Multi-Valued Symbolic Model-Checking

MARSHA CHECHIK, BENET DEVEREUX, STEVE EASTERBROOK
and ARIE GURFINKEL
University of Toronto

This article introduces the concept of multi-valued model-checking and describes a multi-valued symbolic model-checker, χChek. Multi-valued model-checking is a generalization of classical model-checking, useful for analyzing models that contain *uncertainty* (lack of essential information) or *inconsistency* (contradictory information, often occurring when information is gathered from multiple sources). Multi-valued logics support the explicit modeling of uncertainty and disagreement by providing additional truth values in the logic.

This article provides a theoretical basis for multi-valued model-checking and discusses some of its applications. A companion article [Chechik et al. 2002b] describes implementation issues in detail. The model-checker works for any member of a large class of multi-valued logics. Our modeling language is based on a generalization of Kripke structures, where both atomic propositions and transitions between states may take any of the truth values of a given multi-valued logic. Properties are expressed in χCTL, our multi-valued extension of the temporal logic, CTL.

We define the class of logics, present the theory of multi-valued sets and multi-valued relations used in our model-checking algorithm, and define the multi-valued extensions of CTL and Kripke structures. We explore the relationship between χCTL and CTL, and provide a symbolic model-checking algorithm for χCTL. We also address the use of fairness in multi-valued model-checking. Finally, we discuss some applications of the multi-valued model-checking approach.

Categories and Subject Descriptors: D.2.4 [**Software Engineering**]: Software/Program Verification—*Formal methods, Model-checking*; D.2.1 [**Software Engineering**]: Requirements/ Specifications—*Tools*; F.4.1 [**Mathematical Logic and Formal Languages**]: Mathematical Logic—*Temporal Logic*

General Terms: Documentation, Verification

Additional Key Words and Phrases: CTL, multi-valued logic, model-checking, partiality, inconsistency, fairness, χChek.

1. INTRODUCTION

This article introduces the concept and the general theory of multi-valued model-checking and describes our multi-valued symbolic model-checker, χChek. Multi-valued model-checking can best be explained as a generalization

This work was financially supported by NSERC and CITO.
Authors' addresses: Department of Computer Science, University of Toronto, Toronto, ON M5S 3G4, Canada; email: {chechik,benet,sme,arie}@cs.toronto.edu.

of classical model-checking. A classical model-checker takes a model, M, of a system (expressed as a finite state machine), and a temporal correctness property, φ, (expressed as a formula in a suitable temporal logic), and determines whether or not the model satisfies the property [Clarke et al. 1986]. In other words, it returns the value of the predicate $M \models \varphi$. Multi-valued model-checking permits reasoning with additional truth values beyond just True and False. In particular, the satisfaction relation, $M \models \varphi$, can be multi-valued. χChek [Chechik et al. 2002a] is a generalization of an existing symbolic model-checking algorithm [McMillan 1993] for a multi-valued extension of the temporal logic, CTL.

Our motivation stems from two observations about the application of model-checking in software engineering. The first is that to make model-checking practical for verification of real software systems, abstract models of the software behavior must be constructed. When working with abstractions, it is natural to consider three-valued logics, with the third value, Maybe, used to indicate elided information in the model [Bruns and Godefroid 1999], or to indicate the result of checking when a definite answer is not possible using the chosen abstraction [Sagiv et al. 1999; Chechik and Ding 2002]. The second observation is that model-checking has a natural application for model exploration, where the goal is to arrive at a good model of the desired system through successive approximations. Each model is likely to be incomplete and/or wrong, but by exploring its properties, the analyst learns how to improve it. Again, three-valued logics provide a natural way of indicating missing information [Bruns and Godefroid 2000]. However, it is also appealing to consider a more general family of logics with additional truth values, for example, to distinguish levels of uncertainty, levels of priority, or disagreements between knowledge sources [Easterbrook and Chechik 2001].

In this sense, our interest in multi-valued reasoning parallels a similar interest in philosophy and AI, where multi-valued logics have been explored for reasoning with information with associated degrees of belief or credibility weightings [Ginsberg 1988]. We draw on that work to provide us with a suitable class of multi-valued logics for our model-checker, in particular, the work of Kleene [1952] who originally explored the use of three-valued logics for reasoning with missing information and Belnap [1977] who extended Kleene's strong three-valued logic to a four-valued logic to account for inconsistency. Belnap observed that the truth values of these logics admit to two intuitive (partial) orders: a knowledge order, which places Maybe below both True and False, and a truth order which places False below Maybe below True. Finally, Fitting [1991b] used this observation to characterize an entire family of multi-valued logics based on Kleene's logic and offers several intuitive constructions for them. Fitting also explored a multi-valued generalization of modal logic, using Kripke's possible world semantics in which not only do formulae take values from a multi-valued space in each possible world, but the accessibility relationships between worlds can also be multi-valued [Fitting 1991a; Fitting 1992].

Applying these ideas to model-checking, our approach supports all of the following generalizations:

—Variables in the finite state machine can be multi-valued or boolean.
—Transitions between states in the finite state machine can be multi-valued or boolean.
—The satisfaction relation can be multi-valued or boolean.

We achieve this generalization by defining model-checking algorithms over a large class of logics, including the family of Kleene-like logics identified by Fitting. In particular, we pose the following requirements to this class: (a) many of the desired properties of classical logic operators are preserved, for example associativity, commutativity, and idempotance; (b) the logics can be used for representing a large class of systems; (c) model-checking using these logics remains tractable. We intentionally leave probabilistic systems outside the scope of this article, concentrating instead on logics with a finite set of truth values. To meet these requirements, we restrict ourselves to logics whose truth values form a finite distributive lattice under the truth ordering, with a negation operator that preserves De Morgan laws and involution ($\neg\neg a = a$). The resulting structures are called *quasi-boolean algebras* [Rasiowa 1978]. Classical boolean logic, as well as the logics described by Kleene [1952] and Belnap [1977], are examples of quasi-boolean algebras. Unlike Heyting algebras [Fitting 1992], quasi-boolean algebras allow us to preserve the duality between the "next-time" operators: $EX\neg\varphi = \neg AX\,\varphi$. Our model-checker operates on any multi-valued logic whose truth values form a quasi-boolean algebra—the particular logic to be used in each analysis is selected as a run-time parameter. We define quasi-boolean algebras formally and discuss their properties in Section 3. Throughout the article, we use terms "algebras" and "logics" interchangeably, to indicate a set of truth values closed under logical operations.

Having identified a suitable class of logics, we develop the theory of multi-valued model-checking as follows. We first apply a theory of multi-valued sets and relations to create the core structure for our symbolic model-checking algorithm. Multi-valued sets are sets whose membership functions are multi-valued [Goguen 1967]. We use multi-valued sets to represent the partition of the state-space over the set of truth values in the logic, induced by a given property. We extend the notion of multi-valued set membership to multi-valued relations which we use to represent the transition relations in our models. We present the theory of multi-valued sets and relations in Section 4.

Second, we define a multi-valued semantics for CTL and demonstrate that this semantics preserves the desired properties. We call the resulting logic χCTL. We provide a model-based semantics for χCTL by extending the notion of Kripke structures, so that both atomic propositions and transitions between states range over values of a given quasi-boolean algebra. We call the resulting models χKripke structures. We present χCTL and χKripke structures in Section 5. We also show that χCTL is decidable and analyze fixpoint properties of its operators.

Third, we give a characterization of multi-valued model-checking with fairness. Fairness is used in classical model-checking to simplify modeling by allowing the user to build a model with more behaviors than is desired, and then to restrict the analysis to just those behaviors that are fair, that is, occur under reasonable assumptions about occurrence of events in the environment. We argue that fairness conditions in multi-valued model-checking should be boolean-valued and give a formulation of fairness for each χCTL operator in Section 6.

Combining these ideas yields a clean extension of the theory of classical model-checking, applicable to a variety of tasks. We describe the implementation details and some potential applications of multi-valued model-checking in Section 7. We further note that the multi-valued model-checking decision procedure can be either implemented directly or reduced to classical. The trade-offs between these choices are studied in the companion article, Chechik et al. [2002b].

We conclude the article with a brief discussion of the relationship between our work and other recent work on multi-valued model-checking and discuss some planned extensions of our work (Section 8).

Throughout the article we use these notational conventions: (1) we refer to an unnamed function over the domain D as $\lambda x \in D \cdot$ *F-n Body*; (2) we use *nat* to refer to the set of natural numbers; (3) we use $\exists!$ to mean "exists unique". Proofs of selected theorems can be found in the Appendix.

2. CTL MODEL-CHECKING

In this section, we give a brief overview of classical CTL model-checking.

CTL model-checking is an automatic technique for verifying properties expressed in a propositional branching-time temporal logic called *Computation Tree Logic* (CTL) [Clarke et al. 1986]. A model is a Kripke structure whose properties are evaluated on a tree of infinite computations produced by the model. The standard notation $M, s \models \varphi$ indicates that a formula φ holds in a state s of a model M. If a formula holds in the initial state, it is considered to hold in the model.

A Kripke structure consists of a set of states, S, a transition relation, $R \subseteq S \times S$, an initial state, $s_0 \in S$, a set of atomic propositions, A, and a labeling function, $I : S \to 2^A$. R must be total, that is, $\forall s \in S,\ \exists t \in S$, such that $(s, t) \in R$. Finite computations are modeled by adding a self-loop to the final state of the computation. For each $s \in S$, the labeling function provides a set of atomic propositions which hold in the state S.

The syntax of CTL is as follows:

(1) Every atomic proposition $a \in A$ is a CTL formula.
(2) If φ and ψ are CTL formulas, then so are $\neg\varphi$, $\varphi \wedge \psi$, $\varphi \vee \psi$, $EX\varphi$, $AX\varphi$, $EF\varphi$, $AF\varphi$, $E[\varphi\ U\ \psi]$, $A[\varphi\ U\ \psi]$, $AG\varphi$, $EG\varphi$.

The logic connectives $\neg$, $\wedge$ and $\vee$ have their usual meanings. The existential and universal quantifiers E and A are used to quantify over paths. The operator X means "in the next state", F represents "sometime in the future", U is "until", and G is "globally". For example, $EX\varphi$ is True in state s if φ holds in some immediate successor of s, while $AX\varphi$ is True if φ holds in every immediate successor of s. $EF\varphi$ is True in s if φ holds in the future along some path from s; $E[\varphi\ U\ \psi]$ is True in s if along some path from s, φ continuously holds until

$$\begin{array}{rcll}
AG\varphi &=& \nu Z.(\varphi \wedge AXZ) & (AG \text{ fixpoint}) \\
EG\varphi &=& \nu Z.(\varphi \wedge EXZ) & (EG \text{ fixpoint}) \\
AF\varphi &=& \mu Z.(\varphi \vee AXZ) & (AF \text{ fixpoint}) \\
EF\varphi &=& \mu Z.(\varphi \vee EXZ) & (EF \text{ fixpoint}) \\
A[\varphi\ U\ \psi] &=& \mu Z.(\psi \vee (\varphi \wedge AXZ)) & (AU \text{ fixpoint}) \\
E[\varphi\ U\ \psi] &=& \mu Z.(\psi \vee (\varphi \wedge EXZ)) & (EU \text{ fixpoint})
\end{array}$$

Fig. 1. Fixpoint formulations of CTL operators. Note: $\mu Z.f(Z)$ and $\nu Z.f(Z)$ indicate the least and the greatest fixpoints of f, respectively.

ψ becomes TRUE. $EG\varphi$ hold in s if φ holds in every state along some path from s. $AF\varphi$, $A[\varphi\ U\ \psi]$ and $AG\varphi$ are defined similarly, replacing the quantification over some paths by the one over all paths. Formally,

$$\begin{array}{rll}
M, s \models a & \text{iff} & a \in I(s) \\
M, s \models \neg\varphi & \text{iff} & M, s \not\models \varphi \\
M, s \models \varphi \wedge \psi & \text{iff} & M, s \models \varphi\ \wedge\ M, s \models \psi \\
M, s \models \varphi \vee \psi & \text{iff} & M, s \models \varphi\ \vee\ M, s \models \psi \\
M, s \models EX\varphi & \text{iff} & \exists t \in S,\ (s,t) \in R\ \ \wedge\ M, t \models \varphi \\
M, s_i \models EG\varphi & \text{iff} & \text{there exists some path } s_i, s_{i+1}, \ldots \text{ s.t. } \forall j \geq i \cdot M, s_j \models \varphi \\
M, s_i \models E[\varphi\ U\ \psi] & \text{iff} & \text{there exists some path } s_i, s_{i+1}, \ldots, \text{ s.t.} \\
& & \exists j \geq i \cdot M, s_j \models \psi\ \wedge\ \forall k \cdot i \leq k < j \Rightarrow M, s_k \models \varphi.
\end{array}$$

Note that these definitions give us a "strong until", that is, $E[\varphi\ U\ \psi]$ is TRUE only if ψ eventually occurs. Further, note that we have used EG, EX, and EU as an adequate set of temporal operators, following Huth and Ryan [2000] and Clarke et al. [1999]. The remaining temporal operators are defined in terms of these:

$$\begin{array}{lll}
A[\varphi\ U\ \psi] & \triangleq \neg E[\neg\psi\ U\ \neg\varphi \wedge \neg\psi]\ \wedge\ \neg EG\neg\psi & \text{def. of } AU \\
AX\varphi & \triangleq \neg EX\neg\varphi & \text{def. of } AX \\
AF\varphi & \triangleq A[\top\ U\ \varphi] & \text{def. of } AF \\
EF\varphi & \triangleq E[\top\ U\ \varphi] & \text{def. of } EF \\
AG\varphi & \triangleq \neg EF\neg\varphi & \text{def. of } AG
\end{array}$$

Alternatively, CTL operators can be described using their fixpoint formulations as shown in Figure 1. This description is most useful for symbolic model-checking [McMillan 1993].

3. QUASI-BOOLEAN LOGICS

Our motivation for developing multi-valued model-checking is to enable automated reasoning over models where there are uncertainties or disagreements. For different applications, we expect that different multi-valued logics will be appropriate. We therefore need to identify a class of multi-valued logics that are natural for describing realistic problems, but which still enable tractable model-checking. Where possible, we wish to build upon the existing body of work in constructing efficient model-checkers by reusing existing algorithms and data structures. Hence, we need logics whose operators have most of the same properties as their classical counterparts.

Following the work of Fitting [1991b], we observe that many of the desired properties can be obtained if we insist that the truth values of the logic form a complete lattice under the truth order, with conjunction and disjunction defined as the lattice operations meet and join, respectively. Further, to preserve the relationships between the temporal operators described in Section 2, we will require that conjunction and disjunction distribute over each other and that De Morgan's laws hold for negation. Distributive lattices have the former property, but for the latter, we need additional constraints on the choice of the negation operator.

One possible choice is to use boolean algebras which are very well known and have all the properties described above, together with the law of non-contradiction (LNC) and the law of excluded middle (LEM). However, this choice would exclude many interesting logics, including those of Kleene [1952] and Belnap [1977], where LNC and LEM do not hold. Instead, we use quasi-boolean algebras which have all the properties of boolean algebras except LNC and LEM. Quasi-boolean algebras, also known as De Morgan algebras, are a familiar concept in logic [Bolc and Borowik 1992; Dunn 1999].

The remainder of this section provides a formal treatment of the above discussion. We start with the lattice theory background in Section 3.1. We then define quasi-boolean algebras in Section 3.2, and describe some examples.

3.1 Lattice Theory

Definition 1. A *partial order*, $\sqsubseteq$, on a set $\mathcal{L}$ is a binary relation on $\mathcal{L}$ such that the following conditions hold:

$$\begin{array}{rl} \forall a \in \mathcal{L} : a \sqsubseteq a & \text{reflexivity} \\ \forall a, b \in \mathcal{L} : a \sqsubseteq b \wedge b \sqsubseteq a \Rightarrow a = b & \text{anti-symmetry} \\ \forall a, b, c \in \mathcal{L} : a \sqsubseteq b \wedge b \sqsubseteq c \Rightarrow a \sqsubseteq c & \text{transitivity.} \end{array}$$

A partially ordered set, $(\mathcal{L}, \sqsubseteq)$, has a *bottom* element if there exists $\bot \in \mathcal{L}$ such that $\bot \sqsubseteq a$ for all $a \in \mathcal{L}$. Dually, $(\mathcal{L}, \sqsubseteq)$ has a *top* element if there exists $\top \in \mathcal{L}$ such that $a \sqsubseteq \top$ for all $a \in \mathcal{L}$.

Definition 2. A partially ordered set, $(\mathcal{L}, \sqsubseteq)$, is a *lattice* if a unique greatest lower bound and least upper bound exist for every finite subset of $\mathcal{L}$.

Given lattice elements a and b, their greatest lower bound is referred to as *meet* and denoted $a \sqcap b$, and their least upper bound is referred to as *join* and denoted $a \sqcup b$. It follows from Definition 2 that every (finite) lattice has a top and a bottom.

Lattices enjoy a number of useful properties, some of which are given below:

$$\begin{array}{rcll} a \sqcup \top & = & \top & \text{base} \\ a \sqcap \bot & = & \bot & \\ a \sqcap \top & = & a & \text{identity} \\ a \sqcup \bot & = & a & \\ a \sqcup a & = & a & \text{idempotence} \\ a \sqcap a & = & a & \\ a \sqcup b & = & b \sqcup a & \text{commutativity} \end{array}$$

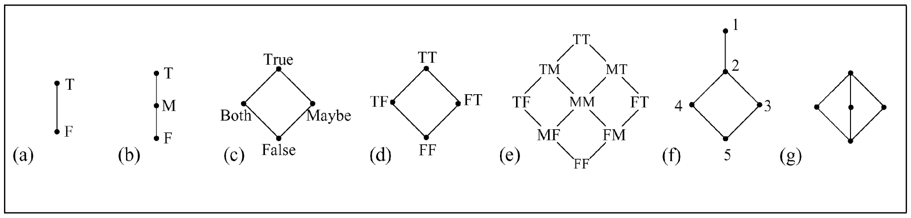

Fig. 2. Example lattices.

$$
\begin{array}{rcll}
a \sqcap b & = & b \sqcap a & \\
a \sqcup (b \sqcup c) & = & (a \sqcup b) \sqcup c & \text{associativity} \\
a \sqcap (b \sqcap c) & = & (a \sqcap b) \sqcap c & \\
a \sqcup (a \sqcap b) & = & a & \text{absorption} \\
a \sqcap (a \sqcup b) & = & a & \\
a \sqsubseteq a' \ \wedge \ b \sqsubseteq b' & \Rightarrow & a \sqcap b \sqsubseteq a' \sqcap b' & \text{monotonicity} \\
a \sqsubseteq a' \ \wedge \ b \sqsubseteq b' & \Rightarrow & a \sqcup b \sqsubseteq a' \sqcup b' & \\
a \sqcap b \sqsubseteq b & \text{and} & a \sqcap b \sqsubseteq a & \sqcap \text{ elimination} \\
a \sqsubseteq b \ \wedge \ a \sqsubseteq c & \Rightarrow & a \sqsubseteq b \sqcap c & \sqcap \text{ introduction} \\
a \sqsubseteq a \sqcup b & \text{and} & b \sqsubseteq a \sqcup b & \sqcup \text{ introduction} \\
a \sqsubseteq c \ \wedge \ b \sqsubseteq c & \Rightarrow & a \sqcup b \sqsubseteq c & \sqcup \text{ elimination.}
\end{array}
$$

Definition 3. A lattice is *distributive* if and only if

$$
\begin{array}{rcll}
a \sqcup (b \sqcap c) & = & (a \sqcup b) \sqcap (a \sqcup c) & \text{distributivity} \\
a \sqcap (b \sqcup c) & = & (a \sqcap b) \sqcup (a \sqcap c). &
\end{array}
$$

Figure 2 gives some example lattices. The lattice in Figure 2(g) is non-distributive, whereas all other lattices are distributive.

3.2 Quasi-Boolean Algebras

In this section we define quasi-boolean algebras and study their properties.

Definition 4. A quasi-boolean algebra is a tuple $(\mathcal{L}, \sqcap, \sqcup, \neg)$, where:

—$(\mathcal{L}, \sqsubseteq)$ is a finite distributive lattice, with $a \sqsubseteq b$ iff $a \sqcap b = a$;

—Conjunction ($\sqcap$) and disjunction ($\sqcup$) are meet and join operators of $(\mathcal{L}, \sqsubseteq)$, respectively;

—Negation $\neg$ is a function $\mathcal{L} \to \mathcal{L}$ such that every element $a \in \mathcal{L}$ corresponds to a unique element $\neg a \in \mathcal{L}$ satisfying the following conditions:

$$
\begin{array}{rcll}
\neg(a \sqcap b) & = & \neg a \sqcup \neg b & \text{De Morgan} \quad \neg\neg a \ = \ a \quad \neg \text{ involution} \\
\neg(a \sqcup b) & = & \neg a \sqcap \neg b & \quad a \sqsubseteq b \Leftrightarrow \neg a \sqsupseteq \neg b \quad \neg \text{ antimonotonic}
\end{array}
$$

where $b \in \mathcal{L}$. $\neg a$ is called *a quasi-complement* of a [Rasiowa 1978].

Note that the negation operator satisfying the above properties is a *lattice dual isomorphism* with period 2 [Birkhoff 1967].

Definition 5. A *product* of two algebras, $L_1 = (\mathcal{L}_1, \sqcap_1, \sqcup_1, \neg_1)$ and $L_2 = (\mathcal{L}_2, \sqcap_2, \sqcup_2, \neg_2)$, is an algebra, $L_1 \times L_2 = (\mathcal{L}_1 \times \mathcal{L}_2, \sqcap, \sqcup, \neg)$, where

$$\begin{array}{rcll} \neg(a,b) & = & (\neg_1 a, \neg_2 b) & \neg \text{ of pairs} \\ (a,b) \sqcap (a',b') & = & (a \sqcap_1 a', b \sqcap_2 b') & \sqcap \text{ of pairs} \\ (a,b) \sqcup (a',b') & = & (a \sqcup_1 a', b \sqcup_2 b') & \sqcup \text{ of pairs.} \end{array}$$

Thus, the operations on the product algebra are the component-wise extensions of their individual counterparts. Similar properties hold for $\top$, $\bot$, and the ordering:

$$\begin{array}{rcll} \bot_{\mathcal{L}_1 \times \mathcal{L}_2} & = & (\bot_{\mathcal{L}_1}, \bot_{\mathcal{L}_2}) & \bot \text{ of pairs} \\ \top_{\mathcal{L}_1 \times \mathcal{L}_2} & = & (\top_{\mathcal{L}_1}, \top_{\mathcal{L}_2}) & \top \text{ of pairs} \\ (a,b) \sqsubseteq (a',b') & \Leftrightarrow & a \sqsubseteq_1 a' \ \wedge \ b \sqsubseteq_2 b' & \sqsubseteq \text{ of pairs.} \end{array}$$

THEOREM 1. *A product of two quasi-boolean algebras is quasi-boolean, that is,*

$$\begin{array}{lrcl} (1) & \neg\neg(a,b) & = & (a,b) \\ (2) & \neg((a_1,b_1) \sqcap (a_2,b_2)) & = & (\neg a_1, \neg b_1) \sqcup (\neg a_2, \neg b_2) \\ (3) & \neg((a_1,b_1) \sqcup (a_2,b_2)) & = & (\neg a_1, \neg b_1) \sqcap (\neg a_2, \neg b_2) \\ (4) & (a_1,b_1) \sqsubseteq (a_2,b_2) & \Leftrightarrow & \neg(a_1,b_1) \sqsupseteq \neg(a_2,b_2). \end{array}$$

PROOF: See Appendix.

We now give some example quasi-boolean algebras using the lattices in Figure 2.

(1) The lattice in Figure 2(a), with ¬T = F and ¬F = T, gives us classical logic which we refer to as **2**. Note that in this case, $\sqcup$ and $\sqcap$ are conventionally written $\vee$ and $\wedge$, respectively. We use these notations interchangeably when the interpretation is clear from the context.
(2) The three-valued logic **3** is defined on the lattice in Figure 2(b), where ¬T = F, ¬F = T, ¬M = M. This is Kleene's strong 3-valued logic [Kleene 1952].
(3) Belnap's 4-valued logic can be defined over the lattice in Figure 2(c), with ¬N = N and ¬B = B. This logic has been used for reasoning about inconsistent databases [Belnap 1977; Anderson and Belnap 1975].
(4) The lattice in Figure 2(d) shows the product algebra **2x2**, where ¬TF = FT and ¬FT = TF. This logic can be used for reasoning about disagreement between two knowledge sources [Easterbrook and Chechik 2001]. The underlying lattice is isomorphic to the one in Figure 2(c) but the resulting quasi-boolean algebras are not isomorphic because of the choice of negations.
(5) The lattice in Figure 2(e) shows a nine-valued logic constructed as the product algebra **3x3**. Like **2x2**, this logic can be used for reasoning about the disagreement between two sources, but also allows missing information in each source.

Note that we generally label $\top$ and $\bot$ of the lattice with the values TRUE and FALSE of the logic, respectively.

The lattice in Figure 2(f) cannot be used as a basis for a quasi-boolean algebra because no suitable quasi-complement can be found for element 2. The lattice in Figure 2(g) cannot be used either, because it is non-distributive.

The class of quasi-boolean algebras includes (finite) boolean algebras as a special case:

Definition 6. A tuple, $L = (\mathcal{L}, \sqcap, \sqcup, \neg)$, is a *finite Boolean algebra* if L is a quasi-boolean algebra and additionally, for every element, $a \in \mathcal{L}$,

$$\begin{array}{rcll} a \sqcap \neg a & = & \bot & \neg \text{ contradiction or LNC} \\ a \sqcup \neg a & = & \top & \neg \text{ exhaustiveness or LEM.} \end{array}$$

For example, the algebra **2** is boolean, whereas **3** is not ($\text{M} \sqcap \neg\text{M} \neq \bot$). Also, as the product of two boolean algebras is a boolean algebra [Birkhoff 1967], then the product algebra **2x2** shown in Figure 2(d) is boolean. The product algebra **3x3**, shown in Figure 2(e), is quasi-boolean but not boolean.

The identification of a suitable negation operator is greatly simplified by the observation that quasi-boolean algebras have underlying lattices that are symmetric about their horizontal axes:

Definition 7. A lattice $(\mathcal{L}, \sqsubseteq)$ is *symmetric* iff there exists a bijective function H such that for every pair $a, b \in \mathcal{L}$,

$$\begin{array}{rcll} a \sqsubseteq b & \Leftrightarrow & H(a) \sqsupseteq H(b) & H \text{ antimonotonic} \\ & & H(H(a)) = a & H \text{ involution.} \end{array}$$

Notice that H is a lattice dual automorphism with period 2. Thus, this symmetry is a sufficient condition for defining a quasi-boolean algebra over a distributive lattice with a potential negation defined as $\neg a = H(a)$ for each element of the lattice. Lattices in Figure 2(a)–(e) exhibit this symmetry and thus are quasi-boolean, whereas the lattice in Figure 2(f) is not. Note that in Belnap's 4-valued logic, defined on the lattice in Figure 2(c), the chosen negation, $\neg\text{N} = \text{N}$, $\neg\text{B} = \text{B}$, is not the one offered by symmetry.

Finally, we define implication and equivalence as follows:

$$\begin{array}{rcll} a \rightarrow b & \triangleq & \neg a \sqcup b & \text{material implication} \\ a \leftrightarrow b & \triangleq & (a \rightarrow b) \sqcap (b \rightarrow a) & \text{equivalence.} \end{array}$$

Note that from the underlying partial order, we also have *equality*:

$$a = b \triangleq (a \sqsubseteq b) \wedge (b \sqsubseteq a) \quad \text{equality.}$$

In boolean algebras, equality is the same as equivalence. In quasi-boolean algebras, this is not necessarily the case. For example, for algebra **3**, $x = \text{M}$ and $y = \text{M}$: $x = y$ is $(\text{M} \sqsubseteq \text{M}) \wedge (\text{M} \sqsubseteq \text{M})$, which is $\top$, whereas $x \leftrightarrow y$ is $(\text{M} \rightarrow \text{M}) \sqcap (\text{M} \rightarrow \text{M})$, which is M.

4. MULTI-VALUED SETS AND RELATIONS

In order to define multi-valued model-checking later in this article, we begin by creating a data structure that allows definition and reasoning about operations on sets of states in which a property holds. Such operations include union, intersection, complement, and backward image for computing predecessors. Given a quasi-boolean algebra, we can treat these as operations over multi-valued sets: sets whose membership functions are multi-valued. We define the

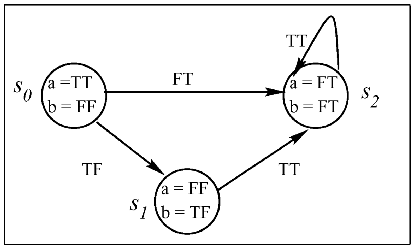

Fig. 3. Ex1: a simple χKripke structure.

concept of multi-valued sets and relations over quasi-boolean algebras in this section. This treatment is similar to the definition of L-fuzzy sets [Goguen 1967].

4.1 Multi-Valued Sets

In classical set theory, a set is defined by a boolean predicate, also called a *membership* or a *characteristic* function. Typically, it is written using a *set comprehension notation*: a predicate P defines the set $S = \{x \mid P(x)\}$. For instance, if $P = \lambda x \in nat \cdot 0 \leq x \leq 10$, then S is the set of all integers between 0 and 10 inclusive. If instead of using a boolean predicate, we allow the membership function to range over elements of a given algebra, we obtain a *multi-valued* set theory in which it is possible to make statements like "element x is more in set $\mathbb{S}$ than element y". We call the result *mv-sets*.

Definition 8. Given an algebra, $L = (\mathcal{L}, \sqcap, \sqcup, \neg)$, and a classical set, S, an *L-valued set* on S, referred to as $\mathbb{S}$, is a total function $S \to \mathcal{L}$.

Where the underlying algebra, L, is clear from context, we refer to an L-valued set just as an mv-set. For an mv-set, $\mathbb{S}$, and a candidate element, x, we use $\mathbb{S}(x)$ to denote the membership degree of x in $\mathbb{S}$. In the classical case, this amounts to representing a set by its characteristic function.

We illustrate *mv-sets* using a simple state machine shown in Figure 3. This machine uses the quasi-boolean algebra **2x2** where the logical values form the lattice in Figure 2(d) and exemplifies χKripke structures – multi-valued generalizations of Kripke structures, defined formally in Section 5.1. In classical symbolic model-checking, each (boolean-valued) expression, x, partitions the state space into states where x is TRUE and states where it is FALSE. Likewise, we use multi-valued expressions to partition the state space of the system. For example, the variable, a. partitions the states of the χKripke structure in Figure 3: for each value, ℓ, of **2x2**, we get the set of states where a has value ℓ. In this case, a has value TT in $\{s_0\}$, FT in $\{s_2\}$, FF in $\{s_1\}$ and TF in $\{\}$. The resulting **2x2**-valued set, referred to as $[\![a]\!]$, can be graphically represented as shown in Figure 4(a), where the structure corresponds to that of the underlying lattice.

We extend some standard set operations to the multi-valued case by lifting the lattice meet and join operations as follows[1]:

[1]The subscript on mv-set operations $\cap_L, \cup_L, \subseteq_L$, and so forth refers to a given algebra, $L = (\mathcal{L}, \sqcap, \sqcup, \neg)$.

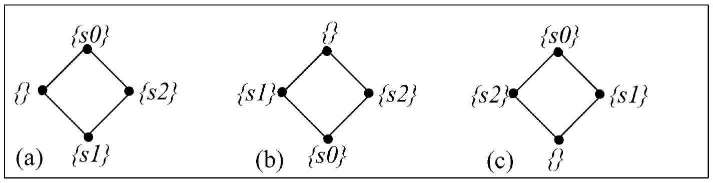

Fig. 4. Several mv-sets for the example in Figure 3: (a) corresponding to variable a; (b) corresponding to variable b; (c) $\overline{[\![b]\!]}$ – a multi-valued complement of the mv-set in (b).

$$
\begin{array}{rcll}
(\mathbb{S} \cap_L \mathbb{S}')(x) & \triangleq & (\mathbb{S}(x) \sqcap \mathbb{S}'(x)) & \text{multi-valued intersection} \\
(\mathbb{S} \cup_L \mathbb{S}')(x) & \triangleq & (\mathbb{S}(x) \sqcup \mathbb{S}'(x)) & \text{multi-valued union} \\
\mathbb{S} \subseteq_L \mathbb{S}' & \triangleq & \forall x \cdot (\mathbb{S}(x) \sqsubseteq \mathbb{S}'(x)) & \text{set inclusion} \\
\mathbb{S} = \mathbb{S}' & \triangleq & \forall x \cdot (\mathbb{S}(x) = \mathbb{S}'(x)) & \text{extensional equality.}
\end{array}
$$

For example, in computing intersection of *mv-set*s $[\![a]\!]$ and $[\![b]\!]$ given in Figure 4(a) and (b), respectively, we note that in state s_1, a is FF and b is TF. Thus,

$$([\![a]\!] \cap_L [\![b]\!])(s_1) = \text{FF} \sqcap \text{TF} = \text{FF}.$$

We also extend the notion of *set complement* to the multi-valued case by defining it in terms of the quasi-complement of L and denoting it with a bar:

$$\overline{\mathbb{S}}(x) \triangleq \neg(\mathbb{S}(x)) \quad \text{multi-valued complement}$$

Mv-set $\overline{[\![b]\!]}$ is given in Figure 4(c).

We then obtain the desired properties:

$$
\begin{array}{rcll}
\overline{\mathbb{S} \cup_L \mathbb{S}'} & = & \overline{\mathbb{S}} \cap_L \overline{\mathbb{S}'} & \text{De Morgan 1} \\
\overline{\mathbb{S} \cap_L \mathbb{S}'} & = & \overline{\mathbb{S}} \cup_L \overline{\mathbb{S}'} & \text{De Morgan 2} \\
\mathbb{S} \subseteq_L \mathbb{S}' & = & \overline{\mathbb{S}'} \subseteq_L \overline{\mathbb{S}} & \text{antimonotonicity.}
\end{array}
$$

Note that we obtain classical set theory in the special case where the algebra is **2** and the multi-valued intersection, union, and complement are equivalent to their classical counterparts:

THEOREM 2. *For a* **2***-valued set* $\mathbb{S}$ *on* S*, the following hold:*

(1) *The membership function* $\mathbb{S}(x)$ *is a boolean predicate*
(2) $(\mathbb{S} \cap_{\mathbf{2}} \mathbb{S}') = \{x \mid \mathbb{S}(x) \wedge \mathbb{S}'(x)\} = (\mathbb{S} \cap \mathbb{S}')$
(3) $(\mathbb{S} \cup_{\mathbf{2}} \mathbb{S}') = \{x \mid \mathbb{S}(x) \vee \mathbb{S}'(x)\} = (\mathbb{S} \cup \mathbb{S}')$
(4) $\overline{\mathbb{S}}(x) = x \in (S - \{y \mid \mathbb{S}(y) = \top\})$.

4.2 Multi-Valued Relations

Now we extend the concept of degrees of membership in an *mv-set* to degrees of relatedness of two entities. This concept, formalized by *multi-valued relations*, allows us to define multi-valued transitions in state machine models.

Definition 9. For a given algebra L, an L-valued relation $\mathbb{R}$ on two sets S and T is an L-valued set on $S \times T$.

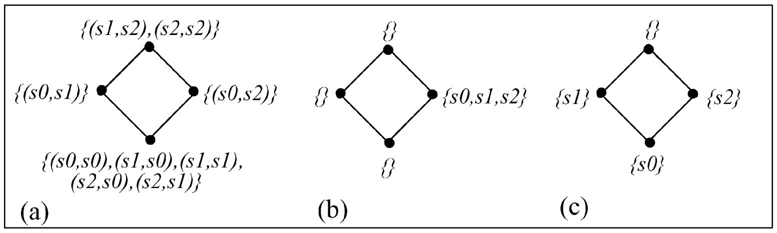

Fig. 5. (a) The multi-valued relation between pairs of states of Ex1; (b) Forward image of $[\![a]\!]$ over the relation in (a); (c) Backward image of $[\![a]\!]$ over the relation in (a).

Let S be the set of states of the χKripke structure in Figure 3, referred to as Ex1. The multi-valued relation over $S \times S$ represents values of transitions between pairs of states of Ex1 and is shown in Figure 5(a). We will refer to this mv-relation as $\mathbb{A}$. For example, the value of the transition (s_0, s_1) is TF, so $\mathbb{A}((s_0, s_1)) = \text{TF}$.

Definition 10. Given an algebra, L, an L-valued relation, $\mathbb{R}$, on sets S and T, and an L-valued set, $\mathbb{S}$, on S, the *forward image* of $\mathbb{S}$ under $\mathbb{R}$, denoted $\overrightarrow{\mathbb{R}}(\mathbb{S})$, is an L-valued set on T, defined as:

$$\overrightarrow{\mathbb{R}}(\mathbb{S}) \triangleq \lambda t \in T \cdot \bigsqcup_{s \in S} (\mathbb{S}(s) \sqcap \mathbb{R}(s, t))$$

and for an L-valued set, $\mathbb{T}$, on T, the *backward image* of $\mathbb{T}$ under $\mathbb{R}$ is

$$\overleftarrow{\mathbb{R}}(\mathbb{T}) \triangleq \lambda s \in S \cdot \bigsqcup_{t \in T} (\mathbb{T}(t) \sqcap \mathbb{R}(s, t)).$$

Intuitively, the forward image of an *mv-set*$\mathbb{S}$ under the relation $\mathbb{R}$ represents all elements reachable from $\mathbb{S}$ by $\mathbb{R}$ where multi-valued memberships of $\mathbb{R}$ and $\mathbb{S}$ are taken into consideration. Similarly, a backward image of an *mv-set*$\mathbb{T}$ under $\mathbb{R}$ represents all elements that can reach $\mathbb{T}$ by $\mathbb{R}$.

We now consider computing the forward and the backward images of $[\![a]\!]$ (see Figure 4(a)) under the multi-valued relation $\mathbb{A}$ between the pairs of states of the χKripke structure Ex1. These are shown in Figures 5(b) and (c), respectively. For example, when we compute backward image of s_0, we get

$$\bigsqcup_{t \in S} ([\![a]\!](t) \sqcap \mathbb{A}(s_0, t)) = (\text{TT} \sqcap \text{FF}) \sqcup (\text{FF} \sqcap \text{TF}) \sqcup (\text{FT} \sqcap \text{FT}) = \text{FT}$$

which indicates that there exists an FT transition from state s_0 to another state (actually, s_2), where a is FT.

THEOREM 3. *The forward and backward image of a* **2***-valued set,* $\mathbb{Q}$*, under a* **2***-valued relation,* $\mathbb{R}$*, are as follows:*

$$\begin{aligned}(1)\ \overrightarrow{\mathbb{R}}(\mathbb{Q}) &= \lambda t \in T \cdot \textstyle\bigvee_{\{s \in S \mid \mathbb{R}(s,t)\}} \mathbb{S}(s)\\ (2)\ \overleftarrow{\mathbb{R}}(\mathbb{Q}) &= \lambda s \in S \cdot \textstyle\bigvee_{\{t \in T \mid \mathbb{R}(s,t)\}} \mathbb{T}(t).\end{aligned}$$

In other words, when the underlying algebra is **2**, forward and backward images are equivalent to their classical counterparts [Clarke et al. 1999].

5. MULTI-VALUED CTL MODEL-CHECKING

In this section, we extend the notion of boolean model-checking described in Section 2 by defining multi-valued Kripke structures, which we call χKripke structures, and multi-valued CTL (χCTL).

5.1 Semantics

M is a χ*Kripke structure* if $M = (S, s_0, \mathbb{R}, I, A, L)$, where:

—$L = (\mathcal{L}, \sqcap, \sqcup, \neg)$ is a quasi-boolean algebra, used for all *mv-set*s in the model;
—A is a (finite) set of atomic propositions that evaluate to elements of the algebra, L;
—S is a (finite) set of states;
—$s_0 \in S$ is the initial state;
—$\mathbb{R} : S \times S \to \mathcal{L}$ is the multi-valued transition relation;
—$I : S \to (A \to \mathcal{L})$ is a (total) labeling function that maps states in S into L-valued sets on A.

Intuitively, for any atomic proposition, $a \in A$, $(I(s))(a) = \ell$ means that the variable a has value ℓ in state s. Given an atomic proposition, $a \in A$, $I'_a : S \to \mathcal{L}$ is a (total) multi-valued characteristic function for an *mv-set*on S. I'_a is defined as follows:

$$I'_a \triangleq \lambda s \in S \cdot (I(s))(a).$$

Thus, for each proposition, a, I'_a *partitions* the state-space with respect to it, that is for each state, s, $\exists!\ell \cdot I'_a(s) = \ell$.

Note that a χKripke structure is a completely connected graph. As with classical model-checking, we ensure that all traces have infinite length by requiring that there is at least one non-$\bot$ transition out of each state (if necessary, by adding a non-$\bot$ self-loop to terminal states). Formally,

$$\forall s \in S \cdot \exists t \in S \cdot \mathbb{R}(s, t) \neq \bot.$$

To avoid clutter, when we present finite-state machines graphically, we follow the convention of not showing $\bot$ transitions. An example χKripke structure, shown in Figure 3, was introduced in Section 4.

5.2 Multi-Valued CTL

Here we give semantics of CTL operators on a χKripke structure M over a quasi-boolean algebra L. We refer to this language as *multi-valued CTL*, or χCTL.

In extending the CTL operators, we want to ensure that the desired properties of EX, EG and EU which form the adequate set for CTL, are still preserved.

Definition 11. A *computation* of a χKripke structure M from a (reachable) state s is an infinite sequence of states, $s_0, s_1, \ldots$, s.t. $s = s_0$, and $\mathbb{R}(s_i, s_{i+1}) \neq \bot$. This sequence of states is also referred to as a *path*.

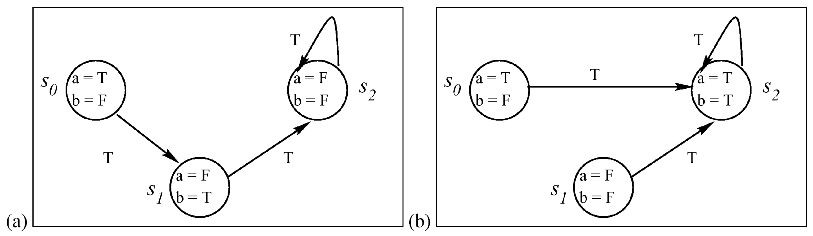

Fig. 6. Two classical Kripke structures: (a) Ex_l; (b) Ex_r.

We also note that evaluating a formula, φ, in a state, s, is the same as evaluating φ on a tree of all computations emanating from s.

We start defining χCTL by giving the semantics of propositional operators. We use the double-brace notation, adopted from denotational semantics, and write $[\![\varphi]\!]$ to denote the *mv-set* of states representing a degree to which φ holds. Note that we have already used this notation when illustrating *mv-set*s in Section 4.

The semantics is as follows:

$$\begin{aligned} [\![a]\!] &\triangleq I'_a \\ [\![\neg\varphi]\!] &\triangleq \overline{[\![\varphi]\!]} \\ [\![\varphi \wedge \psi]\!] &\triangleq [\![\varphi]\!] \cap_L [\![\psi]\!] \\ [\![\varphi \vee \psi]\!] &\triangleq [\![\varphi]\!] \cup_L [\![\psi]\!]. \end{aligned}$$

We proceed by defining the EX operator. Recall from Section 2 that in classical CTL, this operator is defined using existential quantification over next states. We extend the notion of existential quantification for multi-valued reasoning through the use of disjunction. This treatment of quantification is standard [Belnap 1977; Rasiowa 1978]. The semantics of EX is:

$$[\![EX\varphi]\!] \triangleq \overleftarrow{\mathbb{R}}([\![\varphi]\!]) \qquad \text{def. of } EX.$$

Note that we use our definition of backward image (Definition 9), that is for a state s,

$$[\![EX\varphi]\!](s) = \bigsqcup_{t\in S}([\![\varphi]\!](t) \sqcap \mathbb{R}(s,t)).$$

When reasoning about a model which was produced by merging two (classical) models, we can think of $EX\varphi$ as representing a question "does there exist a next state in each individual model where φ is TRUE, even if the two individual models do not agree on what this state is". For example, consider the two classical Kripke structures, Ex_l and Ex_r, shown in Figure 6. χKripke structure Ex1, shown in Figure 3, constitutes one possible merge of Ex_l and Ex_r. In this case, states with the same name are merged. For example, a variable b has values T and F in state s_1 of Ex_l and Ex_r, respectively; therefore, in Ex1, this variable has value TF. Similarly, a transition (s_0, s_1) is present in Ex_l and absent in Ex_r; therefore, it has value TF in Ex1. Consider evaluating a property EXb in state s_0 of these three models. This property is T in Ex_l, because b is T in s_1, and T in Ex_r, because b is T in s_2. In Ex1, this property evaluates to TF on path (s_0, s_1)

and to FT on path (s_0, s_2). Their disjunction, and, therefore, the value of EXb in state s_0, is TT.

AX is then defined, following the AX duality in Section 2, as

$$[\![AX\varphi]\!] \triangleq \overline{[\![EX\neg\varphi]\!]} \quad \text{def. of } AX.$$

Expanding this definition, $[\![AX\varphi]\!] = \overline{\overleftarrow{\mathbb{R}}\,(\overline{[\![\varphi]\!]})} = \lambda s \cdot \bigsqcap_{t\in S}([\![\varphi]\!](t) \sqcup \neg\mathbb{R}(s,t))$, we see that universal quantification in the AX operator is replaced by conjunction.

Note that our definitions of EX and AX enjoy some familiar properties of their CTL counterparts. In particular,

$$\begin{array}{rcll} [\![EX(\varphi \vee \psi)]\!] & = & [\![EX\varphi]\!] \cup_L [\![EX\psi]\!] & EX \text{ of disjunction} \\ [\![AX(\varphi \wedge \psi)]\!] & = & [\![AX\varphi]\!] \cap_L [\![AX\psi]\!] & AX \text{ of conjunction.} \end{array}$$

We further define EG and EU using the EG and EU fixpoint properties in Figure 1:

$$\begin{array}{rcll} [\![EG\varphi]\!] & \triangleq & \nu\mathbb{Z}.[\![\varphi]\!] \cap_L [\![EX\mathbb{Z}]\!] & \text{def. of } EG \\ [\![E[\varphi\ U\ \psi]]\!] & \triangleq & \mu\mathbb{Z}.[\![\psi]\!] \cup_L ([\![\varphi]\!] \cap_L [\![EX\mathbb{Z}]\!]) & \text{def. of } EU. \end{array}$$

Then, $A[\varphi\ U\ \psi]$ becomes

$$[\![A[\varphi\ U\ \psi]]\!] \triangleq \overline{[\![E[\neg\psi\ U\ \neg\varphi \wedge \neg\psi]]\!]} \cap_L \overline{[\![EG\neg\psi]\!]} \quad \text{def. of } AU$$

and the remaining χCTL operators are defined as their classical counterparts (see Section 2):

$$\begin{array}{rcll} [\![AF\varphi]\!] & \triangleq & [\![A[\top\ U\ \varphi]]\!] & \text{def. of } AF \\ [\![EF\varphi]\!] & \triangleq & [\![E[\top\ U\ \varphi]]\!] & \text{def. of } EF \\ [\![AG\varphi]\!] & \triangleq & \overline{[\![EF\neg\varphi]\!]} & \text{def. of } AG. \end{array}$$

Note that our definition of EU also preserves the familiar property of its CTL counterpart:

$$[\![E[\varphi\ U\ \psi]]\!] = [\![E\left[\varphi\ U\ E[\varphi\ U\ \psi]\right]]\!] \quad EU \text{ expansion.}$$

5.3 Properties of χCTL

We begin with some sanity checks on χCTL.

THEOREM 4. *χCTL reduces to CTL when the algebra is **2**. That is,*

$$\begin{array}{lrcl} (1) & [\![EX\varphi]\!] & = & [\![EX^B\varphi]\!] \\ (2) & [\![EG\varphi]\!] & = & [\![EG^B\varphi]\!] \\ (3) & [\![E[\varphi\ U\ \psi]]\!] & = & [\![E[\varphi\ U^B\ \psi]]\!] \end{array}$$

where EG^B, EU^B, and EX^B are classical CTL operators defined in Section 2.

We now consider monotonicity of "next-time" operators and ensure that χCTL is well defined, that is, each property, φ, has exactly one value in each state of the system.

THEOREM 5. *χCTL operators AX and EX are monotone.*

THEOREM 6. *The definition of χCTL ensures that for each φ, $[\![\varphi]\!]$ forms a partition.*

We now ensure that algorihtms for multi-valued model-checking can be found.

THEOREM 7. *Multi-valued model-checking is decidable.*

THEOREM 8. *Fixpoint properties of (derived) χCTL operators are the same as for CTL operators. That is,*

$$\begin{array}{llll}
(1) & [\![AG\varphi]\!] = \nu\mathbb{Z}.[\![\varphi]\!] \cap_L [\![AX\mathbb{Z}]\!] & AG \text{ fixpoint} \\
(2) & [\![AF\varphi]\!] = \mu\mathbb{Z}.[\![\varphi]\!] \cup_L [\![AX\mathbb{Z}]\!] & AF \text{ fixpoint} \\
(3) & [\![EF\varphi]\!] = \mu\mathbb{Z}.[\![\varphi]\!] \cup_L [\![EX\mathbb{Z}]\!] & EF \text{ fixpoint} \\
(4) & [\![A[\varphi\ U\ \psi]]\!] = \mu\mathbb{Z}.[\![\psi]\!] \cup_L ([\![\varphi]\!] \cap_L [\![AX\mathbb{Z}]\!]) & AU \text{ fixpoint.}
\end{array}$$

Note that our ability to prove the above properties of χCTL operators was dependent on the fact that our model-checking is defined over quasi-boolean algebras. For a treatment of properties of χCTL when the model-checking is defined over a more general class of algebras, please see Devereux [2002] and Chechik and MacCaull [2003].

5.4 Running Time

To determine the running time of our algorithm, we note that this time is dominated by the fixpoint computations of EG and EU. In what follows, we first show that the fixpoint computation converges in $O(|S|)$ iterations, where S is the state space of the model under analysis, and then analyze the complexity of each iteration.

5.4.1 *Number of iterations.* We start with the property $[\![EF\varphi]\!](s) = [\![E[\top\ U\ \varphi]]\!](s)$, where φ is a propositional formula, and s is an arbitrary state of the model. Intuitively, the nth iteration of the fixpoint algorithm computes the least upper bound (join) over the values of φ on states reachable from s by a path of length at most n, weighted by "the value of the path". Formally, the value of a path, $s_0, s_1, \ldots, s_n$, is $\bigsqcap_{i=0}^{n-1} \mathbb{R}(s_i, s_{i+1})$. In any model with a finite state space, S, a state that is reachable by a path, π, of length greater or equal to $|S| + 1$, is also reachable by a sub-path of π of length at most $|S|$. That is, any path longer than $|S|$ necessarily contains a cycle, and, therefore, has a corresponding acyclic sub-path. Combining this with the fact that a value of a sub-path is always above a value of the full path, we conclude that the fixpoint computation converges after at most $|S| + 1$ iterations.

THEOREM 9. *Model-checking a χCTL property $EF\varphi$ on a χKripke structure with a state space S takes at most $|S| + 1$ iterations* [Gurfinkel 2002].

We now extend this result to the EU operator. The result of model-checking a χCTL property $E[\varphi\ U\ \psi]$ on a χKripke structure, M, with the transition relation, $\mathbb{R}$, is equivalent to model-checking $EF\psi$ of a χKripke structure, M', obtained from M by replacing its transition relation with $\mathbb{R}'(s,t) = \mathbb{R}(s,t) \wedge [\![\varphi]\!](s)$.

THEOREM 10. *Model-checking a χCTL formula $E[\varphi\ U\ \psi]$ on a χKripke structure with a state space S takes at most $|S| + 1$ iterations* [Gurfinkel 2002].

For the EG operator, we start with its simplest form, $[\![EG\top]\!](s)$. The ith iteration of the fixpoint computation of $[\![EG\top]\!](s)$ computes the least upper bound of the values of all paths of length i emanating from s. Since the state space S is finite, for any path π of length greater than $|S|+1$, there exists a path π' of length at most $|S|+1$, whose value is above the value of π. Thus, the fixpoint computation converges after at most $|S|+2$ iterations. The result is extended to the general case by the fact that computing $EG\varphi$ on a χKripke structure, M, with transition relation, $\mathbb{R}$, is equivalent to computing $EG\top$ on a χKripke structure, M', obtained from M by replacing its transition relation with $\mathbb{R}'(s,t) = \mathbb{R}(s,t) \wedge [\![\varphi]\!](s)$.

Theorem 11. *Model-checking a χCTL formula $EG\varphi$ on a χKripke structure with a state space S takes at most $|S|+2$ iterations* [Gurfinkel 2002].

5.4.2 *Running Time of Each Iteration.* Given an algebra $\mathcal{L}$, assume that conjunctions and disjunctions of lattice elements take $t_{\mathcal{L}}$ time[2]. To understand the running time of each iteration, we need to analyze the running time of individual operations: *mv-set*union, intersection, complement, and backward image. The first three operations can be done in the time linear in the size of the representation of the corresponding *mv-sets* ($O(|S| \times t_{\mathcal{L}})$). Backward image includes a disjunction of conjunctions between the formula and the transition relation, taking at most $O(|K| \times t_{\mathcal{L}})$, where $|K| = |S| + |R|$ is the size of the Kripke structure K [Clarke et al. 1999].

5.4.3 *Putting It All Together.* We established that there are $O(|S|)$ iterations before a fixpoint is reached, and each iteration is bounded by $O(|K| \times t_{\mathcal{L}})$. Since a given χCTL formula, φ, contains at most $|\varphi|$ different subformulas, the running time of our model-checking algorithm is $O(|K| \times |S| \times t_{\mathcal{L}} \times |\varphi|)$. This running time is also obtained by reducing multi-valued model-checking to several questions to the classical model-checker, as shown in Gurfinkel and Chechik [2003b]. If we fix the lattice $\mathcal{L}$, for example, by letting it be **2**, the running time reduces to $(|K| \times |S| \times |\varphi|)$, which is the expected running time of a classical model-checking algorithm [Clarke et al. 1999].

6. FAIRNESS

In this section, we address the problem of multi-valued model-checking with fairness. We discuss fairness in classical and multi-valued model-checking in Sections 6.1 and 6.2. We proceed by giving a formulation of fair counterparts for all χCTL operators, starting with EG (Section 6.3) and then using it to define other fair χCTL operators (Section 6.4). Finally, we analyze the running time of model-checking with fairness in Section 6.5.

6.1 Intuition

In classical model-checking, it is often easier to specify all behaviors of the system being modeled, plus some additional "unwanted" behaviors, and then

[2] $t_{\mathcal{L}}$ is linear in the number of *join-irreducible* elements of $\mathcal{L}$ [Davey and Priestley 1990].

restrict the analysis to just the "wanted" behaviors of the system. This approach is often taken in practice because it allows complicated systems to be specified more compactly. Since computations considered in classical model-checking are infinite, a natural way to partition behaviors into "wanted" and "unwanted" is by specifying progress that should be made on a fair computation (path). Thus, we define a computation as fair if and only if a certain progress state, or a sequence of states, occurs in it infinitely often [Clarke et al. 1986]. Formally,

Definition 12. A path is fair w.r.t. a set of fairness conditions, $C = \{c_1, c_2, \ldots, c_n\}$, iff every predicate, c_i, is TRUE on it infinitely often.

THEOREM 12. *The following statements are equivalent for a path, π, and fairness conditions, $C = \{c_1, \ldots, c_k\}$:*

(1) *Each fairness condition, c_i, occurs infinitely often in π;*
(2) *A sequence $c_1, c_2, \ldots, c_k$ occurs infinitely often in π.*

6.2 Fairness in Multi-Valued Model-Checking

In the multi-valued case, we want to preserve the ability to specify a larger set of computations than necessary and then restrict our attention to the "wanted", or fair ones. Multi-valued models already have a notion of "possible" computation: it is a computation where the conjunction of values of transitions between states is non-$\bot$, and "impossible" otherwise. Thus, if the goal of fairness in the multi-valued model-checking is to enable specification of a system in a concise form, fairness must be able to effectively turn some "possible" computations into "impossible" ones. Therefore, a "wanted" path in the fair system is a "possible" path conjoined with the appropriate fairness condition. Further, fair paths should preserve the "possibility" values of their underlying models, whereas unfair paths should have value $\bot$. One easy way to guarantee this is by ensuring that the fairness condition is 2-valued, because $\top$ and $\bot$ give us the desired base and identity laws ($x \sqcap \top = x$ and $x \sqcap \bot = \bot$). Thus, we assume that fairness constraints are given by a set of χCTL formulas, $C = \{c_1, c_2, \ldots, c_n\}$, such that each formula always evaluates to either $\top$ or $\bot$. Intuitively, such expressions consist of boolean predicates ($\sqsubseteq$, $\sqsupseteq$, $=$, $\neq$) on χCTL formulas. For example, for an arbitrary φ, $AX\varphi$ may evaluate to M when the logic is **3**, and, therefore, cannot be used to specify a fairness condition. On the other hand, $\psi \sqsubseteq AX\varphi$ (for some arbitrary φ and ψ) always evaluates to $\top$ or $\bot$, and thus can be used to specify fairness. Fairness conditions partition the sets of states into *mv-set*s. For notational convenience we assume that these *mv-set*s are over the same algebra, $L = (\mathcal{L}, \sqcap, \sqcup, \neg)$, as the model, even though for each fairness condition, c_i, $\forall s \in S \cdot [\![c_i]\!](s) \in \{\top, \bot\}$.

We begin defining multi-valued fairness by introducing the concept of *mv-trace*. In classical model-checking, a *trace* from s is a single computation, emanating from s, of the corresponding Kripke structure. On the other hand, a trace in multi-valued model-checking may correspond to several computations, that is, a witness to an EX operator is not necessarily a single path [Gurfinkel and Chechik 2003a]. For example, consider the χKripke structures Ex$_l$, Ex$_r$ and Ex1, shown in Figures 6 and 3, respectively. As indicated earlier, Ex1 is the merge of the other two models. Next-state computations from s_0 in models Ex_l and Ex_r are s_0, s_1 and s_0, s_2, respectively. Yet, as shown in Section 5.2, both are necessary to evaluate *EXb*. So, even existential χCTL operators, and their fair counterparts, are defined and evaluated on *sets of computations* which we refer to as *mv-traces*.

Definition 13. An mv-trace in a χKripke structure, M, is *fair* w.r.t. a set of fairness conditions, $C = \{c_1, c_2, \ldots, c_n\}$, if and only if each computation comprising it is fair w.r.t. C.

Following Huth and Ryan [2000], we write A_c and E_c for the operators A and E restricted to fair paths. For example, $[\![A_c G\varphi]\!](s) = \top$ means that φ is TRUE in every fair mv-trace.

6.3 Fair *EG*

As in CTL, χCTL operators E_cG, $E_c[\varphi\ U\ \psi]$ and E_cX form an adequate set. Given a formulation for E_cG, we can define other fair χCTL operators, as shown in Section 6.4.

Note that $[\![E_cG\varphi]\!](s) = \ell$ means that there exists an mv-trace beginning with state s on which $EG\varphi$ holds with value ℓ, and each formula in C is $\top$ infinitely often along each path. Alternatively, if $C = \{c_1, c_2\}$, it is the repetition of the following sequence: φ holds until c_1, and from that point on, φ holds until c_2. Formally, we can define this using the following fixpoint formulation:

$$[\![E_cG\varphi]\!] \triangleq \nu\mathbb{Z}\cdot[\![\varphi]\!] \cap_L [\![EX\,E\left[\varphi\ U\ \varphi \wedge c_1 \wedge EX\,E[\varphi\ U\ \varphi \wedge c_2 \wedge \mathbb{Z}]\right]]\!] \qquad \text{def. of } E_cG.$$

When $C = \{c_1, c_2, \ldots, c_k\}$, the above definition can be extended appropriately. The problem with this definition, however, is that it is dependent on the size of C. We thus seek an alternative definition, calling the new operator E_cG'.

$$[\![E_cG'\varphi]\!] \triangleq \nu\mathbb{Z}\cdot[\![\varphi]\!] \cap_L \bigcap\nolimits_{Lk=1}^{n}[\![EX\,E[\varphi\ U\ \varphi \wedge \mathbb{Z} \wedge c_k]]\!] \qquad \text{def. of } E_cG'$$

We are now ready to study properties of E_cG and E_cG'. We begin by showing that E_cG' becomes EG when there are no fairness conditions present, and then proceed to show that the operators E_cG and E_cG' are equivalent.

THEOREM 13. *When $C = \{\top\}$ (no fairness), E_cG' becomes*

$$[\![E_cG'\varphi]\!] = \nu\mathbb{Z}\cdot[\![\varphi]\!] \cap_L [\![EX\,E[\varphi\ U\ \varphi \wedge \mathbb{Z}]]\!] = \nu\mathbb{Z}\cdot[\![\varphi]\!] \cap_L [\![EX\,\mathbb{Z}]\!] = [\![EG\varphi]\!]$$

THEOREM 14. *Operators E_cG and E_cG' are equivalent.*

6.4 Fairness in Other χCTL Operators

Computing $E_cX\varphi$ in state s amounts to finding successors of s which are at the start of some fair computation path and computing $EX\varphi$ using only these successors. In such states $E_cG\top$ has a value other than $\bot$. Thus, the formulation for $E_cX\varphi$ is

$$[\![E_cX\varphi]\!] \triangleq [\![EX(\varphi\ \wedge\ (E_cG\top = \bot))]\!].$$

For a similar reason, the formulation for $E_C[\varphi\ U\ \psi]$ is

$$[\![E_C[\varphi\ U\ \psi]]\!] = [\![E[\varphi\ U\ (\psi\ \wedge\ (E_C G\top = \bot))]]\!].$$

Note that both formulations are similar to those of classical CTL.

6.5 Running Time

Running time of the model-checker under fairness conditions, C, is dominated by the computation of $E_C G$ that includes a nested fixpoint. The inner fixpoint is used to compute $E[\varphi\ U\ (\mathbb{Z}\ \wedge\ c_k)]$ and takes, using a regular model-checking algorithm, $O(|S|^3)$. The outer fixpoint converges after at most $|S|$ iterations, and each iteration involves computing $|C|$ inner fixpoints. Therefore, $E_C G\varphi$ can be computed in $O(|C| \times |S|^4)$ time. Since a given formula, φ, contains at most $|\varphi|$ different subformulas, running time of the model-checker under fairness conditions, C, is in $O(|\varphi| \times |C| \times |S|^4)$. Note that running time for χCTL with fairness reduces to that of the classical CTL model-checker when the underlying logic is classical.

7. IMPLEMENTATION AND APPLICATIONS

In this section, we briefly discuss implementation choices for χChek and describe some potential applications for it.

7.1 Implementation

As a proof of concept, we have developed a prototype implementation (in Java) of a multi-valued model-checker called χChek [Chechik et al. 2002a]. The checking engine takes as input a list of χCTL formulas to verify, a model of the system represented as a χKripke structure, and a specification of the underlying quasi-boolean algebra. For each χCTL formula, χChek calculates its value in the initial state, returning a counter-example or a witness, if appropriate. The counter-example generator for χCTL is discussed in detail elsewhere [Gurfinkel and Chechik 2003a].

Practical symbolic model-checking in a given domain (probabilistic, multi-valued, timed, etc.) depends on efficient algorithms for storing and manipulating sets of states in which a property holds. In our case, we need efficient implementations of operations (union, intersection, complement, and backward image) on the mv-set datatype. χChek uses a general mv-set interface and we are experimenting with alternative implementations of mv-sets. As in classical symbolic model-checking, we represent mv-sets using decision diagrams. Several varieties of decision diagrams are suitable. For example, if the mv-set membership function is kept multi-valued, then mv-sets can be easily implemented using Multi-Valued Decision Diagrams (MDDs) [Srinivasan et al. 1990; Chechik et al. 2001a]. Alternatively, each mv-set can be thought of as a collection of classical sets. Symbolically, this approach can be implemented using Multi-Valued Binary-Terminal Decision Diagrams (MBTDDs) [Sasao and Butler 1996]. Of course, the multi-valued model-checking problem also reduces to several queries to the classical model-checker, run on top of Binary Decision Diagrams (BDDs) [Konikowska and Penczek 2003; Gurfinkel and Chechik

2003b]. The tradeoffs between these encodings depend on a number of factors, including the types of questions asked, the size and the shape of the elements of the underlying lattice, and the variable ordering. We describe the implementation and evaluate the performance characteristics of different implementations of the mv-set datatype in a companion article [Chechik et al. 2002b].

7.2 Applications

Multi-valued model-checking has a number of potential applications in software engineering, such as analyzing models that contain uncertainty, disagreement, or relative priority, and for general model exploration. For example:

— The intermediate values of the logic can be used to represent incomplete information (or uncertainty). Such applications typically use a 3-valued logic, with the values $\top$, $\bot$ and MAYBE . A 3-valued model can be interpreted as a compact representation for a set of *completions* [Bruns and Godefroid 2000], where a completion is generated by replacing each MAYBE value in the model by either $\top$ or $\bot$. If a property is $\top$ (respectively, $\bot$) in a partial model, then it is $\top$ ($\bot$) in all completions. If a property is MAYBE in a partial model, then it takes different values in different completions: the missing information affects the property. Thus, we can use a 3-valued model-checker to determine if particular properties hold even though the model is incomplete. We can also use this approach to reduce the size of classical model-checking problems by creating (partial) abstractions of models that have large state-spaces. We describe one such case study below. It is possible to generalize this approach to logics with more than three values, to distinguish levels of uncertainty for the incomplete information, but we have not yet explored such applications.

— The intermediate values of the logic can be used to represent disagreement. Such applications typically use quasi-boolean algebras defined over product lattices. A model based on a product lattice can be interpreted as a compact representation for a set of models (or *views*), where the views may disagree on the values of some transitions or propositions. For example, a model based on a logic **2x2** can be formed by merging information from two separate 2-valued views. One such 4-valued model and its corresponding classical models were shown in Figures 3 and 6, respectively. If a property is $\top$ (respectively, $\bot$) in each individual view, then it is $\top$ ($\bot$) in the merged model. If a property is FT or TF in the merged model, then the disagreement affects the property. Multi-valued model-checking over such merged models is particularly useful if the views are partial, representing, for example, different modules, features or slices of a larger system. In this case, a multi-valued model-checker can check properties that cannot be expressed in the individual views because the properties combine vocabulary of several views or refer to interactions between different views. We are exploring this approach for the feature interaction problem in telephony [Easterbrook and Chechik 2001], and as a tool to support stakeholder negotiations in requirements engineering by tracing specific disagreements to the properties they affect.

— The intermediate values of the logic can be used to represent relative desirability (or criticality). Such applications typically use chain lattices, also known as total orders. A model based on a chain lattice can be interpreted as a compact representation for a set of partial *layers*, where each successive layer specifies values for transitions left unspecified by previous layers. For example, a model based on a 4-valued chain lattice can be used to represent a system with two levels of criticality. Transitions labeled $\top$ (respectively, $\bot$) represent core functionality—transitions that must (must not) occur. Transitions labeled with the remaining values represent optional functionality. If a property is $\top$ (respectively, $\bot$) in this model, then it is true (false) in just the core layer, irrespective of behaviors at the optional layer. We are exploring this approach for reasoning about requirements prioritization and for analyzing survivable systems. In each of these applications, the multi-valued model-checker allows us to check which properties are supported by which layer, but avoids having to maintain separate models of the individual layers.

—Elements of our quasi-boolean algebras need not be interpreted as logical values. Consider the *query-checking* problem [Chan 2000] for which the inputs are a (classical) model and a temporal logic query (TLQ). A TLQ is a temporal logic formula with placeholders for some subformulas, for example, $AG?$. A query-checker finds the strongest set of assignments of propositional formulas for each placeholder, such that replacing each placeholder with any assignment chosen from its set results in a temporal logic formula that holds in the model. Thus, query-checking is a form of model exploration—it can be used to discover invariants, guards, and postconditions of (sets of) transitions in the model. The query-checking problem can be formulated as a multi-valued model-checking problem on *upset* lattices[3], where the elements of the lattices are sets of propositional formulas ordered by set inclusion. The reduction of the query-checking problem to multi-valued model-checking problem is described in Gurfinkel et al. [2003].

We now demonstrate the use of χChek for reasoning about state-space abstraction. Note that this is a *demonstration* rather than a case study aimed at showing the scalability of our approach or the quality of the engineering. Larger case studies as well as experiments aimed at studying the impact of the use of various decision diagrams and other engineering decisions are given in the companion article, Chechik et al. [2002b].

The use of abstraction has long been proposed as a way to overcome the state-space explosion problem in classical model-checking. Abstraction collapses sets of concrete states into a single abstract state, indicating that any differences between the concrete states within a single abstract state are ignored [Cousot and Cousot 1977; Dams et al. 1997; Dams 1996]. One way to ensure property preservation during abstraction is to guarantee that a set of states in the concrete model is composed into a single abstract state only if these states have an equivalent transition relation (one can refer to them as *symmetric*). This is a very strong condition, but sufficient for the purposes of our presentation. For

[3]Given the ordered set $(\mathcal{L}, \sqsubseteq)$ and a subset $B \subseteq \mathcal{L}$, then $\uparrow B$ is the set $\{\ell \in \mathcal{L} \mid \exists b \in B \cdot b \sqsubseteq \ell\}$. A subset B of $\mathcal{L}$ is an *upset* if $\uparrow B = B$.

(a)

```
MODULE Button (reset)
VAR
  pressed : boolean;
ASSIGN
  init (pressed)  := 0;
  next (pressed) :=
    case
      reset     : 0;
      pressed : 1;
      1           : {0, 1};
    esac
```

(b)

```
MODULE Button (reset)
VAR
  pressed : boolean;
  button   : boolean;
ASSIGN
  init (button)  := 0;
  next (button) := {0, 1};

  init (pressed)  := 0;
  next (pressed) :=
    case
      button : 1;
      reset   : 0;
      1          : pressed;
    esac
```

(c)

```
MODULE Button (reset)
VAR
  pressed : boolean;
  button   : {T, M, F};
ASSIGN
  button :=
    case
      reset | pressed : M
      1                       : {T, F}
    esac
  init (pressed)  := 0;
  next (pressed) :=
    case
      button = T : 1;
      reset         : 0;
      1               : pressed;
    esac
```

Fig. 7. Three models of the elevator button: (a) the original module Button of Plath & Ryan (in SMV); (b) a modified module Button; (c) an abstracted module Button.

example, states s_1 and s_2 can become part of the same abstract state if

$$\forall t \cdot (R(s_1, t) \Leftrightarrow R(s_2, t)) \wedge (R(t, s_1) \Leftrightarrow R(t, s_2)).$$

If s_1 and s_2 disagree on a value of a variable, we cannot assign either TRUE (T, $\top$) or FALSE (F, $\bot$) to this variable in the abstract state. Instead, we can model disagreement using the value MAYBE (M), resulting in a 3-valued logic. This abstraction guarantees *state-wise preservation* [Dams et al. 1997]: if a formula evaluates to $\top$ ($\bot$) in an abstract state, it evaluates to $\top$ ($\bot$) in all corresponding concrete states.

For the case study, we have used the SMV elevator model of Plath and Ryan [1999][4]. This model consists of a single elevator that accepts requests made by users pressing buttons at the floor landings or inside the elevator. The elevator moves up and down between floors and opens and closes its doors in response to these requests, according to the Single Button Collective Control (SBCC) strategy [Berney and dos Santos 1985].

The model is implemented by several SMV modules. The Main module declares several instances of the module Button (one per floor, called landingBut$_i$), parameterized by the condition under which the request is considered fulfilled (reset), and one instance of the module Lift, called lift. The Lift module declares the variables floor, door, and direction as well as further instances of Button to indicate requests from within the elevator (also one per floor, called liftBut$_i$).

The SMV module Button is shown in Figure 7(a). Once a button is pressed, it latches and remains pressed until the elevator fulfills the request. We modified this module by modeling the latching explicitly: each variable pressed in the module Button is decomposed into two variables, with button representing the actual button that users can press, and pressed representing the latching. The modified button is shown in Figure 7(b), and its state machine in Figure 8(a).

[4]SMV uses 0 and 1 to represent logic values $\bot$ and $\top$.

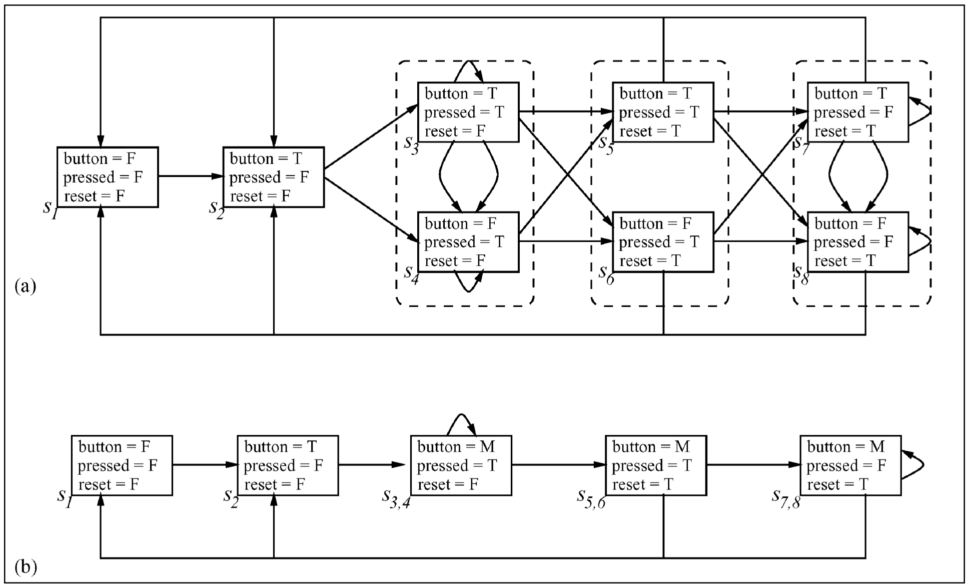

Fig. 8. State machines: (a) of the modified module `Button`; (b) of the abstracted module `Button`.

The model has eight possible states, corresponding to the evaluation of the tuple (`button`, `pressed`, `reset`). To simplify the presentation, in the state-machine description, we assume that a button cannot be reset until it has been latched, that is, `reset` cannot become $\top$ if `pressed` is $\bot$.

Each of the pairs of states, $\{s_3, s_4\}$, $\{s_5, s_6\}$, and $\{s_7, s_8\}$, (indicated by dashed lines in Figure 8(a)) has a symmetric transition relation and can be abstracted. This corresponds to the value of `button` being irrelevant when `pressed` or `reset` are $\top$. Thus, we can model `button` by a 3-valued variable as shown in Figure 7(c). The state machine model of the abstract system is shown in Figure 8(b). When this module is composed with the rest of the elevator model, we get a 3-valued model that cannot be directly verified using a classical model-checker. We proceed with the verification using two techniques: (a) the reduction to classical model-checking proposed by Bruns & Godefroid [2000], and (b) directly, using χChek.

The first technique involves two queries to a classical model-checker and is applicable to formulas where negation is applied only to atomic propositions. The first step is the computation of the *complement closure* [Bruns and Godefroid 2000] of the model by adding an extra variable $\bar{a}$ for each variable a, such that in each state of the model, $\bar{a}$ is equal to $\neg a$. The second step is the building of two versions of the model: the *pessimistic* version replaces each M value with $\bot$, while the *optimistic* version replaces each M with $\top$. The property to be checked must also be converted into the positive normal form by pushing all negations to the level of atomic propositions and replacing each negated variable, a with the corresponding variable, $\bar{a}$. The model-checker is called on the pessimistic and the optimistic models and the results are combined as follows: if the pessimistic model yields $\top$, return $\top$; else if the optimistic model

1. "If the door closes, it will eventually open":
   $AG(\texttt{lift.door} = \texttt{closed} \rightarrow AF\ \texttt{lift.door} = \texttt{open})$
2. "Pressing a landing button guarantees that the lift will arrive at that landing and open its doors":
   $AG(\texttt{landingBut2.button} \rightarrow AF(\texttt{lift.floor} = 2 \wedge \texttt{lift.door} = \texttt{open}))$
3. "If a button inside the lift is pressed, the lift will eventually arrive at the corresponding floor":
   $AG(\texttt{lift.liftBut2.button} \rightarrow AF(\texttt{lift.floor} = 2 \wedge \texttt{lift.door} = \texttt{open}))$
4. "The lift may stop at floor 2 for landing calls when traveling downwards":
   $\neg AG((\neg \texttt{lift.floor} = 2\ \wedge\ \neg \texttt{lift.liftBut2.button}\ \wedge\ \texttt{lift.direction} = \texttt{down})$
   $\rightarrow \texttt{lift.door} = \texttt{closed})$
5. "Whenever a button indicator is on, a button is being pressed"
   $AG(\texttt{lift.liftBut2.pressed} \rightarrow \texttt{lift.liftBut2.button})$

Fig. 9. Properties of the elevator system.

yields $\perp$, return $\perp$; otherwise, return M. Alternatively, the order of checks can be reversed: if the optimistic model yields $\perp$, return $\perp$; else if the pessimistic model yields $\top$, return $\top$; otherwise, return M. Both versions of this technique have the same worst-case complexity as χChek, that is, linear in the size of the model and the size of the formula. Yet, given a model of interest, it is not clear whether the Bruns and Godefroid [2000] technique or χChek performs better.

The properties of the elevator system that we verified are given in Figure 9. Properties 1-4 are taken directly from Plath and Ryan [1999] with the variable `pressed` replaced by `button` in all terms involving landing or elevator buttons because of our change to the module `Button`. Property 5 is our own addition. Similar properties can be formulated for all other floors and all other landing and elevator buttons. In a correct elevator system, we expect property 1 to evaluate to $\perp$, properties 2-4 to evaluate to $\top$, and property 5 to evaluate to $\perp$.

Given classical logic as input, χChek acts as a classical model-checker. Thus, we can compare the two approaches using the same model-checking engine, and, hence, factor out implementation issues in the experiments. We parameterized the model by the number of floors and ran our experiments using models with 3 and 4 floors. For both approaches, we ran χChek with mv-sets implemented using MDDs on a Pentium III with 850 MHz processor and 256 MB RAM, running Sun JDK 1.3 under Linux 2.2.19. Table I summarizes the results. Since it cannot be determined *a priori* which version of the Bruns and Godefroid [2000] technique yields the best performance, we give running times on pessimistic and optimistic models separately and then list their total (if the choice is made incorrectly and both checks need to be run) and the best time (if the choice is made correctly, and, where possible, only one check is needed). For example, verification of property 1 on the 4-floor elevator can be done in $4.638 + 4.594 = 9.232$ seconds using two queries to "classical" χChek if we started with the pessimistic model, and in 4.594 seconds if we started with the optimistic model. The same property can be verified in 2.29 seconds when χChek uses 3-valued logic directly. Note that property 5 evaluates to M in both models as opposed to the expected $\perp$. This was caused by the abstraction we made to the module `Button`: it is possible that `pressed` is $\top$ while `button` is M.

The size of the transition relation, as encoded into decision diagrams, does not change from property to property so in Table I, we show it only once for

Table I. Elevator Abstraction: Comparison between (up to) two runs of the classical model-checker and a run of χChek.

Model	CTL Property Number	Result	Bruns & Godefroid [2000] Pessimistic	Optimistic	Total	Best	χChek
3-floor	1.	$\bot$	0.756 s	0.774 s	1.53 s	0.774 s	0.306 s
	2.	$\top$	0.273 s	0.182 s	0.455 s	0.273 s	0.114 s
	3.	$\top$	0.249 s	0.173 s	0.422 s	0.249 s	0.119 s
	4.	$\top$	0.608 s	0.634 s	1.242 s	0.608 s	0.299 s
	5.	M	0.087 s	0.155 s	0.242 s	0.242 s	0.105 s
Size of trans. relation			2130	2153			954
4-floor	1.	$\bot$	4.638 s	4.594 s	9.232 s	4.594 s	2.29 s
	2.	$\top$	0.936 s	0.942 s	1.878 s	0.936 s	0.463 s
	3.	$\top$	0.869 s	1.044 s	1.913 s	0.869 s	0.494 s
	4.	$\top$	3.767 s	3.698 s	7.465 s	3.767 s	2.122 s
	5.	M	0.047 s	0.502 s	0.549 s	0.549 s	0.298 s
Size of trans. relation			5249	5307			2367

each elevator model. The process of constructing the complement closure in the Bruns and Godefroid [2000] approach roughly doubles the size of the models and slows down the analysis, as confirmed by the experiments. Replacing MDDs by other decision diagram implementations preserves the same relationship between the sizes of the encoding [Chechik et al. 2002a].

Also, note that in our comparisons we did not optimize either method. Potentially, by determining which atomic propositions are negated in the formulas to be verified and only including these in the complement closure, the size of the transition relation and the running time in the Bruns and Godefroid [2000] method can be improved. However, in the case of the elevator model, most of the atomic propositions can appear on the left-hand side of the implication, and thus need to be negated. Multi-valued model-checking can also be improved: currently we represent all variables as if they can range over all values of the logic, for example, `pressed` and `reset` are 3-valued, even though they do not need to be. Representing boolean variables explicitly can lead to faster verification times.

Finally, other experiments (see Chechik et al. [2002b]) seem to indicate that the above relationship between the performance of the two approaches holds in general but further investigation is necessary to confirm this hypothesis.

8. CONCLUSION

In this section, we summarize the article, compare the work presented here with that of other researchers, and outline directions for future work.

8.1 Summary

Multi-valued algebras can be useful in a variety of verification tasks. For example, they can help reason about partial systems, solve feature interaction problems, and support general model exploration.

In this article, we introduced an extension of classical CTL model-checking to reasoning with quasi-boolean algebras. We gave semantics to and categorized properties of a multi-valued extension of CTL, called χCTL. We also described a notion of multi-valued Kripke structures and showed how model-checking can be extended to dealing with systems containing fairness. Finally, we presented a multi-valued symbolic model-checker, χChek, and illustrated its behavior and performance.

8.2 Related Work

Multi-valued algebras, often called "logics", have been explored for a variety of applications in databases [Gaines 1979], knowledge representation [Ginsberg 1987], machine learning [Michalski 1977], and circuit design [Hazelhurst 1996]. A number of specific propositional multi-valued logics have been proposed and studied. For example, [Lukasiewicz 1970] first introduced a 3-valued logic to allow for propositions whose truth values are 'unknown', and Kleene [1952] studied several alternative 3-valued logics. Belnap [1977] proposed a 4-valued logic that introduced the value "both" (i.e. both TRUE *and* FALSE), to handle inconsistent assertions in database systems. Each of these logics can be generalized to allow for additional levels of uncertainty or disagreement. The class of quasi-boolean algebras defined in this article includes many existing multi-valued propositional logics, such as those of Kleene [1952] and Belnap [1977]. Work has also been done on deciding a more general class of logics. In particular, the work of Hähnle [1994] and others [Sofronie-Stokkermans 2001] has led to the development of several theorem-provers for first-order multi-valued logics.

Multi-valued extensions of modal logics have been explored by Fitting [1991a, 1992] who introduced a notion of multi-valued models and extended propositional modal logic (i.e. a fragment of CTL where the modal operators are limited to AX and EX) to reasoning over such models. In his work, values of propositions and transitions of the model come from a Heyting instead of a quasi-boolean algebra. Since boolean algebras (Definition 6) lie in the intersection of quasi-boolean and Heyting algebras, our work can be seen as (1) extending Fitting's multi-valued modal logic with additional modal operators, and (2) extending multi-valued modal models to quasi-boolean algebras.

A number of recent papers [Bruns and Godefroid 1999; Bruns and Godefroid 2000; Godefroid et al. 2001; Huth et al. 2001; Huth et al. 2003] addressed the problem of model-checking over the algebra **3** on a variety of 3-valued finite-state transition systems. Bruns and Godefroid [1999, 2000] investigated 3-valued model-checking on partial Kripke structures where propositions are 3-valued, but the transition relation is boolean. They extended branching-time temporal logic to this case, proposing a 3-valued modal logic for expressing properties of partial models. Model-checking of positive properties (properties that do not contain negation) in this logic reduces to two questions to a classical model-checker. This approach can also be applied to full μ-calculus by computing *complement closure* [Bruns and Godefroid 2000] of the model at the expense of increasing the size of the model and verification time. To make the analysis more precise, the authors describe a *thorough semantics* of 3-valued model-checking under which a property evaluates to MAYBE if and only if there are two refinements of the partial model that disagree on the value of this property.

Godefroid et al. [2001] provided an extension of the original 3-valued model-checking algorithm to Modal Transition Systems (MTS)—a generalization of Labeled Transition Systems of Larsen and Thomsen [1988], in which the transition relation is allowed to become 3-valued. Such systems have "must", "may" and "must not" type transitions. The authors define a 3-valued extension of the modal μ-calculus for MTS and describe an algorithm for model-checking in a fragment of this language using classical model-checking. The idea is further extended by Huth et al. [2001, 2003] to Kripke Modal Transition Systems which are equivalent to our χKripke structures when the algebra is **3**. All of these modeling formalisms have been shown to be equivalent [Godefroid and Jagadeesan 2003].

When 3-valued algebras are applied to reasoning about inconsistencies, all inconsistencies are represented using the value M. When model-checking returns $\top$ or $\perp$, this indicates that inconsistencies do not matter. However, when model-checking returns M, there is insufficient support for discovering sources of inconsistencies or for negotiation. If model-checking on a larger class of algebras is possible, such as with χChek, we can refine the algebra when model-checking returns M, for example, keeping track of exact sources of all disagreements, and allow the users to determine which inconsistencies matter and help focus potential negotiations.

Huth and Pradhan [2003] study multi-valued model-checking where the underlying algebra is defined on AC-lattices rather than De Morgan lattices. AC lattices are a pair of lattices with negation mapping between them. In particular, the authors study the problem of discovering sources of inconsistency between multiple viewpoints. Each of the C stakeholders, arranged in a partial order of dominance, submits a partial model, consisting of valid ("must") and consistent ("may") statements about states and transitions. The methodology assumes that each viewpoint has a possibly incomplete but consistent description over the same global vocabulary. The systems are on different levels of abstraction. Given a first-order property, the model-checking problem is to determine sets of stakeholders for which the property is valid or consistent, respectively. The model-checking problem is reduced to reasoning about C single-view partial models. Verification of each model is performed by switching between "valid" and "consistent" interpretations of satisfiability of properties. Our work is complementary to the above: Huth and Pradhan propose to handle inconsistencies between refinements of the same system, whereas multi-valued models encode inconsistencies between the different descriptions on the same level of abstraction.

Symbolic probabilistic model-checking has been implemented as part of the tool PROBVERUS [Baier et al. 1997]. The models used in this work are Kripke structures where edges are labeled with probabilities assigned to the corresponding transitions and state variables are classically-valued. Thus, the data structures used by PROBVERUS are *Multi-Terminal Binary Decision Diagrams* (MTBDDs) [Baier and Clarke 1998], which are equivalent to the *Algebraic*

Decision Diagrams (ADDs) of Bahar et al. [1993]. Each nonterminal node of MTBDDs has two children, and the number of terminal nodes depends on the range of the function being represented.

8.3 Future Work

We plan to extend the work presented in this article in a number of directions. First of all, success of multi-valued model-checking depends in part on our ability to engineer the model-checker to handle nontrivial problems. To this effect, we are currently working on optimizations of symbolic representations of mv-sets Chechik et al. [2002b] and empirically characterizing the tradeoffs between different symbolic representations.

Preliminary work on multi-valued LTL (χLTL) model-checking has been reported in [Chechik et al. 2001b]. We are now interested in extending χChek to handle χLTL properties symbolically. We are also interested in conducting a number of case studies that use the multi-valued model-checking approach described in this article.

APPENDIX

We give proofs of selected theorems here. Our proofs follow the *calculational style* [Hehner 1993; Back and von Wright 1998].

THEOREM 1. *A product of two quasi-boolean algebras is quasi-boolean, that is,*

$$\begin{array}{lrcl}
(1) & \neg\neg(a,b) & = & (a,b) \\
(2) & \neg((a_1,b_1)\sqcap(a_2,b_2)) & = & (\neg a_1,\neg b_1)\sqcup(\neg a_2,\neg b_2) \\
(3) & \neg((a_1,b_1)\sqcup(a_2,b_2)) & = & (\neg a_1,\neg b_1)\sqcap(\neg a_2,\neg b_2) \\
(4) & (a_1,b_1)\sqsubseteq(a_2,b_2) & \Leftrightarrow & \neg(a_1,b_1)\sqsupseteq\neg(a_2,b_2)
\end{array}$$

PROOF.

$$\begin{array}{lcr}
(1) & \neg\neg(a,b) & \neg\text{ of pairs} \\
\Leftrightarrow & \neg(\neg a,\neg b) & \neg\text{ of pairs} \\
\Leftrightarrow & (\neg\neg a,\neg\neg b) & \neg\text{ involution} \\
\Leftrightarrow & (a,b) &
\end{array}$$

$$\begin{array}{lcr}
(2) & \neg((a_1,b_1)\sqcap(a_2,b_2) & \sqcap\text{ of pairs} \\
\Leftrightarrow & \neg((a_1\sqcap a_2),(b_1\sqcap b_2)) & \neg\text{ of pairs} \\
\Leftrightarrow & (\neg(a_1\sqcap a_2),\neg(b_1\sqcap b_2)) & \text{De Morgan} \\
\Leftrightarrow & (\neg a_1\sqcup\neg a_2,\neg b_1\sqcup\neg b_2) & \sqcup\text{ of pairs} \\
\Leftrightarrow & (\neg a_1,\neg b_1)\sqcup(\neg a_2,\neg b_2) &
\end{array}$$

$$\begin{array}{lcr}
(4) & (a_1,b_1)\sqsubseteq(a_2,b_2) & \sqsubseteq\text{ of pairs} \\
\Leftrightarrow & a_1\sqsubseteq a_2\ \wedge\ b_1\sqsubseteq b_2 & \neg\text{ antimonotonic} \\
\Leftrightarrow & \neg a_1\sqsupseteq\neg a_2\ \wedge\ \neg b_1\sqsupseteq\neg b_2 & \sqsupseteq\text{ of pairs} \\
\Leftrightarrow & (\neg a_1,\neg b_1)\sqsupseteq(\neg a_2,\neg b_2) & \neg\text{ of pairs} \\
\Leftrightarrow & \neg(a_1,b_1)\sqsupseteq\neg(a_2,b_2) &
\end{array}$$

The proof of (3) is similar to that of (2). □

THEOREM 2. *For a* **2***-valued set* $\mathbb{S}$ *on S, the following holds:*

(1) *The membership function* $\mathbb{S}(x)$ *is a boolean predicate*
(2) $(\mathbb{S} \cap_{\mathbf{2}} \mathbb{S}') = \{x \mid \mathbb{S}(x) \wedge \mathbb{S}'(x)\} = (\mathbb{S} \cap \mathbb{S}')$
(3) $(\mathbb{S} \cup_{\mathbf{2}} \mathbb{S}') = \{x \mid \mathbb{S}(x) \vee \mathbb{S}'(x)\} = (\mathbb{S} \cup \mathbb{S}')$
(4) $\overline{\mathbb{S}}(x) = x \in (S - \{y \mid \mathbb{S}(y) = \top\})$

PROOF. The proof follows from the the fact that the set membership function $\mathbb{S}(x)$ is boolean. Then, each *mv-set*is boolean and thus union, intersection and complement reduce to classical. □

THEOREM 3. *The forward and backward image of a* **2***-valued set,* $\mathbb{Q}$*, under a* **2***-valued relation,* $\mathbb{R}$*, are as follows:*

$$\begin{aligned}
(1)\ \overrightarrow{\mathbb{R}}(\mathbb{Q}) &= \lambda t \in T \cdot \bigvee\nolimits_{\{s \in S \mid \mathbb{R}(s,t)\}} \mathbb{S}(s) \\
(2)\ \overleftarrow{\mathbb{R}}(\mathbb{Q}) &= \lambda s \in S \cdot \bigvee\nolimits_{\{t \in T \mid \mathbb{R}(s,t)\}} \mathbb{T}(t)
\end{aligned}$$

PROOF.

$$\begin{array}{ll}
\quad \overrightarrow{\mathbb{R}}(\mathbb{Q}) & \text{def. of } \overrightarrow{\mathbb{R}} \\
= \lambda t \cdot \bigsqcup_{s \in S} (\mathbb{Q}(s) \sqcap \mathbb{R}(s,t)) & \mathbb{R} \text{ is a boolean relation} \\
= \lambda t \cdot \bigsqcup_{\{s \in S \mid \mathbb{R}(s,t)\}} \mathbb{Q}(s) & \text{Theorem 2} \\
= \lambda t \cdot \bigvee_{\{s \in S \mid \mathbb{R}(s,t)\}} \mathbb{Q}(s) &
\end{array}$$

The proof of (2) is similar. □

THEOREM 4. *χCTL reduces to CTL when the algebra is* **2***. That is,*

$$\begin{array}{lrcl}
(1) & [\![EX\varphi]\!] & = & [\![EX^B\varphi]\!] \\
(2) & [\![EG\varphi]\!] & = & [\![EG^B\varphi]\!] \\
(3) & [\![E[\varphi\ U\ \psi]]\!] & = & [\![E[\varphi\ U^B\ \psi]]\!]
\end{array}$$

where EG^B*,* EU^B*, and* EX^B *are classical CTL operators defined in Section 2.*

PROOF. (1) holds by Theorem 3. The proof for (2) is based on the fact that $[\![EG\varphi]\!]$ can be represented by $\nu\mathbb{Z} \cdot F(\mathbb{Z})$, where $F(\mathbb{Z}) = [\![\varphi]\!] \cap_L [\![EX\mathbb{Z}]\!]$. Since $F(\mathbb{Z})$ reduces to its boolean version syntactically, $[\![EG\varphi]\!]$ reduces to $[\![EG^B\varphi]\!]$. The proof for (3) is similar to that of (2). □

THEOREM 5. *χCTL operators AX and EX are monotone.*

PROOF. We begin by reciting some properties of monotone functions and fixpoints. Assume that F and G are monotone functions. Then, $F(\mathbb{Z}) \cup G(\mathbb{Z})$, $F(\mathbb{Z}) \cap G(\mathbb{Z})$, and $\overline{F(\overline{\mathbb{Z}})}$ are monotone.

We want to show that EX is monotone:

$$\begin{array}{ll}
\quad \mathbb{Z} \subseteq_L \mathbb{Y} & \text{def. of } \subseteq_L \\
\Rightarrow \forall t \in S \cdot \mathbb{Z}(t) \sqsubseteq \mathbb{Y}(t) & \sqcap \text{ is monotone} \\
\Rightarrow \forall s \in S \cdot \forall t \in S \cdot \mathbb{R}(s,t) \sqcap \mathbb{Z}(t) \sqsubseteq \mathbb{R}(s,t) \sqcap \mathbb{Y}(t) & \bigsqcup \text{ is monotone} \\
\Rightarrow \forall s \in S \cdot \bigsqcup_{t \in S} \mathbb{R}(s,t) \sqcap \mathbb{Z}(t) \sqsubseteq \bigsqcup_{t \in S} \mathbb{R}(s,t) \sqcap \mathbb{Y}(t) & \text{def. of } EX \\
\Rightarrow \forall s \in S \cdot [\![EX\mathbb{Z}]\!](s) \sqsubseteq [\![EX\mathbb{Y}]\!](s) & \text{def. of } \subseteq_L \\
\Rightarrow [\![EX\mathbb{Z}]\!] \subseteq_L [\![EX\mathbb{Y}]\!] &
\end{array}$$

AX is monotone because $[\![AX]\!] = \overline{[\![EX\neg\mathbb{Z}]\!]}$ and EX is monotone. □

THEOREM 6. *The definition of χCTL ensures that for each φ, $\llbracket\varphi\rrbracket$ forms a partition.*

PROOF. To prove this theorem, it suffices to prove that the computation of $EX\varphi$ forms a partition. All other operators are computed using fixpoints and applications of $\cup_L$, $\cap_L$, and $\neg$ operators which, given *mv-set*s where the characteristic function is total, produce *mv-set*s with a total characteristic function, thereby forming a partition. We now turn to showing that the computation of $EX\varphi$ forms a partition.

$$\begin{array}{ll}
 & \forall s \in S\ \exists!\ell \cdot \llbracket EX\varphi\rrbracket(s) = \ell \\
= & \text{by def. of } EX \\
 & \forall s \in S\ \exists!\ell \cdot \bigsqcup_{t\in S}(\llbracket\varphi\rrbracket(t) \sqcap \mathbb{R}(s,t)) = \ell \\
\Leftarrow & \text{since } \llbracket\varphi\rrbracket \text{ is a partition, } \mathbb{R}(s,t) \text{ is an mv-relation s.t.} \forall (s,t)\ \exists!\ell' \in \mathcal{L} \cdot \mathbb{R}(s,t) = \\
 & \ell'\text{, and by Definition 2} \\
 & \forall s \in S\ \exists!\ell\ \exists!\ell_t \cdot \bigsqcup_{t\in S} \ell_t = \ell \\
\Leftarrow & \text{because } \bigsqcup \text{ preserves partition property} \\
 & \top
\end{array}$$

□

THEOREM 7. *Multi-valued model-checking is decidable.*

PROOF. From Theorem 5 and monotonicity of $\cap_L$ and $\cup_L$, we conclude that all χCTL operators involve computation of fixpoints over monotone functions, thus resulting in natural algorithms. The termination of these algorithms is guaranteed by the usual application of the Knaster-Tarski theorem. □

THEOREM 8. *Fixpoint properties of (derived) χCTL operators are the same as for CTL operators. That is,*

$$\begin{array}{lrcll}
(1) & \llbracket AG\varphi\rrbracket & = & \nu\mathbb{Z} \cdot \llbracket\varphi\rrbracket \cap_L \llbracket AX\mathbb{Z}\rrbracket & AG \text{ fixpoint} \\
(2) & \llbracket AF\varphi\rrbracket & = & \mu\mathbb{Z} \cdot \llbracket\varphi\rrbracket \cup_L \llbracket AX\mathbb{Z}\rrbracket & AF \text{ fixpoint} \\
(3) & \llbracket EF\varphi\rrbracket & = & \mu\mathbb{Z} \cdot \llbracket\varphi\rrbracket \cup_L \llbracket EX\mathbb{Z}\rrbracket & EF \text{ fixpoint} \\
(4) & \llbracket A[\varphi\ U\ \psi]\rrbracket & = & \mu\mathbb{Z} \cdot \llbracket\psi\rrbracket \cup_L (\llbracket\varphi\rrbracket \cap_L \llbracket AX\mathbb{Z}\rrbracket) & AU \text{ fixpoint}
\end{array}$$

PROOF. We structure the proof by showing that definitions for the temporal operators AG, AF, EF and AU are the same as their fixpoints. First we recall the property relating least and greatest fixpoints [Kozen 1983]

$$\mu\mathbb{Z} \cdot F(\mathbb{Z}) = \overline{\nu\mathbb{Z} \cdot \overline{F(\overline{\mathbb{Z}})}} \quad \text{negation fixpoint}$$

$$\begin{array}{lll}
(1) & \llbracket AG\varphi\rrbracket & \text{def. of } AG \\
= & \overline{\llbracket EF\neg\varphi\rrbracket} & EF \text{ fixpoint} \\
= & \overline{\mu\mathbb{Z} \cdot \llbracket\neg\varphi\rrbracket \cup_L \llbracket EX\mathbb{Z}\rrbracket} & \text{negation fixpoint} \\
= & \nu\mathbb{Z} \cdot \overline{\llbracket\neg\varphi\rrbracket \cup_L \llbracket EX\neg\mathbb{Z}\rrbracket} & \text{De Morgan} \\
= & \nu\mathbb{Z} \cdot \llbracket\varphi\rrbracket \cap_L \overline{\llbracket EX\neg\mathbb{Z}\rrbracket} & \text{def. of } AX \\
= & \nu\mathbb{Z} \cdot \llbracket\varphi\rrbracket \cap_L \llbracket AX\mathbb{Z}\rrbracket &
\end{array}$$

$$\begin{array}{lll}
(2) & [\![AF\varphi]\!] & \text{def. of } AF \\
= & [\![A[\top\ U\ \varphi]]\!] & AU \text{ fixpoint} \\
= & \mu\mathbb{Z}\cdot[\![\varphi]\!]\cup_L([\![\top]\!]\cap_L[\![AX\mathbb{Z}]\!]) & \text{identity of } \top \\
= & \mu\mathbb{Z}\cdot[\![\varphi]\!]\cup_L[\![AX\mathbb{Z}]\!] &
\end{array}$$

$$\begin{array}{lll}
(3) & [\![EF\varphi]\!] & \text{def. of } EF \\
= & [\![E[\top\ U\ \varphi]]\!] & EU \text{ fixpoint} \\
= & \mu\mathbb{Z}\cdot[\![\varphi]\!]\cup_L([\![\top]\!]\cap_L[\![EX\mathbb{Z}]\!]) & \text{identity of } \top \\
= & \mu\mathbb{Z}\cdot[\![\varphi]\!]\cup_L[\![EX\mathbb{Z}]\!] &
\end{array}$$

We now show (4). We start by reformulating the definition of AU:

$$\begin{array}{ll}
& [\![A[\varphi\ U\ \psi]]\!] \\
= & \text{by def. of } AU \\
& \overline{[\![E[\neg\psi\ U\ \neg\varphi\wedge\neg\psi]]\!]}\cap_L\overline{[\![EG\neg\psi]\!]} \\
= & \text{expanding } EU \text{ and } EG \text{ using their definitions} \\
& \overline{\mu\mathbb{Z}\cdot[\![\neg\varphi\ \wedge\ \neg\psi]\!]\cup_L([\![\neg\psi]\!]\cap_L[\![EX\mathbb{Z}]\!])}\cap_L\overline{\nu\mathbb{Z}\cdot[\![\neg\psi]\!]\cap_L[\![EX\mathbb{Z}]\!]} \\
= & \text{using negation fixpoint, def. of } AX \\
& \\
& (\nu\mathbb{Z}\cdot[\![\varphi\vee\psi]\!]\cap_L([\![\psi]\!]\cup_L[\![AX\mathbb{Z}]\!]))\cap_L(\mu\mathbb{Z}\cdot[\![\psi]\!]\cup_L[\![AX\mathbb{Z}]\!]) \\
= & \text{by distributivity and absorption} \\
& (\nu\mathbb{Z}\cdot[\![\psi]\!]\cup_L(([\![\varphi]\!]\cup_L[\![\psi]\!])\cap_L[\![AX\mathbb{Z}]\!]))\cap_L(\mu\mathbb{Z}\cdot[\![\psi]\!]\cup_L[\![AX\mathbb{Z}]\!]) \\
= & \text{by distributivity and absorption} \\
& (\nu\mathbb{Z}\cdot[\![\psi]\!]\cup_L([\![\varphi]\!]\cap_L[\![AX\mathbb{Z}]\!]))\cap_L(\mu\mathbb{Z}\cdot[\![\psi]\!]\cup_L[\![AX\mathbb{Z}]\!])
\end{array}$$

Now, let $F(\mathbb{Z})=[\![\psi]\!]\cup_L([\![\varphi]\!]\cap_L[\![AX\mathbb{Z}]\!])$ and $G(\mathbb{Z})=[\![\psi]\!]\cup_L[\![AX\mathbb{Z}]\!]$. Then $\overline{[\![E[\neg\psi\ U\ \neg\varphi\wedge\neg\psi]]\!]}=\mathbb{K}=\nu\mathbb{Z}\cdot F(\mathbb{Z})$, $\overline{[\![EG\neg\psi]\!]}=\mathbb{Y}=\mu\mathbb{Z}\cdot G(\mathbb{Z})$, and $[\![A[\varphi\ U\ \psi]]\!]=\mathbb{W}=\mu\mathbb{Z}\cdot F(\mathbb{Z})$. We need to show that $\mathbb{W}=\mathbb{K}\cap_L\mathbb{Y}$.

Recall that if a function F is monotone and continuous, then there exists $n\in nat$ s.t. $\mu\mathbb{Z}\cdot F(\mathbb{Z})=F^n([\![\bot]\!])$[5] and $\nu\mathbb{Z}\cdot F(\mathbb{Z})=F^n([\![\top]\!])$. We also name ith iterations of F and G: $\mathbb{K}_i=F^i([\![\top]\!])$, $\mathbb{W}_i=F^i([\![\bot]\!])$ and $\mathbb{Y}_i=G^i([\![\bot]\!])$.

We first show that $\forall i\in nat\cdot\mathbb{K}_i\cap_L\mathbb{Y}_i=\mathbb{W}_i$. The proof is by induction.

$$\begin{array}{rl}
\text{Base Case:} & \mathbb{K}_0\cap_L\mathbb{Y}_0 \\
= & \text{by def. of } \mathbb{K}_0,\ \mathbb{Y}_0 \\
& [\![\top]\!]\cap_L[\![\bot]\!] \\
= & \text{expanding mv-sets} \\
& [\![\bot]\!] \\
= & \text{by def. of } \mathbb{W}_0 \\
& \mathbb{W}_0 \\
\text{IH:} & \text{Assume } \mathbb{K}_i\cap_L\mathbb{Y}_i=\mathbb{W}_i \text{ for } i=k \\
\text{Inductive Case:} & \text{Proof for } i=k+1 \\
& \mathbb{K}_{k+1}\cap_L\mathbb{Y}_{k+1} \\
= & \text{expanding each function once} \\
& ([\![\psi]\!]\cup_L([\![\varphi]\!]\cap_L[\![AX\,\mathbb{K}_k]\!]))\cap_L([\![\psi]\!]\cup_L[\![AX\,\mathbb{Y}_k]\!])
\end{array}$$

[5] F^n stands for applying F n times.

$$
\begin{aligned}
&= \text{by distributivity and absorption}\\
&\quad [\![\psi]\!] \cup_L ([\![\psi]\!] \cap_L [\![AX\,\mathbb{K}_k]\!] \cap_L [\![AX\,\mathbb{Y}_k]\!])\\
&= \text{by } AX \text{ of conjunction}\\
&\quad [\![\psi]\!] \cup_L ([\![\psi]\!] \cap_L [\![AX(\mathbb{K}_k \cap_L \mathbb{Y}_k)]\!])\\
&= \text{by inductive hypothesis}\\
&\quad [\![\psi]\!] \cup_L ([\![\psi]\!] \cap_L [\![AX(\mathbb{W}_k)]\!])\\
&= \text{by def. of } \mathbb{W}_{k+1}\\
&\quad \mathbb{W}_{k+1}
\end{aligned}
$$

Therefore, $\forall i \in nat \cdot \mathbb{W}_i = \mathbb{K}_i \cap_L \mathbb{Y}_i$ which implies that $\mathbb{W} = \mathbb{K} \cap_L \mathbb{Y}$ and thus the definition and the fixpoint formulation of AU are identical. □

THEOREM 9. *The following statements are equivalent for a path, π, and fairness conditions, $C = \{c_1, \ldots, c_k\}$:*

(1) *Each fairness condition, c_i, occurs infinitely often in π;*
(2) *A sequence $c_1, c_2, \ldots, c_k$ occurs infinitely often in π.*

PROOF. (1) ⇒ (2): Starting at the beginning of π, find the first occurrence of c_1 (this can always be done because c_1 occurs infinitely often in π). After that point, find the first occurrence of c_2, etc. This process can be repeated forever, and thus a sequence $c_1, c_2, \ldots, c_k$ occurs infinitely often in π.
(2) ⇒ (1): if a sequence $c_1, c_2, \ldots, c_k$ occurs infinitely often in π, then each element of it occurs infinitely often in π, so π is fair. □

THEOREM 10. *When $C = \{\top\}$ (no fairness), $E_C G'$ becomes*

$$[\![E_C G'\varphi]\!] = \nu\mathbb{Z} \cdot [\![\varphi]\!] \cap_L [\![EX\,E[\varphi\ U\ \varphi \wedge \mathbb{Z}]]\!] = \nu\mathbb{Z} \cdot [\![\varphi]\!] \cap_L [\![EX\mathbb{Z}]\!] = [\![EG\varphi]\!]$$

PROOF. Let $F(\mathbb{Z}) = [\![\varphi]\!] \cap_L [\![EX\,E[\varphi\ U\ \varphi \wedge \mathbb{Z}]]\!]$ and $G(\mathbb{Z}) = [\![\varphi]\!] \cap_L [\![EX\mathbb{Z}]\!]$. By definition, $[\![E_C G'\varphi]\!] = \mathbb{W} = \nu\mathbb{Z} \cdot F(\mathbb{Z})$ and $[\![EG\varphi]\!] = \mathbb{Y} = \nu\mathbb{Z} \cdot G(\mathbb{Z})$. We start by proving an intermediate result indicating that $[\![E[\varphi\ U\ \varphi \wedge \mathbb{W}]]\!]$ is the same as $\mathbb{W}$:

$$
\begin{array}{llr}
& [\![E[\varphi\ U\ \varphi \wedge \mathbb{W}]]\!] & EU \text{ fixpoint}\\
= & ([\![\varphi]\!] \cap_L \mathbb{W}) \cup_L ([\![\varphi]\!] \cap_L [\![EX\,E[\varphi\ U\ \varphi \wedge \mathbb{W}]]\!]) & \text{absorption, def. of } F\\
= & \mathbb{W} \cup_L F(\mathbb{W}) & \mathbb{W} \text{ is a fixpoint of } F\\
= & \mathbb{W} &
\end{array}
$$

To show that $[\![E_C G\varphi]\!] = [\![EG\varphi]\!]$, we need to show that $\mathbb{Y} = \mathbb{W}$. The proof consists of two parts: (1) showing that $\mathbb{W}$ is a fixpoint of G and thus $\mathbb{W} \subseteq_L \mathbb{Y}$ (because $\mathbb{Y}$ is the greatest fixpoint of G); and (2) showing that $\mathbb{W} \supseteq_L \mathbb{Y}$.

$$
\begin{array}{llr}
(1) & G(\mathbb{W}) & \text{def. of } G\\
= & [\![\varphi]\!] \cap_L [\![EX\mathbb{W}]\!] & \mathbb{W} = [\![E[\varphi\ U\ \varphi \wedge \mathbb{W}]]\!]\\
= & [\![\varphi]\!] \cap_L [\![EX\,E[\varphi\ U\ \varphi \wedge \mathbb{W}]]\!] & \text{def. of } F\\
= & F(\mathbb{W}) & \mathbb{W} \text{ is the fixpoint of } F\\
= & \mathbb{W} &
\end{array}
$$

To prove (2), we start by defining $\mathbb{W}_i = F^i([\![\top]\!])$ and $\mathbb{Y}_i = G^i([\![\top]\!])$. Since F and G are monotone and continuous, there exists $n \in nat$ s.t. $\mathbb{W} = \mathbb{W}_n \wedge \mathbb{Y} = \mathbb{Y}_n$. We now show that $\forall i \in nat \cdot \mathbb{W}_i \supseteq_L \mathbb{Y}_i$.

Base Case: $\mathbb{W}_0 = [\![\top]\!] = \mathbb{Y}_0$
IH: Assume $\mathbb{W}_i \supseteq_L \mathbb{Y}_i$ for $i = k$
Ind. Case: Proof for $i = k + 1$
Note that $\mathbb{W}_{k+1} = [\![\varphi]\!] \cap_L [\![EX\, E[\varphi\ U\ \varphi \wedge \mathbb{W}_k]]\!] = G([\![E[\varphi\ U\ \varphi \wedge \mathbb{W}_k]]\!])$and $\mathbb{Y}_{k+1} = [\![\varphi]\!] \cap_L [\![EX\mathbb{Y}_k]\!] = G(\mathbb{Y}_k)$

$$
\begin{array}{lll}
 & G([\![E[\varphi\ U\ \varphi \wedge \mathbb{W}_k]]\!]) \supseteq_L G(\mathbb{Y}_k) & G \text{ is monotone} \\
\Leftarrow & [\![E[\varphi\ U\ \varphi \wedge \mathbb{W}_k]]\!] \supseteq_L \mathbb{Y}_k & EU \text{ fixpoint} \\
\Leftarrow & (\mathbb{W}_k \cup_L ([\![\varphi]\!] \cap_L [\![EX\, E[\varphi\ U\ \varphi \wedge \mathbb{W}_k]]\!])) \supseteq_L \mathbb{Y}_k & \text{monotonicity of } \cup_L\text{, absorption} \\
\Leftarrow & \mathbb{W}_k \supseteq_L \mathbb{Y}_k & \text{inductive hypothesis} \\
\Leftarrow & \top &
\end{array}
$$

Thus, by induction, $\forall n \in nat \cdot \mathbb{W}_n \supseteq_L \mathbb{Y}_n$, so $\mathbb{W} \supseteq_L \mathbb{Y}$. Combining this with results of part (1), we get that $\mathbb{W} = \mathbb{Y}$, so, by definition, $[\![E_C G'\varphi]\!] = [\![EG\varphi]\!]$. □

Now we set out to show that $E_C G$ and $E_C G'$ are equivalent. We assume that $C = \{c_1, c_2\}$ for brevity. The reasoning can be expanded for an arbitrary $C = \{c_1, \ldots, c_k\}$. Let $F(\mathbb{Z}) = [\![\varphi]\!] \cap_L [\![EX\, E\big[\varphi\ U\ \varphi \wedge c_1 \wedge EX\, E[\varphi\ U\ \varphi \wedge c_2 \wedge \mathbb{Z}]\big]]\!]$. Then, by definition, $E_C G\varphi = \nu\mathbb{Z} \cdot F(\mathbb{Z})$. Also, let $G(\mathbb{Z}) = [\![\varphi]\!] \cap_L \bigcap_{L k=\{1,2\}} [\![EX\, E[\varphi\ U\ \varphi \wedge c_k \cap_L \mathbb{Z}]]\!]$. Then, by definition, $E_C G'\varphi = \nu\mathbb{Z} \cdot G(\mathbb{Z})$.

We are interested in representing paths on which the sequence c_1, c_2 (respectively, c_2, c_1) holds i times. We do so by encoding the states from which these paths emanate, using *mv-set*s $\mathbb{K}_i$ and $\mathbb{M}_i$, respectively. These are defined recursively as follows:

$$
\begin{array}{ll}
\mathbb{K}_0 = [\![\top]\!] & \mathbb{M}_0 = [\![\top]\!] \\
\multicolumn{2}{l}{\mathbb{K}_n = [\![\varphi]\!] \cap_L [\![EX\, E[\varphi\ U\ \varphi \wedge c_1 \wedge \mathbb{M}_{n-1}]]\!]} \\
\multicolumn{2}{l}{\mathbb{M}_n = [\![\varphi]\!] \cap_L [\![EX\, E[\varphi\ U\ \varphi \wedge c_2 \wedge \mathbb{K}_{n-1}]]\!]}
\end{array}
$$

We also define the nth iteration of $\nu\mathbb{Z} \cdot G(\mathbb{Z})$ explicitly:

$$
\begin{array}{rcl}
G^0([\![\top]\!]) & = & [\![\top]\!] \\
G^{n+1}([\![\top]\!]) & = & G_1(G^n([\![\top]\!])) \cap_L G_2(G^n([\![\top]\!]))
\end{array}
$$

Note that $\mathbb{K}_{2n} = F^n([\![\top]\!])$. We are therefore interested in the degree to which $\mathbb{K}_n$ and $\mathbb{M}_n$ approximate $G^n([\![\top]\!])$. We characterize this formally in the following lemma:

Lemma 1. $\forall n \in nat$,

$$
\begin{array}{ll}
(1)\ \mathbb{K}_n \supseteq_L G^n([\![\top]\!]) & (2)\ \mathbb{M}_n \supseteq_L G^n([\![\top]\!]) \\
(3)\ \mathbb{K}_{2n} \subseteq_L G^n([\![\top]\!]) & (4)\ \mathbb{M}_{2n} \subseteq_L G^n([\![\top]\!])
\end{array}
$$

Proof. In the proof we use the following results, proofs of which are omitted for brevity:

$\mathbb{K}_n \supseteq_L \mathbb{K}_{n+1}$ and $\mathbb{M}_n \supseteq_L \mathbb{M}_{n+1}$ — monotonicity of $\mathbb{K}_n$, $\mathbb{M}_n$
$[\![\varphi]\!] \cap_L [\![EX\, E[\varphi\ U\ c_2 \wedge \varphi \wedge \mathbb{K}_n]]\!] \subseteq_L \mathbb{M}_n$ — relation between $\mathbb{K}_n$ and $\mathbb{M}_n$
The above holds because $\mathbb{M}_n = [\![\varphi]\!] \cap_L [\![EX\, E[\varphi\ U\ \varphi \wedge c_2 \wedge \mathbb{K}_{n-1}]]\!]$
$[\![E[\varphi\ U\ \psi]]\!] \supseteq_L [\![E[\varphi\ U\ \varphi \wedge EX\, E[\varphi\ U\ \psi]]]\!]$ — monotonicity 1 of EU
The above holds because of EU expansion
$[\![\varphi]\!] \supseteq_L [\![\psi]\!] \Rightarrow [\![E[p\ U\ \varphi]]\!] \supseteq_L [\![E[p\ U\ \psi]]\!]$ — monotonicity 2 of EU

We are now ready to prove (1)-(4), which we do by induction on n.

Base Case: $G^0([\![\top]\!]) = \top$ def. of $G^0([\![\top]\!])$
IH: Assume (1)-(4) hold for $n = k$
Ind. Case: Proof for $n = k + 1$

(1) Enough to show $\mathbb{K}_{n+1} \supseteq_L G_1(G^n([\![\top]\!]))$

	$\top$	IH
$\Rightarrow$	$\mathbb{M}_n \supseteq_L G^n([\![\top]\!])$	monotonicity 2 of EU
$\Rightarrow$	$[\![\varphi]\!] \cap_L [\![EX\, E[\varphi\ U\ \varphi \wedge c_1 \wedge \mathbb{M}_n]]\!]$	
	$\supseteq_L [\![\varphi]\!] \cap_L [\![EX\, E[\varphi\ U\ \varphi \wedge c_1 \wedge G^n([\![\top]\!])]]\!]$	def. of $\mathbb{K}_{n+1}$, G_1, G^{n+1}
$\Rightarrow$	$\mathbb{K}_{n+1} \supseteq_L G_1(G^n([\![\top]\!])) \supseteq_L G^{n+1}([\![\top]\!])$	

(2) Proof is similar to that of (1).

(3) Need to show $\mathbb{K}_{2n+2} \subseteq_L G^{n+1}([\![\top]\!])$
We show (3a) $\mathbb{K}_{2n+2} \subseteq_L G_1(G^n([\![\top]\!]))$
(3b) $\mathbb{K}_{2n+2} \subseteq_L G_2(G^n([\![\top]\!]))$
Then by $\cap_L$ elimination, we have the desired property.

(3a)	$\mathbb{K}_{2n+2}$	def. of $\mathbb{K}_{2n+2}$
$=$	$[\![\varphi]\!] \cap_L [\![EX\, E[\varphi\ U\ \varphi \wedge c_1 \wedge EX\, E$ $[\varphi\ U\ \varphi \wedge c_2 \wedge \mathbb{K}_{2n}]]]\!]$	relation between $\mathbb{K}_n$ and $\mathbb{M}_n$
$\subseteq_L$	$[\![\varphi]\!] \cap_L [\![EX\, E[\varphi\ U\ \varphi \wedge c_1 \wedge \mathbb{M}_{2n}]]\!]$	IH and monotonicity
$\subseteq_L$	$[\![\varphi]\!] \cap_L [\![EX\, E[\varphi\ U\ \varphi \wedge c_1 \wedge G^n([\![\top]\!])]]\!]$	def. of G_1
$=$	$G_1(G^n([\![\top]\!]))$	

(3b)	$\mathbb{K}_{2n+2}$	def. of $\mathbb{K}_{2n+2}$
$=$	$[\![\varphi]\!] \cap_L [\![EX\, E[\varphi\ U\ \varphi \wedge c_1 \wedge EX\, E$ $[\varphi\ U\ \varphi \wedge c_2 \wedge \mathbb{K}_{2n}]]]\!]$	monotonicity
$\subseteq_L$	$[\![\varphi]\!] \cap_L [\![EX\, E[\varphi\ U\ \varphi \wedge EX\, E$ $[\varphi\ U\ \varphi \wedge c_2 \wedge \mathbb{K}_{2n}]]]\!]$	monotonicity 1 of EU
$\subseteq_L$	$[\![\varphi]\!] \cap_L [\![EX\, E[\varphi\ U\ \varphi \wedge c_2 \wedge \mathbb{K}_{2n}]]\!]$	IH and monotonicity
$\subseteq_L$	$[\![\varphi]\!] \cap_L [\![EX\, E[\varphi\ U\ \varphi \wedge c_2 \wedge G^n([\![\top]\!])]]\!]$	def. of G_2
$=$	$G_2(G^n([\![\top]\!]))$	

(4) Proof is similar to that of (3). □

THEOREM 11. *Operators $E_C G$ and $E_C G'$ are equivalent.*

PROOF. Recall that $\mathbb{K}_{2n} = F^n([\![\top]\!])$. Since F^n converges, $\exists N_1 \in nat \cdot \forall n \geq N_1 \cdot \nu\mathbb{Z} \cdot F(\mathbb{Z}) = \mathbb{K}_{2n}$. Since G^n converges, $\exists N_2 \in nat \cdot \forall n \geq N_2 \cdot \nu\mathbb{Z} \cdot G(\mathbb{Z}) = G^n([\![\top]\!])$. Further, by Lemma 1, $\forall n \geq N_2$

$$\begin{aligned} \mathbb{K}_{2n} &\subseteq_L G^n([\![\top]\!]) = \nu\mathbb{Z} \cdot G(\mathbb{Z}) \\ \mathbb{K}_{2n} &\supseteq_L G^{2n}([\![\top]\!]) = \nu\mathbb{Z} \cdot G(\mathbb{Z}) \end{aligned}$$

So, $\forall n \geq N_2 \cdot \mathbb{K}_{2n} = \nu\mathbb{Z} \cdot G(\mathbb{Z})$.

Let $m = \max\{N_1, N_2\}$. Then, $\nu\mathbb{Z} \cdot F(\mathbb{Z}) = \mathbb{K}_{2m} = \nu\mathbb{Z} \cdot G(\mathbb{Z})$. So, operators $E_C G$ and $E_C G'$ are equivalent. □

ACKNOWLEDGMENTS

We would like to thank Wendy MacCaull, Albert Lai, Christopher Thompson-Walsh, and Victor Petrovykh for many interesting discussions and for their help in implementing the model-checker. We are also indebted to Albert Lai for his help with several aspects of lattice theory presented in this article. Finally, we are grateful to the members of the University of Toronto's Formal Methods Reading Group and the anonymous referees for helping us refine the ideas presented in this article and improve the clarity of the presentation.

REFERENCES

ANDERSON, A. AND BELNAP, N. 1975. *Entailment. Vol. 1*. Princeton University Press.

BACK, R.-J. AND VON WRIGHT, J. 1998. *Refinement Calculus: A Systematic Approach*. Springer-Verlag.

BAHAR, R., FROHM, E., GAONA, C., HACHTEL, G., MACII, E., PARDO, A., AND SOMENZI, F. 1993. Algebraic decision diagrams and their applications. In *IEEE /ACM International Conference on Computer-Aided Disign (ICCAD'93)* (Santa Clara, CA). IEEE Computer Society Press, pp. 188–191.

BAIER, C. AND CLARKE, E. M. 1998. The algebraic Mu-calculus and MTBDDs. In *Proceedings of the 5th Workshop on Logic, Language, Information and Computation, (WoLLIC'98)*, pp. 27–38.

BAIER, C., CLARKE, E. M., HARTONAS-GARMHAUSEN, V., KWIATKOWSKA, M. Z., AND RYAN, M. 1997. Symbolic model checking for probabilistic processes. *In Automata, Languages and Programming, 24th Annual Colloquium*, (Bologna, Italy). P. Degano, R. Gorrieri, and A. Marchetti-Spaccamela, eds., Lecture Notes in Computer Science, vol. 1256, Springer, pp. 430–440.

BELNAP, N. 1977. A useful four-valued logic. In *Modern Uses of Multiple-Valued Logic*, Donn and Epstein, eds., Reidel, pp. 30–56.

BERNEY, G. AND DOS SANTOS, S. 1985. *Elevator Analysis, Design and Control*. IEE Control Engineering Series 2. Peter Peregrinus Ltd.

BIRKHOFF, G. 1967. *Lattice Theory* (3rd Edition). Americal Mathematical Society, Providence, RI.

BOLC, L. AND BOROWIK, P. 1992. *Many-Valued Logics*. Springer-Verlag.

BRUNS, G. AND GODEFROID, P. 1999. Model checking partial state spaces with 3-valued temporal logics. In *Proceedings of Proceedings of the 11th International Conference on Computer-Aided Verification (CAV'99)*, (Trento, Italy). Lecture Notes in Computer Science, vol. 1633, Springer, pp. 274–287.

BRUNS, G. AND GODEFROID, P. 2000. Generalized model checking: Reasoning about partial state spaces. In *Proceedings of the 11th International Conference on Concurrency Theory (CONCUR'00)*, C. Palamidessi, eds., Lecture Notes in Computer Science, vol. 1877, Springer, pp. 168–182.

CHAN, W. 2000. Temporal-logic queries. In *Proceedings of the 12th Conference on Computer Aided Verification (CAV'00)*, E. Emerson and A. Sistla, eds., Lecture Notes in Computer Science, vol. 1855, Springer, pp. 450–463.

CHECHIK, M., DEVEREUX, B., AND EASTERBROOK, S. 2001a. Implementing a multi-valued symbolic model-checker. In *Proceedings of the 7th International Conference on Tools and Algorithms for the Construction and Analysis of Systems (TACAS'01)*, Lecture Notes in Computer Science, vol. 2031, Springer, pp. 404–419.

CHECHIK, M., DEVEREUX, B., AND GURFINKEL, A. 2001b. Model-checking infinite state-space systems with fine-grained abstractions using SPIN. In *Proceedings of the 8th SPIN Workshop on Model Checking Software*, Toronto, Canada. Lecture Notes in Computer Science, vol. 2057, Springer, pp. 16–36,

CHECHIK, M., DEVEREUX, B., AND GURFINKEL, A. 2002a. χChek: a multi-valued model-checker. In *Proceedings of the 14th International Conference on Computer-Aided Verification (CAV'02)*, Copenhagen, Denmark. Lecture Notes in Computer Science, Springer, pp. 505–509.

CHECHIK, M. AND DING, W. 2002. Lightweight reasoning about program correctness. *Inf. Syst. Frontiers*, *4*, 4, pp. 363–377.

CHECHIK, M., GURFINKEL, A., DEVEREUX, B., LAI, A., AND EASTERBROOK, S. 2002b. Symbolic data structures for multi-valued model-checking. CSRG Tech Report 446, University of Toronto. Submitted for publication.

CHECHIK, M. AND MACCAULL, W. 2003. CTL model-checking over logics with non-classical negation. In *Proceedings of the 33rd IEEE International Symposium on Multi-Valued Logics (ISMVL'03)* (Tokyo, Japan). pp. 293–300, CLARKE, E., EMERSON, E., AND SISTLA, A. 1986. Automatic verification of finite-state concurrent systems using temporal logic specifications. *ACM Trans. Program. Lang. Syst.*, *8*, 2, pp. 244–263.

CLARKE, E., GRUMBERG, O., AND PELED, D. 1999. *Model Checking*. MIT Press.

COUSOT, P. AND COUSOT, R. 1977. Static determination of dynamic properties of generalized type unions. *SIGPLAN Notices*, *12*, 3.

DAMS, D. 1996. *Abstract Interpretation and Partition Refinement for Model Checking*. PhD Thesis, Eindhoven University of Technology, The Netherlands.

DAMS, D., GERTH, R., AND GRUMBERG, O. 1997. Abstract interpretation of reactive systems. *ACM Trans. Program. Lang. Syst.*, *2*, 19, pp. 253–291.

DAVEY, B. AND PRIESTLEY, H. 1990. *Introduction to Lattices and Order*. Cambridge University Press.

DEVEREUX, B. 2002. Strong next-time operators for multiple-valued μ-calculus. In *Proceedings of FLOC'02 Workshop on Fixpoints in Computer Science (FICS)* (Copenhagen, Denmark), pp. 40–43,

DUNN, J. 1999. A comparative study of various model-theoretic treatments of negation: a history of formal negation. In *What is Negation*, D. Gabbay and H. Wansing, eds., Kluwer Academic Publishers.

EASTERBROOK, S. AND CHECHIK, M. 2001. A framework for multi-valued reasoning over inconsistent viewpoints. In *Proceedings of the International Conference on Software Engineering (ICSE'01)* (Toronto, Canada), IEEE Computer Society Press, pp. 411–420.

FITTING, M. 1991a. Many-valued modal logics. *Fund. Info.*, *15*, 3–4, pp. 335–350.

FITTING, M. C. 1991b. Kleene's logic, generalized. *J. Log. Comput.*, *1*, 6, pp. 797–810.

FITTING, M. 1992. Many-valued modal logics II. *Fund. Info.*, *17*, pp. 55–73.

GAINES, B. R. 1979. Logical foundations for database systems. *Intern. J. Man-Mach. Studies*, *11*, 4, pp. 481–500.

GINSBERG, M. 1987. Multi-valued logic. In *Readings in Nonmonotonic Reasoning*, M. Ginsberg, ed., Morgan-Kaufmann Publishing, pp. 251–255.

GINSBERG, M. L. 1988. Multivalued logics: a uniform approach to reasoning in artificial intelligence. *Comput. Intell.*, *4*, 3, pp. 265–316.

GODEFROID, P., HUTH, M., AND JAGADEESAN, R. 2001. Abstraction-based model checking using modal transition systems. In *Proceedings of the 12th International Conference on Concurrency Theory (CONCUR'01)* (Aalborg, Denmark), K. Larsen and M. Nielsen, eds., Lecture Notes in Computer Science, vol. 2154, Springer, pp. 426–440.

GODEFROID, P. AND JAGADEESAN, R. 2003. On the expressiveness of 3-valued models. In *Proceedings of the 4th International Conference on Verification, Model Checking, and Abstract Interpretation (VMCAI'03)*, Lecture Notes in Computer Science, vol. 2575, Springer, pp. 206–222.

GOGUEN, J. 1967. L-fuzzy sets. *J. Math. Anal. Applic.*, *18*, 1, pp. 145–174.

GURFINKEL, A. 2002. *Multi-valued symbolic model-checking: fairness, counter-examples, running time*. Master's Thesis, Department of Computer Science, University of Toronto.

GURFINKEL, A. AND CHECHIK, M. 2003a. Generating counterexamples for multi-valued model-checking. In *Proceedings of Formal Methods Europe (FME'03*, Pisa, Italy.

GURFINKEL, A. AND CHECHIK, M. 2003b. Multi-valued model-checking via classical model-checking. In *Proceedings of the 14th International Conference on Concurrency Theory (CONCUR'03)*, Marseille, France.

GURFINKEL, A., CHECHIK, M., AND DEVEREUX, B. 2003. Temporal logic query checking: a tool for model exploration. *IEEE Trans. Softw. Eng*. To appear.

Hähnle, R. 1994. *Automated Deduction in Multiple-Valued Logics*, International Series of Monographs on Computer Science. vol. 10, Oxford University Press.

HAZELHURST, S. 1996. *Compositional Model Checking of Partially Ordered State Spaces*. PhD Thesis, Department of Computer Science, University of British Columbia.

HEHNER, E. 1993. *A Practical Theory of Programming*. Texts and Monographs in Computer Science. Springer-Verlag, New York.

HUTH, M., JAGADEESAN, R., AND SCHMIDT, D. 2003. A domain equation for refinement of partial systems. *Math. Struct. Comput. Sci*. Accepted for publication.

HUTH, M., JAGADEESAN, R., AND SCHMIDT, D. A. 2001. Modal transition systems: a foundation for three-valued program analysis. In *Proceedings of the 10th European Symposium on Programming (ESOP'01), Lecture Notes in Computer Science*, vol. 2028, Springer, pp. 155–169.

Huth, M. and Pradhan, S. 2003. An ontology for consistent partial model checking. *Elect. Notes Theoret. Comput. Sci.*, *23*.

Huth, M. and Ryan, M. 2000. *Logic in Computer Science: Modeling and Reasoning About Systems*. Cambridge University Press.

Kleene, S. C. 1952. *Introduction to Metamathematics*. Van Nostrand, New York.

Konikowska, B. and Penczek, W. 2003. Model checking for multi-valued computation tree logics. In *Beyond Two: Theory and Applications of Multiple Valued Logic*, M. Fitting and E. Orlowska, eds., Physica-Verlag, pp. 193–210.

Kozen, D. 1983. Results on the propositional μ-calculus. *Theoret. Comput. Sci.*, *27*, pp. 334–354.

Larsen, K. and Thomsen, B. 1988. A modal process logic. In *Proceedings of the 3rd Annual Symposium on Logic in Computer Science (LICS'88)*, IEEE Computer Society Press, pp. 203–210.

Lukasiewicz, J. 1970. *Selected Works*. North-Holland, Amsterdam, Holland.

McMillan, K. 1993. *Symbolic Model Checking*. Kluwer Academic.

Michalski, R. S. 1977. Variable-valued logic and its applications to pattern recognition and machine learning. In *Computer Science and Multiple-Valued Logic: Theory and Applications*, D. C. Rine, eds., North-Holland, Amsterdam, pp. 506–534.

Plath, M. and Ryan, M. 1999. SFI: a feature integration tool. In *Tool Support for System Specification, Development and Verification*, R. Berghammer and Y. Lakhnech, eds., Advances in Computer Science, Springer, pp. 201–216.

Rasiowa, H. 1978. *An Algebraic Approach to Non-Classical Logics. Studies in Logic and the Foundations of Mathematics*. Amsterdam: North-Holland.

Sagiv, M., Reps, T., and Wilhelm, R. 1999. Parametric shape analysis via 3-valued logic. In *Proceedings of the 26th Annual ACM Symposium on Principles of Programming Languages*. ACM, New York, NY, pp. 105–118.

Sasao, T. and Butler, J. 1996. A method to represent multiple-output switching functions using multi-valued decision diagrams. In *Proceedings of IEEE International Symposium on Multiple-Valued Logic (ISMVL'96)* (Santiago de Compostela, Spain). pp. 248–254.

Sofronie-Stokkermans, V. 2001. Automated theorem proving by resolution for finitely-valued logics based on distributive lattices with operators. *An Intern. J. Multip. Val. Log. 6*, 3–4, pp. 289–344.

Srinivasan, A., Kam, T., Malik, S., and Brayton, R. 1990. Algorithms for discrete function manipulation. In *IEEE/ACM International Conference on Computer-Aided Design (ICCAD'90)* (Santa Clara, CA). IEEE Computer Society, pp. 92–95.

Received October 2001; revised August 2002 and November 2003; accepted December 2003