Motivation

Overview

Overview

1. Introduction

Overview

2.1 Preliminaries: Boolean Transition System

- A Boolean Transition System $S = (X, I, T)$ consists of
  - Set of boolean variables X
  - A conjunction representing the initial state I
  - A propositional formula T over variables in X and $X' = \{x \in X \mid x' \in X'\}$, called Transition Relation

- States in S are cubes containing each variable from X with a boolean valuation of it

  ➔ Finite number of states: $2^{|X|}$

- Transitions @Todo

2.1 Preliminaries: Formulas

- Given a formula φ over X, we get a primed formula φ' by replacing each variable with its corresponding variable in X'

- A literal is a variable or ist negation
- A cube is a conjunction of literals
- A clause is a disjunction of literals
  - ➔Negation of a cube is a clause and vice versa

- A Safety Property P is a formula over X that should be satisfiable by every state reachable from I
  - ➔$\bar{P}$ being a set of bad states

2.2 Algorithm: Overview

- PDR on hardware checks if states in $\bar{P}$ are reachable from I

- For that it uses cubes of clauses, called Frames
  - Frame F_i represents an over-approximation of reachable states in at most i transitions from I

- PDR maintains sequence of frames $[F_0, F_1, \ldots, F_k]$, called trace

2.2 Algorithm: Pseudo-Code

procedure PDR-PROVE(I, T, P)
    check for 0-counter-example
    $trace.push(new\ frame(I))$

    loop
        while $\exists$ cube c, s.t. $trace.last() \land T \land c'$ is SAT and $c \Rightarrow \bar{P}$ **do**
            recursively block proof-obligation(c, trace.size() - 1)
            and strengthen the frames of the trace.
            if a proof-obligation(p, 0) is generated **then**
                return false

        $F_{k+1} = new\ frame(P)$
        for all clause c $\in trace.last()$ **do**
            if $trace.last() \land T \land \bar{c}'$ is UNSAT **then**
                $F_{k+1} = F_{k+1} \land c$
        if $trace.last() == F_{k+1}$ **then**
            return true
        $trace.push(F_{k+1})$

2.2 Algorithm: Pseudo-Code

procedure PDR-PROVE(I, T, P)
  check for 0-counter-example
  $trace.push(new\ frame(I))$

  loop
    while $\exists$ cube c, s.t. $trace.last() \wedge T \wedge c'$ is SAT and $c \Rightarrow \bar{P}$ **do**
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        $F_{k+1} = F_{k+1} \wedge c$
    if $trace.last() == F_{k+1}$ **then**
      return true
    $trace.push(F_{k+1})$

2.2 Algorithm: Checking for 0-Counter-Example

- Is $I \land \bar{P}$ satisfiable?

  - ➔ If satisfiable:
    - Algorithm terminates and returns that a bad state is reachable

  - ➔ If unsatisfiable:
    - Algorithm initializes the first frame in the trace: $F_0 = I$ and continues

2.2 Algorithm: Pseudo-Code

```
procedure PDR-PROVE(I, T, P)
    check for 0-counter-example
    trace.push(new frame(I))

                              Next Transition Phase
    loop
        while ∃ cube c, s.t. trace.last() ∧ T ∧ c' is SAT and c ⇒ P̄ do
            recursively block proof-obligation(c, trace.size() - 1)
            and strengthen the frames of the trace.
            if a proof-obligation(p, 0) is generated then
                return false

        F_{k+1} = new frame(P)
        for all clause c ∈ trace.last() do
            if trace.last() ∧ T ∧ c̄' is UNSAT then
                F_{k+1} = F_{k+1} ∧ c
        if trace.last() == F_{k+1} then
            return true
        trace.push(F_{k+1})
```

2.2 **Algorithm:** Next Transition Phase

- Checking if the next state is a good state:
  - Let $[F_0, F_1, \ldots, F_k]$ be the current trace
  - Is $F_k \wedge T \wedge \overline{P'}$ satisfiable?

➔ If unsatisfiable:
- Continue with the next phase

2.2 Algorithm: Next Transition Phase

- Checking if the next state is a good state

  - Let $[F_0, F_1, \dots, F_k]$ be the current trace
  - Is $F_k \land T \land \overline{P'}$ satisfiable?

    → If satisfiable:

    - Take satisfying assignment $\vec{x} = \left\{x_1, x_2, \dots, x_{|X|}, x'_1, x'_2, \dots, x'_{|X'|}\right\}$
    - The algorithm gets new bad state: $b = x_1 \land x_2 \land \dots \land x_{|X|}$
    - Construct the tuple $t = (b, k)$, called proof-obligation

2.2 Algorithm: Pseudo-Code

procedure PDR-PROVE(I, T, P)
  check for 0-counter-example
  $trace.push(new\ frame(I))$

  loop
    while $\exists$ cube c, s.t. $trace.last() \wedge T \wedge c'$ is SAT and $c \Rightarrow \bar{P}$ **do**
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    if $trace.last() == F_{k+1}$ **then**
      return true
    $trace.push(F_{k+1})$

Blocking-Phase

```
loop
    while ∃ cube c, s.t. trace.last() ∧ T ∧ c' is SAT and c ⇒ P̄ do
        recursively block proof-obligation(c, trace.size() - 1)
        and strengthen the frames of the trace.
        if a proof-obligation(p, 0) is generated then
            return false
```

2.2 Algorithm: Blocking-Phase

Note: useful to have
Piece of pseudo-code?

- Proving that new bad states are not reachable

➢ If there are proof-obligations:
  - Algorithm takes proof-obligation (b, i)
  - Tries to block bad state b by checking $F_{i-1} \land T \land b'$ for satisfiability

➔ If satisfiable:
  - Frame F_{i-1} is not strong enough to block b
  - Take satisfying assignment $\vec{x} = \{x_1, x_2, \ldots, x_{|X|}, x_1', x_2', \ldots, x_{|X'|}'\}$
  - The algorithm gets another new bad state: $c = x_1 \land x_2 \land \ldots \land x_{|X|}$
  - Construct new proof-obligation $u = (c, i - 1)$

2.2 Algorithm: Blocking-Phase

- Proving that new bad states are not reachable

➢ If there are proof-obligations:

  - Algorithm takes proof-obligation (b, i)
  - Tries to block bad state b by checking $F_{i-1} \wedge T \wedge b'$ for satisfiability

    ➔ If unsatisfiable:

      - Algorithm strenghthens F_i with $\bar{b}$

        ➔ $F_i = F_i \wedge \bar{b}$
      - Blocking bad state b at F_i

2.2 Algorithm: Blocking-Phase

- This continues recursively until:
  - There are no proof-obligations left

    ➔Algorithm continues with the next phase

  - A proof-obligation $(d, 0)$ is created

    ➔Proving that a bad state can be reached, terminating the algorithm

2.2 Algorithm: Pseudo-Code

procedure PDR-PROVE(I, T, P)
  check for 0-counter-example
  $trace.push(new\ frame(I))$

  loop
    while $\exists$ cube c, s.t. $trace.last() \wedge T \wedge c'$ is SAT and $c \Rightarrow \bar{P}$ **do**
      recursively block proof-obligation(c, trace.size() - 1)
      and strengthen the frames of the trace.
      if a proof-obligation(p, 0) is generated **then**
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    $F_{k+1} = new\ frame(P)$
    for all clause c $\in trace.last()$ **do**
      if $trace.last() \wedge T \wedge \bar{c}'$ is UNSAT **then**
        $F_{k+1} = F_{k+1} \wedge c$
    if $trace.last() == F_{k+1}$ **then**
      return true
    $trace.push(F_{k+1})$

Propagation-Phase

2.2 **Algorithm:** Propagation-Phase

- Propagating learned information

➢ After no proof-obligations are left, the algorithm initzializes new frame $F_{k+1} = \mathrm{P}$

➢ Algorithm passes on learned informations, e.g, which states are blocked:

- For each clause c in F_k check: $F_k \wedge T \wedge \bar{c}'$ for satisfiability

  ➔ If satisfiable:

  - Do nothing, continue with next clause

2.2 **Algorithm:** Propagation-Phase

- Propagating learned information

➢ After no proof-obligations are left, the algorithm initzializes new frame $F_{k+1} = \mathrm{P}$

➢ Algorithm passes on learned informations, e.g, which states are blocked:

- For each clause c in F_k check: $F_k \land T \land \bar{c}'$ for satisfiability

➔ If unsatisfiable:

  - Algorithm strengthens F_{k+1} with c

    ➔ $F_{k+1} = F_{k+1} \land c$

2.2 Algorithm: Propagation-Phase

- Check for termination

➢ After all clauses have been tested, algorithm checks if $F_k \equiv F_{k+1}$

  - If so, the algorithm has found a fixpoint and terminates

    ➔ No states of $\bar{P}$ are reachable

  - If not, the algorithm continues with a new Next Transition Phase

2.2 Algorithm: Propagation-Phase

- Check for termination

➢ After all clauses have been tested, algorithm checks if $F_k \equiv F_{k+1}$

- If so, the algorithm has found a fixpoint and terminates

  ➔ No states of $\bar{P}$ are reachable

- If not, the algorithm continues with a new Next Transition Phase

➢ Algorithm repeats the three phases until a fixpoint is found, or a proof-obligation $(d, 0)$ is created

2.2 Algorithm: Pseudo-Code TEMPLATE

```
procedure PDR-PROVE(I, T, P)
    check for 0-counter-example
    trace.push(new frame(I))

    loop
        while ∃ cube c, s.t. trace.last() ∧ T ∧ c′ is SAT and c ⇒ P̄ do
            recursively block proof-obligation(c, trace.size() - 1)
            and strengthen the frames of the trace.
            if a proof-obligation(p, 0) is generated then
                return false

        F_{k+1} = new frame(P)
        for all clause c ∈ trace.last() do
            if trace.last() ∧ T ∧ c̄′ is UNSAT then
                F_{k+1} = F_{k+1} ∧ c
        if trace.last() == F_{k+1} then
            return true
        trace.push(F_{k+1})
```

2.3 Example

2.4 Possible Improvements

- Blocking one state at a time is ineffective:
  - Generalize blocked states

    ➔ Eliminate insignificant cubes from states, that are not used by UNSAT-cores

- Ternary Simulation to reduce proof-obligations:
  - Extend binary variables with a new value: unknown
  - Check state variables of proof-obligations for importance

    ➔ Eliminate unimportant state variables

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3.1 Preliminaries

- To use PDR on software, we need to lift the algorithm from propositional-logic based systems to first-order logic based systems

3.1 Preliminaries

- To use PDR on software, we need to lift the algorithm from propositional-logic based systems to first-order logic based systems

- For that we first need new definitions

3.1 Preliminaries: Control Flow Graph

- A control flow graph (CFG) $A = (X, L, G, \ell_0, \ell_E)$ is a graph consisting of
  - A finite set of variables X
  - A finite set of locations L
  - A finite set of transitions $G \subseteq L \times FO \times L$
    - ➔ FO being a quantifier free first-order logic formula over variables in X and $X' = \{x \in X \mid x' \in X'\}$
  - An initial location $\ell_0 \in L$
  - An error location $\ell_E \in L$

3.1 Preliminaries: Control Flow Graph

- The transition formula $T_{\ell_1 \to \ell_2}$ from location ℓ_1 to location ℓ_2 is defined as:
  - $$T_{\ell_1 \to \ell_2} = \begin{cases} (\ell_1, t, \ell_2), & (\ell_1, t, \ell_2) \in G \\ false, & otherwise \end{cases}$$

3.1 Preliminaries: Control Flow Graph

- The transition formula $T_{\ell_1 \to \ell_2}$ from location ℓ_1 to location ℓ_2 is defined as:

  - $T_{\ell_1 \to \ell_2} = \begin{cases} (\ell_1, t, \ell_2), & (\ell_1, t, \ell_2) \in G \\ false, & otherwise \end{cases}$

➔ Global Transition Formula $T = \bigvee_{(\ell_1, t, \ell_2) \in G} T_{\ell_1 \to \ell_2}$

3.2 Lifted Algorithm: Pseudo-Code

procedure PDR-PROVE(I, T, P)
  check for 0-counter-example
  $trace.push(new\ frame(I))$

  loop
    while $\exists$ cube c, s.t. $trace.last() \wedge T \wedge c'$ is SAT and $c \Rightarrow \bar{P}$ **do**
      recursively block proof-obligation(c, trace.size() - 1)
      and strengthen the frames of the trace.
      if a proof-obligation(p, 0) is generated **then**
        return false

    $F_{k+1} = new\ frame(P)$
    for all clause c $\in trace.last()$ **do**
      if $trace.last() \wedge T \wedge \bar{c}'$ is UNSAT **then**
        $F_{k+1} = F_{k+1} \wedge c$
    if $trace.last() == F_{k+1}$ **then**
      return true
    $trace.push(F_{k+1})$

procedure LIFTED-PDR-PROVE(L, G)
  check for 0-counter-example
  $\ell_0.trace.push(new\ frame(true))$
  for all $\ell \in L \backslash \{\ell_0, \ell_E\}$ **do**
    $\ell.trace.push(new\ frame(false))$
  $level := 0$

  loop
    for all $\ell \in L \backslash \{\ell_E\}$ **do**
      $\ell.trace.push(new\ frame(true))$
    $level := level + 1$
    get initial proof-obligations

    while $\exists$ proof-obligation (t, ℓ, i), **do**
      Recursively block proof-obligation
      if a proof-obligation$(p, \ell, 0)$ is generated **then**
        return false

    for $i = 0;\ i \leq level;\ i := i + 1$ **do**
      for $\ell \in L \backslash \{l_E\}$ **do**
        if $\ell.trace[i] \neq \ell.trace[i-1]$ **then**
          break
      return true

3.2 Lifted Algorithm: Pseudo-Code

```
procedure PDR-PROVE(I, T, P)
    check for 0-counter-example
    trace.push(new frame(I))

    loop
        while ∃ cube c, s.t. trace.last() ∧ T ∧ c′ is SAT and c ⇒ P̄ do
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        F_{k+1} = new frame(P)
        for all clause c ∈ trace.last() do
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        if trace.last() == F_{k+1} then
            return true
        trace.push(F_{k+1})
```

```
procedure LIFTED-PDR-PROVE(L, G)
    check for 0-counter-example
    ℓ_0.trace.push(new frame(true))
    for all ℓ ∈ L\{ℓ_0, ℓ_E} do
        ℓ.trace.push(new frame(false))
    level := 0

    loop
        for all ℓ ∈ L\{ℓ_E} do
            ℓ.trace.push(new frame(true))
        level := level + 1
        get initial proof-obligations

        while ∃ proof-obligation (t, ℓ, i), do
            Recursively block proof-obligation
            if a proof-obligation(p, ℓ, 0) is generated then
                return false

        for i = 0; i ≤ level; i := i + 1 do
            for ℓ ∈ L\{l_E} do
                if ℓ.trace[i] ≠ ℓ.trace[i − 1] then
                    break
            return true
```

3.2 Lifted Algorithm: Checking for 0-Counter-Example

- Is $\ell_0 = \ell_E$?

➔ Yes:

- Algorithm terminates, returning that ℓ_E is reachable

➔ No:

- Algorithm continues

3.2 Lifted Algorithm: Pseudo-Code

procedure PDR-PROVE(I, T, P)
  check for 0-counter-example
  $trace.push(new\ frame(I))$

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    while $\exists$ cube c, s.t. $trace.last() \wedge T \wedge c'$ is SAT and $c \Rightarrow \bar{P}$ **do**
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procedure LIFTED-PDR-PROVE(L, G)
  check for 0-counter-example
  $\ell_0.trace.push(new\ frame(true))$
  for all $\ell \in L \backslash \{\ell_0, \ell_E\}$ **do**
    $\ell.trace.push(new\ frame(false))$
  $level := 0$

  loop
    for all $\ell \in L \backslash \{\ell_E\}$ **do**
      $\ell.trace.push(new\ frame(true))$
    $level := level + 1$
    get initial proof-obligations

    while $\exists$ proof-obligation (t, ℓ, i), **do**
      Recursively block proof-obligation
      if a proof-obligation$(p, \ell, 0)$ is generated **then**
        return false

    for $i = 0;\ i \leq level;\ i := i + 1$ **do**
      for $\ell \in L \backslash \{l_E\}$ **do**
        if $\ell.trace[i] \neq \ell.trace[i-1]$ **then**
          break
      return true

3.2 Lifted Algorithm: Pseudo-Code

procedure PDR-PROVE(I, T, P)
  ~~check for 0-counter-example~~
  $trace.push(new\ frame(I))$

  loop
    while $\exists$ cube c, s.t. $trace.last() \wedge T \wedge c'$ is SAT and $c \Rightarrow \bar{P}$ **do**
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  $\ell_0.trace.push(new\ frame(true))$
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    $\ell.trace.push(new\ frame(false))$
  $level := 0$

  loop
    for all $\ell \in L \backslash \{\ell_E\}$ **do**
      $\ell.trace.push(new\ frame(true))$
    $level := level + 1$
    get initial proof-obligations

    while $\exists$ proof-obligation (t, ℓ, i), **do**
      Recursively block proof-obligation
      if a proof-obligation$(p, \ell, 0)$ is generated **then**
        return false

    for $i = 0;\ i \leq level;\ i := i + 1$ **do**
      for $\ell \in L \backslash \{l_E\}$ **do**
        if $\ell.trace[i] \neq \ell.trace[i-1]$ **then**
          break
      return true

3.2 Lifted Algorithm: Local Traces

- There is no global trace $[F_0, F_1, \dots, F_k]$

  ➔ Every location $\ell \in L \setminus \{\ell_E\}$ has its own local trace $[F_{0,\ell}, F_{1,\ell}, \dots, F_{k,\ell}]$

  ➔ Lifted frames are cubes of first-order formulas

  ➔ @ToDo, explain changes to proofobligations

3.2 Lifted Algorithm: Pseudo-Code

procedure PDR-PROVE(I, T, P)
~~check for 0-counter-example~~
$trace.push(new\ frame(I))$

loop
while $\exists$ cube c, s.t. $trace.last() \wedge T \wedge c'$ is SAT and $c \Rightarrow \bar{P}$ **do**
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if a proof-obligation(p, 0) is generated **then**
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$F_{k+1} = new\ frame(P)$
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$F_{k+1} = F_{k+1} \wedge c$
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$trace.push(F_{k+1})$

procedure LIFTED-PDR-PROVE(L, G)
check for 0-counter-example
$\ell_0.trace.push(new\ frame(true))$
for all $\ell \in L \backslash \{\ell_0, \ell_E\}$ **do**
$\ell.trace.push(new\ frame(false))$
$level := 0$

loop
for all $\ell \in L \backslash \{\ell_E\}$ **do**
$\ell.trace.push(new\ frame(true))$
$level := level + 1$
get initial proof-obligations

while $\exists$ proof-obligation (t, ℓ, i), **do**
Recursively block proof-obligation
if a proof-obligation$(p, \ell, 0)$ is generated **then**
return false

for $i = 0;\ i \leq level;\ i := i + 1$ **do**
for $\ell \in L \backslash \{l_E\}$ **do**
if $\ell.trace[i] \neq \ell.trace[i-1]$ **then**
break
return true

3.2 Lifted Algorithm: Initialization

- Initialize each local frames:
  - $F_{0,\ell} = \begin{cases} true, & \ell = \ell_0 \\ false, & otherwise \end{cases}$

3.2 Lifted Algorithm: Pseudo-Code

procedure PDR-PROVE(I, T, P)
  check for 0-counter-example
  $trace.push(new\ frame(I))$

  loop
    while $\exists$ cube c, s.t. $trace.last() \wedge T \wedge c'$ is SAT and $c \Rightarrow \bar{P}$ **do**
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      if a proof-obligation(p, 0) is generated **then**
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    $F_{k+1} = new\ frame(P)$
    for all clause c $\in trace.last()$ **do**
      if $trace.last() \wedge T \wedge \bar{c}'$ is UNSAT **then**
        $F_{k+1} = F_{k+1} \wedge c$
    if $trace.last() == F_{k+1}$ **then**
      return true
    $trace.push(F_{k+1})$

procedure LIFTED-PDR-PROVE(L, G)
  check for 0-counter-example
  $\ell_0.trace.push(new\ frame(true))$
  for all $\ell \in L \backslash \{\ell_0, \ell_E\}$ **do**
    $\ell.trace.push(new\ frame(false))$
  $level := 0$

  loop
    for all $\ell \in L \backslash \{\ell_E\}$ **do**
      $\ell.trace.push(new\ frame(true))$
    $level := level + 1$
    get initial proof-obligations

    while $\exists$ proof-obligation (t, ℓ, i), **do**
      Recursively block proof-obligation
      if a proof-obligation$(p, \ell, 0)$ is generated **then**
        return false

    for $i = 0;\ i \leq level;\ i := i + 1$ **do**
      for $\ell \in L \backslash \{l_E\}$ **do**
        if $\ell.trace[i] \neq \ell.trace[i-1]$ **then**
          break
      return true

3.2 Lifted Algorithm: Next Level Phase

- Initializing the next level:

  - Let k be the current level

    ➔ Every location $\ell \in L \setminus \{\ell_E\}$ has trace $[F_{0,\ell}, \dots, F_{k,\ell}]$

  - Algorithm initzializes new level k+1 for all locations $\ell \in L \setminus \{\ell_E\}$

    ➔ Adding new frame $F_{k+1,\ell} = true$

3.2 **Lifted Algorithm:** Next Level Phase

- Initializing the next level:
  - Let k be the current level
    - ➔ Every location $\ell \in L \setminus \{\ell_E\}$ has trace $[F_{0,\ell}, \dots, F_{k,\ell}]$
  - Additionally, algorithm computes initial proof-obligations:
    - Because of the structure of CFAs, we always know the transitions to ℓ_E
      - ➔ Check G for transitions of the form (ℓ, t, ℓ_E)
      - ➔ For each transition, get proof-obligation (t, ℓ, k)
      - ➔ @ToDo explain lifted proof-obligations

3.3 Example

3.4 Possible Improvements

Overview

4.1 Implementation

4.2 Implemented Improvements

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5.1 Data Comparison

5.2 Discussion

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6. Related Work

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7.1 Further Improvements

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