

Bounded Model Checking

(Based on [Biere et al. 1999, Benedetti and Cimatti 2003])

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Outline

- 🌐 Introduction
- 🌐 An Illustrative Example
- 🌐 Part I: Bounded Model Checking for LTL (with future only)
- 🌐 Part II: Bounded Model Checking for LTL with Past (or Full PTL)
- 🌐 References:
 - [Biere *et al.*] A. Biere, A. Cimatti, E. Clarke, and Y. Zhu, “Symbolic Model Checking without BDD,” *TACAS 1999*, LNCS1579.
 - [Benedetti and Cimatti] M. Benedetti and A. Cimatti, “Bounded Model Checking for Past LTL,” *TACAS 2003*, LNCS 2619.

Introduction

- 🌐 In *symbolic model checking*, **BDDs** had traditionally been used for boolean encodings.
- 🌐 Drawbacks of BDDs:
 - ☀️ For large systems (with over a few hundred boolean variables), they can be prohibitively large.
 - ☀️ Selecting the right variable ordering is often time-consuming or needs manual intervention.
- 🌐 Propositional decision procedures, or **SAT solvers**, also operate on boolean expressions, but do not use canonical forms.
- 🌐 SAT solvers can handle thousands of variables or even more.

Introduction (cont.)

- 🌐 Basic ideas of **bounded model checking** (BMC):
 - ☀️ Consider counterexamples of a particular length k .
 - ☀️ Generate a propositional formula that is satisfiable iff such a counterexample exists.
 - ☀️ The propositional formula can be tested for satisfiability by a SAT solver.
- 🌐 Advantages of BMC:
 - ☀️ It finds counterexamples very **fast**.
 - ☀️ It finds counterexamples of **minimal** length.
 - ☀️ It uses much **less space** than BDD-based approaches.
 - ☀️ It does not need a manually selected variable ordering or time-consuming dynamic reordering.

An Example

- Consider a three-bit shift register.
- Let $M = \langle X, I, T \rangle$ be its state machine:
 - $X \triangleq \{x[0], x[1], x[2]\}$ contains the three bits.
 - $I(X) \triangleq true$, posing no restriction on the initial states.
 - $T(X, X') \triangleq (x'[0] \Leftrightarrow x[1]) \wedge (x'[1] \Leftrightarrow x[2]) \wedge x'[2]$.
- Suppose we want to check if eventually all three bits are set to 0, i.e., if LTL formula $p \triangleq \diamond(\neg x[0] \wedge \neg x[1] \wedge \neg x[2])$ holds on all paths in M .
- To do so, we search for a path in M such that $\neg p \triangleq \square(x[0] \vee x[1] \vee x[2])$ on the path.
- If we succeed, then p does not hold on all paths; otherwise, it does.

An Example (cont.)

- 🌐 We look for (looping) paths with at most $k + 1$ states, for instance $k = 2$.
- 🌐 Let X_i denote the set $\{x_i[0], x_i[1], x_i[2]\}$.
- 🌐 The first 3 states of such a path can be characterized by the following boolean formula:

$$f_M \triangleq I(X_0) \wedge T(X_0, X_1) \wedge T(X_1, X_2)$$

- 🌐 A witness for $\neg p$ must contain a loop from X_2 back to X_0 , X_1 , or X_2 :

$$L_i \triangleq T(X_2, X_i)$$

- 🌐 The path must fulfill the constraints imposed by $\neg p$:

$$S_i \triangleq x_i[0] \vee x_i[1] \vee x_i[2]$$

An Example (cont.)

- 🌐 The following formula is satisfiable iff there is a counterexample of length 2 for p .

$$f_M \wedge \bigvee_{i=0}^2 L_i \wedge \bigwedge_{i=0}^2 S_i$$

- 🌐 Here is a satisfying assignment:

$$\begin{aligned} & x_0[0] = x_0[1] = x_0[2] \\ = & x_1[0] = x_1[1] = x_1[2] \\ = & x_2[0] = x_2[1] = x_2[2] \\ = & 1. \end{aligned}$$

Part I:

Bounded Model Checking for LTL

Kripke Structures

- 🌐 A Kripke structure is a tuple $M = (S, I, T, L)$ with
 - ☀️ a finite set of states S ,
 - ☀️ the set of initial states $I \subseteq S$,
 - ☀️ a transition relation between states $T \subseteq S \times S$, and
 - ☀️ the labeling of the states $L : S \rightarrow \mathcal{P}(A)$ with atomic propositions A .
- 🌐 Every state of M is required to have a successor.
- 🌐 We write $s \rightarrow t$ for $(s, t) \in T$.
- 🌐 For an infinite sequence π of states s_0, s_1, \dots , we define
 - ☀️ $\pi(i) = s_i$
 - ☀️ $\pi^i = s_i, s_{i+1}, \dots$
- 🌐 An infinite sequence π is a path if $\pi(i) \rightarrow \pi(i+1)$ for all $i \in \mathbb{N}$.

Linear Temporal Logic (LTL)

- Let M be a Kripke structure, π be a path in M , and f be an LTL formula (in negation normal form).
- $\pi \models f$ (f is valid along π) is defined as follows:

$\pi \models p$	iff	$p \in L(\pi(0))$
$\pi \models \neg p$	iff	$p \notin L(\pi(0))$
$\pi \models f \wedge g$	iff	$\pi \models f$ and $\pi \models g$
$\pi \models f \vee g$	iff	$\pi \models f$ or $\pi \models g$
$\pi \models \Box f$	iff	$\forall j \in [0, \infty). \pi^j \models f$
$\pi \models \Diamond f$	iff	$\exists j \in [0, \infty). \pi^j \models f$
$\pi \models \bigcirc f$	iff	$\pi^1 \models f$
$\pi \models f \mathcal{U} g$	iff	$\exists j \in [0, \infty). (\pi^j \models g \text{ and } \forall k \in [0, j). \pi^k \models f)$
$\pi \models f \mathcal{R} g$	iff	$\forall j \in [0, \infty). (\pi^j \models g \text{ or } \exists k \in [0, j). \pi^k \models f)$

Model Checking

- 🌐 An LTL formula f is **valid** in a Kripke structure M , denoted as $M \models \mathbf{A} f$, iff $\pi \models f$ for all paths π in M with $\pi(0) \in I$.
- 🌐 An LTL formula f is **satisfiable** in a Kripke structure M , denoted as $M \models \mathbf{E} f$, iff there is a path π in M such that $\pi \models f$ and $\pi(0) \in I$.
- 🌐 Given a Kripke structure M and an LTL formula f , the model checking problem is to determine whether $M \models \mathbf{A} f$, which is equivalent to determine whether $M \not\models \mathbf{E} \neg f$.
- 🌐 In the following, the problem is restricted to find a witness for formulae of the form $\mathbf{E} f$.

Bounded Model Checking

- Consider only a finite prefix of a path that may be a witness of $\mathbf{E} f$.
- We restrict the length of the prefix to a certain bound k .
- Generate a propositional formula that is satisfiable iff there is a witness within the bound k .
- The propositional formula can be solved by a SAT solver.
- If there is no witness within bound k , we increase the bound and look for longer and longer possible witnesses.

Infinite Paths from the Prefix

- 🌐 Though the prefix of a path is finite, it still might represent an infinite path if there is a **back loop** from the last state of the prefix to any of the previous states.
- 🌐 If there is no such back loop, then the prefix does not say anything about the infinite behavior of the path.
- 🌐 Only a prefix with a back loop can represent a witness for $\square f$.

Loops

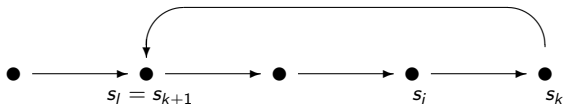
🌐 A path π is a (k, l) -loop for $l \leq k$ if

☀️ $\pi(k) \rightarrow \pi(l)$ and

☀️ $\pi = u \cdot v^\omega$ with

👤 $u = \pi(0), \dots, \pi(l-1)$ and

👤 $v = \pi(l), \dots, \pi(k)$



🌐 A path π is a k -loop if there is an $l \in \mathbb{N}$ with $l \leq k$ for which π is a (k, l) -loop.

Bounded Semantics

- 🌐 In bounded semantics, we only consider a finite prefix of a path which may or may not be a loop.
- 🌐 In particular, we only use the first $k + 1$ states of a path to determine the validity of a formula along that path.
- 🌐 The bounded semantics $\pi \models_k f$ states that the LTL formula f is valid along the path π with bound k .

Bounded Semantics for a Loop

- Let $k \in \mathbb{N}$ and π be a k -loop.
- $\pi \models_k f$ iff $\pi \models f$.
- This is so, because all information about π is contained in the prefix of length k .

Bounded Semantics without a Loop

Let $k \in \mathbb{N}$ and π be a path that is not a k -loop.

$\pi \models_k f$ iff $(\pi, 0) \models_k f$ where

$(\pi, i) \models_k p$	iff	$p \in L(\pi(i))$
$(\pi, i) \models_k \neg p$	iff	$p \notin L(\pi(i))$
$(\pi, i) \models_k f \wedge g$	iff	$(\pi, i) \models_k f$ and $(\pi, i) \models_k g$
$(\pi, i) \models_k f \vee g$	iff	$(\pi, i) \models_k f$ or $(\pi, i) \models_k g$
$(\pi, i) \models_k \Box f$	iff	<i>false</i>
$(\pi, i) \models_k \Diamond f$	iff	$\exists j \in [i, k]. (\pi, j) \models_k f$
$(\pi, i) \models_k \bigcirc f$	iff	$i < k$ and $(\pi, i + 1) \models_k f$
$(\pi, i) \models_k f \mathcal{U} g$	iff	$\exists j \in [i, k]. ((\pi, j) \models_k g$ and $\forall n \in [i, j]. (\pi, n) \models_k f)$
$(\pi, i) \models_k f \mathcal{R} g$	iff	$\exists j \in [i, k]. ((\pi, j) \models_k f$ and $\forall n \in [i, j]. (\pi, n) \models_k g)$

Note: $(\pi, i) \models_k f$ is written as $\pi \models_k^i f$ in the paper.

- 🌐 Note that the bounded semantics without a loop imply that the following two dualities no longer hold:
- ☀️ the duality of \Box and \Diamond ($\neg\Box f = \Diamond\neg f$), and
 - ☀️ the duality of \mathcal{U} and \mathcal{R} ($\neg(f \mathcal{U} g) = (\neg f) \mathcal{R} (\neg g)$).

Reduction to Bounded Model Checking

Lemma

Let h be an LTL formula and π a path, then $\pi \models_k h \Rightarrow \pi \models h$.

Lemma


Let f be an LTL formula and M a Kripke structure. If $M \models \mathbf{E} f$ then there exists $k \in \mathbb{N}$ with $M \models_k \mathbf{E} f$.

Theorem


Let f be an LTL formula and M a Kripke structure. Then $M \models \mathbf{E} f$ iff there exists $k \in \mathbb{N}$ with $M \models_k \mathbf{E} f$.


Proof of Lemma 1

Let h be an LTL formula and π a path, then $\pi \models_k h \Rightarrow \pi \models h$.

 Case 1: π is a k -loop.

 The conclusion follows by the definition.

 Case 2: π is not a loop.






 Prove by induction over the structure of f and $i \leq k$ the stronger property $\pi \models_k^i h \Rightarrow \pi^i \models h$.

Proof of Lemma 1 (cont.)

$$\begin{aligned} & \pi \models_k^i f \mathcal{R} g \\ \Leftrightarrow & \exists j \in [i, k]. (\pi \models_k^j f \text{ and } \forall n \in [i, j]. \pi \models_k^n g) \\ \Rightarrow & \exists j \in [i, k]. (\pi^j \models f \text{ and } \forall n \in [i, j]. \pi^n \models g) \\ \Rightarrow & \exists j \in [i, \infty]. (\pi^j \models f \text{ and } \forall n \in [i, j]. \pi^n \models g) \\ \Rightarrow & \exists j' \in [0, \infty). (\pi^{i+j'} \models f \text{ and } \forall n' \in [0, j']. \pi^{i+n'} \models g) \\ & \text{(with } j' = j - i \text{ and } n' = n - i) \\ \Rightarrow & \exists j \in [0, \infty). [(\pi^i)^j \models f \text{ and } \forall n \in [0, j]. (\pi^i)^n \models g] \\ \Rightarrow & \forall n \in [0, \infty). [(\pi^i)^n \models g \text{ or } \exists j \in [0, n]. (\pi^i)^j \models f] \\ & \text{(see next slide)} \\ \Rightarrow & \pi^i \models f \mathcal{R} g \end{aligned}$$

Proof of Lemma 1 (cont.)

$$\exists m[\pi^m \models f \text{ and } \forall l, l \leq m. \pi^l \models g] \Rightarrow \forall n[\pi^n \models g \text{ or } \exists j, j < n. \pi^j \models f]$$

-  Assume that m is the smallest number such that $\pi^m \models f$ and $\pi^l \models g$ for all l with $l \leq m$.
-  Case 1: $n > m$.
 -  Based on the assumption, there exists $j < n$ such that $\pi^j \models f$ (choose $j = m$).
-  Case 2: $n \leq m$.
 -  Because $\pi^l \models g$ for all $l \leq m$ we have $\pi^n \models g$ for all $n \leq m$.

Proof of Lemma 2

Let f be an LTL formula and M a Kripke structure. If $M \models \mathbf{E} f$ then there exists $k \in \mathbb{N}$ with $M \models_k \mathbf{E} f$.

- 🌐 If f is satisfiable in M , then there exists a path in the product structure of M and the tableau of f that starts with an initial state and ends with a cycle in the strongly connected component of fair states.
- 🌐 This path can be chosen to be a k -loop with k bounded by $|S| \cdot 2^{|f|}$ which is the size of the product structure.
- 🌐 If we project this path onto its first component, the original Kripke structure, then we get a path π that is a k -loop and in addition fulfills $\pi \models f$.
- 🌐 By definition of the bounded semantics this also implies $\pi \models_k f$.

From BMC to SAT

- Given a Kripke structure M , an LTL formula f , and a bound k , we will construct a propositional formula $\llbracket M, f \rrbracket_k$.
- The bounded model checking problem can be reduced in polynomial time to propositional satisfiability.
 - The size of $\llbracket M, f \rrbracket_k$ is polynomial in the size of f if common sub-formulae are shared.
 - It is quadratic in k and linear in the size of the propositional formulae for T , I , and the $p \in A$.

Unfolding the Transition Relation

🌐 For a Kripke structure M and $k \in \mathbb{N}$,

$$\llbracket M \rrbracket_k \triangleq I(s_0) \wedge \bigwedge_{i=0}^{k-1} T(s_i, s_{i+1})$$

🌐 For an LTL formula f and $k, i \in \mathbb{N}$, with $i \leq k$,

$$\begin{aligned} \llbracket p \rrbracket_k^i &\triangleq p(s_i) \\ \llbracket \neg p \rrbracket_k^i &\triangleq \neg p(s_i) \\ \llbracket f \wedge g \rrbracket_k^i &\triangleq \llbracket f \rrbracket_k^i \wedge \llbracket g \rrbracket_k^i \\ \llbracket f \vee g \rrbracket_k^i &\triangleq \llbracket f \rrbracket_k^i \vee \llbracket g \rrbracket_k^i \\ \llbracket \Box f \rrbracket_k^i &\triangleq \text{false} \\ \llbracket \Diamond f \rrbracket_k^i &\triangleq \bigvee_{j=i}^k \llbracket f \rrbracket_k^j \\ \llbracket \bigcirc f \rrbracket_k^i &\triangleq \text{if } i < k \text{ then } \llbracket f \rrbracket_k^{i+1} \text{ else } \text{false} \\ \llbracket f \mathcal{U} g \rrbracket_k^i &\triangleq \bigvee_{j=i}^k (\llbracket g \rrbracket_k^j \wedge \bigwedge_{n=i}^{j-1} \llbracket f \rrbracket_k^n) \\ \llbracket f \mathcal{R} g \rrbracket_k^i &\triangleq \bigvee_{j=i}^k (\llbracket f \rrbracket_k^j \wedge \bigwedge_{n=i}^j \llbracket g \rrbracket_k^n) \end{aligned}$$

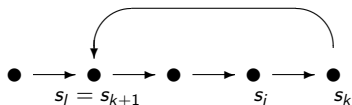
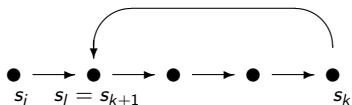
Trans. of an LTL formula for a Loop

🌐 For an LTL formula f and $k, l, i \in \mathbb{N}$, with $l, i \leq k$,

$$\begin{aligned}{}_l \llbracket p \rrbracket_k^i &\triangleq p(s_i) \\{}_l \llbracket \neg p \rrbracket_k^i &\triangleq \neg p(s_i) \\{}_l \llbracket f \wedge g \rrbracket_k^i &\triangleq {}_l \llbracket f \rrbracket_k^i \wedge {}_l \llbracket g \rrbracket_k^i \\{}_l \llbracket f \vee g \rrbracket_k^i &\triangleq {}_l \llbracket f \rrbracket_k^i \vee {}_l \llbracket g \rrbracket_k^i\end{aligned}$$

Trans. of an LTL formula for a Loop

$$\begin{aligned}
 I[\Box f]_k^i &\triangleq \bigwedge_{j=\min(i,l)}^k I[f]_k^j \\
 I[\Diamond f]_k^i &\triangleq \bigvee_{j=\min(i,l)}^k I[f]_k^j \\
 I[\bigcirc f]_k^i &\triangleq I[f]_k^{\text{succ}(i)}
 \end{aligned}$$

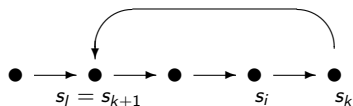
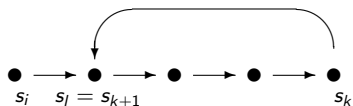


Let $k, l, i \in \mathbb{N}$, with $l, i \leq k$.

$$\text{succ}(i) \triangleq \begin{cases} i + 1 & \text{for } i < k \\ l & \text{for } i = k \end{cases}$$

$${}_i\llbracket f \mathcal{U} g \rrbracket_k^i \triangleq \bigvee_{j=i}^k ({}_i\llbracket g \rrbracket_k^j \wedge \bigwedge_{n=i}^{j-1} {}_i\llbracket f \rrbracket_k^n) \vee \bigvee_{j=l}^{i-1} ({}_i\llbracket g \rrbracket_k^j \wedge \bigwedge_{n=i}^k {}_i\llbracket f \rrbracket_k^n \wedge \bigwedge_{n=l}^{j-1} {}_i\llbracket f \rrbracket_k^n)$$

$${}_i\llbracket f \mathcal{R} g \rrbracket_k^i \triangleq \bigwedge_{j=\min(i,l)}^k {}_i\llbracket g \rrbracket_k^j \vee \bigvee_{j=i}^k ({}_i\llbracket f \rrbracket_k^j \wedge \bigwedge_{n=i}^j {}_i\llbracket g \rrbracket_k^n) \vee \bigvee_{j=l}^{i-1} ({}_i\llbracket f \rrbracket_k^j \wedge \bigwedge_{n=i}^k {}_i\llbracket g \rrbracket_k^n \wedge \bigwedge_{n=l}^j {}_i\llbracket g \rrbracket_k^n)$$



Loop Condition

🌐 The loop condition L_k is used to distinguish paths with bound k which are loops or not loops.

🌐 For $k, l \in \mathbb{N}$, let

$$\text{☀ } {}_l L_k \triangleq T(s_k, s_l)$$

$$\text{☀ } L_k \triangleq \bigvee_{l=0}^k {}_l L_k.$$

General Translation

🌐 Let f be an LTL formula, M a Kripke structure, and $k \in \mathbb{N}$.

$$\llbracket M, f \rrbracket_k \triangleq \llbracket M \rrbracket_k \wedge ((\neg L_k \wedge \llbracket f \rrbracket_k^0) \vee (\bigvee_{l=0}^k (l L_k \wedge l \llbracket f \rrbracket_k^0)))$$

Note: is the term $\neg L_k$ redundant?

Theorem

$\llbracket M, f \rrbracket_k$ is satisfiable iff $M \models_k \mathbf{E} f$.

Corollary

$M \models \mathbf{A} \neg f$ iff $\llbracket M, f \rrbracket_k$ is unsatisfiable for all $k \in \mathbb{N}$.

Bounds for LTL

- 🌐 LTL model checking is known to be PSPACE-complete.
- 🌐 A polynomial bound on k with respect to the size of M and f for which $M \models_k \mathbf{E} f \Leftrightarrow M \models \mathbf{E} f$ is unlikely to be found.

Theorem

Given an LTL formula f and a Kripke structure M , let $|M|$ be the number of states in M , then $M \models \mathbf{E} f$ iff there exists $k \leq |M| \times 2^{|f|}$ with $M \models_k \mathbf{E} f$.

- 🌐 For the subset of LTL formulae that involves only temporal operators \diamond and \square , LTL model checking is NP-complete.
- 🌐 For this subset of LTL formulae, there exists a bound on k linear in the number of states and the size of the formula.

Bounds for LTL (cont.)

Definition (Loop Diameter)

A Kripke structure is lasso shaped if every path p starting from an initial state is of the form $u_p v_p^\omega$, where u_p and v_p are finite sequences of length less or equal to u and v , respectively. The loop diameter of M is defined as (u, v) .

Theorem

Given an LTL formula f and a lasso-shaped Kripke structure M , let the loop diameter of M be (u, v) , then $M \models \mathbf{E} f$ iff there exists $k \leq u + v$ with $M \models_k \mathbf{E} f$.

Part II:

Bounded Model Checking for LTL with Past

Note: (k, l) -loop here corresponds to $(k - 1, l)$ -loop in Part I. For easy cross-referencing with the original paper, we have not attempted to unify the notion.

- 🌐 The full propositional temporal logic (PTL) is LTL with past operators.

$$\begin{aligned}(\pi, i) \models \ominus f & \text{ iff } i > 0 \text{ and } (\pi, i - 1) \models f \\(\pi, i) \models \odot f & \text{ iff } i = 0 \text{ or } (\pi, i - 1) \models f \\(\pi, i) \models \diamond f & \text{ iff } \exists j, j \leq i. (\pi, j) \models f \\(\pi, i) \models \boxminus f & \text{ iff } \forall j, j \leq i. (\pi, j) \models f \\(\pi, i) \models f \mathcal{S} g & \text{ iff } \exists j, j \leq i. ((\pi, j) \models g \text{ and } \forall k, j < k \leq i. (\pi, k) \models f) \\(\pi, i) \models f \mathcal{T} g & \text{ iff } \forall j, j \leq i. ((\pi, j) \models g \text{ or } \exists k, j < k \leq i. (\pi, k) \models f)\end{aligned}$$

- 🌐 Every PTL formula can be converted into the negation normal form.

Extend the Translation without Loops

Let $k, i \in \mathbb{N}$ with $i \leq k$.

$$\llbracket \ominus f \rrbracket_k^i \triangleq \begin{cases} \text{false} & i = 0 \\ \llbracket f \rrbracket_k^{i-1} & i > 0 \end{cases}$$

$$\llbracket \odot f \rrbracket_k^i \triangleq \begin{cases} \text{true} & i = 0 \\ \llbracket f \rrbracket_k^{i-1} & i > 0 \end{cases}$$

$$\llbracket \diamond f \rrbracket_k^i \triangleq \bigvee_{j=0}^i \llbracket f \rrbracket_k^j$$

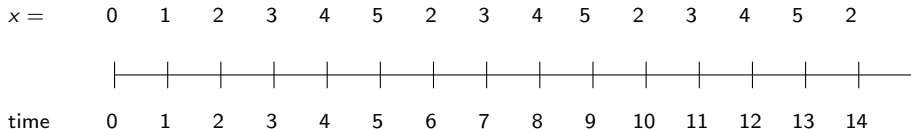
$$\llbracket \Box f \rrbracket_k^i \triangleq \bigwedge_{j=0}^i \llbracket f \rrbracket_k^j$$

$$\llbracket f \mathcal{S} g \rrbracket_k^i \triangleq \bigvee_{j=0}^i (\llbracket g \rrbracket_k^j \wedge \bigwedge_{n=j+1}^i \llbracket f \rrbracket_k^n)$$

$$\llbracket f \mathcal{T} g \rrbracket_k^i \triangleq \bigwedge_{j=0}^i (\llbracket g \rrbracket_k^j \vee \bigvee_{n=j+1}^i \llbracket f \rrbracket_k^n)$$

Extend the Translation with Loops


- 🌐 The extension is not straightforward.
- 🌐 For example, consider the path $01(2345)^\omega$ which can be seen as a $(6, 2)$ -loop.
 - ☀️ In the future case, the encoding of a specification is based on the idea that, for every time in the encoding, exactly one successor time exists.
 - ☀️ Past formulae do not enjoy the above property.
 - 👤 The predecessor of 2 may be 1 or 5.



The Solution: Intuition


- 🌐 The formula $\diamond(x = 2 \wedge \diamond(x = 3 \wedge \diamond(x = 4 \wedge (\diamond(x = 5))))))$ is true in all the occurrences of $x = 2$ after the fourth.
- 🌐 The key idea is that every formula has a finite discriminating power for events in the past.
- 🌐 When evaluated sufficiently far from the origin of time, a formula becomes unable to distinguish its past sequence from infinitely many other past sequences with a "similar" behavior.
- 🌐 The idea is then to collapse the undistinguishable versions of the past together into the same equivalence class.

Past Temporal Horizon

-  The **past temporal horizon** (PTH) $\tau_\pi(f)$ of a PTL formula f with respect to a (k, l) -loop π (with period $p = k - l$) is the smallest value $n \in \mathbb{N}$ such that






$$\forall i, l \leq i < k. ((\pi, i + np) \models f \text{ iff } (\forall n' > n. (\pi, i + n'p) \models f)).$$


PTH of a PTL Formula

-  The PTH $\tau(f)$ of a PTL formula f is defined as $\tau(f) \triangleq \max_{\tau \in \Pi} \tau_{\pi}(f)$ where Π is the set of all the paths which are (k, l) -loops for some $k > l \geq 0$.









Theorem

Let f and g be PTL formulae. Then, it holds that:

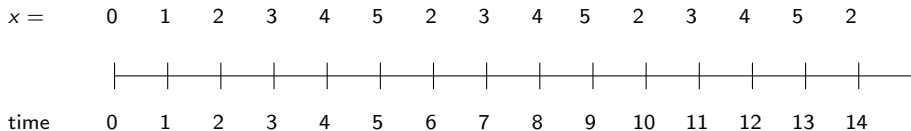
-  $\tau(p) = 0$, when $p \in A$ and $\tau(f) = \tau(\neg f)$;
-  $\tau(\circ f) \leq \tau(f)$, when $\circ \in \{\circ, \diamond, \square\}$;
-  $\tau(\circ f) \leq \tau(f) + 1$, when $\circ \in \{\ominus, \odot, \diamond, \square\}$;
-  $\tau(f \circ g) \leq \max(\tau(f), \tau(g))$, when $\circ \in \{\wedge, \vee, \mathcal{U}, \mathcal{R}\}$;
-  $\tau(f \circ g) \leq \max(\tau(f), \tau(g)) + 1$, when $\circ \in \{\mathcal{S}, \mathcal{T}\}$;


-  The PTH of a PTL formula is bounded by its structure regardless of the particular path π .


Borders and Intervals


-  We call
-  $\mathbf{LB}(n) \triangleq l + np$ the n -th left border of π ,
 -  $\mathbf{RB}(n) \triangleq k + np$ the n -th right border of π , and
 -  the interval $M(n) \triangleq [0, \mathbf{RB}(n))$ the n -th main domain of a (k, l) -loop.
-  We call
-  $\mathbf{LB}(f) \triangleq \mathbf{LB}(\tau(f))$ the left border of f ,
 -  $\mathbf{RB}(f) \triangleq \mathbf{RB}(\tau(f))$ the right border of f , and
 -  $M(f) \triangleq M(\tau(f))$ the main domain of f .


Borders and Intervals (cont.)



 **LB**(0) = 2

 **RB**(0) = 6

 **LB**(1) = 6

 **RB**(1) = 10

Projection of Points

- Let $i \in \mathbb{N}$.
- The projection of the point i in the n -th main domain of a (k, l) -loop is $\rho_n(i)$, defined as

$$\rho_n(i) \triangleq \begin{cases} i & i < \mathbf{RB}(n) \\ \rho_n(i - p) & \text{otherwise} \end{cases}$$

- The projection of the point i onto the main domain of f is defined as $\rho_f(i) \triangleq \rho_{\tau(f)}(i)$.

Projection of Intervals

- The projection of the interval $[a, b)$ onto the main domain of f is defined as $\rho_f([a, b)) \triangleq \rho_{\tau(f)}([a, b))$.

Lemma

For an open interval $[a, b)$,

$$\rho_n([a, b)) = \begin{cases} \emptyset & \text{if } a = b, \text{ else} \\ [a, b) & \text{if } b < \mathbf{RB}(n), \text{ else} \\ [\min(a, \mathbf{LB}(n)), \mathbf{RB}(n)) & \text{if } b - a \geq p, \text{ else} \\ [\rho_n(a), \rho_n(b)) & \text{if } \rho_n(a) < \rho_n(b), \text{ else} \\ [\rho_n(a), \mathbf{RB}(n)) \cup [\mathbf{LB}(n), \rho_n(b)) & \end{cases}$$

Extended Projection of Intervals

- An **extended intervals** is of the form $[a, b)$ where b is possibly less than a (or even it is equal to ∞).
- Let $[a, b)$ be an extended interval.
- The extended projection of $[a, b)$ onto the n -th main domain of a (k, l) -loop is defined as follows




$$\rho_n^*([a, b)) \triangleq \begin{cases} \rho_n^*([a, \max(a, \mathbf{RB}(n)) + p)) & b = \infty \\ \rho_n^*([a, b + p)) & b < a \\ \rho_n^*([a, b)) & \text{otherwise} \end{cases}$$

- As before, $\rho_f^*([a, b)) \triangleq \rho_{\tau(f)}^*([a, b))$.

Equivalent Counterparts

Theorem

For

-  any PTL formula f ,
-  any (k, l) -loop π , and
-  any extended interval $[a, b)$,

a point $i \in [a, b)$ such that $(\pi, i) \models f$ exists iff a point $i' \in \rho_f^*([a, b))$ exists such that $(\pi, i') \models f$.

Extend the Translation with Loops

- 🌐 The translation of a PTL formula on a (k, l) -loop π at time point i (with $k, l, i \in \mathbb{N}$ and $0 \leq l < k$) is a propositional formula inductively defined as follows.

$$\begin{aligned}
 {}_l \llbracket p \rrbracket_k^i &\triangleq p^{\rho_0(i)} \\
 {}_l \llbracket \neg p \rrbracket_k^i &\triangleq \neg p^{\rho_0(i)} \\
 {}_l \llbracket f \wedge g \rrbracket_k^i &\triangleq {}_l \llbracket f \rrbracket_k^{\rho_f(i)} \wedge {}_l \llbracket g \rrbracket_k^{\rho_g(i)} \\
 {}_l \llbracket f \vee g \rrbracket_k^i &\triangleq {}_l \llbracket f \rrbracket_k^{\rho_f(i)} \vee {}_l \llbracket g \rrbracket_k^{\rho_g(i)}
 \end{aligned}$$

Extend the Translation with Loops (cont.)

$$\begin{aligned}
 I[\diamond f]_k^i &\triangleq \bigvee_{j \in \rho_f^*([i, \infty))} I[f]_k^j \\
 I[\square f]_k^i &\triangleq \bigwedge_{j \in \rho_f^*([i, \infty))} I[f]_k^j \\
 I[f \mathcal{U} g]_k^i &\triangleq \bigvee_{j \in \rho_g^*([i, \infty))} (I[g]_k^j \wedge \bigwedge_{n \in \rho_f^*([i, j])} I[f]_k^n) \\
 I[f \mathcal{R} g]_k^i &\triangleq \bigwedge_{j \in \rho_g^*([i, \infty))} (I[g]_k^j \vee \bigvee_{n \in \rho_f^*([i, j])} I[f]_k^n) \\
 I[\ominus f]_k^i &\triangleq i > 0 \wedge I[f]_k^{\rho_f(i-1)} \\
 I[\odot f]_k^i &\triangleq i = 0 \vee I[f]_k^{\rho_f(i-1)} \\
 I[\diamond f]_k^i &\triangleq \bigvee_{j \in \rho_f^*([0, i])} I[f]_k^j \\
 I[\square f]_k^i &\triangleq \bigwedge_{j \in \rho_f^*([0, i])} I[f]_k^j \\
 I[f \mathcal{S} g]_k^i &\triangleq \bigvee_{j \in \rho_g^*([0, i])} (I[g]_k^j \wedge \bigwedge_{n \in \rho_f^*([j, i])} I[f]_k^n) \\
 I[f \mathcal{T} g]_k^i &\triangleq \bigwedge_{j \in \rho_g^*([0, i])} (I[g]_k^j \vee \bigvee_{n \in \rho_f^*([j, i])} I[f]_k^n)
 \end{aligned}$$

Correctness of the Translation

Theorem

For any PTL formula f , a (k, l) -loop path π in M such that $\pi \models f$ exists iff $\llbracket M \rrbracket_k \wedge _l L_k \wedge _l \llbracket f \rrbracket_k^0$ is satisfiable.