Combining SAT solving with Integer Programming for Inductive Verification of Lustre Programs

3rd December 2004

Outline

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1. Introduction
   - The Lustre programming language
   - Temporal induction
   - Propositional logic
2. Verification
   - The decision procedure (SAT + Integer Programming)
   - Variants of the basic algorithm
3. Analysis
   - Test plan
   - Comparison with Luke

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Lustre

```
node Counter ( X : bool ) returns ( C : int );
    var PC : int;
let
    PC = 0 → pre C;
    C = if X then PC + 1 else PC;
tel

node Prop( X : bool ) returns ( OK : bool );
let
    OK = Counter( X ) ≥ 0;
tel
```

Verification by induction

- Prove property valid in initial time point

- Assume property valid at time n, prove property valid at time $n+1$

- Induction incomplete for unbounded integers
- Lustre with unbounded integers Turing-complete

Verification by induction

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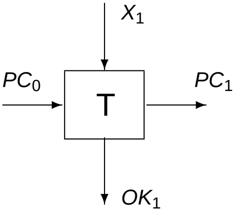

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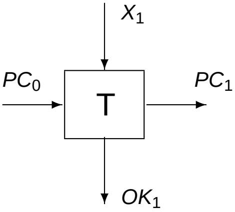

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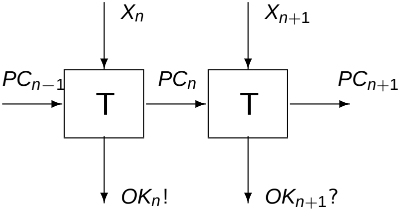

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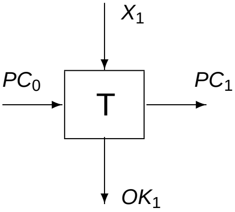

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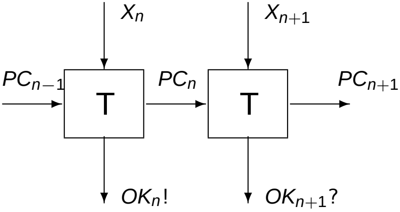

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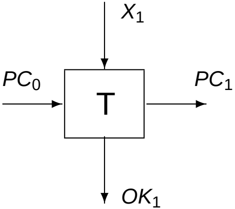

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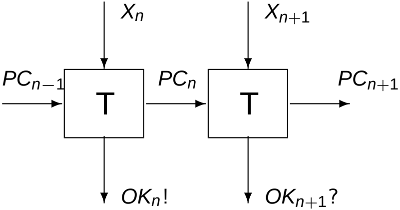

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Propositional logic

Example

$$\{p, q\}$$

Short introduction

- A clause is a set of literals. At least one literal must be true.
- A formula is a set of clauses. All clauses must be true.

Propositional logic

Example

$$\{p, q\}$$
$$\{p, \neg q, r\}$$
$$\{\neg q, \neg r\}$$

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SAT solving

Example

$$\{p, q\}$$
$$\{p, \neg q, r\}$$
$$\{\neg q, \neg r\}$$

Search for a satisfying variable assignment

- Choose a variable, and assign at value to it
- Infer consequences
- Repeat until all variables assigned, or a *conflict* found

SAT solving

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$$\{\mathbf{p}, q\}$$
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$$p = \perp$$

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A small example

The formula in CNF

A simple counter

node Counter() **returns** (OK : bool);
    var C : int;
let
    C = 0 $\rightarrow$ **pre** C + 1;
    OK = C $\geq$ 0;
tel

- Translate to logic
- Assume property invalid
- Is there a variable assignment satisfying the formula?

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$$\{\ C_1 \leq 0\ \}$$
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Step 1: Create *in-place* variables

Create a fresh propositional variable for each constraint

$$p_1 \mapsto C_1 \leq 0$$
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And replace all constraints with their in-place variable.

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Step 2: Run through SAT solver

A SAT model is returned

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Run constraint problem trough ILP solver

$$\begin{array}{ll} (1) & C_1 \leq 0 \\ (2) & C_1 \geq 0 \\ (3) & C_1 < 0 \\ (4) & C_1 \leq -1 \end{array}$$

Constraint 2 and 4 contradict each other. Add explanation to SAT problem. Goto step 2.

The basic algorithm

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Step 2: Run through SAT solver

The formula is unsatisfiable

$$\Rightarrow$$

The original formula is unsatisfiable.

The property is valid in first time point

The basic algorithm

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The algorithm

φ is a propositional + constraints formula

loop
    $\mathbb{I}_p \leftarrow \text{Psat}(\varphi)$
    if $\mathbb{I}_p = \emptyset$ **then**
        return *unsatisfiable*
    else
        $C \leftarrow \text{generate}(\varphi, \mathbb{I}_p)$
        if $\text{Csat}(C)$ **then**
            return *satisfiable*
        else
            $\varphi \leftarrow \varphi \cup \text{explain}(C)$
        end if
    end if
end loop

Other ideas

- Check *partial* SAT models
  Everytime the SAT solver assigns an in-place variable, check the constraint problem generated by the set of assigned in-place variables.
- Several methods of creating explanations
  Several algorithms exist. Finding multiple explanations.
- Preprocessing
  Find contradictions in the set of constraints before the decision procedure starts.
- Faster (incomplete) integer programming procedure
  Use a cheap procedure that can find the most commonly occuring contradictions in constraint problems.

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Rantanplan

- Implements all ideas outlined here
- Based on Luke
- SAT solver changed to MiniSat
- Integer programming package GLPK

Test plan

Aim

- What combinations of ideas work well?
- How do these ideas compare to Luke and NBAC?

- Find “good” combinations of ideas
- Compare these to Luke & NBAC

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Test suite

Every test should be verifyable by every tool in the tests.

- The test suite consists of 137 tests.
- Some of these are invalid properties. Can not be verified in NBAC.
- Some have too weak properties. Can not be verified in Rantanplan.
- Some used unbounded integers. Can not be verified in Luke.
- Some uses modulo. Can not be verified in NBAC.
- Some generates constraint problems where branch-and-bound does not terminate. Can not be verified in Rantanplan.

We are left with 72 tests.

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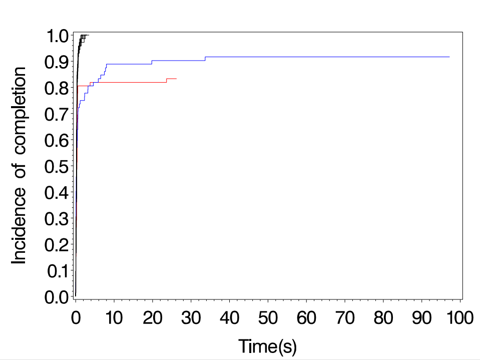
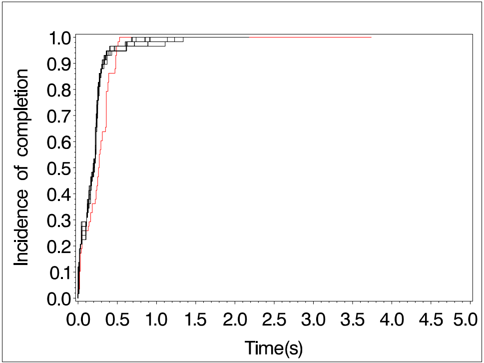
Comparisons

Tests of the 11 best variants against Luke and NBAC



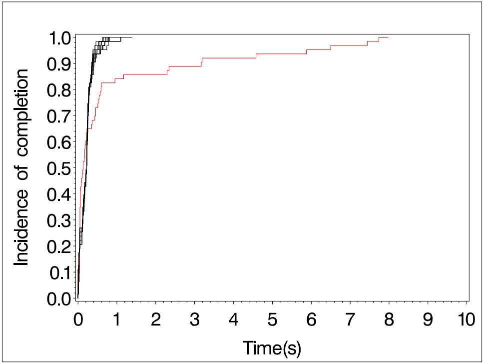
Comparison with Luke

Tests with execution time $>$ 10s in Luke removed (58 remaining)



Comparison with NBAC

Tests with execution time $>$ 10s in NBAC removed (63 remaining)



Summary

- Rantanplan competitive on the test suite used here
- The branch-and-bound algorithm is incomplete
- For longer induction depth (e.g. invalid properties w. long counter-examples), Luke outperforms Rantanplan

- Outlook
  - Complete integer programming procedure
  - Improvements for larger induction depths
  - Invariant strengthening