CBMC

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CBMC

1. CBMC concepts
2. Verification of concurrent programs
3. Closer look on memory models

CBMC Concept

- Bounded Model Checker for C and C++ programs
  - constructs a propositional formula ϕ describing all possible executions of the system of bounded length
  - ($\phi \wedge \neg$*specification*) is fed do SAT solver
- can deal with pointers, arrays and real size integers
- threads, and simulate various memory models

CBMC Workflow

- create SSA form of program – such program can be viewed as set of constraints

1. unroll loops
2. inline functions and bound number of recursion calls – create goto program
3. transform to SSA form (generate set of constraints)

Example

- bound is 2

$$
\begin{array}{lll}
x = 3; & & \\
while & (x > 1)\{ & \\
 & if\ (x\%2 == 0) & x = x/2; \\
 & else & x = 3 * x + 1; \\
\} & &
\end{array}
$$

Example – Unroll Loops

- bound is 2

$$
\begin{array}{l}
x = 3; \\
while \quad (x > 1)\{ \\
\qquad if\ (x\%2 == 0) \quad x = x/2; \\
\qquad else \qquad\qquad\quad\;\; x = 3 * x + 1; \\
\}
\end{array}
$$

$$
\begin{array}{l}
x = 3; \\
if\ (x > 1)\{ \\
\quad if\ (x\%2 == 0) \\
\qquad x = x/2; \\
\quad else\ \ x = 3 * x + 1; \\
\quad if(x > 1)\{ \\
\qquad if\ (x\%2 == 0) \\
\qquad\quad x = x/2; \\
\qquad else\ \ x = 3 * x + 1; \\
\qquad assert(x <= 1); \\
\quad \} \\
\}
\end{array}
$$

Example – Generating Constraints

$$
\begin{array}{l}
x = 3; \\
if\ (x > 1)\{ \\
\quad if\ (x\%2 == 0) \\
\qquad x = x/2; \\
\quad else\ \ x = 3 * x + 1; \\
\quad if(x > 1)\{ \\
\qquad if\ (x\%2 == 0) \\
\qquad\quad x = x/2; \\
\qquad else\ \ x = 3 * x + 1; \\
\qquad assert(x <= 1); \\
\quad \} \\
\}
\end{array}
$$

$$
\begin{array}{ll}
(0) & x_0 = 3 \\
(1) & guard_1 = x_0 > 1 \\
(2) & guard_2 = guard_1\ \&\ x_0\%2 == 0 \\
(3) & x_1 = (guard_2 ? x_0/2 : x_0) \\
(4) & guard_3 = guard_1\ \&\ !(x_0\%2 == 0) \\
(5) & x_2 = (guard_3 ? 3 * x_1 + 1 : x_1) \\
(6) & guard_4 = guard_1\ \&\ x_2 > 1 \\
(7) & guard_5 = guard_4\ \&\ x_2\%2 == 0 \\
(8) & x_3 = (guard_5 ? x_2/2 : x_2) \\
(9) & guard_6 = guard_4\ \&\ !(x_2\%2 == 0) \\
(10) & x_4 = (guard_6 ? 3 * x_3 + 1 : x_3)
\end{array}
$$

Specification: $!(x_4 <= 1)$

Pointers and Arrays

- every assignment to a dereference of pointer is instantiated to several assignments (one for each possible value of pointer)

```
*p_1 = 3;
```

- possible generated constraints:

```
x_12 = (p_1 == &x) ? 3 : x_11;
y_7 = (p_1 == &y) ? 3 : y_6;
z_4 = (p_1 == &z) ? 3 : z_3;
...
```

- assignment to an array cell is treated similarly (instantiating for each possible value of the array index)
- allocated memory is treated as a regular global variable
- number of malloc calls is bounded

CBMC for Concurrent Programs

- **Problems**:
  - access to global variables
    - race conditions
    - it is not possible to index assignments to global variables statically
  - modeling threads in bounded environment
    - allowing context switches only before visible statements
- **Translation process**:
  1. preprocessing - modeling nonatomic statements
  2. applying CBMC separately on each thread
  3. generating constraints for concurrency

Stage 1 – Preprocessing

- problems with access to more than one global variable

```
    x_1 = g_1 + g_2;
```

- in assembly:

```
    r_a = g_1; r_b = g_2; r_c = r_a + r_b; x_1 = r_c;
```

- have to allow context switches between instructions
- CBMC generates similar code:

```
    y_1 = g_1; y_2 = g_2; x_1 = y_1 + y_2;
```

- accesses in conditions and loops are treated similarly

- create list of constraints for each thread - **template**
  - each variable has several copies
  - each copy appears only once on left-hand side of constraint
- created assignment statement types:

1. expression over local variables to local variable

$$l_k = (guard_r ? lx_c * 2 : l_{k-1})$$

2. expression over local variables to global variable

$$g_k = (guard_r ? lx_c * 2 : g_{k-1})$$

3. global variable to local variable

$$l_k = (guard_r ? gx_k : l_{k-1})$$

4. assignment to a guard variable

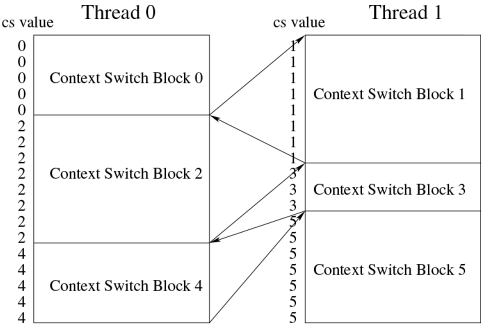
$$guard_r = guard_{r-1} \wedge x_k > y_c$$

Stage 3 – Generating Constraints for Concurrency

1. constraints on context switches
2. constraints on global variables
3. constraints on assignment statements

- main idea – to associate with each line in template a variable indicating number of context switches that occurs before this line $thread_t\_cs(l)$
- assignment to $thread_t\_cs(l)$ determines a concurrent execution over the thread templates
- added constraints on $thread_t\_cs(l)$:
  - **Monotonicity** $\forall_{0 \leq l < m-1} thread_t\_cs(l) \leq thread_t\_cs(l+1)$
  - **Interleaving bound** $thread_t\_cs(m-1) \leq n$
  - **Parity** $\forall_{0 \leq l < m-1} (thread_t\_cs(l) \mod 2) = t$
- $m - 1$ – number of constraints in template
- n – interleaving bound

Stage 3 – Context Switching



Stage 3 – Constraints on Global Variables

- generate n new variables x_val_i for each global variable x
  - x_val_i is value of variable x at the end of i-th context switch block
- x_val_i should get its value according to the last assignment that was made to x in the i-th context switch block
  - if x was assigned in the i-th context switch block, x_val_i will be equal to the last assignment to x in this block
  - else $x\_val_i = x\_val_{i-1}$ preserves the value it had at the end of the previous block

Stage 3 – Translation of Statements to Constraints

1. expression over local variables to local variable
   - add the thread prefix
2. assignment of global variable x_i to local variable l_k
   - if assignment to x_i in the same context, simply add thread prefix
   - otherwise is used *x_val* of previous block
3. expression over local variables to global variable
   - similarly as previous
4. assignment to a guard variable
   - guards are local, so add only prefixes

Concurrency - Pointers and Arrays

- no special treatment to support assignments to a pointer dereference or to cell in an array
- only problem is dereference of pointer to global variable

```
v_1 = *p + v_2;
```

- break statement to more small statements:

```
y = *p; v_1 = y + v_2;
```

More Than Two Threads

- change to parity constraint

1. round-robin
   - thread may do nothing, but increases number of context switches
2. add new variables run_i representing thread that runs in context switch block

atomic sections - add constraints to force *thread*$_t$*_cs* values to be identical in atomic section

mutexes - model only *wait-free* executions – if a thread tries to lock a mutex, it either succeeds or this execution is eliminated - own mutex implementation of lock and unlock:

- lock:

```
atomic {
    assume(*mutex == U);
    *mutex = L;
}
```

- unlock:

```
atomic {
    assert(*mutex == L);
    *mutex = U;
}
```

Detecting races

- created new variable *x_write_flag* that is raised whenever *x* is defined and lowered in the next instruction

```
atomic {
    assert(x_write_flag == 0);
    x = 3;
    x_write_flag = 1;
}
x_write_flag = 0;
```

- on every access to *x* is added assert that its *x_write_flag* is low

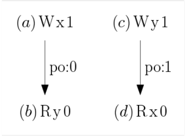
```
atomic{
    assert(x_write_flag == 0);
    y = x;
}
```

- on assignment to dereference of pointer *p* flag is raised to all possible variables which *p* might point to

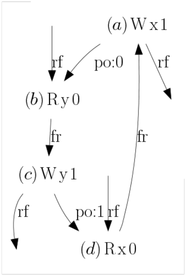
Weak Memory Models Introduction

Init: x=0; y=0;	
P_0	P_1
(a) `x` $\leftarrow$ `1`	(c) `y` $\leftarrow$ `1`
(b) `r1` $\leftarrow$ `y`	(d) `r2` $\leftarrow$ `x`
Observed? `r1=0; r2=0;`	

(a) Program



(b) Events and Program Order



(c) An execution witness

- *po* – program order
- *rf* – read from:
  $(w, r) \in rf \iff r$ reads value written by w
- *ws* – write serialization – total order on writes to the same location
- *fr* – from read:
  $(r, w) \in fr \iff \exists w'.(w', r) \in rf \wedge (w', w) \in ws$

Init: `x=0; y=0;`

P_0	P_1
(a) `x` $\leftarrow$ `1`	(b) `x` $\leftarrow$ `2`

Allowed `x=1` $\vee$ `x=2`

(a) Program

$$\begin{tikzcd} (a)\,\mathrm{W\,x\,1} \arrow[d, "\mathrm{ws}"] \\ (b)\,\mathrm{W\,x\,2} \end{tikzcd}$$

(b) An execution witness for the final state **`x=1`**

$$\begin{tikzcd} (b)\,\mathrm{W\,x\,2} \arrow[d, "\mathrm{ws}"] \\ (a)\,\mathrm{W\,x\,1} \end{tikzcd}$$

(c) An execution witness for the final state **`x=2`**

CBMC Weak Memory Models

- modern architectures modeled by relaxer relations
  - *rfi* – internal read from, corresponds to read from the store buffer (TSO)
  - *ppo* – program order pairs (e.g., write-read pairs on x86)
  - *rfe* – external read from, when two processors can communicate privately via a cache (Power, ARM)
  - ab_A – relation induced by fences of architecture A
  - *dp* – dependencies between instructions
- execution is valid on A when following holds:
  1. SC holds per address $= acyclic(ws \cup rf \cup fr \cup \text{po-loc})$
  2. Values do not come out of thin air $= acyclic(rf \cup dp)$
  3. ...
- symbolic event structure

Thank you.