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# Context-Bounded Model Checking of LTL Properties for ANSI-C Software


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# Model Checking C



Model checking:

- normally applied to formal state transition systems
- checks safety and temporal properties

Sofware model checking:

- models are abstractions, not necessarily precise
- no guarantee that model and software agree

**BUT:** C is difficult to model check:

- weakly typed ⇒ conversion increase model complexity
- pointers ⇒ indirections increase model complexity
- infinite state
- parts deliberately undefined, implementation- or host-specific

  ⇒ need to handle useful or common interpretations

# ESBMC



SMT-based bounded model checker for C, based on CBMC:

- symbolically executes C into SSA, produces QF formulae
- unrolls loops up to a maximum bound
- assertio…
  - safety properti… …ounds, pointer dereferences, overflows,...)
  - user-specified properties

**Goal: support LTL formulas in properties**

Multi-threaded programs:

- produces one SSA program for each possible thread interleaving
- interleaves only at "visible" instructions
- optional context bound

# LTL – Linear Temporal Logic



Supported operators:

- U: *p* holds **until** *q* holds — *p* U *q*
- F: *p* will hold eventually in the **future** — F *p*
- G: *p* **always** holds in the future — G *p*

- X is not well defined for C
  - no notion of "next"

- C expressions used as atoms in LTL:

```
{keyInput == 1} -> F {displayKeyUp}
({keyInput != 0} | {intr}) -> G{numInputs > 0}
```

"event": change of global variable used in LTL formula

# Büchi Automata (BA)

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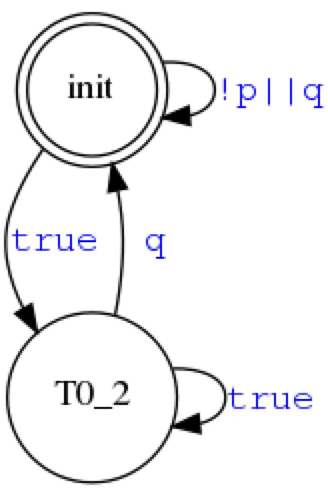
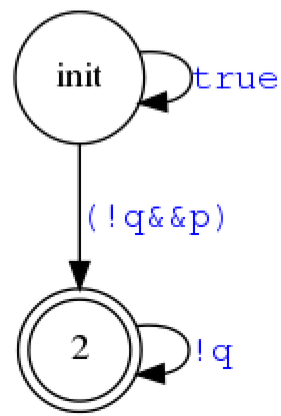
- non-deterministic FSM over propositional expressions
- inputs infinite length traces
- acceptance == trace passes through an accepting state infinitely often

- can convert from LTL to an equivalent BA
  – use `ltl2ba`, modified to produce C




`p -> Fq`




`!(p -> Fq)`

# Using BAs to check the program

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- Theory: check product of model and *never claim* for accepting state
- SPIN: execute *never claim* in lockstep with model
- ESBMC:
  - technically difficult to alternate between normal program and *never claim* program
  - instead: run *never claim* program as a monitor thread concurrently with other program thread(s)

  ⇒ no distinction between monitor thread and other threads

# Ensuring soundness of monitor thread

Monitor thread will miss events:

- interleavings will exist where events are skipped (monitor thread scheduled out of sync)

⇒ can cause false violations of the property being verified

⇒ monitor thread must be run immediately after events

Solution:

- ESBMC maintains (global) current count of events
- monitor checks it processes events one at a time (using assume statements)

⇒ causes ESBMC to discard interleavings where monitor does not act on relevant state changes

# Example monitor thread

```
bool cexpr_0;  // “pressed”
bool cexpr_1;  // “charge > min”

typedef enum {T0_init, accept_S2 } ltl2ba_state;
ltl2ba_state state = T0_init;
unsigned int visited_states[2];
unsigned int trans_seen;
extern unsigned int trans_count;

void ltl2ba_fsm(bool state_stats) {
  unsigned int choice;
  while(1) {
    choice = nondet_uint();
    /* Force a context switch */
    yield();
    atomic_begin();
    assume(trans_count <=  trans_seen + 1);
    trans_seen = trans_count;
```

State transition and “event” counter setup

nondeterminism

only interleave whole block

reject unsafe interleavings

# Example monitor thread

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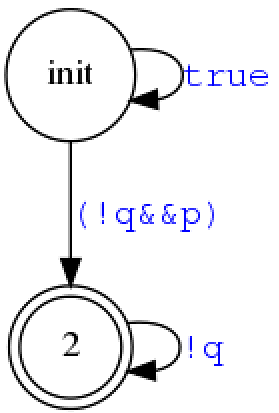
```
    switch(state) {
    case T0_init:
      if(choice == 0) {
        assume((1));
        state = T0_init;
      } else if (choice == 1) {
        assume((!cexpr_1 && cexpr_0));
        state = accept_S2;
      } else assume(0);
      break;
    case accept_S2:
      if(choice == 0) {
        assume((!cexpr_1));
        state = accept_S2;
      } else assume(0);
      break;
    }
    atomic_end();
  }
}
```

automata transitions representing the formula `!(p → Fq)`



# Infinite traces and BMC?

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BMC forces program execution to eventually end
– but BA are defined over infinite traces...

Solution:

- follow SPINs stuttering acceptance approach: pretend final state extends infinitely
- re-run monitor thread after program termination, with enough loop iterations to pass through each state twice
- if an accepting state is visited at least twice while stuttering, BA accepts extended trace
  - LTL property violation found

# Experiments

- checked properties of medical device firmware
- mostly of the form `p -> Fq` or `(!p && Fp) -> Fq`
- tested against original code base,
  and code with seeded errors
- all properties shown to hold on original code,
  all seeded errors were found

| Test name | Interleavings | Elapsed time(s) |
|---|---|---|
| start_btn | 7764 | 199 |
| up_btn | 3775 | 83 |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| serial_rx | 5454 | 324 |

approach requires large context switch bounds

unwind bound:1, context bound: **40**

# State Hashing

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- used to counter the state explosion problem in explicit-state model checking:
  - variable assignments concatenated into state vector
  - hash values used to record which states have been explored
  - hash collisions prevent unique parts of the state space from being explored
- cannot be applied directly to symbolic model checking: variable assignments can contain non-deterministic values with constraints

# Symbolic State Hashing

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Exploit SSA form:

- normalize RHS of each assignment in SSA form
- compute hash value and associate with LHS variable
- replace variable occurrences in RHS by variable hashes
  - ... and re-hash

⇒ variables with same set of constraints hash to same values

⇒ independent of non-deterministic choices

- variable hashes and thread program counters concatenated into state vector
- rest as before...
- hash algorithm not important, we use SHA256

# Symbolic State Hashing – Limitations

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- Equivalent states can have different hash values if:
  - constraints are arranged in different orders
  - (semantically) different sets of constraints

⇒ not all redundant states are removed

- However, we are primarily interested in reducing symmetry

# State Hashing Experiments

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- same experiments, with state hashing enabled
- all tests decreased total runtime
- observable increase in amount of runtime per interleaving

| Test name | Interleavings | w / hashing | Elapsed time(s) | w / hashing |
|---|---|---|---|---|
| start_btn | 7764 | 2245 | 199 | 71 |
| up_btn | 3775 | 1385 | 83 | 37 |
| keyb_start | 92795 | 49017 | 9796 | 4489 |
| baud_conf | 485 | 419 | 17 | 16 |
| serial_rx | 5454 | 3108 | 324 | 212 |

# Relation to partial order reductions

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- Partial order reductions are the more common way to reduce number of redundant states explored
  - demonstrably optimal method of doing this exists...
  - ... but incurs additional complexity in detecting which context switches are redundant
- state hashing only eliminates the most obvious and immediate duplicate states...
- ... but only at the cost of extra overhead in symbolic execution
- detailed comparison remains future work

# Conclusions

- BMC framework can be extended to check ANSI-C software against an LTL formula (with reasonable efficiency)
- State hashing can be extended to symbolic model checking
- Runtime performance is improved by a modest amount by the use of state hashing

# Future Work

- Full comparison of state hashing with POR
- Evaluate how effective such optimisations are when run on a distributed system