

CSC2/455 Software Analysis and Improvement Model Checking

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URCS

Outline

A Tour of CBMC

Some (unneeded?) History

Model Checking

Liveness Properties

Postscript

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Wrong Min

```
#include <assert.h>

int nondet_int();

int min(int a, int b) {
    if(a < b)
        return a;
    else
        return a;
}

void check_min() {
    int x, y, r;

    x = nondet_int();
    y = nondet_int();

    r = min(x, y);

    assert(r == x || r == y);
    assert(r <= x && r <= y);
}
```

```
$ cbmc --function check_min wrong_min.c
CBMC version 5.10 (cbmc-5.10) 64-bit x86_64 linux
Parsing wrong_min.c
Converting
Type-checking wrong_min
Generating GOTO Program
Adding CPROVER library (x86_64)
Removal of function pointers and virtual functions
Generic Property Instrumentation
Running with 8 object bits, 56 offset bits (default)
Starting Bounded Model Checking
size of program expression: 48 steps
simple slicing removed 2 assignments
Generated 2 VCC(s), 2 remaining after simplification
Passing problem to propositional reduction
converting SSA
Running propositional reduction
Post-processing
Solving with MiniSAT 2.2.1 with simplifier
403 variables, 1026 clauses
SAT checker: instance is SATISFIABLE
Solving with MiniSAT 2.2.1 with simplifier
403 variables, 0 clauses
SAT checker inconsistent: instance is UNSATISFIABLE
Runtime decision procedure: 0.00148068s

** Results:
[check_min.assertion.1] assertion r == x || r == y: SUCCESS
[check_min.assertion.2] assertion r <= x && r <= y: FAILURE

** 1 of 2 failed (2 iterations)
VERIFICATION FAILED
```

Tracing CBMC

```
$ cbmc --trace --function check_min wrong_min.c
...
[check_min.assertion.2] assertion r <= x && r <= y: FAILURE
Trace for check_min.assertion.2:
...
State 20 file wrong_min.c line 15 function check_min thread 0
-----
x=1073741824 (01000000 00000000 00000000 00000000)
State 21 file wrong_min.c line 16 function check_min thread 0
-----
y=1 (00000000 00000000 00000000 00000001)
State 24 file wrong_min.c line 18 function check_min thread 0
-----
a=1073741824 (01000000 00000000 00000000 00000000)
State 25 file wrong_min.c line 18 function check_min thread 0
-----
b=1 (00000000 00000000 00000000 00000001)
State 30 file wrong_min.c line 18 function check_min thread 0
-----
r=1073741824 (01000000 00000000 00000000 00000000)
Violated property:
file wrong_min.c line 21 function check_min
assertion r <= x && r <= y
r <= x && r <= y
```

Generating test cases

```
$ cbmc --cover branch --function min wrong_min_2.c
CBMC version 5.10 (cbmc-5.10) 64-bit x86_64 linux
...
converting SSA
Aiming to cover 3 goal(s)
Running propositional reduction
Post-processing
Solving with MiniSAT 2.2.1 with simplifier
334 variables, 569 clauses
SAT checker: instance is SATISFIABLE
Covered function min entry point
Covered function min block 1 branch false
Solving with MiniSAT 2.2.1 with simplifier
334 variables, 0 clauses
SAT checker: instance is SATISFIABLE
Covered function min block 1 branch true
Runtime decision procedure: 0.00146064s

** coverage results:
[min.coverage.1] file wrong_min_2.c line 6 function min entry point: SATISFIED
[min.coverage.2] file wrong_min_2.c line 6 function min block 1 branch false: SATISFIED
[min.coverage.3] file wrong_min_2.c line 6 function min block 1 branch true: SATISFIED

** 3 of 3 covered (100.0%)
** Used 2 iterations
Test suite:
a=0, b=1
a=1, b=0
```

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A Tour of CBMC

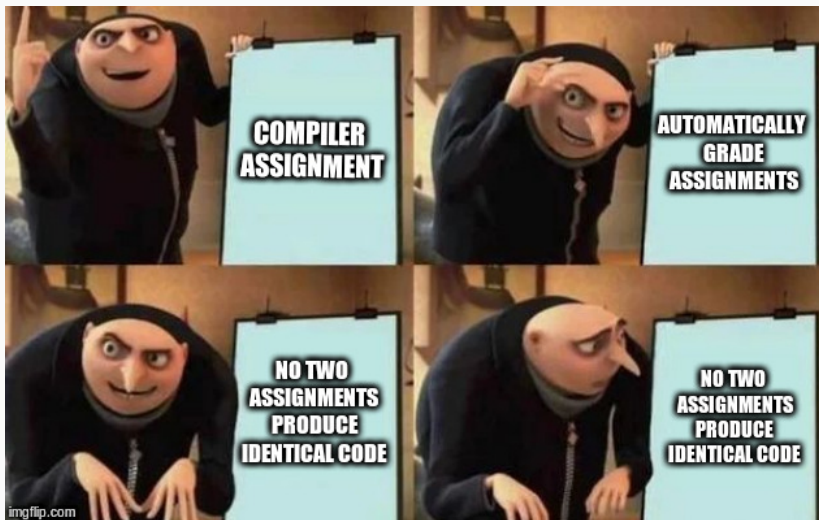
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The Plan



Check for Equivalence

- A : Original source program
- B : Compiler-generated program (e.g. your 3-address code)
- Is $A = B$?
 - Program equivalence problem
 - Undecidable in general

Test?

- Develop test cases
- Run B with these test cases
 - Works
 - Tests may miss bugs
- Also, many programs harder to test
 - Don't have `main`
 - Accept input interactively
 - Buggy compilers may introduce infinite loops

Solution

- Ended up using bounded model checking for C
 - CBMC
- Allows me to check that certain properties hold across all executions
- Can still require manual inspection

Computing the minimum of three numbers

```
int min_of_3_before(int x, int y, int z) {
    int min3;

    if(x > y) {
        if(y > z) {
            min3 = z;
        } else {
            min3 = y;
        }
    } else {
        if(x > z) {
            min3 = z;
        } else {
            min3 = x;
        }
    }

    return min3;
}
```

Another implementation

```
int min_of_3_after(int x, int y, int z) {
    int min3;

    if(x > y && y > z) {
        min3 = z;
    } else {
        if(x > y)
            min3 = y;
        else
            min3 = x;
    }

    return min3;
}
```

Checking equivalence: before and after

```
int nondet_int();
void check_eqv() {
    int a, b, c;

    a = nondet_int();
    b = nondet_int();
    c = nondet_int();

    assert(min_of_3_before(a, b, c) == min_of_3_after(a, b, c));
}
```

Results

```
$ cbmc --trace --function check_eqv min3.c
CBMC version 5.10 (cbmc-5.10) 64-bit x86_64 linux
...
[check_eqv.assertion.1] assertion return_value_min_of_3_before == return_value_min_of_3_after: FAIL

State 20 file min3.c line 45 function check_eqv thread 0
-----
  a=1 (00000000 00000000 00000000 00000001)

State 21 file min3.c line 46 function check_eqv thread 0
-----
  b=1073741824 (01000000 00000000 00000000 00000000)

State 22 file min3.c line 47 function check_eqv thread 0
-----
  c=0 (00000000 00000000 00000000 00000000)

...

State 32 file min3.c line 13 function min_of_3_before thread 0
-----
  min3=0 (00000000 00000000 00000000 00000000)

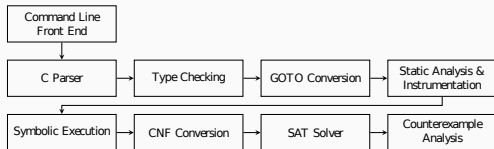
...

State 46 file min3.c line 33 function min_of_3_after thread 0
-----
  min3=1 (00000000 00000000 00000000 00000001)

Violated property:
  file min3.c line 49 function check_eqv
  assertion return_value_min_of_3_before == return_value_min_of_3_after
  return_value_min_of_3_before == return_value_min_of_3_after

** 1 of 1 failed (1 iteration)
VERIFICATION FAILED
```


CBMC Architecture



- CBMC translates entire program into a “GOTO” program in SSA form
- It then “executes” every statement in the program
 - Values it does not know about are turned into “symbols” (Symbolic Execution)
- Program is then converted into boolean formulae (CNF)
- The formula is handed off to a SAT solver

Loops: Definite Bounds

```
for(i = 0; i < 10; i++) {  
  ...  
}
```

CBMC will unroll loop.

Loops: Symbolic Bounds

```
for(i = 0; i < N; i++)  
    B;
```

gets unrolled by a fixed number (B is body), with unroll assert:

```
i = 0;  
if(i < N) {  
    B;  
    i++;  
  
    if(i < N) {  
        B;  
        i++;  
  
        assert(N == 2);  
    }  
}
```

- If assert fails, unrolling was insufficient.
 - Not sound!
 - Otherwise, conclusion is sound

Other complications

- Pointers, arrays, dynamic memory allocation, etc.
- See CPROVER manual for more details

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Basic Ideas

- Formula φ
 - Correctness (Safety) property
 - Propositional logic
 - Example: the argument to the assert statements
- Interpretation \mathcal{K}
 - More on this later
- We ask: $\mathcal{K} \models \varphi$?
 - Is φ true in \mathcal{K} ?

Transition System

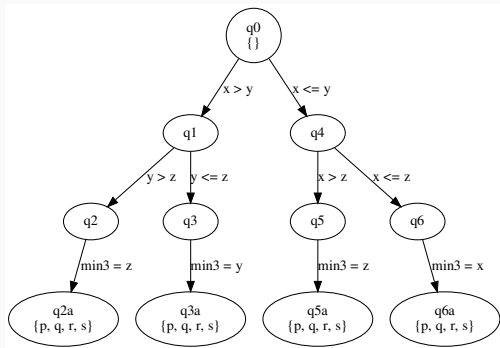
- $\mathcal{T} = (Q, I, E, \delta)$
 - set of states Q (e.g. values of all variables)
 - initial states $I \in Q$
 - action labels E (e.g. program statements)
 - (total) transition relation $\delta \subset Q \times E \times Q$
- A run of \mathcal{T} is the same as a trace of states
 - $s_0 e_0 s_1 \dots$ where $(s_0, e_0, s_1) \in \delta$, and $s_0 \in I$
- A reachable state is a state that exists in some run.

Kripke Structures

```
min3 = min_of_3(x, y, z);  
assert(min3 == x || min3 == y || min3 == z);  
assert(min3 <= x);  
assert(min3 <= y)  
assert(min3 <= z)
```

- Let \mathcal{V} be a set of propositions
 - e.g. $\text{min3} \leq x$
 - e.g. $\text{min3} \leq y$
- A Kripke structure $\mathcal{K} = (Q, I, E, \delta, \lambda)$ is a transition system where:
 - $\lambda : Q \rightarrow 2^{\mathcal{V}}$
- λ is a function that maps a state q to the (subset) of propositions from \mathcal{V} that are true in that state
 - $q \models P$ where $P \in \mathcal{V}$

Kripke structure for our min-of-3 example



- Let p be the “must be one of inputs” proposition
- Let q, r, s be the $\leq x, \leq y, \leq z$ proposition
- (Note: True propositions in internal states not shown)

Invariants

- An invariant is a *safety property* for the system that holds in every reachable state
- An inductive invariant holds in the initial state, and is preserved by all transitions
 - including transitions from unreachable states
 - more on this when we discuss Hoare Logic

Invariant Checking Algorithm: High level details

- Assume finite Kripke structure
- Given an invariant to check,
 - Enumerate all reachable states
 - Check that invariant holds in all of them

Invariant Checking Algorithm: Pseudocode

```
def verify_inv(ks, inv):
    done = set()
    todo = set()

    for s in ks.initial_states():
        if s in done: continue

        todo.add(s)

    while len(todo) > 0:
        ss = todo.pop()
        done.add(ss)

        if not ss.satisfies(inv): return False

        for succ in ss.successors():
            if succ not in done: todo.add(succ)

    return True
```

based on Figure 3.3 in S. Merz, An introduction to Model Checking.

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- Does something “good” eventually happen?
- Does the system ever deadlock?
- Does the system livelock?
 - An action e is no longer possible after a particular state q_i
- These require reasoning over *sequences* of states
 - These can be infinite even in a finite Kripke structure

These properties need a *temporal* logic, that incorporates notions of (logical) “time points” into formulae we want to check.

Specifying temporal properties in PTL

- Let $\sigma = q_0q_1\dots$ be a sequence of states
 - σ_i is the state i
 - $\sigma|_i$ is the suffix $q_iq_{i+1}\dots$ of σ
- Let φ be a formula
- $\sigma \models \varphi$ if $\varphi \in \lambda(\sigma_0)$
- $X\varphi$ (also a formula), read as “next φ ”,
 - $\sigma \models X\varphi$ if $\sigma|_1 \models \varphi$
- $\varphi U \psi$ (also a formula), read as “ φ until ψ ”
 - $\sigma \models \varphi U \psi$ if and only if there exists $k \in \mathbb{N}$
 - $\sigma|_k \models \psi$
 - for all $1 \leq i < k$, $\sigma|_i \models \varphi$
 - Note: φ can continue to hold after k

More temporal properties

- $F\varphi$, “eventually φ ”
 - $\text{true}U\varphi$
- $G\varphi$, “always φ ”
 - $\neg F\neg\varphi$
- $\varphi W\psi$, “ φ unless ψ ”
 - $(\varphi U\psi) \vee G\psi$
- $GF\varphi$
- $FG\varphi$

Some examples of invariants

- $G\neg(own_1 \wedge own_2)$
 - where own_1 and own_2 are propositions representing states in which locks for resource are obtained by process 1 and 2
- Other properties (see the reading)
 - weak and strong fairness
 - precedence
 - etc.

Existential and Universal Properties: CTL

- Branching time logic for properties of systems
 - Computation Tree Logic (CTL)
- $EX\varphi$, there exists a transition where φ holds from current state
- $EG\varphi$, exists a path from current state where φ holds on all states
- EU , exists a path until...
- Also Ax properties, properties that hold on all possible paths from current state

Verifying PTL and CTL invariants?

- State sequences of infinite length possible
- How do we check invariants?

Büchi Automata

- ω -automaton
 - run on infinite strings
- strings represent state sequences (actually $\lambda(q_0)\lambda(q_1)\dots$)
- non-deterministic as well as deterministic
 - but non-deterministic Büchi automata more powerful

But, but SAT, Logic?

Büchi-automata have a very close relation to logic.

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Further Reading and Links

- Stephan Merz, An Introduction to Model Checking
 - Accessible and good introduction, with links to other material
- Javier Esparza, Automata Theory: An algorithmic approach
 - See Chapters 8, 9 and 14
- Spin Model Checker
- Selected industrial applications
 - CACM, “How Amazon Web Services Uses Formal Methods”
 - CACM, “A Decade of Software Model Checking with SLAM”
- A segue into compiler verification
 - Ken Thompson, Reflections on Trusting Trust, Turing Award Lecture 1984
 - The COMPCERT project