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A Dynamic Constraint-Based BMC Strategy For Generating Counterexamples

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Outline

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DPVS, informal presentation

The Flasher Manager Application

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Formal proof methods that ensure the ***absence of all bugs*** are **too expensive**, or require manual efforts

→ **Automatic generation of counterexamples** violating a property on a limited model of the program is very useful

→ **Challenge**: finding bugs for **realistic time periods** for **real time applications**

Key points of DPVS

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- **Context: constraint-programming framework** for bounded program verification
- A **new search strategy** for verifying a restricted class of Java or C programs:

  → **Non sequential dynamic exploration of the CFG**

Constraint-Programming Framework

Constraint-Programming Framework For Bounded Program Verification

- Falsification of a given property is checked for a given **bound**
- Mainly involves three steps:
  1. The **program is unwound k** times,
  2. An annotated and simplified **CFG** (Control Flow Graph) is built
  3. **Different exploration strategies** of the CFG
     - → **CPBPV: Depth first dynamic exploration** of the CFG
     - → **DPVS: Non-sequential exploration** of the CFG
- Generation of **counterexamples** (**= input values for a test cases)** violating a property on a limited model

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CP versus BMC

Bounded Model Checking

- Falsification of a given property is checked for a given **bound**
- Mainly involves three steps:
  1. The **program is unwound k** times,
  2. The unwound program and the property are translated into a propositional formula ϕ
     ϕ **is satisfiable iff there exists a counterexample of depth less than** k
  3. **A SAT-solver or SMT-solver** is used for checking the satisfiability of ϕ
- Generation of **execution traces** ($\neq$ input values for a test cases) violating a property on a limited model

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Building the constraint store: principle

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- Each **expression** is mapped to a **constraint**:
  ρ transforms program expressions into constraints
- SSA-like **variable renaming**: σ[**v**] is the current renaming of variable **v**
- JML :
  - **forall i** $\longrightarrow$ conjunction of conditions
  - **exist i** $\longrightarrow$ disjunction of conditions

  (**i** has bounded values)

Building the constraint store ...

- **scalar assignment**
  Program
  ```
  x=x+1; y=x*y; x=x+y;
  ```
  Constraints
  $\{x_1 = x_0 + 1, y_1 = x_1 * y_0, x_2 = x_1 * y_1\}$
- **array assignment**
  Program (a.length=8)
  ```
  a[i] = x;
  ```
  Constraints
  $\{a_1[i_0] = x_0, i_0 \neq 0 \rightarrow a_1[0] = a_0[0],$
  $i_0 \neq 1 \rightarrow a_1[1] = a_0[1], ..., i_0 \neq 7 \rightarrow a_1[7] = a_0[7]\}$

  guard $\rightarrow$ *body* is a **guarded constraint**
  $a[i] = x$ is the **element constraint**: i and x are constrained variables whose values may be unknown

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Solving the constraints

- **Dedicated solvers**
  - **ad-hoc simplifier** : trivial simplifications and calculus on constants
  - **linear solver** (LP algorithm) + **MIP solver**
  - **Boolean solver** (SAT solver)
    (Boolean relaxation of the **non linear** constraints)
  - **CSP solver** : used if none of the other solver did find an inconsistency

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Different exploration strategies

- **CPBPV: Depth first dynamic exploration** of the CFG

  → *Postcondition is used very late* because of the variables renaming

- **DPVS: Non-sequential exploration** of the CFG

  → *Starts from the postcondition and jumps to the locations where the variables are assigned*

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Non sequential dynamic constraint based exploration strategy

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Why can we do it ?

Essential observation

When the program is in an SSA-like form, **a path can be built in a non-sequential dynamic way**

CFG does not have to be explored in a top down (or bottom up) way: compatible blocks can just be collected in a non-deterministic way

Non sequential dynamic constraint based exploration strategy

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Why does it pay off

- **DPVS starts from the post-condition** and dynamically collects program blocks which involve **variables of the post-condition**
- Collecting as much information as possible on a given variable

  → **enforces the constraints on its domain and reduces the search space**

- **Constraint solving is integrated with state exploration** to prune the state space as early as possible

A small exemple


```
void foo(int a, int b)
int c, d, e, f;
if(a >= 0) {
      if(a < 10) {f = b - 1;}
      else {f = b - a; }
      c = a;
      if(b >= 0) {d = a; e = b;}
      else {d = a; e = -b;}  }
  else {
      c = b; d = 1; e = -a;
      if(a > b) {f = b + e + a;}
      else {f = e * a - b;}  }
  c = c + d + e;
  assert(c >= d + e); // property p1
  assert(f >= -b * e); // property p2
```


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A small exemple(continued)

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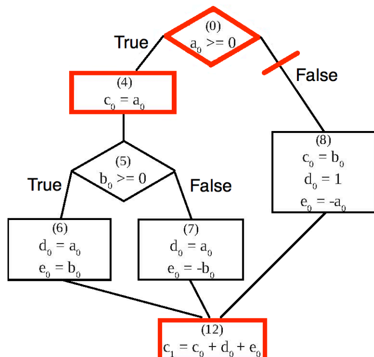



```
void foo(int a, int b)
int c, d, e, f;
if(a >= 0) {
      if(a < 10) {f = b - 1;}
      else {f = b - a; }
      c = a;
      if(b >= 0) {d = a; e = b;}
      else {d = a; e = -b;}  }
  else {
      c = b; d = 1; e = -a;
      if(a > b) {f = b + e + a;}
      else {f = e * a - b;}  }
  c = c + d + e;
  assert(c >= d + e); // property p1
  assert(f >= -b * e); // property p2
```

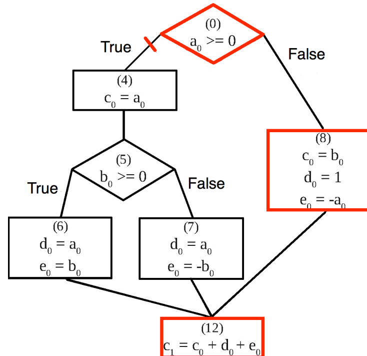
To prove property p_1, select node (12), then select node (4)

$\rightarrow$ the condition in node (0) must be true

$S = \{c_1 < d_0 + e_0 \wedge c_1 = c_0 + d_0 + e_0 \wedge c_0 = a_0 \wedge a_0 \geq 0\}$

$= \{a_0 < 0 \wedge a_0 \geq 0\}$ **... inconsistent**

A small exemple(continued)



Select node (8) $\rightarrow$ condition in node (0) must be false

$$S = \{c_1 < d_0 + e_0 \wedge c_1 = c_0 + d_0 + e_0 \wedge c_0 = b_0 \wedge a_0 < 0 \wedge d_0 = 1 \wedge e_0 = -a_0\}$$

$$= \{a_0 < 0 \wedge b_0 < 0\}$$

Solution $\{a_0 = -1, b_0 = -1\}$

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DPVS, pre-processing

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Pre-processing

1. P is **unwound k times** $\rightarrow \; P_{uw}$
2. $P_{uw} \rightarrow \; DSA_{P_{uw}}$, **Dynamic Single Assignment form** (each variable is assigned exactly once on each program path)
3. $DSA_{P_{uw}}$ is **simplified according to the specific property** *prop* by applying slicing techniques
4. Domains of all variables are filtered by **propagating constant values** along G, the simplified CFG

DPVS, Algorithm (scheme)

$S \leftarrow$ negation of *prop % constraint store*
$Q \leftarrow$ variables in *prop % queue of variables*

- IF $Q \neq \emptyset, v \leftarrow$ POP(Q)
  - **Search for a program block $PB(v)$ where v is defined**
    PUSH(Q, new_var), $new_var =$ new variables ($\neq$ input variables) of $PB(v)$
    $S \leftarrow S \cup$ {definition of v and conditions required to reach definition of v }
  - IF S **is inconsistent, backtrack & search another definition** (otherwise the dual condition is cut off)
- IF $Q = \emptyset$ search for an **instantiation of the input variables (= counterexample)**

  If no solution exists, DPVS backtracks.

FM Application: Description of the module

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- **A real time industrial application** from a car manufacturer (provided by Geensoft)
- **Flasher Manager (FM)**: controller that drives several functions related to the flashing lights

  Purpose:

  - to indicate a direction change
  - to lock and unlock the car from the distance
  - to activate the warning lights
- **Simulink model** of FM $\rightarrow$ C function f_1

FM Application: Simulink model

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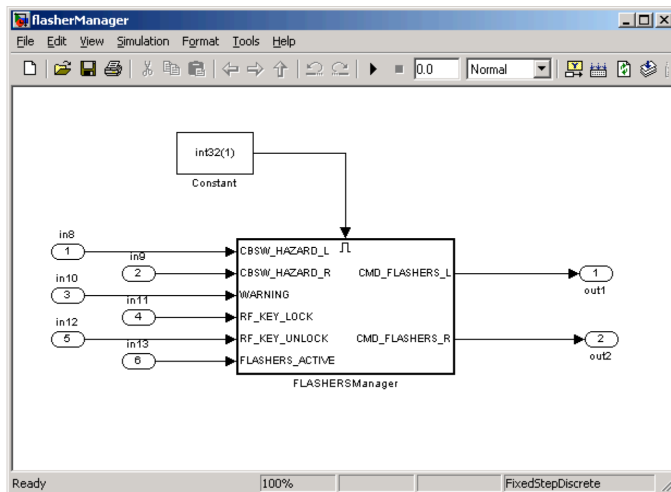

FM Application: Function f_1

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Simulink model of FM $\longrightarrow$ C function f_1

- 81 Boolean variables (6 inputs, 2 outputs) and 28 integer variables
- 300 **lines of code: nested conditionals including linear operations** and constant assignments

  Piece of code:

```
and1_a=((Switch5==TRUE)&&(TRUE!=Unit_Delay3_a_DSTATE));
if ((TRUE==((and1_a-Unit_Delay_c_DSTATE)!= 0))) {
   rtb_Switch_b=0;
}
else {
  add_a = (1+Unit_Delay1_b_DSTATE);
  rtb_Switch_b = add_a;
}
superior_a = (rtb_Switch_b>=3);
```

FM Application: property p_1

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- Property p_1: ***The lights should never remain lit***

  Property p_1 concerns the behaviour of FM for an **infinite time period**

  $\rightarrow$ p_1 is violated when the lights remain on for ***N*** **consecutive time period**

  $\rightarrow$ a loop (bounded by N) that counts the number of times where the output of FM has consecutively been true

Challenge: bound N **as great as possible**

Experiments: tools

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- **DPVS, implemented in Comet**, a hybrid optimization platform for solving combinatorial problems
- **CPBPV***, an optimized version of CPBPV based on a dynamic **top down strategy**
- **CBMC**, one of the best bounded model checkers

Experiments were performed on a Quad-core Intel Xeon X5460 3.16GHz clocked with 16Gb memory
All times are given in seconds.

Experiments (results)

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Solving time:

N	CBMC	DPVS	CPBPV*
5	0.03	**0.02**	0.84
100	57.27	**1.95**	TO
200	232.19	**3.45**	TO
400	TO	**4.66**	TO

Pre-processing time:

N	CBMC	DPVS	CPBPV*
5	0.366	**0.480**	0.480
100	65.190	**9.750**	9.750
200	395.46	**21.65**	21.65
400	TO	**50.90**	50.90

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Experiments on the binary search

Length	CBMC	DPVS	CPBPV*
4	5.732	0.529	**0.107**
8	110.081	35.074	**0.298**
16	TO	TO	**1.149**
64	TO	TO	**27.714**
128	TO	TO	**153.646**

- **DPVS and CBMC waste a lot of time in exploring the different paths**
- **CPBPV* incrementally adds the decisions taken along a path**
  $\rightarrow$ well adapted for the *Binary Search* program

Discussion (continued)

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Future work

- **Experiments on other applications**
- **Extension of our prototype**
  - → **handling pointers**
  - → **interfacing with a floating point number solver**
- **Combining strategies**
- **Using counter examples for errors localization**