of an infinite two-player graph game. We also introduce a language of coalgebraic fixed point logic for F -coalgebras, and we provide a game semantics for this language. Finally we show that any formula p of the language can be transformed into an F -automaton \mathbb{A}_p which is equivalent to p in the sense that \mathbb{A}_p accepts precisely those pointed F -coalgebras in which p holds.

Keywords coalgebra, automata, modal logic, fixed point operators, game semantics, bisimulation, parity games

1 Introduction

There is a long and respectable tradition in theoretical computer science linking the research fields of automata theory and logic. This link becomes particularly strong when automata are used to classify *infinite* objects like words, trees or graphs. Interestingly, this research area has provided not only fundamental theoretical results, such as Rabin's decidability theorem [19], but also quite concrete applications in computer science, such as tools for the automatic verification of reactive systems, see for instance [6] on model checking. Over the last ten years, the links between logic and automata theory have only grown stronger, to the effect that in many cases, the distinction between automata and formulas has almost disappeared. Of the many interesting results that have been obtained we just mention the connection that JANIN & WALUKIEWICZ [12] established between modal fixed point logics, such as the modal μ -calculus, and alternating parity automata operating on labeled transition systems. For an up to date introduction to the world of automata, logic and infinite games, we refer the reader to GRÄDEL, THOMAS & WILKE [7].

Although this has to our knowledge never been exploited, or even made explicit, much of the work relating logic and automata theory has a strong *coalgebraic flavor*. In itself this

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should not come as a surprise since both (modal) logic and automata theory admit a lucrative coalgebraic perspective.

This certainly applies to logic, and to modal logic in particular. Since coalgebra can be seen as a very general model of state-based dynamics, and modal logic as a logic for dynamic systems, there are interesting links between the two fields. One of the first to realize this, in the late 1980s, was ABRAMSKY [1]. BARWISE & MOSS [4], a rich source of material on a great variety of circular systems, contains the outline of Moss’ general approach towards coalgebraic logic, discussed in more detail by MOSS [15]. Over subsequent years, the development and study of modal languages for the specification of properties of coalgebras has been actively pursued and studied by various authors, including JACOBS [9], KURZ [13], PATTINSON [18], and RÖSSIGER [20]. However, given the intended application of coalgebraic modal languages as specification formalisms restricting the behavior of state-based systems, it is rather surprising that until now no languages have been developed that incorporate explicit fixed point operators. In addition, the only work on coalgebraic modal languages in which specimens of fixed point formulas are admitted, or in which the need for coalgebraic modal fixed point logics is discussed, seems to be by JACOBS ([11] and [10], respectively).

The coalgebraic perspective on automata may not have been developed so systematically, automata theory contains some of the paradigmatic examples of coalgebras, as any introduction to the field of coalgebra witnesses. As examples we confine ourselves to mentioning Rutten’s work on automata for finite and infinite words ([21] and [23], respectively).

Summarizing the above discussion, we find that the relation between automata theory and (modal) logic has been investigated intensively and successfully, but not uniformly or systematically. Various modal languages have been developed, in a uniform fashion, for coalgebras of arbitrary type, but none of these languages admit explicit fixed point operators. And lastly, we see that certain kinds of automata have been studied from a coalgebraic perspective, but automata for arbitrary coalgebras have not been developed. It thus seems that there is a clear gap here, and it is precisely this gap that we intend to start filling with this paper.

We believe that the connections between automata and logic could and perhaps should be studied from a general, coalgebraic perspective, and it is the main purpose of this paper to introduce a framework for doing so. We confine our attention to functors $F : \mathbf{Set} \rightarrow \mathbf{Set}$ which are standard and preserve weak pullbacks — such functors will be called *R-standard*. For each such functor F , we will define the notion of an F -automaton; the purpose of these devices is to classify pointed F -coalgebras (pairs consisting of an F -coalgebra and an element of the carrier set of the coalgebra). The criterion under which such an automaton \mathbb{A} accepts or rejects such a pointed coalgebra (\mathbb{S}, s) is formulated in terms of an infinite two-player game, to be played on a certain graph induced by \mathbb{A} and \mathbb{S} .

We also introduce a language $\mu\mathcal{L}^F$ of coalgebraic fixed point logic for F -coalgebras. This language is finitary in the sense that every formula comes with a *finite* set of subformulas. Combining ideas from the game semantics for the modal μ -calculus as formulated by JANIN & WALUKIEWICZ [12], and the semantic games for coalgebraic languages introduced by BALTAG [3], in Theorem 1 we provide a game-theoretic semantics for this language $\mu\mathcal{L}^F$. Finally, the resemblance between these games and the acceptance games for F -automata leads to the

main result of the paper: Theorem 2 states that any $\mu\mathcal{L}^F$ -formula can be transformed into a certain kind of F-automaton that accepts precisely those pointed F-coalgebras in which the formula is true. However, we do not put much focus on technical results, since we believe that the main contribution of the paper is of a conceptual nature.

It should be mentioned that there are other approaches in which the notion of automaton is lifted to a category-theoretic level. For instance, there is a series of articles by Arbib and Manes and a theory of functorial automata developed by Adámek, Trnková and others, see [2] (also for further references). Although this work bears some resemblance to ours, there are at least two differences: first, the mentioned research focuses on an algebraic rather than a coalgebraic framework, and second, it generalizes automata for finite rather than for infinite objects. Nevertheless, it would be useful to investigate the precise connection with this line of research.

Overview We first fix notation and terminology on Set-based functors and coalgebras, and define R-standard functors; we also give a brief introduction to two-person infinite parity games. In section 3 we introduce our coalgebraic perspective on automata theory by reviewing some of the more familiar kinds of automata. Section 4 provides the general definition of F-automata for R-standard functors, and gives a detailed description of the acceptance games for F-automata. Then we move to logic: in section 5 we introduce the syntax and semantics of the coalgebraic fixed point logic $\mu\mathcal{L}^F$ for coalgebras over an R-standard functor F. The next section provides the details of the game-theoretic approach to the semantics of this language. Section 7, the briefest section of the paper, states the above-mentioned main result of the paper. We finish the paper with a list of ideas for further research.

2 Preliminaries

This paper presupposes some familiarity with the basic concepts of category theory and universal coalgebra. The main purpose of this section is to fix notation and terminology. We also give a very brief introduction to so-called *graph games*.

2.1 Set-based functors and coalgebras

Basics We let \mathbf{Set} denote the category of sets with functions. For an endofunctor $F : \mathbf{Set} \rightarrow \mathbf{Set}$, an *F-coalgebra* is a pair $\mathbb{S} = (S, \sigma)$ consisting of a set S and a function $\sigma : S \rightarrow FS$. A *pointed F-coalgebra* is a pair (\mathbb{S}, s) such that \mathbb{S} is an F-coalgebra and s is an element of (the underlying set of) \mathbb{S} . Given two F-coalgebras $\mathbb{S} = (S, \sigma)$ and $\mathbb{T} = (T, \tau)$, a function $f : S \rightarrow T$ is an *F-coalgebra morphism* or *F-homomorphism* if $F(f) \circ \sigma = \tau \circ f$. The category $\mathbf{Coalg}(F)$ has the F-coalgebras as objects and the F-homomorphisms as arrows. A relation $Z \subseteq S \times T$ is an *F-bisimulation* if we can impose coalgebra structure $\zeta : Z \rightarrow FZ$ on Z in such a way that the two projections $\pi_1 : Z \rightarrow S$ and $\pi_2 : Z \rightarrow T$ are F-coalgebra morphisms. We write $Z : \mathbb{S}, s \rightleftharpoons \mathbb{T}, t$ if Z is a bisimulation between \mathbb{S} and \mathbb{T} that links $s \in S$ to $t \in T$, and $\mathbb{S}, s \rightleftharpoons \mathbb{T}, t$ if there is such a Z .

Functors and relators Let \mathbf{Rel} denote the category with sets as objects and binary relations as morphisms. Identity arrows in this category are given, for any set S , by $\Delta_S = \{(s, s) \mid s \in S\}$; composition of arrows in this category is ordinary relation composition, but we will write composition as is usual for functions. A functor $Q : \mathbf{Rel} \rightarrow \mathbf{Rel}$ is called a *relator*.

It is well-known that \mathbf{Set} can be embedded in \mathbf{Rel} by the graph functor φ which is the identity on sets and maps a function $f : S \rightarrow T$ to its *graph* $\varphi(f) = \{(s, f(s)) \mid s \in S\}$. We say that a relator $Q : \mathbf{Rel} \rightarrow \mathbf{Rel}$ *extends* a functor $F : \mathbf{Set} \rightarrow \mathbf{Set}$ if it satisfies (i) $QS = FS$ for all sets S , and (ii) $Q(\varphi(f)) = \varphi(F(f))$ for all functions $f : S \rightarrow T$. Extensions need not always exist, but are unique if they do; we denote the extension of the functor F by \bar{F} . It can be proved that an endofunctor on \mathbf{Set} can be extended to a relator if and only if it preserves weak pullbacks. This result is usually attributed to CARBONI, KELLY & WOOD [5], but it also follows as a special case of an earlier result by Trnková, see [24, Observation 2.10], or [2, section V.2.10] for a proof. In the sequel we will need the following fact; for details, consult RUTTEN [22].

Fact 2.1 *Let $F : \mathbf{Set} \rightarrow \mathbf{Set}$ be a functor that preserves weak pullbacks. Then*

1. *The unique relator \bar{F} extending F is given, for $R \subseteq S \times S'$, by $\bar{F}(R) = F(\pi) \circ F(\pi')^{-1}$.*
2. *\bar{F} is monotone, that is, if $R \subseteq Q$ then $\bar{F}(R) \subseteq \bar{F}(Q)$.*
3. *Z is a bisimulation between \mathbb{S} and \mathbb{T} iff $(s, t) \in Z$ implies $(\sigma(s), \tau(t)) \in \bar{F}Z$, for all s, t .*

The image $\bar{F}(R) \subseteq FS \times FT$ of a relation $R \subseteq S \times T$ is called the *relation lifting* of R under F .

R-standard functors A functor $F : \mathbf{Set} \rightarrow \mathbf{Set}$ is called *standard* if it preserves inclusions; that is, whenever $f : A \hookrightarrow B$ is an inclusion, then so is $F(f) : FA \hookrightarrow FB$. We need the following property, proved in ADÁMEK & TRNKOVÁ [2].

Fact 2.2 *Let F be a standard endofunctor on \mathbf{Set} . Then F preserves finite intersections, that is: $F(A \cap B) = FA \cap FB$.*

Through most of this paper we will be working with endofunctors on \mathbf{Set} that are both standard and preserve weak pullbacks. Hence, it is convenient to introduce terminology.

Definition 2.3 A functor $F : \mathbf{Set} \rightarrow \mathbf{Set}$ is called *R-standard* if it is standard and preserves weak pullbacks. ◁

2.2 Graph games

Two-player infinite graph games, or *graph games* for short, are defined as follows. For a more comprehensive account of these games, the reader is referred to GRÄDEL, THOMAS & WILKE [7].

First some preliminaries on sequences. Given a set A , let A^* , A^ω and A^\star denote the collections of finite, infinite, and all, sequences over A , respectively. (Thus, $A^\star = A^* \cup A^\omega$.) Given $\alpha \in A^*$ and $\beta \in A^*$ we define the *concatenation* of α and β in the obvious way, and we denote this element of A^* simply by juxtaposition: $\alpha\beta$. Given an infinite sequence $\alpha \in A^\omega$, let $\text{Inf}(\alpha)$ denote the set of elements $a \in A$ that occur infinitely often in α .

A graph game is played on a *board* B , that is, a set of *positions*. Each position $b \in B$ belongs to one of the two *players*, \exists (Éloise) and \forall (Abélard). Formally we write $B = B_{\exists} \cup B_{\forall}$, and for each position b we use $P(b)$ to denote the player i such that $b \in B_i$. Furthermore, the board is endowed with a binary relation E , so that each position $b \in B$ comes with a set $E[b] \subseteq B$ of *successors*. Formally, we say that the *arena* of the game consists of a directed bipartite graph $\mathbb{B} = (B_{\exists}, B_{\forall}, E)$.

A *match* of the game consists of the two players moving a pebble around the board, starting from some *initial position* b_0 . When the pebble arrives at a position $b \in B$, it is player $P(b)$'s turn to move; (s)he can move the pebble to a new position of their liking, but the choice is restricted to a successor of b . Should $E[b]$ be empty then we say that player $P(b)$ got stuck at the position. A *match* or *play* of the game thus constitutes a (finite or infinite) sequence of positions $b_0 b_1 b_2 \dots$ such that $b_i E b_{i+1}$ (for each i such that b_i and b_{i+1} are defined). A *full play* is either (i) an infinite play or (ii) a finite play in which the last player got stuck. A non-full play is called a *partial play*.

The rules of the game associate a *winner* and (thus) a *loser* for each full play of the game. A finite full play is lost by the player who got stuck; the winning condition for infinite games is given by a subset Ref of B^ω (Ref is short for ‘referee’): our convention is that \exists is the winner of $\beta \in B^\omega$ precisely if $\beta \in Ref$. A *graph game* is thus formally defined as a structure $\mathcal{G} = (B_{\exists}, B_{\forall}, E, Ref)$. Sometimes we want to restrict our attention to matches of a game with a certain initial position; in this case we will speak of a game that is *initialized* at this position.

Various kinds of winning conditions are known. In a *parity game*, the set Ref is defined in terms of a *parity function* on the board B , that is, a map $\Omega : B \rightarrow \omega$ with finite range. More specifically, the set Ref is of the form

$$B_{\Omega}^{\omega} := \{\beta \in B^\omega \mid \max\{\Omega(b) : b \in Inf(\beta)\} \text{ is even}\}. \quad (1)$$

A *strategy* for player i is a function mapping partial plays $\beta = b_0 \dots b_n$ with $P(b_n) = i$ to admissible next positions, that is, to elements of $E[b_n]$. In such a way, a strategy tells i how to play: a play β is *conform* or *consistent with* strategy f for i if for every proper initial sequence $b_0 \dots b_n$ of β with $P(b_n) = i$, we have that $b_{n+1} = f(b_0 \dots b_n)$. A strategy is *history free* if it only depends on the current position of the match, that is, $f(\beta) = f(\beta')$ whenever β and β' are partial plays with the same last element (which belongs to the appropriate player). A strategy is *winning for player i* from position $b \in B$ if it guarantees i to win any match with initial position b , no matter how the adversary plays — note that this definition also applies to positions b for which $P(b) \neq i$. A position $b \in B$ is called a *winning position* for player i , if i has a winning strategy from position b ; the set of winning positions for i in a game \mathcal{G} is denoted as $Win_i(\mathcal{G})$.

Parity games form an important game model because they have many attractive properties, such as *history-free determinacy*.

Fact 2.4 *Let $\mathcal{G} = (B_{\exists}, B_{\forall}, E, \Omega)$ be a parity graph game. Then*

1. \mathcal{G} is determined: $B = Win_{\exists}(\mathcal{G}) \cup Win_{\forall}(\mathcal{G})$.
2. Each player i has a history free strategy which is winning from any position in $Win_i(\mathcal{G})$.

The determinacy of parity games follows from a far more general game-theoretic result concerning Borel games, due to MARTIN [14]. The fact that winning strategies in parity games can always be taken to be history free, was independently proved in MOSTOWSKI [16] and EMERSON & JUTLA [8].

3 Automata on infinite objects

In this section we intend to supply a gentle introduction to our general definition of an automaton operating on coalgebras, by discussing the shape of some finite automata that are well known from the literature. While we subsequently increase the (conceptual) complexity of these machines, their overall shape will be fixed as a quadruple $\mathbb{A} = (A, a_I, \Delta, Acc)$, with A some finite set of objects called *states*, $a_I \in A$ the *initial state*, Δ some kind of *transition function*, and $Acc \subseteq A^\omega$ the *acceptance condition*.

There are in fact quite a few dimensions along which one may classify such automata. For instance, an important criterion, and one that we will encounter here as well, concerns the flavor of the transition function; this flavor makes whether we call the automaton *deterministic*, *non-deterministic*, or *alternating*. A second useful criterion is based on the *acceptance condition* of the device; examples that we will encounter here are the *Büchi* and the *parity* condition (both are defined elsewhere in this paper).

However, both of these criteria are fairly orthogonal to the aim of this paper. Our purpose here is to start with a classification of finite automata according to the *kind of object* on which the device operates (words, trees, or graphs). We hope that our presentation will convince the reader that the obvious similarities in the definition of an automaton *accepting* an object, are essentially coalgebraic in nature. This naturally leads to the general definition of an automaton that operates on pointed coalgebras of type F , where F is an arbitrary \mathbf{R} -standard endofunctor on \mathbf{Set} .

Let us first fix some terminology and notation. Throughout this section, we will work with a fixed alphabet, or color set, C .

Definition 3.1 Let F be an endofunctor on the category \mathbf{Set} , and C an arbitrary finite set of objects that we shall call *colors*. We let F_C denote the functor $F_C S = C \times FS$; that is, F_C maps a set S to the set $C \times FS$ (and a function $f : S \rightarrow S'$ to the function $id_C \times Ff : C \times FS \rightarrow C \times FS'$). F_C -coalgebras will also be called *C -colored F -coalgebras*.

We will usually denote F_C -coalgebras as triples $\mathbb{S} = (S, \gamma, \sigma)$, with $\gamma : S \rightarrow C$ the *coloring* and $\sigma : S \rightarrow FS$ the F -coalgebra map. ◁

Infinite words over an alphabet Σ can thus be seen as (special) \mathbf{Id}_Σ -coalgebras, where \mathbf{Id} is the identity functor on \mathbf{Set} . Likewise, infinite Σ -labeled binary trees are special coalgebras for the functor $(\mathbf{Id} \times \mathbf{Id})_\Sigma$. The third and last kind of objects for which we will consider finite automata in this section are the C -colored coalgebras for the power set functor \mathcal{P} . Recall that there are plenty of examples of \mathcal{P} -coalgebras in the literature, since any binary relation $R \subseteq S \times S$ can be presented as the \mathcal{P} -coalgebra map sending a point $s \in S$ to the collection $\{t \in S \mid (s, t) \in R\}$ of its R -successors. As particular examples we mention graphs and Kripke

frames; Kripke models, say, over a collection \mathbf{Prop} of proposition letters, can be seen as Kripke frames that are colored by the collection of subsets of \mathbf{Prop} .

The process of an automaton traversing and scanning a coalgebra structure needs a starting point: the first letter of a word, the root of a tree. In general, it is *pointed* coalgebras (see section 2.1) rather than coalgebras per se that are the objects of investigation for our automata.

Automata on infinite words

To start with, consider simple automata operating on infinite words. In the deterministic flavor, these are objects $\mathbb{A} = (A, a_I, \delta, Acc)$ where the transition function is of the form

$$\delta : A \times C \rightarrow C.$$

If we let such a device operate on an infinite C -word $\gamma = c_0c_1c_2\dots$, the result is a so-called *run*, that is, a sequence $\rho = a_0a_1a_2\dots$ such that $a_0 = a_I$ and $a_{i+1} = \delta(a_i, c_i)$ for all $i \in \omega$. Now \mathbb{A} is defined to *accept* γ if and only if this run, which is uniquely determined by \mathbb{A} and γ , belongs to the set Acc . (In the case of a standard finite automaton, the acceptance condition is given by a subset $F \subseteq A$ of *final*, or more appropriately, *accepting* states. An infinite word is accepted by such a machine if at least one of these accepting states occurs infinitely often in the run. This relatively simple concept is called *Büchi acceptance*.)

In the non-deterministic variant of a word automaton, we are dealing with a transition function

$$\Delta : A \times C \rightarrow \mathcal{P}C.$$

Runs of such machines are no longer uniquely determined: a *run* of \mathbb{A} on an infinite word $\gamma = c_0c_1c_2\dots$ may be any ω -word $\rho = a_0a_1a_2\dots$ over A satisfying $a_0 = a_I$ and $a_{i+1} \in \Delta(a_i, c_i)$ for all $i \in \omega$. \mathbb{A} *accepts* γ if at least one of these runs meets the acceptance condition. A good way to envisage this is to think of the automaton traversing γ and at each time *choosing* a new state a_{i+1} from the set $\Delta(a_i, c_i)$.

It is completely straightforward to generalize these notions from infinite words over C to arbitrary \mathbf{Id}_C -coalgebras. For instance, in the non-deterministic variant, a *run* of \mathbb{A} on a \mathbf{Id}_C -coalgebra $\mathbb{S} = (S, \gamma, \sigma)$ starting at $s \in S$ is an ω -word $\rho = a_0a_1a_2\dots$ such that $a_0 = a_I$ and $a_{i+1} \in \Delta(a_i, \gamma(\sigma^n(s)))$. \mathbb{A} *accepts* (\mathbb{S}, s) if one of these runs is accepting.

Automata on binary trees

Changing the type of the coalgebra functor, we move on to automata that operate on C -labeled binary trees (or on arbitrary structures that can be represented as coalgebras for the functor $(\mathbf{Id} \times \mathbf{Id})_{\Sigma}$). The basic new idea here is that an automaton which scans such a structure, starting at the root of the tree, at each node *splits* into two copies, each of which continues the investigation of the tree at one of the two successors of the current node. Formally, we denote a binary tree as a structure $\mathbb{T} = (2^*, \gamma)$, where 2^* denotes the set of finite words over the alphabet $2 = \{0, 1\}$ and $\gamma : 2^* \rightarrow C$ is the coloring of the tree. A (deterministic) tree automaton $\mathbb{A} = (A, a_I, \delta, Acc)$ has a transition function

$$\delta : A \times C \rightarrow A \times A.$$

A run of such an automaton on a C -labeled binary tree $\mathbb{T} = (2^*, \gamma)$ is now an A -labeled binary tree $\rho = (2^*, L : 2^* \rightarrow A)$ such that for all nodes $s \in 2^*$, $(L(s0), L(s1)) = \delta(L(s), \gamma(s))$. The automaton is defined to *accept* the tree β if *each* path of the run ρ , seen as an infinite word over A , belongs to A .

Deterministic tree automata, just like deterministic word automata, have a unique run on each input tree. And similarly as for word automata, we obtain a non-deterministic variant by taking, as the transition map of the automaton, a function

$$\Delta : A \times C \rightarrow \mathcal{P}(A \times A).$$

Acceptance for such automata may again be formulated in terms of the existence of an accepting run, where an accepting run is now defined as an A -labeled binary tree ρ satisfying $(L(s0), L(s1)) \in \delta(L(s), \gamma(s))$ for every node $s \in 2^*$. It is more convenient however, to rephrase the definition of acceptance within the framework of *game theory*. The combination of the existential ('for some run ...') and universal quantification ('for all paths ...') can be explained quite naturally in terms of the interaction of two players.

With any tree automaton \mathbb{A} and tree \mathbb{T} we associate an *acceptance game* $\mathcal{G}(\mathbb{A}, \mathbb{T})$, which has two players, \exists (Eloise) and \forall (Abélard). For an intuitive understanding of this game, think of \exists as aiming for the automaton to accept the tree, and of \forall as trying to prevent this. Basically, a position of the game is a pair $(a, s) \in A \times 2^*$, which codes the situation of the automaton being in state a , inspecting node s of the tree. In such a position, \exists chooses a pair $(a_0, a_1) \in \Delta(a, \gamma(s))$, after which \forall chooses to move either left or right, thus determining the next node of the tree to be either $s0$ or $s1$, and the next state of the automaton to be either a_0 or a_1 . Any full match of the game thus provides an infinite sequence $\alpha = a_0 a_1 a_2 \dots$ of states in \mathbb{A} (with $a_0 = a_I$), which in its turn determines the winner of the match: it is \exists if $\alpha \in Acc$, and \forall otherwise. The automaton *accepts* the tree \mathbb{T} in case \exists has a winning strategy for the associated game initiated at the pair (a_I, ϵ) , where ϵ is the root of the tree.

Formally, we may represent this game as the graph game (see section 2.2) of which the game positions are given in the following table, and the acceptance condition is given as before.

Position: b	$P(b)$	Admissible moves: $E[b]$
$(a, s) \in A \times 2^*$	\exists	$\{(\xi, s) \in \mathcal{P}(A \times A) \times 2^* \mid \xi \in \Delta(a, \gamma(s))\}$
$((a_0, a_1), s) \in \mathcal{P}(A \times A) \times 2^*$	\forall	$\{(a_0, s0), (a_1, s1)\}$

This game theoretic perspective on acceptance opens up various ways to *generalize* the notion of a tree automaton. A standard way to do so proceeds as follows. First, read the pair $(a_0, a_1) \in \Delta(a, \gamma(s))$ as a *conjunction* of the statements 'go left, and switch to state a_0 ', and 'go right, and switch to state a_1 '. Abbreviate this as $L:a_0 \wedge R:a_1$. Similarly, read the set $\Delta(a, c) = \{(a_0^i, a_1^i) \mid i \in I\}$ *disjunctively*, that is, as the formula $\bigvee_i (L:a_0^i \wedge R:a_1^i)$. The concept of *alternation* then naturally arises if we allow *arbitrary* conjunctions and disjunctions over the set $LR_A := \{L:a, R:a \mid a \in A\}$ in the range of the transition function of the automaton. That is, we let the transition function be of the form

$$\Delta : A \times C \rightarrow \mathcal{DL}(LR_A),$$

where, for any set X , we let $\mathcal{DL}(X)$ denote the set of (distributive) *lattice terms* over X , that is, the smallest collection of objects that includes X and contains the expressions $\bigwedge P$ and $\bigvee P$ for any finite set P of objects in $\mathcal{DL}(X)$. The board of this graph game looks as follows.

Position: b	$P(b)$	Admissible moves: $E[b]$
$(a, s) \in A \times S$	–	$\{\Delta(a, \gamma(s))\}$
$(\bigvee P, s) \in \mathcal{DL}(A \times A) \times S$	\exists	$\{(p, s) \in \mathcal{DL}(A \times A) \times S \mid p \in P\}$
$(\bigwedge P, s) \in \mathcal{DL}(A \times A) \times S$	\forall	$\{(p, s) \in \mathcal{DL}(A \times A) \times S \mid p \in P\}$
$(L:a, s) \in LR_A \times S$	–	$\{(a, s0)\}$
$(R:a, s) \in LR_A \times S$	–	$\{(a, s1)\}$

Note that in the cases where we do not associate a player with a position, the next position of the game is uniquely determined by the current one, and thus it does not matter which player owns this position. Special attention is needed for positions of the form $(\bigvee P, s)$ and $(\bigwedge P, s)$ in case P is the empty set. In a position $(\bigvee \emptyset, s)$, \exists gets stuck since there is no move available for her. Thus, in accordance with the definition of parity games, \exists immediately *loses* the match. Intuitively, this is correct since the disjunction over an empty set of propositions is usually taken to be the falsum formula \perp . Likewise, \forall loses any match ending at a position of the form $(\bigwedge \emptyset, s)$, which is in accordance with the convention that $\bigwedge \emptyset$ is equivalent to the formula \top . In any case, it is important to note that in the acceptance game for alternating tree automata, full matches may be finite. The winner and loser of an infinite match are provided by the acceptance condition of the automaton. Given an infinite match β , consider the infinite sequence of ‘basic’ positions $(a_0, s_0)(a_1, s_1)(a_2, s_2) \dots$ occurring in β . The match β is won by \exists if the induced infinite word $a_0a_1a_2 \dots$ belongs to Acc , and by \forall , otherwise.

For our purposes however, it is more convenient to define the notion of an alternating tree automaton in a slightly different (but equivalent) way. We require the transition function to be of the form

$$\Delta : A \times C \rightarrow \mathcal{DL}(A \times A),$$

with the board of the acceptance game looking as follows.

Position: b	$P(b)$	Admissible moves: $E[b]$
$(a, s) \in A \times S$	–	$\{\Delta(a, \gamma(s))\}$
$(\bigvee P, s) \in \mathcal{DL}(A \times A) \times S$	\exists	$\{(p, s) \in \mathcal{DL}(A \times A) \times S \mid p \in P\}$
$(\bigwedge P, s) \in \mathcal{DL}(A \times A) \times S$	\forall	$\{(p, s) \in \mathcal{DL}(A \times A) \times S \mid p \in P\}$
$((a_0, a_1), s) \in (A \times A) \times S$	\forall	$\{(a_0, s0), (a_1, s1)\}$

In order to see why these two approaches are equivalent, recall that the pair $(a_0, a_1) \in A \times A$ can be represented as the conjunction $L:a_0 \wedge R:a_1$. In the other direction, the atomic formula $L:a$ can be represented by the pair (a, a_\top) where a_\top is a special ‘true’ state, that is, it has $\Delta(a_\top, c) = \{\emptyset\}$ for all colors c .

It is not hard to show that the distributive laws (between \bigvee and \bigwedge) apply to this kind of game, in the sense that replacing a position (φ, s) with (φ', s) , in case φ and φ' are propositionally equivalent formulas, makes no essential change to the game. From this it follows that instead of allowing arbitrary formulas as the value of the transition function, we may confine ourselves to formulas in distributive normal form. This enables the following

set-theoretic, ‘logic-free’, presentation of alternating tree automata, namely, in which the transition map has the form

$$\Delta : A \times C \rightarrow \mathcal{PP}(A \times A).$$

Under this definition of the automaton we may present the board of the acceptance game as in the table below. Here we have also made the amendments necessary to enable the automaton to operate on arbitrary $(\mathbf{Id} \times \mathbf{Id})_C$ -coalgebras.

Position: b	$P(b)$	Admissible moves: $E[b]$
$(a, s) \in A \times S$	\exists	$\{(\Xi, s) \in \mathcal{P}(\mathbf{FA}) \times S \mid \Xi \in \Delta(a)\}$
$(\Xi, s) \in \mathcal{P}(\mathbf{FA}) \times S$	\forall	$\{(\xi, \tau) \in \mathbf{FA} \times \mathbf{FS} \mid \xi \in \Xi \text{ and } \tau = \sigma(s)\}$
$((a_0, a_1), (s_0, s_1)) \in \mathbf{FA} \times \mathbf{FS}$	\forall	$\{(a_0, s_0), (a_1, s_1)\}$

Automata on graphs/amorphous trees

The last kind of objects for which we consider finite automata are the C -colored coalgebras for the power set functor \mathcal{P} . It is important to realize that \mathcal{P} -coalgebras differ from coalgebras for the functor \mathbf{Id}^k (which sends a set X to its k -ary Cartesian power) in one important aspect. In a \mathcal{P} -coalgebra, the collection of successors of a point s is *amorphous* in the sense that one does not have explicit access to the individual points of this set. This means that whereas it is completely trivial to modify the definition of binary tree automata to the case of k -ary trees, some new ideas are required to extend the definition to capture automata for amorphous trees.

There is in fact more than one way to go here. Probably the most intuitive solution generalizes the first-mentioned approach towards alternation for tree automata, i.e., the one in which the transition function takes values in the set of lattice expressions over the set LR_A of ‘atomic formulas’. Think of the atomic formula $L:a$ as a *modal expression* stating that a applies to the L -successor of the current node of the tree. In the case of the power set functor \mathcal{P} , without explicit reference to individual successors, one may use the formulas $\diamond a$ and $\square a$ as the basic building blocks of the distributive lattice expressions. The meaning of these formulas would then be to send a copy of the automaton, switched to state a , to some successor of the current point of the graph or tree. Here the difference is of course that in the case of a diamond formula $\diamond a$, this successor is chosen by \exists , while it is \forall who chooses the next node in the case of a box formula $\square a$. Thus the net effect is that in the case of a diamond formula, a *single* copy of the automaton is sent out to one successor of the current point in the tree, whereas in the case of a box formula, a copy of the automaton is moving to *each* successor node.

The perspective on graph automata that we discuss now is equivalent but different. Our approach roughly follows JANIN & WALUKIEWICZ [12], but we have streamlined the presentation quite a bit in order to bring out the coalgebraic aspect of the definition more clearly. This facilitates the generalization towards arbitrary coalgebras.

The basic idea of this second approach is to use *sets* of states of \mathbb{A} as ‘descriptions’ of *sets* of nodes of the colored graph \mathbb{S} under inspection. Such a ‘description’, say, by a set $B \subseteq A$ of a set $T \subseteq S$, needs to be substantiated by a relation $Z \subseteq A \times S$ which is *full* on B and T , in

the sense that for every $b \in B$ there is a $t \in T$ such that $(b, t) \in Z$, and for every $t \in T$ there is a $b \in B$ such that $(b, t) \in Z$.

In the case of a *deterministic* automaton then, we may simply take the transition map to be of the form

$$\delta : A \times C \rightarrow \mathcal{P}A,$$

and the idea is that when the automaton, in state $a \in A$, inspects a node $s \in S$, the set $\delta(a, \gamma(s))$ provides a description of the collection $\sigma(s)$ of successors of s . It is the task of \exists to come up with a full relation $Z \subseteq \delta(a, \gamma(s)) \times \sigma(s)$ to substantiate the claim that $\delta(a, \gamma(s))$ is an adequate description of $\sigma(s)$. After she has chosen such a relation Z , it is \forall 's turn to pick a pair $(b, t) \in Z$. The automaton then switches to state b and moves to successor t of s , and the acceptance game continues. Thus, different from the case of bounded trees, here even the acceptance game associated with a deterministic automaton witnesses some nontrivial interaction between the two players.

In passing we note that the equivalence of both approaches can be seen quite easily in terms of coalgebraic modal logic. For, our notion of a set $P \subseteq A$ ‘describing’ the set $\sigma(s)$ of successors of s , can be very succinctly formulated by the formula

$$\nabla P := \Box \bigvee \{p \mid p \in P\} \wedge \bigwedge \{\Diamond p \mid p \in P\} \quad (2)$$

holding at s , whereas both the standard modal operators \Box and \Diamond can be expressed using the ∇ operation. And conversely, the standard modal operators can be expressed using the ∇ operation: $\Diamond \varphi \equiv \nabla \{\top, \varphi\}$ and $\Box \varphi \equiv \nabla \emptyset \vee \nabla \{\varphi\}$. Thus, at least in the cases where we have conjunctions and disjunctions at our disposal, we may freely switch between ∇ on the one hand, and \Diamond and \Box on the other.

Given the above description of the deterministic graph automata, it is straightforward to come up with the definition of its nondeterministic and alternating variants. Concerning the latter, one could define the transition function of an alternating automaton \mathbb{A} to take values in the set $\mathcal{DL}(\mathcal{P}A)$ of lattice expressions over the set $\mathcal{P}A$, but it seems cleaner to take the equivalent set-theoretic formulation that is based on the disjunctive normal form of such expressions. That is, the transition function of an alternating graph automaton has the form

$$\Delta : A \times C \rightarrow \mathcal{P}\mathcal{P}\mathcal{P}A.$$

The triple occurrence of the power set operation may seem rather confusing at first sight. Probably the best way to understand this feature is by recalling that there is one \mathcal{P} for \exists , one for \forall , and one for the functor. A better way to type this transition function is as

$$\Delta : A \times C \rightarrow \mathcal{P}\mathcal{P}FA.$$

Formally, the acceptance game of such an automaton is played on the following graph:

Position: b	$P(b)$	Admissible moves: $E[b]$
$(a, s) \in A \times S$	\exists	$\{(\Xi, s) \in \mathcal{P}(FA) \times S \mid \Xi \in \Delta(a, \gamma(s))\}$
$(\Xi, s) \in \mathcal{P}(FA) \times S$	\forall	$\{(\xi, \tau) \in FA \times FS \mid \xi \in \Xi \text{ and } \tau = \sigma(s)\}$
$(\xi, \tau) \in FA \times FS$	\exists	$\{Z \in \mathcal{P}(A \times S) \mid Z \text{ is full on } (\xi, \tau)\}$
$Z \in \mathcal{P}(A \times S)$	\forall	Z

As always, the winning conditions of the game are completely determined by the acceptance condition Acc of the automaton. That is, each match of the game induces, in the most obvious way, a sequence of states of the automaton, and (at least, in case we talking about an infinite match), the winner of the match is \exists if this sequence belongs to Acc , and \forall otherwise.

A coalgebraic perspective

Our presentation of graph automata has provided almost all of the ingredients needed for generalizing the definition of an automaton to a general, coalgebraic level. The key observation still to be made is that our fairly vague story of a subset $P \subseteq A$ ‘describing’ the set $\sigma(s) \in \mathcal{P}S$ is in fact an instance of the coalgebraic notion of *relation lifting* (see section 2.1). More precisely, a relation $Z \subseteq A \times S$ is full on $P \subseteq Q$ and $T \subseteq S$ if and only if the pair $(P, T) \in FA \times FS$ belongs to the relation lifting $\bar{F}Z$.

Also in the cases of word and tree automata, it is relation lifting that determines how a match of the game proceeds. In these cases however, there is no real choice for \exists when it comes to the ‘witnessing relation’ Z . For instance, given $((a_0, a_1), (s_0, s_1)) \in FA \times FS$, where F is the binary tree functor, any relation $Z \subseteq FA \times FS$ satisfies $((a_0, a_1), (s_0, s_1)) \in \bar{F}Z$ if and only if Z contains both (a_0, s_0) and (a_1, s_1) . But since \exists will always choose the witnessing relation Z as small as possible, this means she will always pick the set $\{(a_0, s_0), (a_1, s_1)\}$, and thus effectively, has no choice at all. The reader is invited to check how this is reflected in the definition of the acceptance game of tree automata.

Thus we have arrived at a natural notion of an automaton operating on pointed F_C -coalgebras — at least, for any functor F for which relation lifting ‘works’. In the deterministic case, the transition function could be defined to be of the form

$$\delta : A \times C \rightarrow FA.$$

The acceptance game for such an automaton \mathbb{A} operating on an F_C -coalgebra $\mathbb{S} = (S, \gamma : S \rightarrow C, \sigma : S \rightarrow FS)$ is given by the following table:

Position: b	$P(b)$	Admissible moves: $E[b]$
$(a, s) \in A \times S$	\exists	$\{Z \in \mathcal{P}(A \times S) \mid (\delta(a, \gamma(s)), \sigma(s)) \in \bar{F}Z\}$
$Z \in \mathcal{P}(A \times S)$	\forall	Z

In the acceptance game for the alternating version such an automaton, the players first play, at a position $(a, s) \in A \times S$, a little ‘subgame’ in order to arrive at a position $(\alpha, \sigma(s)) \in FA \times FS$. From there, play proceeds as in the deterministic version. In general, it is interesting to observe that the alternating game proceeds in *rounds*, and that each round witnesses two fairly different kinds of interaction between \exists and \forall .

Finally, it turns out that we can simplify our discussion somewhat by disposing of the colors. In the following section, we develop a framework of F -automata as devices for inspecting coalgebras based on an arbitrary functor, rather than colored coalgebras only. This enables us to work with transition functions that are of the form

$$\Delta : A \rightarrow \mathcal{P}PFA.$$

Obviously, this theory applies to functors of the form F_C as well, and, hence, it does provide us with a notion of an F_C -automaton that will operate on C -colored F -coalgebras, see section 4.5 for more details.

4 Automata for Coalgebras

4.1 Basic definition

The following definition concerns the most important notion of the paper: F -automata.

Definition 4.1 Let F be an R -standard endofunctor on \mathbf{Set} . An (*alternating*) F -automaton is a quadruple $\mathbb{A} = (A, a_I, \Delta, Acc)$, with A some finite set of objects called *states*, $a_I \in A$ the *initial state*, $\Delta : A \rightarrow \mathcal{P}PFA$ the *transition function*, and $Acc \subseteq A^\omega$ the *acceptance condition*.

An F -automaton is called *solitary* (or *non-deterministic*) if all members of each $\Delta(a)$ are singletons. An F -automaton is called *deterministic* if for each $a \in A$ there is an element $\delta(a) \in FA$ such that $\Delta(a) = \{\{\delta(a)\}\}$ (in particular, such an automaton is solitary). \triangleleft

The meaning of this definition should become clear below when we discuss the acceptance games. In the sequel we may drop the adjective ‘alternating’ when referring to such an automaton: in our terminology, the generic automaton is alternating, and deterministic and solitary automata are special instances of alternating ones.

There are various kinds of acceptance conditions known from the literature. For almost all of these, the criterion, whether an infinite sequence $\alpha \in A^\omega$ belongs Acc or not, is formulated in terms of the set $Inf(\alpha)$. For instance, a *Büchi* condition puts $\alpha \in Acc$ if and only if $Inf(\alpha)$ contains at least one of a set of special acceptance states. In the remainder of this paper we will work exclusively with *parity* automata.

Definition 4.2 Let F be an R -standard endofunctor on \mathbf{Set} . A *parity* F -automaton is an F -automaton $\mathbb{A} = (A, a_I, \Delta, Acc)$, such that $Acc = A_\Omega^\omega$ for some parity map $\Omega : A \rightarrow \omega$, see (1). Such an automaton is usually presented as $\mathbb{A} = (A, a_I, \Delta, \Omega)$. The map Ω is called the *parity function* of the automaton. \triangleleft

4.2 Acceptance game

F -automata are supposed to operate on pointed F -coalgebras. Basically, the idea is that an F -automaton will either *accept* or *reject* a given pointed F -coalgebra. The best way to express the evaluation process leading to either acceptance or rejection, is in terms of a two-player infinite graph game, or *graph game*, see section 2. However, it is useful to first consider another example of a graph game.

Example 4.3 There are various ways to put the notion of bisimulation into this game-theoretic framework. At this stage it is instructive to consider the following approach from BALTAG [3].

Let $\mathbb{S} = (S, \sigma)$ and $\mathbb{S}' = (S', \sigma')$ be two F -coalgebras for some endofunctor F on \mathbf{Set} which preserves weak pullbacks. The *bisimulation game* $\mathcal{B}(\mathbb{S}, \mathbb{S}')$ between \mathbb{S} and \mathbb{S}' is defined as the

graph game $(B_{\exists}, B_{\forall}, E, Ref)$ with $B_{\exists} := S \times S'$, $B_{\forall} := \mathcal{P}(S \times S')$, $Ref := B^{\omega}$ (i.e., all infinite matches are winning for \exists), while the edge relation E is given as follows:

- in position (s, s') , \exists may choose any set $Z \subseteq S \times S'$ satisfying $(\sigma(s), \sigma'(s')) \in \overline{F}Z$;
- in position $Z \subseteq S \times S'$, \forall may choose any element (t, t') of Z .

We leave it to the reader to verify that

$$(s, s') \in Win_{\exists}(\mathcal{B}) \text{ iff } \mathbb{S}, s \rightleftharpoons \mathbb{S}', s'.$$

The key observation for the direction from left to right is that the relation $Win_{\exists}(\mathcal{B})$ itself is a bisimulation between \mathbb{S} and \mathbb{S} . For the other direction, let \exists choose, at an arbitrary position (t, t') , any bisimulation between \mathbb{S} and \mathbb{S}' that links t to t' , cf. Fact 2.1(3).

Definition 4.4 Let $\mathbb{A} = (A, a_I, \Delta, \Omega)$ be an F-automaton, and let $\mathbb{S} = (S, \sigma)$ be an F-coalgebra. The *acceptance game* $\mathcal{G}(\mathbb{A}, \mathbb{S})$ associated with \mathbb{A} and \mathbb{S} is the parity graph game $(B_{\exists}, B_{\forall}, E, \overline{\Omega})$ with

$$\begin{aligned} B_{\exists} &:= A \times S \quad \cup \quad FA \times FS \\ B_{\forall} &:= \mathcal{P}(FA) \times S \quad \cup \quad \mathcal{P}(A \times S), \end{aligned}$$

while E and $\overline{\Omega}$ are given by the table below:

Position: b	$P(b)$	Admissible moves: $E[b]$	$\overline{\Omega}(b)$
$(a, s) \in A \times S$	\exists	$\{(\Xi, s) \in \mathcal{P}(FA) \times S \mid \Xi \in \Delta(a)\}$	$\Omega(a)$
$(\Xi, s) \in \mathcal{P}(FA) \times S$	\forall	$\{(\xi, \tau) \in FA \times FS \mid \xi \in \Xi \text{ and } \tau = \sigma(s)\}$	0
$(\xi, \tau) \in FA \times FS$	\exists	$\{Z \in \mathcal{P}(A \times S) \mid (\xi, \tau) \in \overline{F}Z\}$	0
$Z \in \mathcal{P}(A \times S)$	\forall	Z	0

Finally, \mathbb{A} *accepts* the pointed F-coalgebra (\mathbb{S}, s) if (a_I, s) is a winning position for \exists in the game $\mathcal{G}(\mathbb{A}, \mathbb{S})$. \triangleleft

In order to get an understanding of this game, consider an F-automaton \mathbb{A} and an F-coalgebra \mathbb{S} . Of all the positions in the game $\mathcal{G} = \mathcal{G}(\mathbb{A}, \mathbb{S})$, those in $A \times S$ are the basic ones — the other positions are just intermediate stages. Roughly, one should see a pair $(a, s) \in A \times S$ as a situation in which the automaton is in state a , inspecting the point s of the coalgebra. The aim of \exists is to show that this description ‘fits’; while the aim of \forall is to convince her that this is not the case. Going into detail we first look at two special cases.

First suppose that the automaton \mathbb{A} is *deterministic*. That is, there is a map $\delta : A \rightarrow FA$ such that $\Delta(a) = \{\{\delta(a)\}\}$ for each $a \in A$. Now at any position $(a, s) \in A \times S$ of the game \mathcal{G} , \exists can only make one move, namely, to the position $\{(\delta(a), s)\} \in \mathcal{P}(FA) \times S$; after that, \forall has no choice either: he has to move the pebble to $(\delta(a), \sigma(s)) \in FA \times FS$. Note that this position is completely determined by the first position — hence the name ‘deterministic’. A position of the form $(\delta(a), \sigma(s))$ is like the position (a, s) of the bisimulation game of Example 4.3: \exists chooses a relation $Z \subseteq A \times S$ such that $(\delta(a), \sigma(s)) \in FZ$, after that, \forall chooses a new pair $(b, t) \in Z$, and we are back in one of the basic positions. So in the deterministic case, a parity automaton itself can be represented as a ‘decorated’ F-coalgebra: apart from an initial state

it also carries an acceptance condition $\Omega : A \rightarrow \omega$. Likewise, the acceptance game $\mathcal{G}(\mathbb{A}, \mathbb{S})$ for such an automaton is like a ‘decorated’ bisimulation game. Note however, that much of the power of automata working on infinite objects precisely stems from the intricacies of these ‘decorations’.

Now take the more general case in which we only know that \mathbb{A} is *solitary*, and consider a position $(a, s) \in A \times S$. Here \exists has a real choice: she can pick any singleton $\{\alpha\}$ from $\Delta(a)$ and move the pebble to position $\{(\alpha, s)\} \in \mathcal{P}(FA \times S)$. After that, $\forall s$ choice is forced: he must move the pebble to position $(\alpha, \sigma(s)) \in FA \times FS$. Effectively then, at position (a, s) it is \exists on her own who determines the later position $(\alpha, \sigma(s)) \in FA \times FS$ - this explains why we call such an automaton ‘solitary’. Note that at positions of the form $(\alpha, \sigma(s)) \in FA \times FS$ the game proceeds as in the deterministic case, until another central position is reached.

Finally, we consider the most general case, in which \mathbb{A} is an arbitrary automaton. Here it is still the aim to arrive, starting from a position $(a, s) \in A \times S$, at a position $(\alpha, \sigma(s)) \in FA \times FS$, but now \exists and \forall play a little ‘subgame’ in order to get there. In the version presented here, first \exists makes a preselection, that is, she chooses some subset $\Xi \subset FA$; then \forall picks an element $\xi \in \Xi$, and the new position is $(\xi, \sigma(s))$; from here, play proceeds as before. Note that any match of the game is over as soon as the responsible player gets stuck, in the sense that (s)he reaches a position in which no moves are admissible. This happens for instance in a position (a, s) such that $\Delta(a, s) = \emptyset$; in this case \exists gets stuck and immediately loses the match. Likewise, if \exists can choose $\emptyset \in \Delta(a, s)$ then she wins the match since \forall will get stuck in the next move.

4.3 Variation: chromatic F-automata

Familiar automata, such as the ones discussed in section 3, operate on coalgebras that are *colored* by some set C , and have a transition function Δ taking input from the set $A \times C$ (with A the state set of the automaton). Now obviously, our definition 4.1, when applied to a functor of the form F_C , does provide automata that will scan C -colored F -coalgebras, but the reader may worry that their transition function $\Delta : A \rightarrow \mathcal{PP}(C \times FA)$ has the wrong shape since it seems to take input only from A . In this section we will show that the notion of an F -automaton is flexible enough to encode the technicalities involving colors, so that we may work in the simpler framework without making concessions to its scope of applicability.

Let us first introduce a coalgebraic generalization of the notion of automaton that seems to be more in line with standard usage in automata theory. As before, we represent F_C -coalgebras as triples of the form $\mathbb{S} = (S, \gamma, \sigma)$ with $\gamma : S \rightarrow C$ and $\sigma : S \rightarrow C \times FS$.

Definition 4.5 Let F be an R -standard endofunctor on \mathbf{Set} . A *chromatic F-automaton over C* is a quintuple $\mathbb{A} = (A, a_I, C, \Delta, Acc)$ such that $\Delta : A \times C \rightarrow \mathcal{PPFA}$ (and A , a_I , and Acc are as before).

Given such an automaton and an F_C -coalgebra $\mathbb{S} = (S, \gamma, \sigma)$, we define the acceptance game $\mathcal{G}_C(\mathbb{A}, \mathbb{S})$ in a very similar way as before, witnessed by the following table:

Position: b	$P(b)$	Admissible moves: $E[b]$	$\Omega(b)$
$(a, s) \in A \times S$	\exists	$\{(\Xi, s) \in \mathcal{P}(FA) \times S \mid \Xi \in \Delta(a, \gamma(s))\}$	$\Omega(a)$
$(\Xi, s) \in \mathcal{P}(FA) \times S$	\forall	$\{(\xi, \tau) \in FA \times FS \mid \xi \in \Xi \text{ and } \tau = \sigma(s)\}$	0
$(\xi, \tau) \in FA \times FS$	\exists	$\{Z \in \mathcal{P}(A \times S) \mid (\xi, \tau) \in \overline{FZ}\}$	0
$Z \in \mathcal{P}(A \times S)$	\forall	Z	0

◁

We will now show that the differences between the two kinds of automata for recognizing C -colored F -coalgebras are only superficial. That is, we will provide very simple constructions for transforming F_C -automata into equivalent chromatic F -automata over C , and vice versa.

Definition 4.6 Let $\mathbb{A} = (A, a_I, C, \Delta, Acc)$ be a chromatic F -automaton over C . We define its F_C -companion \mathbb{A}^C as the automaton (A, a_I, Δ^C, Acc) , with $\Delta^C : A \rightarrow \mathcal{PP}(C \times FA)$ given by

$$\Delta^C(a) := \{\{c\} \times \Xi \mid \Xi \in \Delta(a, c), c \in C\}.$$

(Note that if $\Xi = \{\xi_1, \dots, \xi_n\}$, then $\{c\} \times \Xi$ is the set $\{(c, \xi_1), \dots, (c, \xi_n)\}$.)

Conversely, given an F_C -automaton $\mathbb{B} = (B, b_I, \Theta, \Psi)$, the structure $(B, b_I, C, \Theta_C, \Psi)$ with

$$\Theta_C(b, c) := \{\Xi \in FB \mid \{c\} \times \Xi \in \Theta(b)\}.$$

is called the *chromatic F -companion* of \mathbb{B} , notation: \mathbb{B}_C .

◁

The following claim shows that the two kinds of automata for F_C -coalgebras are merely variants of one another.

Proposition 4.7 *Let \mathbb{A} be a chromatic F -automaton over C , and \mathbb{B} an F_C -automaton. Then for any pointed F_C -coalgebra (\mathbb{S}, s) it holds that*

$$\mathbb{A} \text{ accepts } (\mathbb{S}, s) \quad \text{iff} \quad \mathbb{A}^C \text{ accepts } (\mathbb{S}, s), \quad (3)$$

$$\mathbb{B} \text{ accepts } (\mathbb{S}, s) \quad \text{iff} \quad \mathbb{B}_C \text{ accepts } (\mathbb{S}, s). \quad (4)$$

Proof. We confine our attention to (4). Fix \mathbb{B} and \mathbb{S} . We will show that

$$Win_{\exists}(\mathcal{G}(\mathbb{B}, \mathbb{S})) = Win_{\exists}(\mathcal{G}_C(\mathbb{B}_C, \mathbb{S})), \quad (5)$$

which clearly suffices to prove the equivalence of \mathbb{B} and \mathbb{B}_C .

For the inclusion \supseteq of (5), note that by Fact 2.4 we may assume that in $\mathcal{G}_C(\mathbb{B}_C, \mathbb{S})$, \exists has a history free strategy f which is winning from every position in $Win_{\exists}(\mathcal{G}_C(\mathbb{B}_C, \mathbb{S}))$. Now define the following map f' on \exists 's positions in the other game, $\mathcal{G}(\mathbb{B}, \mathbb{S})$. For $(b, s) \in B \times S$, let $f^-(b, s)$ denote the unique element $\Xi \in FA$ such that $f(b, s) = (\Xi, s)$, and put

$$\begin{aligned} f'(b, s) &:= (\{g(s)\} \times f^-(b, s), s), \\ f'(\xi, \tau) &:= f(\xi, \tau). \end{aligned}$$

We first show that f' is a legitimate strategy for \exists on each of her positions in the set $Win_{\exists}(\mathcal{G}_C(\mathbb{B}_C, \mathbb{S}))$. This is obvious for positions of the form $(\xi, \tau) \in FB \times FS$. For a position $(b, s) \in B \times S$, from the fact that $f(b, s) \in \Theta_C(b, \gamma(s))$ and the definition of Θ_C , it is immediate that $f'(b, s)$ belongs to $\Theta(b)$, as required.

Now consider an arbitrary match β of $\mathcal{G}(\mathbb{B}, \mathbb{S})$, initiated at a position p that we know to be winning in the game $\mathcal{G}_C(\mathbb{B}_C, \mathbb{S})$, and assume that \exists plays according to her strategy f' . It is not hard to see that with β we may associate a *shadow match* β' of $\mathcal{G}_C(\mathbb{B}_C, \mathbb{S})$ in which \exists plays according to her winning strategy f , and such that β and β' pass through exactly the same basic positions (i.e., in $A \times S$). This immediately implies that \exists wins β , and so her strategy f' must be winning for her in $\mathcal{G}(\mathbb{B}, \mathbb{S})$. This proves the inclusion \supseteq of (5).

For the other inclusion, let f be a history free winning strategy for \exists in $\mathcal{G}(\mathbb{B}, \mathbb{S})$. The key observation is that for any position $(b, s) \in Win_{\exists}(\mathcal{G}(\mathbb{B}, \mathbb{S}))$, $f(b, s)$ must be of the form $(\{c\} \times \Xi, s)$ for some $c \in C$ and $\Xi \in FB$. From this observation it is completely straightforward to define a strategy for \exists in the other game, $\mathcal{G}_C(\mathbb{B}_C, \mathbb{S})$, and to prove, in analogy of the proof just given, that this strategy is winning from every position in $Win_{\exists}(\mathcal{G}(\mathbb{B}, \mathbb{S}))$.

In order to prove the key observation, assume that $f(b, s) = (\Pi, s) \in \mathcal{P}(C \times FB) \times S$, and suppose for contradiction that Π contains elements (c_1, ξ_1) and (c_2, ξ_2) with $c_1 \neq c_2$. The point is that this would always enable \forall to choose, in the next move, a pair $((c_i, \xi_i), s)$ such that c_i is *distinct* from $\gamma(s)$, and thus provide him with an immediate win of the match. Hence we arrive at the desired contradiction, since we assumed that f was a winning strategy on (b, s) .

This justifies our key observation, and hence, we are done with the proof of (5). QED

4.4 Variation: logical automata

A different perspective on the step function Δ of an F-automaton \mathbb{A} is that for all states a , $\Delta(a)$ is a *disjunction of conjunctions* of elements of FA . This suggests the following generalization. Recall that, given a set X , $\mathcal{DL}(X)$ denotes the set of lattice expressions over X .

Definition 4.8 Let F be an R-standard endofunctor on \mathbf{Set} . A *logical F-automaton* is a quadruple $\mathbb{A} = (A, a_I, \Delta, Acc)$ with A , a_I and Acc as before, and $\Delta : A \rightarrow \mathcal{DL}(FA)$. \triangleleft

The acceptance game for this \mathbb{A} is defined in a completely obvious way (see section 3), making \exists choose between disjuncts, moving from $(\bigvee P, s)$ to (p, s) for some $p \in P$, and making \forall choose between conjuncts, moving from $(\bigwedge P, s)$ to a position (p, s) with $p \in P$, until a position (α, s) is reached with $\alpha \in FA$. Play then continues as in the game for the standard automaton.

This generalization to logical automata is nice and useful, but it does not add any recognizing power to our automata:

Proposition 4.9 *F-automata and logical F-automata recognize the same classes of pointed F-coalgebras.*

The proposition can be proved using some standard game-theoretical argumentation, see for instance MULLER & SCHUPP [17, Appendix C]. (Basically, it just involves applying the distributive laws of disjunction over conjunction, and vice versa).

4.5 Variation: delayed F-automata

The automata of Definition 4.1 all have the property that in the acceptance game, the play basically switches from positions in $A \times S$ to ones in $FA \times FS$, perhaps with some alternation between \forall/\exists and \wedge/\vee . For many purposes this is rather restrictive; it would be more convenient to allow moves from a position $(a, s) \in A \times S$ to another position $(b, s) \in A \times S$. That is, while the automaton switches state, it would stay in the same node of the coalgebra. We will call such automata *delayed* because the move to successors of the coalgebra node is delayed.

Definition 4.10 Let F be an R -standard endofunctor on \mathbf{Set} . A *delayed F-automaton* is a quadruple $\mathbb{A} = (A, a_I, \Delta, Acc)$, with A , a_I and Acc as usual, and transition function $\Delta : A \rightarrow \mathcal{PP}(A \cup FA)$. \triangleleft

The *acceptance game* $\mathcal{G}(\mathbb{A}, \mathbb{S})$ associated with \mathbb{A} and an F -coalgebra \mathbb{S} is the parity graph game given by the following table.

Position: b	$P(b)$	Admissible moves: $E[b]$	$\bar{\Omega}(b)$
$(a, s) \in A \times S$	\exists	$\{(\bar{\Xi}, s) \in \mathcal{P}(A \cup FA) \times S \mid \bar{\Xi} \in \Delta(a)\}$	$\bar{\Omega}(a)$
$(\bar{\Xi}, s) \in \mathcal{P}(A \cup FA) \times S$	\forall	$\{(\xi, s) \in (A \times S) \cup (FA \times S) \mid \xi \in \bar{\Xi}\}$	0
$(\xi, s) \in FA \times S$	\exists	$\{Z \in \mathcal{P}(A \times S) \mid (\xi, \sigma(s)) \in \bar{F}Z\}$	0
$Z \in \mathcal{P}(A \times S)$	\forall	Z	0

Note the minor change in notation with respect to the games for ordinary F -automata: For the sake of a smoother notation, positions of the form $(\xi, \sigma(s)) \in FA \times FS$ are now given as $(\xi, s) \in FA \times S$.

Once more, it can be shown that delayed F -automata have the same expressive power as ordinary ones. The proof of this result, which requires a bit more sophistication than earlier results, is left to a future paper.

5 Coalgebraic fixed point logic

5.1 Syntax

Definition 5.1 Let F be an R -standard endofunctor on \mathbf{Set} , and let X be a set of objects to be called *variables*. Inductively we define, for each natural number n , the set $\mu\mathcal{L}_n^F(X)$ of *coalgebraic fixed point formulas over X of depth n* :

- $\mu\mathcal{L}_0^F(X)$ is the smallest set S which contains \top , \perp , and all variables in X and satisfies (i) if p and q belong to S , then so do $p \wedge q$ and $p \vee q$; and (ii) if p belongs to S , then so do $\mu x.p$ and $\nu x.p$, for each $x \in X$.

- $\mu\mathcal{L}_{n+1}^F(X)$ is the smallest superset of $\mu\mathcal{L}_n^F(X)$ containing the formula $\nabla\pi$ for each π that belongs to FQ for some finite $Q \subseteq \mu\mathcal{L}_n^F(X)$, which is closed under the same formation rules (i) and (ii).

The union $\mu\mathcal{L}^F(X) = \bigcup_{n \in \omega} \mu\mathcal{L}_n^F(X)$ is the set of all coalgebraic fixed point formulas over X . \triangleleft

The set X in $\mu\mathcal{L}^F(X)$ refers to *all* variables that occur in the formulas, not just the free ones (to be defined later). Quite often we have no reason to make the set X of variables explicit and so we will frequently write $\mu\mathcal{L}^F$ rather than $\mu\mathcal{L}^F(X)$.

Example 5.2 Our definition is intended to generalize that of the modal μ -calculus to arbitrary \mathbf{R} -standard endofunctors on \mathbf{Set} . Recall that the modal μ -calculus is a language for coalgebras for the functor $\mathbf{FS} = \mathcal{P}(\mathbf{Prop}) \times \mathcal{P}(S)^{\mathbf{Act}}$, where \mathbf{Prop} is some set of propositional variables and \mathbf{Act} some set of atomic actions. In the formulation of the modal μ -calculus of JANIN & WALUKIEWICZ [12], the modal operators $\langle a \rangle$ and $[a]$ are replaced with a single connective ' $a \rightarrow \cdot$ ' operating on finite sets of formulas: if Φ is a finite set of formulas, then $a \rightarrow \Phi$ is a formula. The meaning of $a \rightarrow \Phi$ can be expressed in terms of $\langle a \rangle$ and $[a]$: $a \rightarrow \Phi$ is equivalent to $\bigwedge\{\langle a \rangle p \mid p \in \Phi\} \wedge [a] \bigvee\{p \mid p \in \Phi\}$, cf. the ∇ -operator from (2). This is of course quite familiar in coalgebraic logic, and it would not be difficult to rephrase the language of Janin & Walukiewicz in such a way that a family of modal operators remains, each expressing a condition of the form

$$\bigwedge_{q \in \mathbf{Prop}} \pm q \wedge \bigwedge_{a \in \mathbf{Act}} (a \rightarrow \Phi_a)$$

with $\pm q$ denoting either q or $\neg q$. Doing so, we would have brought the language of the modal μ -calculus exactly in the format of our definition.

Before we turn to the coalgebraic semantics of this language, there are a number of syntactic issues to be settled.

We start with the important observation that every coalgebraic fixed point formula comes with a unique *construction tree*; the key insight here is that every formula p has a unique, naturally defined set of 'immediate subformulas'. In case p is of the form $\nabla\pi \in \mu\mathcal{L}_n^F$ this insight is based on the fact that for all finite sets $Q \subseteq \mu\mathcal{L}_n^F$, and all $\pi \in FQ$ there is a (unique) *smallest* set $Q' \subseteq \mu\mathcal{L}_n^F$ such that $\pi \in FQ'$ — the existence of such a set easily follows from Fact 2.2. We leave it for the reader to give a formal definition of construction trees; we do provide an explicit definition of the notion of subformula.

Definition 5.3 We will write $q \trianglelefteq p$ if q is a *subformula* of p . Inductively we define the set $Sfor(p)$ of subformulas of p as follows:

$$\begin{aligned} Sfor(p) &:= \{p\} && \text{if } p \in \{\top, \perp\} \cup X, \\ Sfor(p \heartsuit q) &:= \{p \heartsuit q\} \cup Sfor(p) \cup Sfor(q) && \text{if } \heartsuit \in \{\wedge, \vee\}, \\ Sfor(\eta x.p) &:= \{\eta x.p\} \cup Sfor(p) && \text{if } \eta \in \{\mu, \nu\}, \\ Sfor(\nabla\pi) &:= \{\nabla\pi\} \cup \bigcup_{p \in Base(\pi)} Sfor(p), \end{aligned}$$

where $Base(\pi)$ denotes the smallest set Q such that $\pi \in FQ$; the elements of $Base(\pi)$ will be called the *immediate subformulas* of $\nabla\pi$. \triangleleft

The following proposition can then be proved by a straightforward induction on the complexity of formulas.

Proposition 5.4 *Every formula $p \in \mu\mathcal{L}^F$ has finitely many subformulas.*

Definition 5.5 The *fixed point operators* μ and ν *bind* the variable that they occur with, everywhere in the subformula to which they are applied. This notion of binding is completely standard, and so are the definitions of the sets $FVar(p)$ and $BVar(p)$ of *free* and *bound* variables, respectively, of a formula $p \in \mu\mathcal{L}^F$. The set $Var(p) = FVar(p) \cup BVar(p)$ denotes the collection of *all* variables occurring in p , free or bound. As in first order logic, we will call a formula without free variables, a *sentence*.

A formula $p \in \mu\mathcal{L}^F$ is called *clean* if no variable occurs both free and bound in p , and no two distinct occurrences of fixed point operators bind the same variable. Hence, in a clean formula p , with each $x \in BVar(p)$ we may associate a unique subformula of p where x is bound; we will denote this formula as $\eta_x x.p_x$, and call x a μ -*variable* if $\eta_x = \mu$, and a ν -*variable* if $\eta_x = \nu$. A formula $p \in \mu\mathcal{L}^F$ is called *guarded* if every subformula $\eta_x q$ of p has the property that all occurrences of x inside q are within the scope of a ∇ .

Now let p be a clean formula. Let $\leq_p \subseteq BVar(p) \times BVar(p)$ denote the relation given by

$$x \leq_p y \text{ if } q_x \trianglelefteq q_y.$$

Clearly, \leq_p is a partial order on $BVar(p)$; it is called the *subformula order* of p . ◁

5.2 Semantics

We now introduce the semantics of coalgebraic fixed point logic. Although we are primarily interested in the interpretation of sentences, we also need to worry about the semantics of formulas with free variables. For this purpose we define the notion of an F-model over a set of variables.

Definition 5.6 Let F be an R-standard endofunctor on \mathbf{Set} , and let X be a set of variables. An *F-model* over X is a triple (S, σ, V) such that $\mathbb{S} = (S, \sigma)$ is an F-coalgebra, and $V : X \rightarrow \mathcal{P}(S)$ is a *valuation* on \mathbb{S} .

Given such a valuation on \mathbb{S} , a variable $x \in X$ and a subset $T \subseteq S$, we define the valuation $V[x \mapsto T]$ as the map given by $V[x \mapsto T](x) = T$ while $V[x \mapsto T](y) = V(y)$ for all variables $y \in X$ that are distinct from x . ◁

Of course, it would be more in style with the coalgebraic paradigm to present an F-model (S, σ, V) over X as a coalgebra for the functor $F_{\mathcal{P}(X)}$ (cf. Definition 3.1). We follow the present approach because it seems to lend itself better towards the treatment of fixed point operators.

Definition 5.7 Inductively we define the notion of *truth*, i.e., we define when a $\mu\mathcal{L}^F(X)$ -formula p is *true* or *holds* at a state s of a coalgebra $\mathbb{S} = (S, \sigma)$ under the valuation V .

More precisely, we define a relation $\Vdash^V \subseteq S \times \mu\mathcal{L}^F(X)$; when the pair (s, p) belongs to \Vdash^V , we say that p is *true at* or *holds in* $s \in \mathbb{S}$ under the valuation V , and usually write $\mathbb{S}, V, s \Vdash p$. We also use $\llbracket \cdot \rrbracket$ for the extension of a formula in a coalgebra: $\llbracket p \rrbracket_{\mathbb{S}, V} := \{s \in S \mid \mathbb{S}, V, s \Vdash p\}$.

The clauses of the inductive truth definition are as follows:

$$\begin{aligned}
\mathbb{S}, V, s &\Vdash \top, \\
\mathbb{S}, V, s &\not\Vdash \perp, \\
\mathbb{S}, V, s &\Vdash x && \text{if } s \in V(x), \\
\mathbb{S}, V, s &\Vdash p \wedge q && \text{if } \mathbb{S}, V, s \Vdash p \text{ and } \mathbb{S}, V, s \Vdash q, \\
\mathbb{S}, V, s &\Vdash p \vee q && \text{if } \mathbb{S}, V, s \Vdash p \text{ or } \mathbb{S}, V, s \Vdash q, \\
\mathbb{S}, V, s &\Vdash \mu x.p && \text{if } s \in \bigcap \{T \subseteq S \mid \llbracket p \rrbracket_{\mathbb{S}, V[x \rightarrow T]} \subseteq T\}, \\
\mathbb{S}, V, s &\Vdash \nu x.p && \text{if } s \in \bigcup \{T \subseteq S \mid T \subseteq \llbracket p \rrbracket_{\mathbb{S}, V[x \rightarrow T]}\}, \\
\mathbb{S}, V, s &\Vdash \nabla \pi && \text{if } (\sigma(s), \pi) \in \overline{F}(\Vdash^V \upharpoonright_{\text{Base}(\pi)}),
\end{aligned}$$

where, in the last clause, the set $\Vdash^V \upharpoonright_{\text{Base}(\pi)} \subseteq S \times \mu\mathcal{L}^F(X)$ is given as $\Vdash^V \upharpoonright_{\text{Base}(\pi)} = \Vdash^V \cap (S \times \text{Base}(\pi))$.

We say that a formula p is true *throughout* a model $\mathbb{M} = (\mathbb{S}, V)$, notation: $\mathbb{M} \Vdash p$, if $\llbracket p \rrbracket_{\mathbb{M}} \subseteq S$. A formula is *valid*, notation: $\models p$, if it is true throughout every model; two formulas p and q are called *equivalent*, notation: $p \equiv q$, if $\llbracket p \rrbracket_{\mathbb{M}} = \llbracket q \rrbracket_{\mathbb{M}}$ for every model \mathbb{M} . \triangleleft

All clauses of this truth definition are completely standard, with the possible exception of the one for $\nabla \pi$. The standard definition from the literature (cf. MOSS [15]) would require that $\mathbb{S}, V, s \Vdash \nabla \pi$ if $(\sigma(s), \pi) \in \overline{F}(\Vdash)$. However, given our definition of the language, and the guideline that the truth of a formula should only depend on the interpretation of its immediate subformulas, the truth definition of $\nabla \pi$ seems to be quite natural. We don't know whether there are instances in which our definition would really deviate from Moss'.

Concerning the fixed point operators, it will be convenient to introduce some further terminology.

Definition 5.8 Let S be a set, and $\varphi : \mathcal{P}(S) \rightarrow \mathcal{P}(S)$ a map. A subset $X \subseteq S$ is called a *pre-fixed point* of φ if $\varphi(X) \subseteq X$, a *post-fixed point* if $X \subseteq \varphi(X)$, and a *fixed point* if $X = \varphi(X)$. \triangleleft

It then immediately follows from the definitions that the set $\llbracket \mu x.p \rrbracket_{\mathbb{M}}$ is the intersection of the collection of all pre-fixed points of the map $\lambda X \in \mathcal{P}(S). \llbracket p \rrbracket_{\mathbb{M}[x \rightarrow X]}$, while $\llbracket \nu x.p \rrbracket_{\mathbb{M}}$ is the union of the collection of all post-fixed points of this map.

5.3 Basic semantic results

Before we can do anything interesting, there are a few technicalities that we have to get out of the way. First, we need a Finiteness Lemma stating that the truth of a formula only depends on its free variables.

Proposition 5.9 (Finiteness) *Let F be an R -standard endofunctor on Set , let $Y \subseteq X$ be two sets of variables, and let (S, σ) be an F -coalgebra. Now suppose that V and V' are two*

X -valuations on \mathbb{S} such that $V(y) = V'(y)$ for all $y \in Y$. Then for all p with $FVar(p) \subseteq Y$, and all $s \in S$ it holds that

$$S, \sigma, V \Vdash p \text{ iff } S, \sigma, V' \Vdash p.$$

Proof. The proof is by induction on the complexity of p . All cases are completely standard, with the possible exception of the case that $p = \nabla\pi$. Inductively we assume that $\Vdash^V \upharpoonright_{Base(\pi)} = \Vdash^{V'} \upharpoonright_{Base(\pi)}$, so that $\bar{F}(\Vdash^V \upharpoonright_{Base(\pi)}) = \bar{F}(\Vdash^{V'} \upharpoonright_{Base(\pi)})$. From this it is immediate by the definition that $S, \sigma, V \Vdash \nabla\pi$ iff $S, \sigma, V' \Vdash \nabla\pi$. QED

For *sentences* in particular, it follows from the previous proposition that it does not matter which valuation we take into consideration. This inspires the following definition.

Definition 5.10 Let F be an R -standard endofunctor on \mathbf{Set} , p a $\mu\mathcal{L}^F$ -sentence, \mathbb{S} an F -coalgebra and s a point in \mathbb{S} . Then we say that p is *true at s* in \mathbb{S} , notation: $\mathbb{S}, s \Vdash p$, if $\mathbb{S}, V, s \Vdash p$ for some valuation V , (or, equivalently, for all valuations V). \triangleleft

Next we turn to the Monotonicity Lemma.

Proposition 5.11 (Monotonicity) *Let F be an R -standard endofunctor on \mathbf{Set} , X a set of variables, and \mathbb{S} an F -coalgebra. Now suppose that V and V' are two X -valuations on \mathbb{S} such that $V(x) \subseteq V'(x)$ for all $x \in X$. Then for all p with $FVar(p) \subseteq X$ it holds that*

$$\llbracket p \rrbracket_{\mathbb{S}, V} \subseteq \llbracket p \rrbracket_{\mathbb{S}, V'},$$

that is: for all $s \in S$ we have that $S, \sigma, V \Vdash p$ only if $S, \sigma, V' \Vdash p$.

Proof. This can be proved by a standard induction on the complexity of p . The proof in the inductive case of $p = \nabla\pi$ is based on the fact that \bar{F} is monotone (Fact 2.1). QED

Remark 5.12 The Monotonicity Lemma justifies the terminology *fixed point* in the name of our formalism: by the Knaster-Tarski Theorem in fixed point theory, every monotone operation φ on a complete lattice (such as a full power set) has a least and a greatest fixed point, and these can be obtained as the intersection of the collections of pre-fixed points and post-fixed points of φ , respectively. In particular, for every formula p and every model $\mathbb{M} = (S, \sigma, V)$, the set $\llbracket \mu x.p \rrbracket_{\mathbb{M}}$ is the least fixed point of the operation $\lambda X \in \mathcal{P}(S). \llbracket p \rrbracket_{\mathbb{M}[x \mapsto X]}$, and the set $\llbracket \nu x.p \rrbracket_{\mathbb{M}}$ is the greatest fixed point of this operation.

Remark 5.13 It also follows from standard fixed point theory that least and greatest fixed points of monotone operations on complete lattices (such as full power set algebras) can be approximated by ordinal unfoldings. This yields a nice connection between our coalgebraic fixed point logic, and more standard coalgebraic logics.

Let $\mathcal{L}^F_\infty(X)$, the language of infinitary coalgebraic F -logic, be the smallest collection S of formulas which includes the set $\{\top, \perp\} \cup X$ and satisfies (i) if β is some ordinal, and $\{p_\alpha \mid \alpha < \beta\}$ is a set of formulas in S , then both $\bigwedge_{\alpha < \beta} p_\alpha$ and $\bigvee_{\alpha < \beta} p_\alpha$ belong to S , and (ii) if π belongs to FQ for some $Q \subseteq S$, then $\nabla\pi$ belongs to S . Note that F -models, with the obvious interpretation for \bigwedge and \bigvee , form a natural semantics for this language.

Now for each ordinal α there is a translation t^α mapping $\mu\mathcal{L}^F$ -sentences to \mathcal{L}_∞^F -formulas. This translation is defined as follows; first, we define, for any $\mathcal{L}_\infty^F(X)$ -formula p , any variable $x \in X$, and any ordinal α , the formulas $\mu_\alpha x.p$ and $\nu_\alpha x.p$ via transfinite induction:

$$\begin{aligned} \mu_0 x.p &:= \perp, & \nu_0 x.p &:= \top, \\ \mu_{\alpha+1} x.p &:= p[\mu_\alpha x.p/x], & \nu_{\alpha+1} x.p &:= p[\nu_\alpha x.p/x], \\ \mu_\lambda x.p &:= \bigvee_{\alpha < \lambda} \mu_\alpha x.p, & \nu_\lambda x.p &:= \bigwedge_{\alpha < \lambda} \nu_\alpha x.p. \end{aligned}$$

Using these formulas, one puts

$$\begin{aligned} t^\alpha p &:= p && \text{for } p \in \{\top, \perp\} \cup X, \\ t^\alpha(p \heartsuit q) &:= t^\alpha p \heartsuit t^\alpha q && \text{for } \heartsuit \in \{\wedge, \vee\}, \\ t^\alpha(\eta x.p) &:= \eta_\alpha x.t^\alpha p && \text{for } \eta \in \{\mu, \nu\}, \\ t^\alpha(\nabla \pi) &:= \nabla(\mathbf{F}t^\alpha(\pi)). \end{aligned}$$

Observe that t^α translates $\mu\mathcal{L}^F$ -sentences into variable-free \mathcal{L}_∞^F -formulas.

One can show that these translations *locally* embed $\mu\mathcal{L}^F$ inside \mathcal{L}_∞^F , in the following sense:

$$\llbracket p \rrbracket_{\mathbb{M}} = \llbracket t^\alpha p \rrbracket_{\mathbb{M}}, \text{ for any } \mathbf{F}\text{-model } \mathbb{M} = (S, \sigma, V) \text{ and any ordinal } \alpha > |S|^+. \quad (6)$$

Note however, that in general, the ‘unfolding ordinal’ α of (6) depends on the size of the model \mathbb{M} . Coalgebraic fixed point logic cannot be embedded in infinitary coalgebraic logic, as is known from the modal μ -calculus.

An important property of our coalgebraic fixed point logic is that truth is bisimulation invariant. Using the appropriate notion of bisimulation for \mathbf{F} -models this can be proven for arbitrary $\mu\mathcal{L}^F$ -formulas, but here we state it just for sentences.

Proposition 5.14 *Let \mathbb{S} and \mathbb{S}' be two \mathbf{F} -coalgebras. Then for any bisimulation $Z \subseteq S \times S'$ and any two points $s \in S$, $s' \in S'$ with $(s, s') \in Z$, and any $\mu\mathcal{L}^F$ -sentence p it holds that*

$$\mathbb{S}, s \Vdash p \text{ iff } \mathbb{S}', s' \Vdash p.$$

Proof. A simple proof for this proposition uses the ordinal unfolding of Remark 5.13, and the easily established fact that truth of \mathcal{L}_∞^F -sentences is a bisimulation invariant property. QED

We are now ready to state our last basic semantic result.

Proposition 5.15 (Normal Form) *Let \mathbf{F} be an R -standard endofunctor on \mathbf{Set} . Then every formula $p \in \mu\mathcal{L}^F$ is equivalent to some clean, guarded formula p' .*

Proof. It is easy to rewrite an arbitrary $\mu\mathcal{L}^F$ -formula into a clean equivalent, by consistently renaming bound variables.

The second part of the proposition is proved by a completely standard induction on the complexity of formulas. We confine ourselves to a proof sketch for the case that p is of the form $\mu x.q$.

By the inductive hypothesis we may assume that q is guarded. Hence, if we replace every fixed point subformula $\eta y.r(x, y)$ of q with its unfolding $r(x, \eta y.r(x, y))$, we obtain an equivalent q' of q , in which the only *unguarded* occurrences of x are *outside* the scope of fixed point operators. Then, using laws of classical propositional logic, it is not hard to rewrite $q'(x)$ in an equivalent form $q''(x) = (x \vee r(x)) \wedge s(x)$, where all occurrences of x in $r(x)$ and $s(x)$ are guarded. It can subsequently be shown that $\mu x.(x \vee r(x)) \wedge s(x)$ is equivalent to the formula $\mu x.r(x) \wedge s(x)$. QED

6 Game semantics

In this section we develop a game-theoretic characterization of the semantics of our coalgebraic fixed point logics, generalizing results on for instance the modal μ -calculus to a general coalgebraic framework.

6.1 Evaluation games

Given an F-model $\mathbb{M} = (S, \sigma, V)$ and a coalgebraic fixed point formula q , we will define the *evaluation game* $\mathcal{E} = \mathcal{E}(\mathbb{M}, p)$ as the following infinite two-player graph game.

Definition 6.1 Let F be an R-standard endofunctor on Set. Given an F-model $\mathbb{M} = (S, \sigma, V)$ and a clean coalgebraic fixed point formula q , we first define the *arena* of the *evaluation game* $\mathcal{E} = \mathcal{E}(\mathbb{M}, q)$.

The board of \mathcal{E} is given as the set

$$B = Sfor(q) \times S \cup \mathcal{P}(Sfor(q) \times S).$$

The partition of B into positions for \exists and \forall , respectively, and the edge relation E of the graph are given by the table of Figure 1. \triangleleft

Position: b	Player: $P(b)$	Admissible moves: $E[b]$
(\perp, s)	\exists	\emptyset
(\top, s)	\forall	\emptyset
$(p_1 \wedge p_2, s)$	\forall	$\{(p_1, s), (p_2, s)\}$
$(p_1 \vee p_2, s)$	\exists	$\{(p_1, s), (p_2, s)\}$
(x, s) with $x \notin BVar(q)$, $s \in V(x)$	\forall	\emptyset
(x, s) with $x \notin BVar(q)$, $s \notin V(x)$	\exists	\emptyset
(x, s) with $x \in BVar(q)$	-	(q_x, s)
$(\eta x.p, s)$	-	(p, s)
$(\nabla \pi, s)$	\exists	$\{Z \subseteq Base(\pi) \times S \mid (\pi, \sigma(s)) \in \bar{F}(Z)\}$
$Z \subseteq Sfor(q) \times S$	\forall	Z

Figure 1: Admissible moves in the evaluation game

Note that positions of the form (x, s) or $(\eta x.p, s)$ have a *unique* successor, whence the moves that are made at such positions are completely determined. Thus it does not matter to which player these positions are assigned.

In order to get some intuitions for this kind of game, the reader is advised to assign the following *aims* to the players. Basically, in a position (p, s) it is the aim of \exists to show that p is actually *true* at s , while \forall tries to convince her that this is not the case. This already explains the rules for positions of the form (p, s) with p an atomic constant, a conjunction, or a disjunction. For instance, in $(p_1 \vee p_2, s)$, \exists may win by winning either (p_1, s) or (p_2, s) , because $p_1 \vee p_2$ holds at s if either p_1 or p_2 does.

Each time during a match when the pebble moves from a position (x, s) to its successor (q_x, s) , we say that the fixed point variable x is *unfolded*. Roughly spoken, the intuition behind this is that the formula $\eta_x.q_x$ (represented by x) is equivalent to the formula $q_x[\eta_x.q_x/x]$ (represented by q_x). This applies to both μ and ν -variables. The difference between the two kinds of fixed point variables, which only comes out in infinite matches, can be put in the following slogan: all fixed points mean unfolding, and least fixed points mean finite unfolding. In order to make this more precise, we need the following observation.

Proposition 6.2 *Let F be an R -standard endofunctor on \mathbf{Set} , q a clean $\mu\mathcal{L}^F$ -formula and \mathbb{M} an F -model. Then in any infinite match β of the game $\mathcal{E}(\mathbb{M}, q)$, the set of variables that are unfolded infinitely often during β contains a maximal member (in the subformula order).*

Proof. Let U be the set of variables that are unfolded infinitely often during β . Since β is an infinite game, and q has only finitely many subformulas, U is non-empty. We claim that U is in fact directed (with respect to the subformula order \leq_q). The claim of the Proposition is then immediate by the fact that U is finite.

Suppose for contradiction that x and y are in U while x and y are incomparable with respect to \leq_q , that is, neither $q_x \trianglelefteq q_y$ nor $q_y \trianglelefteq q_x$. Since both x and y get unfolded infinitely often during β , the match can never go into one of the formulas, say, q_x , and stay there. But then the only way to get back, from a position inside q_x , to a position where y can be unfolded, is through unfolding a variable z such that both q_x and q_y are subformulas of q_z . Since this must happen infinitely often, one such variable z must be in U . Hence U is directed. \square

Definition 6.3 Let F be an R -standard endofunctor on \mathbf{Set} . Given an F -model $\mathbb{M} = (S, \sigma, V)$ and a clean coalgebraic fixed point formula q , we now define the *winning conditions* of the evaluation game $\mathcal{E} = \mathcal{E}(\mathbb{M}, q)$.

Let β be a full match played on the arena of \mathcal{E} .

- If β is finite then it is lost by the player who got stuck (and thus, won by their adversary).
- If β is infinite, let x be the highest ranking fixed point variable that got unfolded infinitely often during β . Now β is won by \exists if x is a ν -variable, and by \forall if x is a μ -variable.

◁

6.2 Adequacy of game semantics

The following theorem states that the evaluation games as introduced above, indeed constitute an equivalent characterization for the semantics of coalgebraic fixed point formulas.

Theorem 1 (Adequacy) *Let F be an R -standard endofunctor on \mathbf{Set} . Then for any clean $\mu\mathcal{L}^F$ -formula q , any F -model $\mathbb{M} = (S, \sigma, V)$ and any state $s \in S$ it holds that*

$$\mathbb{M}, s \Vdash q \text{ iff } (q, s) \in \text{Win}_{\exists}(\mathcal{E}(\mathbb{M}, q)).$$

Proof. The proof of this theorem proceeds by induction on the complexity of the formula q . We leave the base step ($p \in \{\top, \perp\}$ or p is a variable), the boolean cases, and the greatest fixed point case of the inductive step as exercises for the reader.

case $q = \mu x.q'$, \Rightarrow Let W be the set of states $w \in S$ such that (w, q) is a winning position for \exists in $\mathcal{E} = \mathcal{E}(\mathbb{M}, q)$. In order to show that $\llbracket q \rrbracket_{\mathbb{M}} \subseteq W$ it suffices to prove that W is a prefixed point of the map $\lambda X. \llbracket q' \rrbracket_{\mathbb{M}[x \mapsto X]}$. Abbreviate $V' := V[x \mapsto X]$ and $\mathbb{M}' := (S, \sigma, V')$, and let $t \in S$ be an arbitrary state in $\llbracket q' \rrbracket_{\mathbb{M}'}$, that is, $\mathbb{M}', t \Vdash q'$. It suffices to show that $t \in W$; in other words, we have to provide \exists with a winning strategy in $\mathcal{E}(\mathbb{M}, q)$ starting from position (q, t) .

First, note that it follows inductively from $\mathbb{M}', t \Vdash q'$ that \exists has a winning strategy f' from position (q', t) in the evaluation game $\mathcal{E}' = \mathcal{E}(\mathbb{M}', q')$. Now observe that \mathcal{E} and \mathcal{E}' are in fact *very* similar games: apart from the fact that \mathcal{E}' has no positions of the form (q, u) , the only difference between the two games concerns positions of the form (x, u) . In \mathcal{E}' , x is a *free* variable, so in a position (x, u) , the match is over, and the winner of such a match depends on whether u belongs to $V'(x) = W$ or not. In \mathcal{E} on the other hand, x is a *bound* variable, so at a state (x, u) , the variable x will get unfolded.

Second, observe that by definition of W , for every state $w \in W$, \exists has a winning strategy f_w for the game \mathcal{E} initialized at (w, q) . Note that in this initialized game, the second position invariably will be (w, q') . So \exists could not have spoiled her chances in this first round, and hence f_w is winning for \exists in \mathcal{E} at (w, q') as well.

Now suppose that \exists plays \mathcal{E} from (q, t) according to the following strategy g :

- after the initial move, the pebble is in position (q', t) ;
- \exists first plays her strategy f' ;
- as soon as a position (x, u) is reached, distinguish the following two cases:
 1. if $u \in W$ then \exists continues with f_u ;
 2. if $u \notin W$ then \exists continues with a random strategy.

We now claim that this strategy g is in fact a winning strategy for \exists in the game \mathcal{E} initialized at (q, t) . To see why this must be so, make the following case distinction concerning an arbitrary full play β which is consistent with g :

No state (x, u) is ever reached. This means that β doubles as an \mathcal{E} -match and an \mathcal{E}' -match.

As an \mathcal{E}' -match, β is won by \exists . Since \mathcal{E} and \mathcal{E}' only differ when it comes to x , this means that β is also a win for \exists in \mathcal{E} . Note that it does not matter here whether β is finite or infinite.

At some stage a position (x, u) is reached. In the \mathcal{E}' -perspective on π , the match would have reached a final position here. Since f' was a winning strategy for \exists , this can only happen if $u \in V'(x) = W$. (In other words, case 2 mentioned above will never occur.) So \exists consequently plays according to f_u ; the first position after (x, u) is (q', u) . We know that f_u is a winning strategy for \exists in the game \mathcal{E} initialized at (q', u) . It is then easy to see that any continuation of the match in which \exists plays f_u , is won by \exists .

Altogether this shows that indeed, g is a winning strategy for \exists .

case $q = \mu x.q'$, \Leftarrow Assume that \exists has a winning strategy f in the game $\mathcal{E} = \mathcal{E}(\mathbb{M}, \mu x.q')$, and suppose for contradiction that $\mathbb{M}, s \not\models \mu x.q'$. Abbreviating $Q := \llbracket \mu x.q' \rrbracket_{\mathbb{M}}$, this means that $s \notin Q$.

First consider an arbitrary point $t \notin Q$. It follows from $\mathbb{S}, t \not\models \mu x.q'$ that there is a prefixed point $U \subseteq S$ of the map $\lambda X \subseteq S. \llbracket q' \rrbracket_{\mathbb{M}[x \mapsto X]}$ to which t does *not* belong. That is, $t \notin U$ while $\llbracket q' \rrbracket_{\mathbb{M}[x \mapsto U]} \subseteq U$. It follows that $t \notin \llbracket q' \rrbracket_{\mathbb{M}[x \mapsto U]}$, or, equivalently, that $\mathbb{M}[x \mapsto U], t \not\models q'$. By the inductive hypothesis then, \exists does not have a winning strategy in $\mathcal{E}(\mathbb{M}[x \mapsto U], q')$ from (q', t) . But since $Q \subseteq U$ (because U is a prefixed point of the map $\lambda X \subseteq S. \llbracket q' \rrbracket_{\mathbb{M}[x \mapsto X]}$, and Q is the intersection of all such prefixed points), it easily follows from the rules of the game that \exists does not have a winning strategy in the game $\mathcal{E}' := \mathcal{E}(\mathbb{M}[x \mapsto Q], q')$ from (q', t) either. That is, for each strategy g of \exists starting at (q', t) , \forall has a counter strategy \bar{g}_t such that the match of \mathcal{E}' determined by g and \bar{g}_t is won by \forall .

Furthermore, observe that because of the resemblance between the games \mathcal{E} and \mathcal{E}' , any strategy g of \exists in \mathcal{E} , as a map restricted to partial \mathcal{E}' -matches, uniquely determines a strategy in \mathcal{E}' ; this strategy will be denoted as g as well.

Now consider the matches of \mathcal{E} , starting at $(\mu x.q', s)$, in which \exists plays according to her supposedly winning strategy f . Suppose that \forall counters the strategy f as follows:

- \forall starts with the strategy \bar{f}_s ;
- from that moment on, \forall sticks to the current strategy, unless a position (x, u) is reached; now distinguish cases:
 1. if $u \in Q$ then \forall continues with a random strategy;
 2. if $u \notin Q$ then \forall plays as follows. Let β be the match this far (including (x, u)), and let f_β denote the strategy of \exists for the \mathcal{E} -game starting at (q', u) given by $f_\beta(\gamma) = f(\beta\gamma)$. Then by our earlier discussion, f_β can be seen as an \mathcal{E}' -strategy for matches starting at (q', u) , and so \forall may adopt his counter strategy $\overline{(f_\beta)}_u$ from this moment on.

Consider the \mathcal{E} -match β starting at $(\mu x.q', s)$ determined by \exists playing her strategy f and \forall using the strategy defined above. First observe that β can pass through positions of the form (x, u) only finitely many times, for otherwise, the μ -variable x would be the highest fixed point variable unfolded infinitely often, contradicting the assumption that f is winning for \exists . Second, note that the first case of passing a state (x, u) will never occur; since arriving at a position (x, u) with $u \in Q$ would mean that, contrary to our earlier conclusion, \exists would have a successful strategy in \mathcal{E}' at a point $v \notin Q$ after all.

This means, however, that after a certain initial partial play β , ending in a position (x, u) with $u \notin Q$, \forall will stick to his strategy $\overline{(f_\beta)_u}$, while no further position (v, x) is ever reached. It follows from our assumptions on $\overline{(f_\beta)_u}$ that the match γ resulting from \exists playing f_β against \forall playing $\overline{(f_\beta)_u}$ is winning for \forall in \mathcal{E}' , and from this it is not hard to derive that the \mathcal{E} -match $\delta = \beta\gamma$ is won by \forall . This provides the desired contradiction, since it shows that the strategy f is not winning for \exists after all.

case $q = \nabla\pi$, \Rightarrow Suppose that $\mathbb{M}, s \Vdash \nabla\pi$, and consider the game $\mathcal{E} = \mathcal{E}(\mathbb{M}, q)$. Let \exists , in the game \mathcal{E} initialized at $(\nabla\pi, s)$, choose the set $Z := \Vdash_{Base(\pi)}$ as her first move. Note that it follows by definition from $\mathbb{M}, s \Vdash \nabla\pi$ that $(\sigma(s), \pi) \in \Vdash$, so this is a legitimate move. Now suppose that \forall moves at position Z , choosing $(p, t) \in Z$ as the next position. It follows from $(p, t) \in Z$ and the inductive hypothesis that in the game $\mathcal{E}(\mathbb{M}, p)$, \exists has a winning strategy starting from (p, t) . But then it is easy to see that this strategy will also guarantee her winning $\mathcal{E}(\mathbb{M}, \nabla\pi)$ from (p, t) . All in all we have provided her with a strategy winning \mathcal{E} from $(\nabla\pi, s)$.

case $q = \nabla\pi$, \Leftarrow Suppose that \exists wins the game $\mathcal{E} = \mathcal{E}(\mathbb{M}, q)$ starting at position $(\nabla\pi, s)$. Let's say that her choice at position $(\nabla\pi, s)$ is the set $Z \subseteq Base(\pi) \times S$. Since, at position Z , \forall may choose any $(r, t) \in Z$, we may assume that each such (r, t) is winning for \exists in $\mathcal{E}(\mathbb{M}, r)$. It thus follows from the inductive hypothesis that $Z \subseteq \Vdash$, whence we see that $Z \subseteq \Vdash_{Base(\pi)}$. Hence by monotonicity of $\overline{}$ we obtain that $\overline{Z} \subseteq \overline{\Vdash_{Base(\pi)}}$. But we know that $(\pi, \sigma(s)) \in Z$, for if not, then Z would have been illegitimate. So we find that $(\pi, \sigma(s)) \in \overline{\Vdash_{Base(\pi)}}$, precisely what is needed to show that $\mathbb{M}, s \Vdash \nabla\pi$. QED

7 Automata and fixed point logic

The reader will have noticed the similarity between the evaluation game of a formula and the acceptance game of an automaton. But the connection is much tighter than a mere resemblance, witness the Theorem below, which forms the main result of the paper:

Theorem 2 (Formulas are automata) *Let F be an R -standard endofunctor on \mathbf{Set} . Then any $\mu\mathcal{L}^F$ -sentence q can be transformed into a delayed parity F -automaton \mathbb{A}_q such that for any pointed F -coalgebra (\mathbb{S}, s) :*

$$\mathbb{S}, s \Vdash q \text{ iff } \mathbb{A}_q \text{ accepts } (\mathbb{S}, s).$$

Proof. By Proposition 5.15 we can assume without loss of generality that p is clean, and by Proposition 4.9 (or, more precisely, by its variant dealing with delayed automata), it suffices to construct a logical F -automaton \mathbb{A}_p . The structure of \mathbb{A}_p will closely resemble that of the set $Sfor(p)$ of subformulas of p .

In fact, we can *identify* the states of \mathbb{A}_p with the subformulas of p , and let $p := a_I$ be the initial state of \mathbb{A}_p . Now define the following transition function Δ on $Sfor(p)$ (where in order to avoid confusion, we use \sqcup and \sqcap to denote the disjunction and conjunction for the automaton):

$$\Delta(\perp) := \bigvee \emptyset$$

$$\begin{aligned}
\Delta(\top) &:= \bigwedge \emptyset \\
\Delta(q \vee q') &:= q \sqcup q' \\
\Delta(q \wedge q') &:= q \sqcap q' \\
\Delta(\eta x. q_x) &:= q_x \\
\Delta(\nabla \pi) &:= \pi \\
\Delta(x) &:= q_x.
\end{aligned}$$

With this definition, we have established that for any F-coalgebra \mathbb{S} , the *boards* of the acceptance game $\mathcal{G} = \mathcal{G}(\mathbb{A}_p, \mathbb{S})$ and of the evaluation game $\mathcal{E} = \mathcal{E}(p, \mathbb{S})$ are in fact *identical*. Hence in particular, the matches of the two games coincide.

The only thing left is to define a parity function on A that takes proper care of the winning conditions of the evaluation game \mathcal{E} . Using the finiteness of the set $Sfor(p)$, it is easy to define a function $\Omega : Sfor(p) \rightarrow \omega$ such that

- $\Omega(q) = 0$ if $q \notin BVar(p)$,
- $\Omega(x)$ is odd if x is a μ -variable, and even if x is a ν -variable,
- $\Omega(x) \leq \Omega(y)$ if $x \leq_p y$ (i.e., if $\eta_x x. p_x \leq \eta_y y. p_y$).

It is then straightforward to verify that \exists is the winner of a match β in \mathcal{G} if and only if she is the winner of β , seen as a match of \mathcal{E} . From this it is immediate that $Win_{\exists}(\mathcal{G}) = Win_{\exists}(\mathcal{E})$, and hence the theorem follows by the Adequacy Theorem of the game semantics of $\mu\mathcal{L}^F$. QED

Since any delayed automaton can be transformed into an equivalent standard one, a corollary of Theorem 2 is that $\mu\mathcal{L}^F$ -formulas can in fact be represented by standard F-automata. Conversely, one can show that, given a parity F-automaton \mathbb{A} , one can construct a $\mu\mathcal{L}^F$ -formula $q_{\mathbb{A}}$ that holds precisely at those pointed F-coalgebras that are accepted by \mathbb{A} . This means that the F-automata have the same expressive strength as the logical formalism $\mu\mathcal{L}^F$ when it comes to describing pointed F-coalgebras. We intend to come back to the details of these constructions in a future paper.

8 Further research

We believe that it is interesting and useful to develop the automata theory for coalgebras on an (almost) arbitrary functor $F : \mathbf{Set} \rightarrow \mathbf{Set}$, and to apply this theory to the study of coalgebraic fixed point logics. It also seems that our notion of F-automaton is a natural one, given its stability under a number of natural variations, and its equivalence to a natural coalgebraic fixed point logic. It is obvious that in this paper we have only scratched the surface of these topics. Of the many questions that naturally arise we just mention the following.

1. In our opinion, the most interesting line of research concerns the study of the recognizing power of automata from a coalgebraic perspective. The point here is that many familiar theorems concerning the expressivity of automata as mechanisms for recognizing structures, can now be parametrized by the coalgebraic functor type. It is thus a

natural problem to find out whether (the analogs of) these theorems hold for coalgebras of arbitrary type F . If so, it might be of interest to find a uniform, coalgebraic proof for the result, and if not, we have arrived at an interesting *property* that an endofunctor on Set could or could not have.

To be a bit more specific, recall that some of the most important results in automata theory concern the following kinds of questions:

simplification Given an automaton of a certain type (say, a nondeterministic automaton), can it be transformed into a equivalent automaton of a simpler kind (say, a deterministic one)?

Such questions can now be formulated as questions about the functor F . To mention one example: Which functors have the property that that there is, for every alternating parity F -automaton, an equivalent non-deterministic one?

closure properties Call a class C of pointed F -coalgebras *A-recognizable*, where A is a class of F -automata, if there is some automaton \mathbb{A} in A such that C is the class of pointed F -coalgebras that are accepted by \mathbb{A} . Is the collection of *A-recognizable* classes closed under natural operations such as union, intersection, complementation, projection?

Again, varying the functor type adds a new dimension to this problem. To mention, again, a specific question: for which functors F can we prove a *Complementation Lemma*? That is, for which functors F can we always find, given a non-deterministic F -automaton \mathbb{A} , another non-deterministic F -automaton $\overline{\mathbb{A}}$, with the property that a pointed F -coalgebra is accepted by $\overline{\mathbb{A}}$ iff it is rejected by \mathbb{A} ?

2. Our parity F -automata have a coalgebraic shape themselves: the automaton $\mathbb{A} = (A, a_I, \Delta, \Omega)$ can, at least object-wise, be represented as a pointed coalgebra over the functor $F_{\text{Aut}}S = \mathcal{P}(\mathcal{P}(FS)) \times \omega$. This perspective clearly needs investigation – recall that the coalgebraic perspective on ordinary automata (operating on finite words) has already proven to be very enlightening, see RUTTEN [21].
3. Our definition of coalgebraic fixed point logic is only one out of many. In fact, fixed point operators may be added to any kind of language of coalgebraic logic. It would be good to see more case studies on coalgebraic fixed point logics from an automata-theoretic perspective. Related to one of the above questions, one would like to understand what happens if we add negation to the language $\mu\mathcal{L}^F$ discussed in section 5. But also, the relation between the modal μ -calculus and a fixed point extension of the coalgebraic modal logics developed in PATTINSON [18] might be an interesting object of study.
4. As already mentioned in the introduction, there are earlier studies of automata that are based on categories and functors, see for instance ADÁMEK & TRNKOVÁ [2]. This connection clearly has to be investigated further.

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