In this additional file, we present a version of the Computation-Tree Logic (CTL) [1, 3] and a version of the Hybrid Computation-Tree Logic (HCTL) [2]. First, we introduce models for these two logics. Then, we present the syntax of CTL and HCTL. Finally, we give a semantics for HCTL including that of CTL.

The basic notation that we use in this additional file is as follows. If \( D \) is a set, we use \( \mathcal{P}(D) \) for the power set of \( D \), and we use \( \#(D) \) to denote the cardinality of \( D \). If \( R \subseteq D \times D \) is a binary relation, then we say that \( R \) is serial if \( \forall x \in D, \exists y \in D \) such that \((x, y) \in R\). We use \( xRy \) to denote that \((x, y) \in R\).

1 (Hybrid) Kripke models

The semantics of CTL and HCTL respectively need Kripke models and hybrid Kripke models. So we include below a definition Kripke model that can be extended to a definition of hybrid Kripke model.

We assume that \( AP \) is a nonempty finite set and we call the elements of \( AP \) atomic propositions. Besides, we consider a fixed subset of \( AP \), \( N \subseteq AP \), and we call the elements of \( N \) nominals.

**Definition 1.1** (Kripke model). We say that \( M \) is a finite Kripke model for \( AP \) iff \( M = (S, R, L) \) where

1. \( S \neq \emptyset \) is a finite set.
2. \( R \subseteq S \times S \) is a serial relation.
3. \( L : AP \rightarrow \mathcal{P}(S) \).
We call the elements of $S$ states. $R$ is the accessibility relation of $M$, and we call the elements of $R$ transitions. We refer to $L$ as the labeling function of $M$. If $s \in L(p)$, we say that $p$ is a label of $s$. Intuitively, $L(p)$ is the set of states where $p$ is true.

Since we assume that the accessibility relation of a model is serial, no state of the model can deadlock. This requirement is a technical convenience, and does not represent any restriction on the modeling ability of Kripke models (e.g. [3, p. 178]). If we need to model a system having deadlock states, we could add to the Kripke model a state $s_d$ representing deadlock, and transitions $sRs_d$ for each deadlock state $s$, as well as the transition $sRs_d$.

The above definition of labeling function in a Kripke model deviates from the standard definition where $L : S \to \mathcal{P}(AP)$. The definition above, equivalent to the standard definition, is suitable for the treatment of nominals.

To extend the definition of Kripke model to that of hybrid Kripke model, we have to consider the labeling by nominals as a special case:

**Definition 1.2** (Hybrid Kripke model). We say that $M$ is a finite hybrid Kripke model for $AP$ and $N$ iff $M = (S, R, L)$, where

1. $S \neq \emptyset$ is a finite set,
2. $R \subseteq S \times S$ is a serial relation, and
3. $L : AP \to \mathcal{P}(S)$ is such that $\forall n \in N. \#(L(n)) = 1$

Since $n \in N$ implies that there is $s \in S$ such that $L(n) = \{s\}$, we say that state $s$ is named by $n$. Therefore, nominals are true at exactly one state in any hybrid Kripke model. Thus, a state named by a nominal may be mentioned in a formula by using such a nominal.

If $M$ is a (hybrid) Kripke model, when necessary we use a superscript $M$ to denote its components, i.e. $M = (S^M, R^M, L^M)$.

To define the semantics of hybrid operators we will need to modify the labeling by nominals in a model. We make these modifications by forcing a state to be named by a nominal.

**Definition 1.3** (Name change). Let $M$ be a hybrid Kripke model, $n \in N$, and $s \in S^M$.

1. We define the labeling function $L^M[n \mapsto s] : AP \to \mathcal{P}(S^M)$, $L^M$ with $s$ named by $n$, by: $L^M[n \mapsto s](n) = \{s\}$, and for all $p \in AP$ such that $p \neq n$, $L^M[n \mapsto s](p) = L^M(p)$.
2. We define the hybrid Kripke model $M[n \mapsto s]$, $M$ with $s$ named by $n$, by: $S^{M[n \mapsto s]} = S^M$, $R^{M[n \mapsto s]} = R^M$, and $L^{M[n \mapsto s]} = L^M[n \mapsto s]$.

A path in a (hybrid) Kripke model $M$ is an infinite sequence of states, $\pi: \mathbb{N} \rightarrow S^M$, such that for all $i \in \mathbb{N}$, $(\pi_i, \pi_{i+1}) \in R^M$; as usual we use $\pi_i$ instead of $\pi(i)$. The set of paths in $M$ starting at $s$ is $\Pi_{M,s} = \{ \pi \mid \pi$ is a path in $M$ and $\pi_0 = s \}$.

## 2 CTL and HCTL syntax

We present here a syntax for CTL. Then we extend this syntax to get a syntax for HCTL.

We assume that CTL formulas, $\Phi$, have the following syntax in Backus-Naur form (BNF):

$$\Phi ::= \top | p | (\neg \Phi) | (\Phi \land \Phi) | (EX \Phi) | E[\Phi U \Phi] | (AF \Phi)$$

where $p$ ranges over the set of atomic propositions $AP$.

The propositional operators $\top$, $\neg$, and $\land$ have the usual meaning: truth, negation and conjunction, respectively. Intuitively, $E$ and $A$ respectively stand for “there exists a path” and “for all paths”. For the temporal operators we have that $X$ means “at a next state”, $U$ “until”, and $F$ stands for “either now or in the future”.

We can define other operators in terms of that considered above. First, we define other propositional operators, $\bot$ (falsity), $\lor$ (disjunction), $\Rightarrow$ (implication) and $\Leftrightarrow$ (equivalence):

$$\bot = \neg \top \quad \alpha \lor \beta = \neg (\neg \alpha \land \neg \beta) \quad \alpha \Rightarrow \beta = \neg \alpha \lor \beta \quad \alpha \Leftrightarrow \beta = (\alpha \Rightarrow \beta) \land (\beta \Rightarrow \alpha)$$

Second, we define the operators $AX$ and $EG$:

$$AX \alpha = \neg EX \neg \alpha \quad EG \alpha = \neg AF \neg \alpha$$

Then, operator $AU$ has a special definition (e.g. see [3, p. 216]):

$$A[\alpha U \beta] = \neg (E[\neg \beta U (\neg \alpha \land \neg \beta)] \lor EG \neg \beta)$$

Finally, we define other CTL operators:
\[ \begin{align*}
\text{EF} \alpha &= \text{E}[\top \ U \alpha] & \text{AG} \alpha &= \neg \text{EF} \neg \alpha \\
\text{E}[\alpha \ R \beta] &= \neg \text{A}[-\alpha \ U \neg \beta] & \text{A}[\alpha \ R \beta] &= \neg E[-\alpha \ U \neg \beta]
\end{align*} \]

Intuitively, \( \mathbf{G} \) stands for “always” or “globally”, and \( \mathbf{R} \) means “release”.

Hybrid \( \text{CTL} \), denoted by \( \text{HCTL} \), is an extension of \( \text{CTL} \) that considers three hybrid operators: the \textit{at} operator (\( \oplus n \)), the \textit{down-arrow binder} (\( \downarrow n \)), and the \textit{existential binder} (\( \exists n \)).

The syntax in BNF for \( \text{HCTL} \) formulas (\( \Psi \)) is as follows:

\[
\Psi ::= \top \mid p \mid (\neg \Psi) \mid (\Psi \land \Psi) \mid (\text{EX} \Psi) \mid \text{E}[\Psi \ U \Psi] \mid (\text{AF} \Psi) \mid (\oplus n. \Psi) \mid (\downarrow n. \Psi) \mid (\exists n. \Psi)
\]

where \( p \) ranges over \( \text{AP} \), and \( n \) ranges over the set of nominals \( N \).

Intuitively, \( \oplus n \) means “at the state named by \( n \)”, \( \downarrow n \) stands for “bind \( n \) to the current state”, and \( \exists n \) means “(non-deterministically) bind \( n \) to some state”.

### 3 \( \text{CTL} \) and \( \text{HCTL} \) semantics

We now proceed to define the semantics of \( \text{CTL} \). Then, we extend this semantics to a semantics of \( \text{HCTL} \).

**Definition 3.1** (\( \text{CTL} \) semantics). Let \( M \) be a Kripke model, \( s \in S^M \), and \( \varphi \in \text{CTL} \). We define \( (M, s) \models \varphi \), \( M \) satisfies \( \varphi \) at \( s \), recursively on the structure of \( \varphi \):

1. \( (M, s) \models \top \)
2. \( (M, s) \models p \) iff \( s \in L^M(p) \)
3. \( (M, s) \models \neg \alpha \) iff \( (M, s) \not\models \alpha \)
4. \( (M, s) \models \alpha \land \beta \) iff \( (M, s) \models \alpha \) and \( (M, s) \models \beta \)
5. \( (M, s) \models \text{EX} \alpha \) iff \( \exists \pi \in \Pi_{M,s} \) such that \( (M, \pi_1) \models \alpha \)
6. \( (M, s) \models \text{E}[\alpha \ U \beta] \) iff \( \exists \pi \in \Pi_{M,s} \) and \( \exists i \in \mathbb{N} \) such that: \( (M, \pi_i) \models \beta \) and \( \forall j < i \) \( (M, \pi_j) \models \alpha \)
7. \( (M, s) \models \text{AF} \alpha \) iff \( \forall \pi \in \Pi_{M,s} \), \( \exists i \in \mathbb{N} \) such that \( (M, \pi_i) \models \alpha \)
Now, we get the semantics of HCTL by extending the semantics of CTL to hybrid Kripke models.

**Definition 3.2** *(HCTL semantics).* Let $M$ be a hybrid Kripke model, $s \in S^M$, and $\varphi \in HCTL$. We define $(M, s) \models \varphi$, $M$ satisfies $\varphi$ at $s$, recursively on the structure of $\varphi$:

1. $(M, s) \models \top$  
2. $(M, s) \models p$ iff $s \in L^M(p)$  
3. $(M, s) \models \neg \alpha$ iff $(M, s) \not\models \alpha$  
4. $(M, s) \models \alpha \land \beta$ iff $(M, s) \models \alpha$ and $(M, s) \models \beta$  
5. $(M, s) \models \text{EX}\alpha$ iff $\exists \pi \in \Pi^M_{M,s}$ such that $(M, \pi) \models \alpha$  
6. $(M, s) \models \text{E}[\alpha] U \beta$ iff $\exists \pi \in \Pi^M_{M,s}$ and $\exists i \in \mathbb{N}$ such that: $(M, \pi_i) \models \beta$ and $\forall j < i$ $(M, \pi_j) \models \alpha$  
7. $(M, s) \models \text{AF}\alpha$ iff $\forall \pi \in \Pi^M_{M,s}$, $\exists i \in \mathbb{N}$ such that $(M, \pi_i) \models \alpha$  
8. $(M, s) \models @n.\alpha$ iff $L^M(n) = \{s'\}$ and $(M, s') \models \alpha$  
9. $(M, s) \models \downarrow n.\alpha$ iff $(M[n \mapsto s], s) \models \alpha$  
10. $(M, s) \models \exists n.\alpha$ iff $\exists s' \in S^M$ such that $(M[n \mapsto s'], s) \models \alpha$

**4 HCTL denotational semantics**

We define here an appropriate HCTL semantics for the implementation of a model checker. To simplify the definition the denotational semantics of HCTL, we will need the existential and universal preimage of a set of states as well as a mechanism of definition by fixed points.

**Definition 4.1** *(Pre$\exists(X)$, Pre$\forall(X))$. Let $M$ is a (hybrid) Kripke model and $X \subseteq S^M$. The existential preimage of $X$ in $M$ is

$$\text{Pre}\exists(X) = \{ s \in S^M \mid \exists s'. sR^M s' \text{ and } s' \in X \}.$$

The universal preimage of $X$ in $M$ is analogously defined by

$$\text{Pre}\forall(X) = \{ s \in S^M \mid \forall s'. sR^M s' \text{ implies } s' \in X \}.$$  

Note that $\text{Pre}\forall(X) = S^M - \text{Pre}\exists(S^M - X)$.  

5
Definition 4.2 (Fixed points and monotone functions). Let $D$ be a set, $X \subseteq D$, and $F : \mathcal{P}(D) \to \mathcal{P}(D)$ a function. We say that

1. $X$ is a least fixed point of $F$ iff $F(X) = X$ and, for all $Y \in \mathcal{P}(D)$, $F(Y) = Y \Rightarrow X \subseteq Y$

2. $X$ is a greatest fixed point of $F$ iff $F(X) = X$ and, for all $Y \in \mathcal{P}(D)$, $F(Y) = Y \Rightarrow X \supseteq Y$

3. $F$ is monotone iff $X \subseteq Y$ implies $F(X) \subseteq F(Y)$ for all $X, Y \in \mathcal{P}(D)$.

Note that least (greatest) fixed points are unique. Thus, we use $\text{lfp}(F)$ and $\text{gfp}(F)$ to respectively denote the least and the greatest fixed point of $F$. Observe that $\text{Pre}_{\exists}$ and $\text{Pre}_{\forall}$ are monotone functions.

If $F : \mathcal{P}(D) \to \mathcal{P}(D)$ is a function, we use $F^i(X)$ to denote that $F$ should be applied $i$ times: $F^1(X) = F(X)$ and $F^{i+1}(X) = F(F^i(X))$.

The following fact is a special case of a fundamental result cited as the Knaster–Tarski Theorem.

Theorem 4.1 (Existence of fixed points). Let $D$ be a finite set such that $|D| = n + 1$. If $F : \mathcal{P}(D) \to \mathcal{P}(D)$ is a monotone function, then $\text{lfp}(F) = F^{n+1}(\emptyset)$ and $\text{gfp}(F) = F^{n+1}(D)$.

Proof. e.g. see [3, p. 241]. 

Definition 4.3 (HCTL denotational semantics). Let $M$ be a hybrid Kripke model, and $\varphi \in \text{HCTL}$. We define the meaning of $\varphi$ in $M$, $\llbracket \varphi \rrbracket_M$, recursively on the structure of $\varphi$:

1. $\llbracket \top \rrbracket_M = S^M$
2. $\llbracket p \rrbracket_M = L^M(p)$
3. $\llbracket \neg \alpha \rrbracket_M = S^M - \llbracket \alpha \rrbracket_M$
4. $\llbracket \alpha \land \beta \rrbracket_M = \llbracket \alpha \rrbracket_M \cap \llbracket \beta \rrbracket_M$
5. $\llbracket \exists X \alpha \rrbracket_M = \{ s \in S^M \mid \exists s'. sR^Ms' \text{ and } s' \in \llbracket \alpha \rrbracket_M \} = \text{Pre}_{\exists}(\llbracket \alpha \rrbracket_M)$
6. $\llbracket \exists X (\alpha \cup \beta) \rrbracket_M = \text{lfp}(F)$, where $F : \mathcal{P}(S^M) \to \mathcal{P}(S^M)$ and $F(X) = \llbracket \beta \rrbracket_M \cup (\llbracket \alpha \rrbracket_M \cap \text{Pre}_{\exists}(X))$
7. $\llbracket \forall X \alpha \rrbracket_M = \text{lfp}(G)$, where $G : \mathcal{P}(S^M) \to \mathcal{P}(S^M)$ and $G(X) = \llbracket \alpha \rrbracket_M \cup \text{Pre}_{\forall}(X)$
8. \([\mathcal{G}_{n.\alpha}]_M = \begin{cases} S & \text{if } L^M(n) \cap [\alpha]_M \neq \emptyset \\ \emptyset & \text{otherwise} \end{cases}\)

9. \([\downarrow n.\alpha]_M = \{ s \in S^M \mid s \in [\alpha]_{M[n \rightarrow s]} \} = \bigcup_{s \in S^M} ([s] \cap [\alpha]_{M[n \rightarrow s]})\)

10. \([\exists n.\alpha]_M = \{ s \in S^M \mid \exists s' \in S^M. s \in [\alpha]_{M[n \rightarrow s']} \} = \bigcup_{s' \in S^M} ([\alpha]_{M[n \rightarrow s']})\)

Note that above functions \(F\) and \(G\) are monotone. Therefore the least fixed point of both functions exists.

In our model checker, Antelope, operators \(\top, \bot, \neg, \land, E(\alpha U \beta), @, \downarrow, \exists\) are respectively transliterated to \textit{true}, \textit{false}, \textit{~}, \& , \textit{E}(\alpha U \beta), @, !, and \].

References

