On Search Strategies for Constraint-Based Bounded Model Checking

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CP meets CAV

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Outline

A CP framework for Bounded Program Verification

CPBPV, a Depth First Dynamic Exploration of the CFG

DPVS, a Dynamic Backjumping Strategy

The Flasher Manager Application

Discussion

Motivations

→ **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**

Overall view of CP framework

- **Bounded program verification**
  (the array lengths, the variable values and the loops are bounded)
  - **Constraint stores** to represent the specification and the program
  - Program is partially correct if the **constraint store implies the post-conditions**
- **Non deterministically** exploration of execution paths

CP-based BMC ...

CP-based BMC mainly involves three steps:

1. the **program is unwound k** times,
2. An annotated and simplified **CFG** is built
3. Program is translated in constraints **on the fly**

   A **list of solvers** tried in sequence (LP, MILP, Boolean, CP)

CP framework & BMC ...

- **CP framework**
  - Specification → constraints
    Program → constraints **(on the fly)**
  - Solving Process
    → **List of solvers** tried in sequence
    on **each selected node of the CFG**
    → Takes advantage of the **structure** of the program

- **BMC based on SAT / SMT solvers**
  - Program & specification → **Big Boolean formula**
  - Solving Process
    → SAT solvers or SMT solvers have a **"Global view"**
    → Critical issue: **minimum conflict sets**
    (to limit backtracks & spurious solutions)

CP framework, pre-processing

Pre-processing

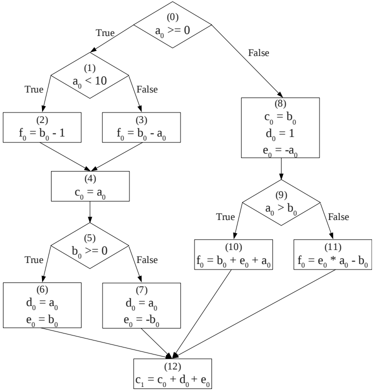
1. P is **unwound k times** $\rightarrow$ P_{uw}
2. $P_{uw} \rightarrow$ DSA, **Dynamic Single Assignment form** (each variable is assigned exactly once on each program path)
3. DSA is **simplified according to the specific property** by applying slicing techniques
4. Domains of all variables are filtered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

A small example


```
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
```

A small example(continued)

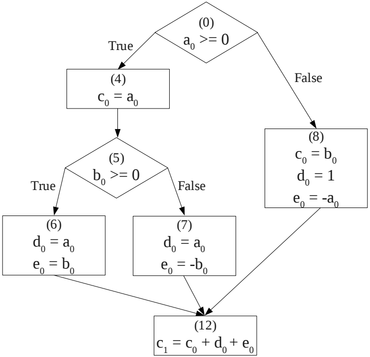
Initial CFG




```
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
```

A small example(continued)

Simplified CFG



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 p_1
assert($f >= -b * e$); // property p_2

CP framework, language

- **Java** programs and **JML** specifications

  JML =

  - Comments in java code ("javadoc" like) (can be compiled and executed at run time)
  - Properties are directly expressed on the **program variables**
    $\rightarrow$ no need for abstraction
  - Pre-conditions and post-relations
  - **Exists** and **Forall** quantifiers

- **C** programs and **assertions**

CP framework, restrictions

- **Unit code** validation
- Data types : Booleans, integers, arrays of integers, [floats]
- **Bounded programs** : array lengths, number of unfoldings of loops, size of integers are known
- Normal behaviours of the method (no exception)
- JML specification :
  - post condition : the conjunction of use cases of the method
  - possibly a precondition

Building the constraint store: principle

- 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** $\rightarrow$ conjunction of conditions
  - **exist i** $\rightarrow$ disjunction of conditions

  (**i** has bounded values)

Building the constraint store ...

- **scalar assignment**

$$\frac{\sigma_2 = \sigma_1[v/\sigma_1(v)+1] \;\;\&\;\; c_2 \equiv (\rho\, \sigma_2\; v) = (\rho\, \sigma_1\; e)}{\langle [v \leftarrow e\;,\;\; l], \sigma_1, c_1 \rangle \longmapsto \langle [l], \sigma_2, c_1 \wedge c_2 \rangle}$$

Program

```
x=x+1; y=x*y; x=x+y;
```

Constraints

$\{x_1 = x_0 + 1, y_1 = x_1 * y_0, x_2 = x_1 * y_1\}$

Building the constraint store ...

- **array assignment**

$$\frac{\begin{array}{l}\sigma_2 = \sigma_1[a/\sigma_1(a)+1] \\ c_2 \equiv (\rho\ \sigma_2\ a)[\rho\ \sigma_1\ e_1] = (\rho\ \sigma_1\ e_2) \\ c_3 \equiv \forall i \in 0..a.length(\rho\ \sigma_1\ e_1) \neq i \rightarrow (\rho\ \sigma_2\ a)[i] = (\rho\ \sigma_1\ a)[i]\end{array}}{\langle [a[e_1] \leftarrow e_2, l], \sigma_1\ , c_1\rangle \longmapsto \langle [l], \sigma_2, c_1 \wedge c_2 \wedge c_3\rangle}$$

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

Building the constraint store ...

- **conditional instruction: if b i ; l**

$$\frac{c \wedge (\rho\ \sigma\ b) \text{ is satisfiable}}{\langle \textit{if}\ b\ i\ ;\ l, \sigma, c\rangle \longmapsto \langle i\ ; l, \sigma, c \wedge (\rho\ \sigma\ b)\rangle}$$

$$\frac{c \wedge \neg(\rho\ \sigma\ b) \text{ is satisfiable}}{\langle \textit{if}\ b\ i\ ;\ l, \sigma, c\rangle \longmapsto \langle l, \sigma, c \wedge \neg(\rho\ \sigma\ b)\rangle}$$

Building the constraint store ...

- **while instruction: while b i ; l**

$$\frac{c \wedge (\rho\ \sigma\ b) \text{ is satisfiable}}{\langle \textit{while b i}\ ;\ l, \sigma, c\rangle \longmapsto \langle i; \textit{while b i}\ ;\ l, \sigma, c \wedge (\rho\ \sigma\ b)\rangle}$$

$$\frac{c \wedge \neg(\rho\ \sigma\ b) \text{ is satisfiable}}{\langle \textit{while b i}; l, \sigma, c\rangle \longmapsto \langle l, \sigma, c \wedge \neg(\rho\ \sigma\ b)\rangle}$$

CPBPV, Overall view

CPBPV, **Depth first exploration** of the CFG

- Translate precondition of the specification (if it exists) into a set of constraints **PRECOND**
- Translate post condition of the specification into a set of constraints **POSTCOND**
- Explore **each branch** B_i of the program and translate instructions of B_i into a set of constraints **PROG_Bi**

CPBPV, the validation process

- For each branch B_i, solve **CSPi = PROG_Bi** $\wedge$ **PRECOND** $\wedge$ **NOT(POSTCOND)**
  - If for each branch B_i **CSPi is inconsistent** , then the program is **conform** with its specification
  - If for a branch B_i **CSPi has a solution** , then this solution is a **counterexample** which illustrates a **non-conformity**

(!) **Inconsistencies of CSPi** are detected at **each node** of the control flow graph

Current prototype – On the fly validation : if c then ... else ...

- If **c** can be **simplified** into constant value "true" or "false", select the branch which corresponds to **c**
- If **c** is linear
  1. add decision **c** in **linear_CSP**
  2. **solve linear_CSP**
     - if **linear_CSP has no solution**, condition **c** is not feasible for the current path
       ⇝ **choose another path**
     - if **linear_CSP has a solution**, we can't conclude anything on **complete_CSP**
       ⇝ **investigate both branches c** and **¬c**

Current prototype – On the fly validation : if c then ... else ...

- If **c** is NOT linear :
  1. **abstract** decision **c** and add it in **boolean_CSP**
  2. solve **boolean_CSP**
     - **boolean_CSP** **has no solution** $\rightsquigarrow$ choose another path
     - if **boolean_CSP** **has a solution** $\rightsquigarrow$ investigate both branches **c** and $\neg$**c**

Boolean abstraction

- hash-table of decisions : keys are decisions, values are Boolean variables
- sub-expressions are shared $\rightarrow$ rewriting

Current prototype – On the fly validation : loops

Let **c** be the entrance condition

- if **c** is **trivially simplified** to “true” or “false”
  $\rightsquigarrow$ **enter** or **exit** the loop
- if {**c** $+$ **linear_CSP** } is **inconsistent**
  $\rightsquigarrow$ add $\neg$**c** to the CSPs and **exit** the loop

In other cases, unfold loop **max** times:

- If **max** is **reached**
  $\rightsquigarrow$ add $\neg$**c** to the CSPs and **exit** the loop
- Else investigate **both** paths

Example: binary search (1)


```
/*@ requires (\forall int i;i>=0
  @                       && i<t.length-1;t[i]<=t[i+1])
  @ ensures
  @  (\result!=-1 ==> t[\result] == v) &&
  @  (\result==-1 ==>
               \forall int k; 0<=k<t.length; t[k]!=v)
@*/

static int binary_search(int[] t, int v)
     int l = 0;
     int u = t.length-1;
     while (l <= u)
          int m = (l + u) / 2;
          if (t[m]==v)   return m;
          if (t[m] > v)
                u = m - 1;
          else
                l = m + 1;  // ERROR else u = m - 1;
   return -1;
```

Example: binary search (2)

- **Precondition**

```
\forall int i;i>=0
            && i<t.length-1;t[i]<=t[i+1]
```

$\mathbf{CSP} \leftarrow t_0[0] \leq t_0[1] \wedge t_0[1] \leq t_0[2] \wedge \ldots \wedge t_0[6] \leq t_0[7]$

- **Initialization**

```
int l=0;int u=t.length-1;
```

$\mathbf{CSP} \leftarrow \mathbf{CSP} \wedge l_0 = 0 \wedge u_0 = 7$

Example: binary search (2)

- **Precondition**

```
\forall int i;i>=0
           && i<t.length-1;t[i]<=t[i+1]
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$\mathbf{CSP} \leftarrow t_0[0] \leq t_0[1] \wedge t_0[1] \leq t_0[2] \wedge \ldots \wedge t_0[6] \leq t_0[7]$

- **Initialization**

```
int l=0;int u=t.length-1;
```

$\mathbf{CSP} \leftarrow \mathbf{CSP} \wedge l_0 = 0 \wedge u_0 = 7$

Example: binary search (3)

- **Loop**

```
while (l<=u)
```

Enter into the loop since $l_0 \leq u_0$ is consistent with the current constraint store
CSP $\leftarrow$ CSP $\wedge$ $l_0 \leq u_0$

- **Assignment**

```
int m=(l+u)/2;
```

CSP $\leftarrow$ CSP $\wedge$ $m_0 = (l_0 + u_0)/2 = 3$

Example: binary search (3)

- **Loop**

```
while (l<=u)
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Enter into the loop since $l_0 \leq u_0$ is consistent with the current constraint store
$CSP \leftarrow CSP \wedge l_0 \leq u_0$

- **Assignment**

```
int m=(l+u)/2;
```

$CSP \leftarrow CSP \wedge m_0 = (l_0 + u_0)/2 = 3$

Example: binary search (4)

- **Conditional**

```
if (t[m]==v) return m;
```

$t_0[m_0] = v_0$ is consistent with the constraint store so take the if part
$CSP \leftarrow CSP \wedge t_0[m_0] = v_0$

- **Complete execution path** *p* whose **constraint store** c_p is:
  $c_{pre} \wedge l_0 = 0 \wedge u_0 = 7 \wedge m_0 = 3 \wedge t_0[m_0] = v_0$

Example: binary search (4)

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if (t[m]==v) return m;
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- **Complete execution path** *p* whose **constraint store** c_p is:
$c_{pre} \wedge l_0 = 0 \wedge u_0 = 7 \wedge m_0 = 3 \wedge t_0[m_0] = v_0$

Example: binary search (5)

Return statement has been reached

- add negation of post condition and link JML \result variable with returned value m_0

```
\result!=-1 ==> t[\result] == v) &&
(\result==-1 ==> \forall int k;
                 0<=k<t.length; t[k]!=v)
```

$\backslash m_0 != -1 \wedge t_0[m_0] != v_0 \vee$
$\backslash m_0 = -1 \wedge (t_0[0] = v_0 \vee t_0[1] = v_0 \vee \ldots \vee t_0[6] = v_0)$

- **solve the CSP**
  There is **No solution** so the program is **correct** along this execution path

Go back to conditional **if (t[m]==v)** to explore the ***else*** part

Example: binary search (5)

Return statement has been reached

- add negation of post condition and link JML \result variable with returned value m_0

```
\result!=-1 ==> t[\result] == v) &&
(\result==-1 ==> \forall int k;
                    0<=k<t.length; t[k]!=v)
```

$\backslash \mathbf{m_0} != -\mathbf{1} \wedge \mathbf{t_0}[\mathbf{m_0}] != \mathbf{v_0} \vee$
$\backslash \mathbf{m_0} = -\mathbf{1} \wedge (\mathbf{t_0}[0] = \mathbf{v_0} \vee \mathbf{t_0}[1] = \mathbf{v_0} \vee \ldots \vee \mathbf{t_0}[6] = \mathbf{v_0})$

- **solve the CSP**
  There is **No solution** so the program is **correct** along this execution path

Go back to conditional **if (t[m]==v)** to explore the ***else*** part

Implementation

- **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
- **Prototype**
  - Solvers : Ilog CPLEX11 and JSolver4verif
  - Written in **Java** using **JDT** (eclipse) for parsing Java programs

!! CPLEX is unsafe but Neumaier & Shcherbina
$\rightarrow$ method for computing a certificate of infeasibility

Binary search

	length	8	16	32	64	128
CPBPV	time	1.08s	1.69s	4.04s	17.01s	136.80s
CBMC	time	1.37s	1.43s	KO		

Table: Results for a correct binary search program

length	CPBPV	CBMC
8	0.027s	1.38s
16	0.037s	1.69s
32	0.064s	7.62s
64	0.115s	27.05s
128	0.241s	189.20s

Table: Results for an incorrect binary search

!! **CBMC only shows the decisions taken along the faulty path (they do not provide any value for the array nor the searched data)**

Role of the different solvers

- **CPLEX, the MIP solver**, plays a key role
- There are only **length calls** to the CP solver (and much more calls to CPLEX)
- Almost **75% of the CPU time is spent in the CP solver**

Critical issues

- We do not need the Boolean abstraction to capture the control structure of the program

  → **Use the CFG** and constraints **to prune the search space**

- **Depth first dynamic exploration of the CFG**
  - **Efficient** if the variables are instantiated early
  - **Blind searching:** post-condition becomes active **very late**

DPVS, a Dynamic Backjumping Strategy

→ Generating ***Counterexamples***

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

A Dynamic Backjumping Strategy

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**

$\rightarrow$ **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**

A Dynamic Backjumping Strategy

DPVS starts from the post-condition and dynamically collects program blocks which involve **variables of the post-condition**

Why does it pay off ?

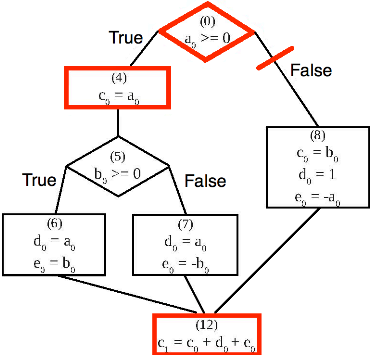
→ **Enforces the constraints** on the domains of the selected variables

→ **Detects inconsistencies earlier**

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
```

A small exemple(continued)




```
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
```

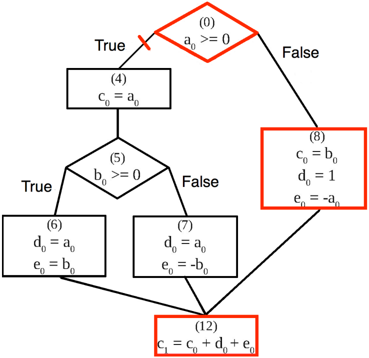
To prove property p_1, select node (12), then select node (4)

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

DPVS, pre-processing

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*

- `While` $Q \neq \emptyset, v \leftarrow$ 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

- **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

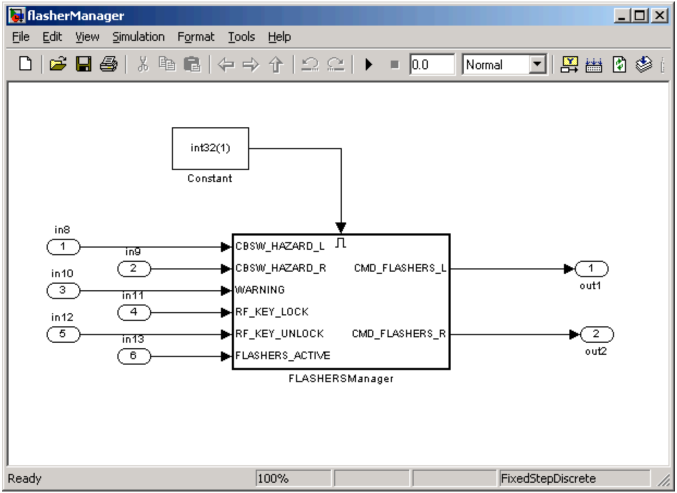
  Purpose:

  - 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

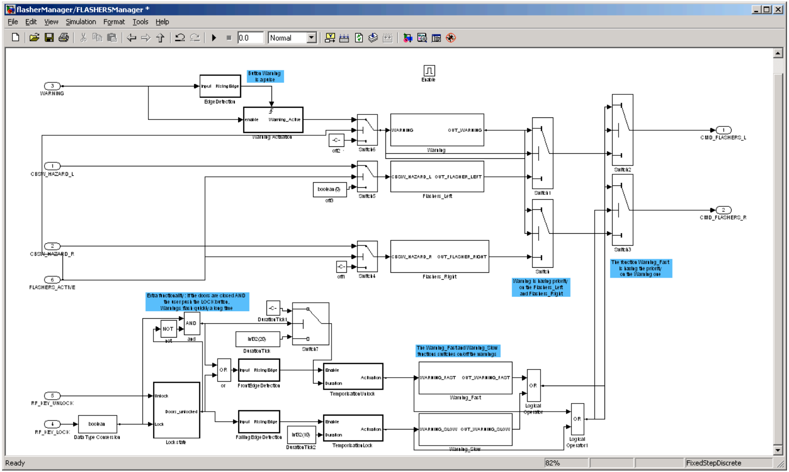
FM Application: functionalities

- **Direction change**: Boolean input *R* or *L* rises from 0 to 1. The corresponding light then oscillates between on/off states with a period of **6 time-units** (e.g. 3 s) $\rightarrow$ output sequence of the form [111000]
- **Lock and unlock of the car**
  - If the unlock button is pressed while the car is unlocked, nothing shall happen.
  - If the unlock button is pressed while the car is locked, both lights shall flash with a **period of 2 time-units during 20 time-units** (fast flashes for a short time)
  - If the lock button is pressed while the car is unlocked, both lights shall go on for **10 time-units**, and then shall go off for another 10 time-units
  - If the lock button is pressed while the car is locked, both lights shall flash during **60 time-units with a period of 2** time-units (fast flashes for a long time) ..
- **Warning function**: when the warning is on, both lights flash with a **period of 6 time-units**

FM Application: Simulink model(1)



FM Application: Simulink model (2)



FM Application: Function f_1

Simulink model of FM $\rightarrow$ *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: properties

- p_1 The lights should never remain lit
- p_2 The `Warning` function has priority over other flashing functions
- p_3 When the warning button has been pushed and then released, the `Warning` function resumes to the `Flashers_left` (or `Flashers_right`) function, if this function was active when the warning button was pushed
- p_4 When the `F` signal (for flasher active) is off, then the `Flashers_left`, `Flashers_right` and `Warning` functions are desabled. On the contrary, all the functions related to the lock and unlock of the car are maintained

FM Application: property p_1

- 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**

FM Application: property p_1

Program under test for Property:

```
void prop4(int d) {
  //number of time where the left  light  has been consecutively  true
  int countL = 0;
  //number of time where the right  light  has been consecutively  true
  int countR = 0;
  //consider d units  of time
  for(int i=0;i<d;i++) {
     //non-deterministic values of the inputs
     L=nondet_in(); R=nondet_in();
     LK=nondet_in(); ULK=nondet_in();
     W=nondet_in(); F=nondet_in();
     //call  to f1() to simulate one pass through the module
     f1();
     if (outL)
       //the left  light has been consecutively  true one more time
       countL++;
     else
       //the left  light has not been consecutively  true
       countL=0;
     if (outR)
       //the right  light has been consecutively  true one more time
       countR++;
     else
       //the right  light has not been consecutively  true
       countR=0;
   }
   //if countL and countR are less than d,
   //then the lights did not remain lit
   assert (countL<d && countR<d);
}
```

Experiments: tools

- **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 (property p1)

Solving time:

N	CBMC	DPVS	CPBPV*
5	0.03	0.02	0.84
100	58.52	1.11	TO
200	232.19	1.7	TO
400	TO	3.83	TO
800	TO	9.35	TO
1600	TO	26.2	TO

Presolving time:

N	CBMC	DPVS & CPBPV*
5	0.366	0.48
100	96.21	14.95
200	395.46	21.65
400	TO	83.81
800	TO	218.15
1600	TO	531.82

Experiments (cont)

- **Presolving, search, and total times in seconds for checking Property p_2 with 10 unfoldings**

Tool	Presolving	Search	Total
CBMC	**0.89**	0.23	**1.12**
$CBMC_{z3}$	**0.85**	2.7	**3.55**
DPVS	3.89	**0.08**	3.97
$DPVS_{z3}$		**0.34**	4.23

This propety **does not hold** (only 3 unfoldings are required)

- **Property 3 and 4 couldn't be checked**

Discussion

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

On going work : **Combining strategies**