Software Model Checking for Cooperative Threaded Programs

Alessandro Cimatti
j.w.w. Iman Narasamdya and Marco Roveri

Fondazione Bruno Kessler - Embedded System Unit, Italy

ATVA'13
October 2013
Hanoi, Vietnam

Motivations

- Multi-threaded software with cooperative scheduling (or cooperative threads) is adopted in many embedded system domains
  - SystemC, SpecC, FairThreads, OSEK/VDX, PLC, ...

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  - Scheduling policy is complex, yet correctness depends on the details
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- Formal verification of cooperative threads is challenging:
  - Scheduling policy is complex, yet correctness depends on the details
  - Threads have inifinite state space
- Existing formal verification approaches are limited:
  - Disregard significant semantics aspects
  - Perform under-approximations
  - Poor scalability

Outline

- Cooperative Threaded Programs (CTPs)
- Background
  - Safe Sequential Programs
  - Model Checking of Sequential Programs
    - Finite Model for Sequential Programs
    - Symbolic Model Checking of Sequential Programs
- Approaches to Model Checking of CTPs
  - Finite-Model for Cooperative Threaded Programs
  - Symbolic Model Checking of Sequential Software
  - Explicit Scheduler and Symbolic Threads (ESST)
- The Kratos Software Model Checker
- Experimental Results
- Related Work
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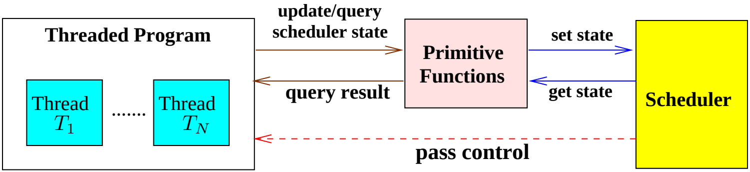
  `wait(EVENT_E), wait(100), notify(EVENT_J), ....`



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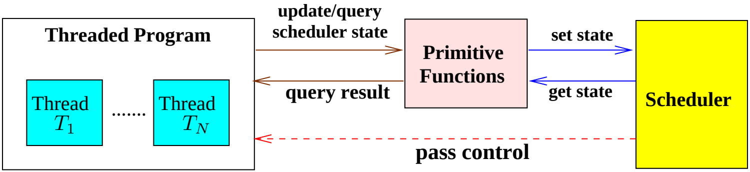
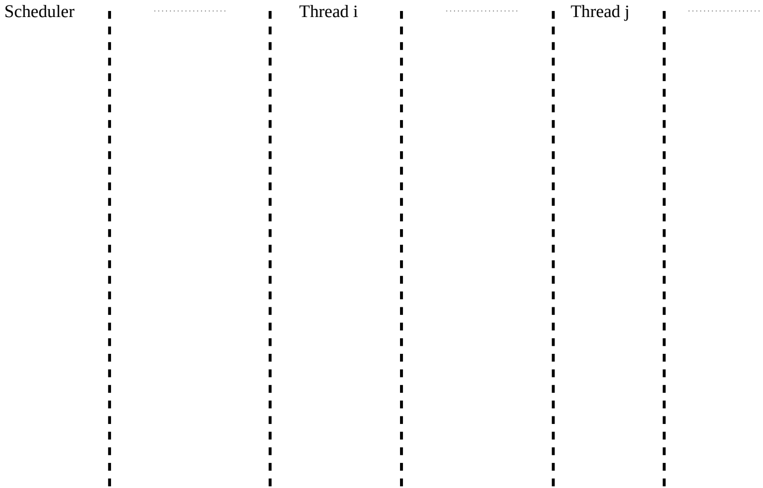


- Scheduler and primitive functions are left abstract, but exhibit cooperative scheduling with exclusive threads execution
  - Scheduler never preempts the running thread
  - At most one running thread at a time

Dynamic View of Cooperative Threads



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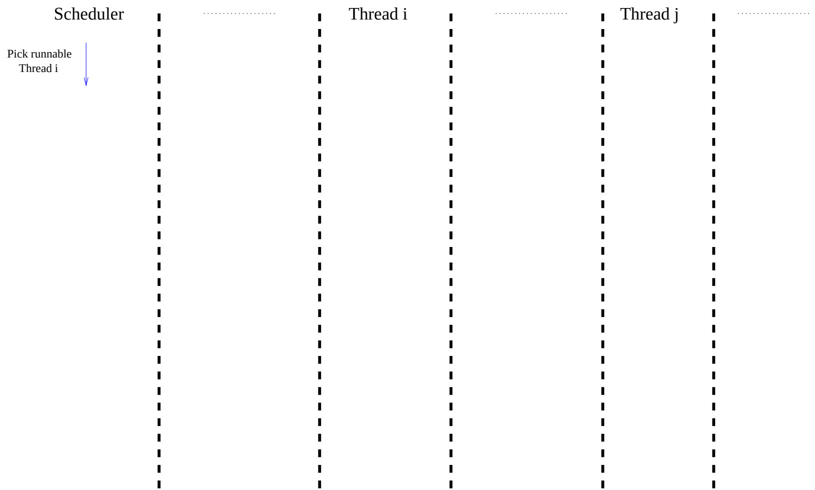

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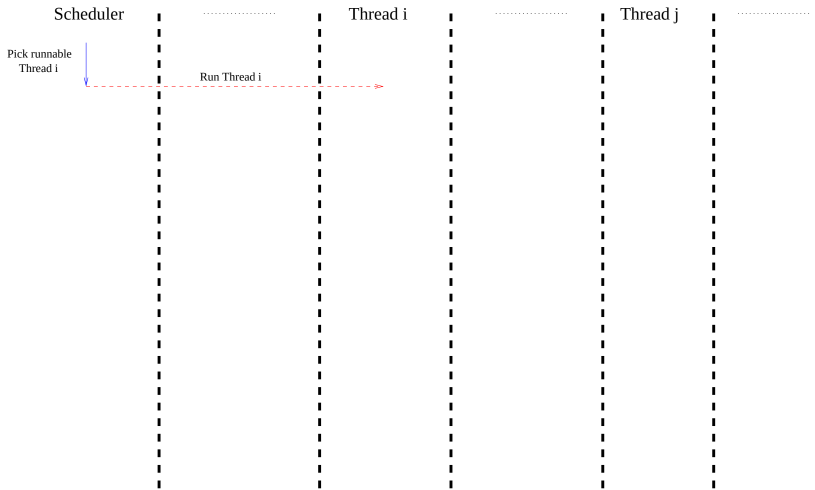

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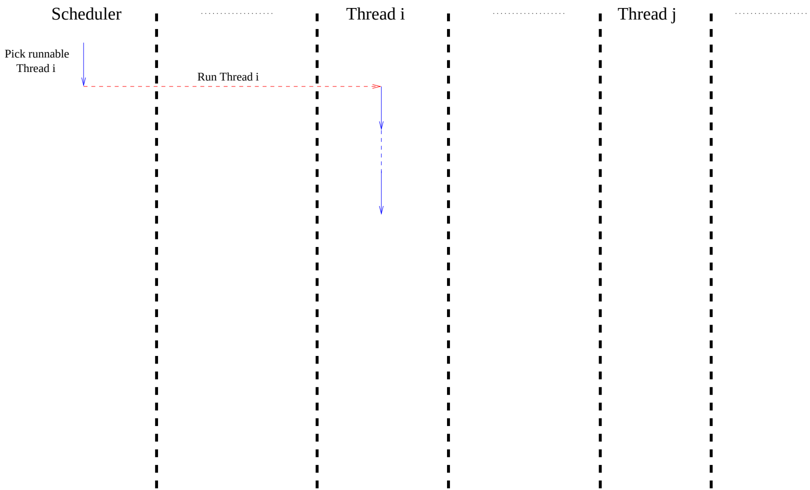

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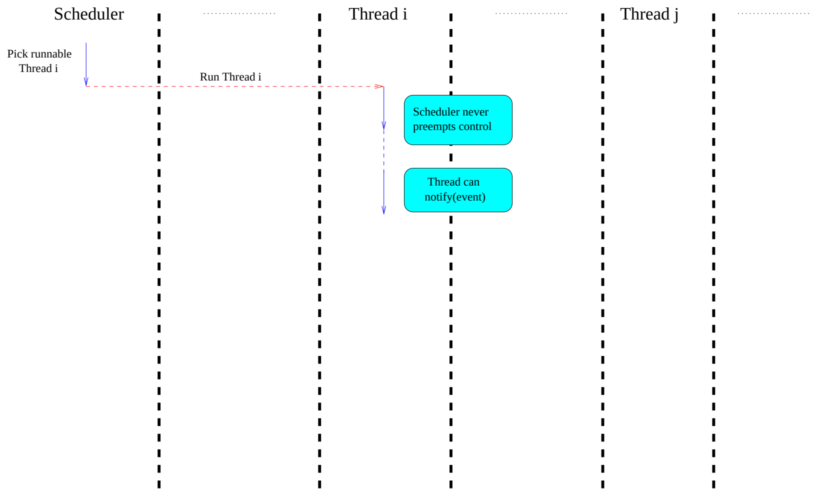

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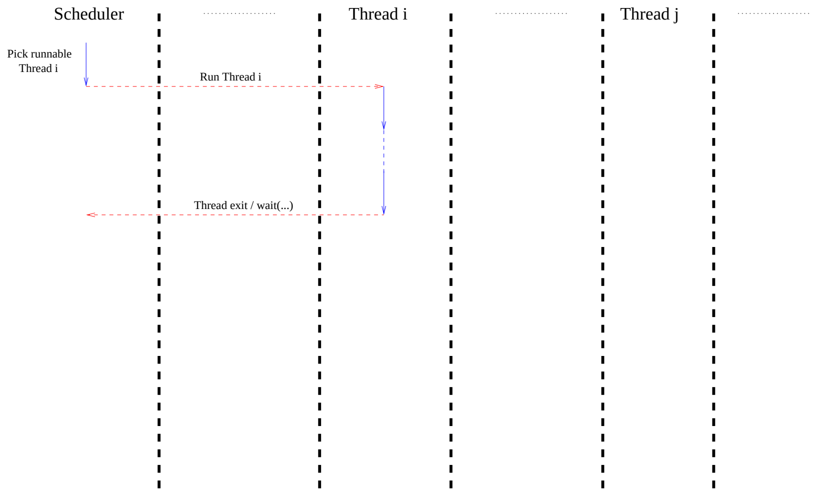

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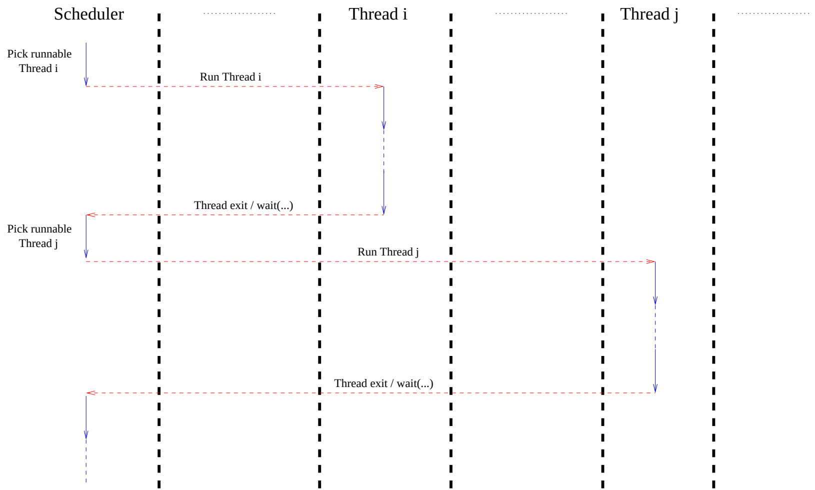

Sequential Program as CFG

Sequential program represented as a control-flow graph (CFG)

- A CFG for a sequential program P is a pair (L, G)
  - L: a set of program locations
  - $G \subseteq L \times Op \times L$: set of edges
  - l_0: unique entry location
  - l_e: error location
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   x--;
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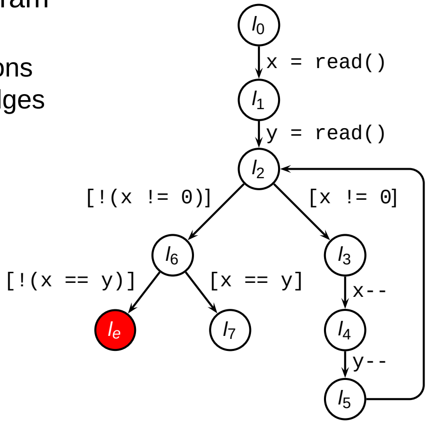

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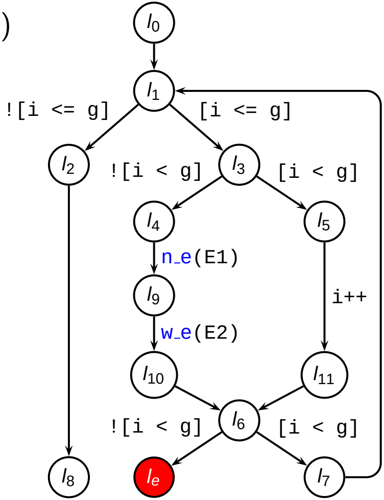
```
while (i <= g) {
  if (i < g) i++;
  else { // n_e and w_e are
         // primitive functions
    n_e(E1);
    w_e(E2); }
  assert(i < g);
}
```



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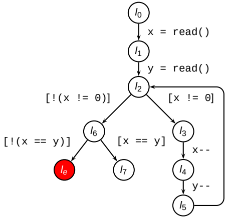

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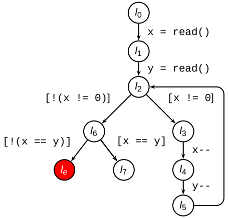
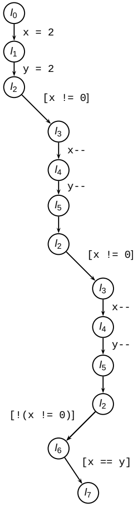


Safe: x = 2, y = 2



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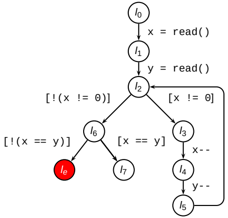

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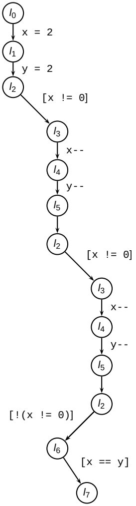
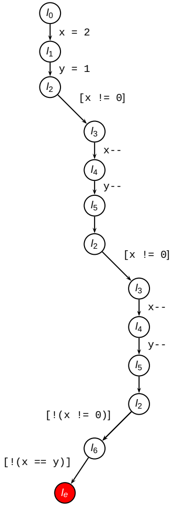


Unsafe: x = 2, y = 1



Model Checking of Sequential Programs

- Finite Model for Sequential Programs
  - Explicit State Model Checking [Hol05]
- Symbolic Model Checking
  - Symbolic Bounded Model Checking of Software [CKL04]
  - Lazy Predicate Abstraction of Software [HJMS02]
  - Lazy Abstraction with Interpolants for Software [McM06]

Finite Model for Sequential Programs

Create a finite-model of the program:

- Decide inputs to be chosen over a finite range
- Fix bounds for memory and recursive calls

Perform verification with an explicit state model checker:

- The SPIN model checker [Hol05]
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Comments:

- It is an under-approximation
  - The ranges for the inputs may hide bugs
- State explosion problem

Bounded Checking of Software

SAT Based Bounded Model Checking [BCC+03] effective in finding bugs in hardware designs

- Build a first order formula that represents a counter-example of length k for the property φ to verify

$$I(X_0) \wedge \bigwedge_{0}^{k-1} R(X_i, X_{i+1}) \wedge \neg\varphi(X_k)$$

- If the formula is satisfiable, then a bug has been found
  - Exploits effectiveness of SAT and SMT solvers
- Otherwise there might be a longer counterexample

Extends to software "trivially"

Bounded Model Checking For Software

- Fix a bound to loop unwinding
- Rewrite the program into single static assignment (SSA)
- Build a first order formula that represents the execution of the resulting program
  - The property to verify is the reachability of the error location
- Check satisfiability of the formula
  - If satisfiable, then a bug has been found
  - Otherwise there might be a bug for a longer unwinding of the loops

Example

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```
x0 = read(); y0 = read();
if (x0 != 0) { // loop 1
  x1 = x0-1; y1 = y0-1;
  if (x1 != 0) { // loop 2
    x2 = x1-1; y2 = y1-1;
  }
  x3 = (x1 != 0) ? x2 : x1;
  y3 = (x1 != 0) ? y2 : y1;
}
x4 = (x0 != 0) ? x3 : x0;
y4 = (x0 != 0) ? y3 : y0;
assert( x4 == y4 );
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}
x4 = (x0 != 0) ? x3 : x0;
y4 = (x0 != 0) ? y3 : y0;
assert( x4 == y4 );
```

$$
\begin{array}{l}
x_0 = read_X \wedge y_0 = read_Y \wedge \\
x_0 \neq 0 \rightarrow (\\
\quad x_1 = x_0 - 1 \wedge y_1 = y_0 - 1 \wedge \\
\quad x_1 \neq 0 \rightarrow (\\
\quad\quad x_2 = x_1 - 1 \wedge y_2 = y_1 - 1 \\
\quad) \wedge \\
\quad x_1 \neq 0 \rightarrow (x_3 = x_2 \wedge y_3 = y_2) \wedge \\
\quad x_1 = 0 \rightarrow (x_3 = x_1 \wedge y_3 = y_1) \\
) \wedge \\
x_0 \neq 0 \rightarrow (x_4 = x_3 \wedge y_4 = y_3) \wedge \\
x_0 = 0 \rightarrow (x_4 = x_0 \wedge y_4 = y_0) \wedge \\
x_4 = y4
\end{array}
$$

Bounded Model Checking For Software

There are many tools:

- CBMC [CKL04]
- LLBMC [FMS13]
- ESBMC [CFMS12]
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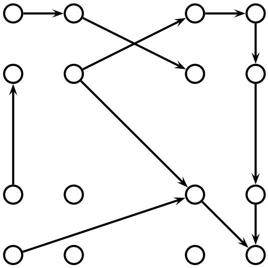
- This is an under-approximation: bound on loops
  - Checks whether loop-unwinding is enough can make the approach complete
- State explosion
  - For some programs, the required unwinding is too large to be handled by state-of-the-art SAT/SMT solvers

Predicate Abstraction

- A concrete program P over states S



Predicate Abstraction

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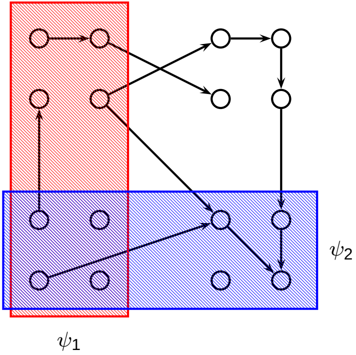

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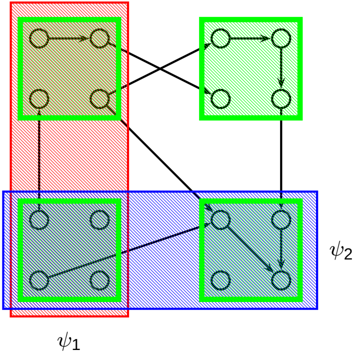

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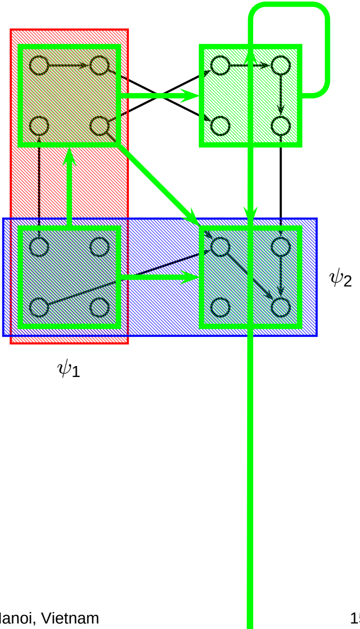
  - from as_0 to as_1 iff there is a transition from cs_0 to cs_1 with $cs_0 \in as_0$ and $cs_1 \in as_1$



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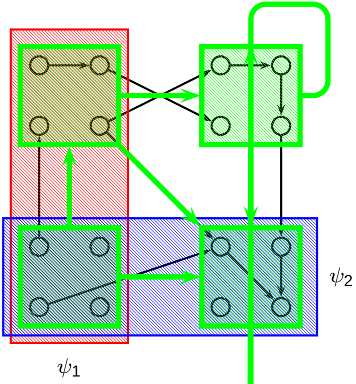
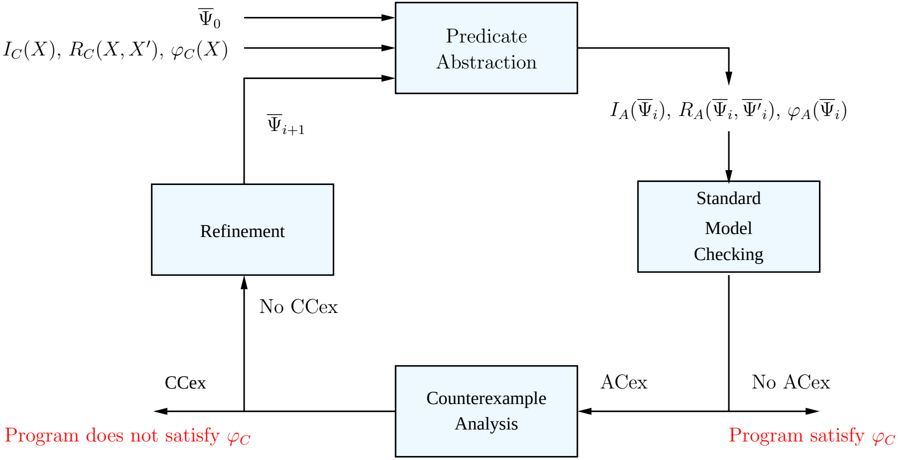


$$R_A(\overline{\Psi}, \overline{\Psi}') = \exists X, X'.(R_C(X, X') \wedge \bigwedge_i (\overline{\psi_i} \leftrightarrow \psi(X) \wedge \overline{\psi_i}' \leftrightarrow \psi(X')))$$

Counter-Example Guided Abstraction Refinement

The Counter-Example Guided Abstraction Refinement (CEGAR) Loop



Lazy Predicate Abstraction of Software

On-the-fly construction of an abstract reachability tree ART with counterexample-guided abstraction refinement

- A node of an ART is a pair (q, φ)
  - q is a location of the CFG
  - φ is the reachable region representing a set of states
- Node expansion from $q \xrightarrow{op} q'$:
  - $(q, \varphi) \rightarrow (q', \varphi')$
  - $\varphi' = SP^{\pi}_{op}(\varphi)$
    - the strongest post-condition for operation *op* w.r.t. set of predicates π
- Node (q, φ) is covered by internal node (q, φ') iff $\varphi \Rightarrow \varphi'$
- ART is safe iff
  - error location l_e is not reachable
  - all the leaves are covered
- If the ART is safe then, the program is safe

Lazy Predicate Abstraction of Software

On-the-fly construction of an ART with CEGAR

1. Pick an ART node

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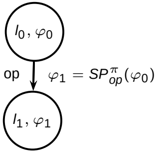

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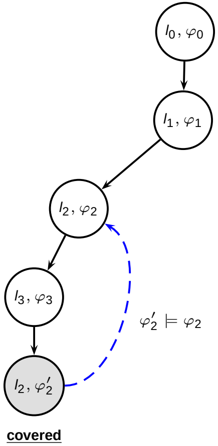

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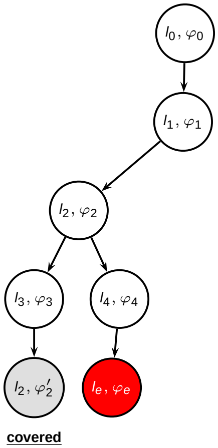

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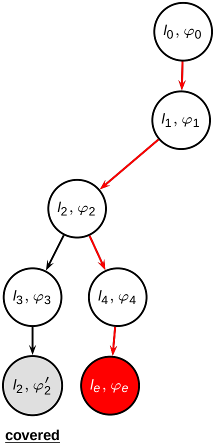

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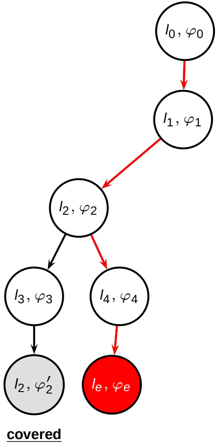

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     - Discover predicates to
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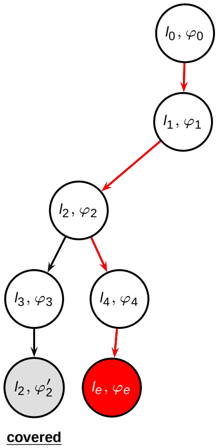

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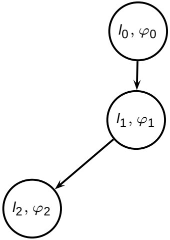

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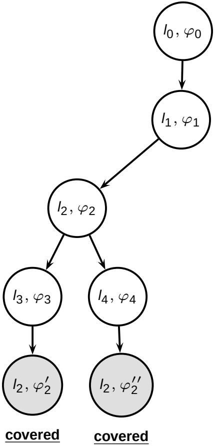
     - Goto 1 to reconstruct subtree



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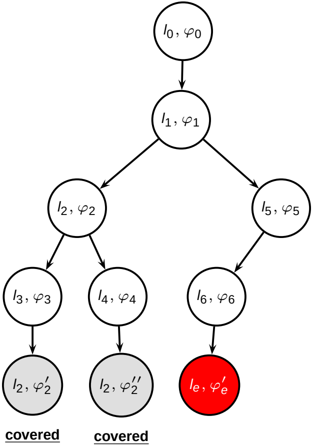
     - Discover predicates to refine abstraction
     - Undo part of ART
     - Goto 1 to reconstruct subtree



Lazy Predicate Abstraction of Software

On-the-fly construction of an ART with CEGAR

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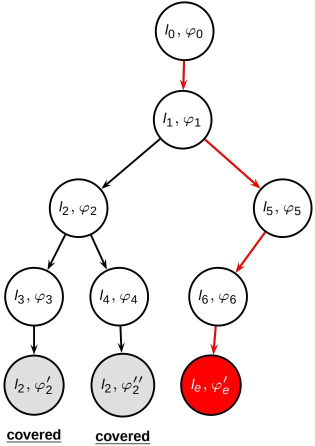

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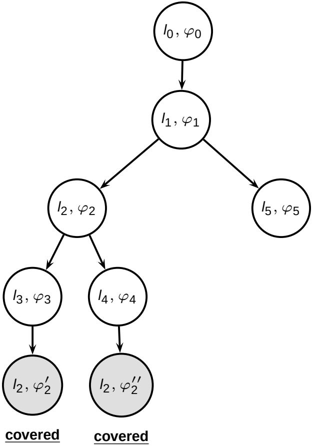

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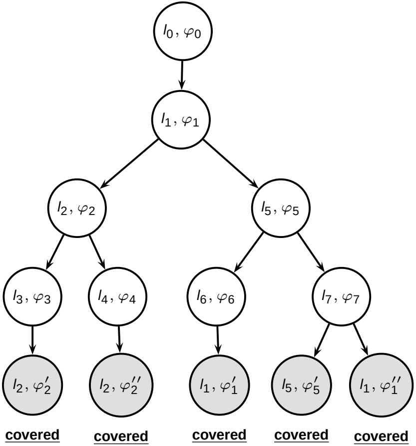

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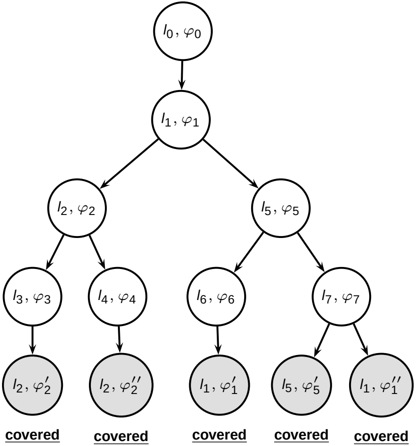
4. ART is safe $\Rightarrow$ program is safe



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- Discovery of new predicates [BHJM07]:
  - Weakest Precondition
  - Unsatisfiable Core
  - Interpolants

Lazy Abstraction with Interpolants

Interpolants:

- Given Φ_1 and Φ_2 such that $\Phi_1 \wedge \Phi_2$ is unsatisfiable
- There exists an interpolant Ψ such that:
  - $\Phi_1 \Rightarrow \Psi$
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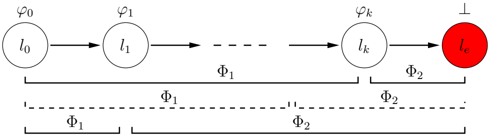
Lazy abstraction with interpolation:

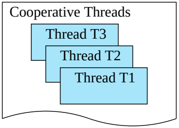
- Similar in spirit to lazy-predicate abstraction
- Avoids computation of $SP_{op}^{\pi}(\varphi)$ by over-approximating reachability regions using interpolants
  - Reachability region of error location set to $\perp$
  - Refine reachability regions on the path using interpolants



Outline

- Cooperative Threaded Programs (CTPs)
- Background
  - Safe Sequential Programs
  - Model Checking of Sequential Programs
    - Finite Model for Sequential Programs
    - Symbolic Model Checking of Sequential Programs
- Approaches to Model Checking of CTPs
  - Finite-Model for Cooperative Threaded Programs
  - Symbolic Model Checking of Sequential Software
  - Explicit Scheduler and Symbolic Threads (ESST)
- The Kratos Software Model Checker
- Experimental Results
- Related Work
- Conclusions

Approaches to Model Checking of CTPs



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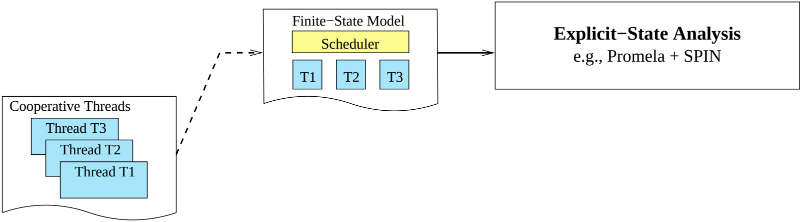

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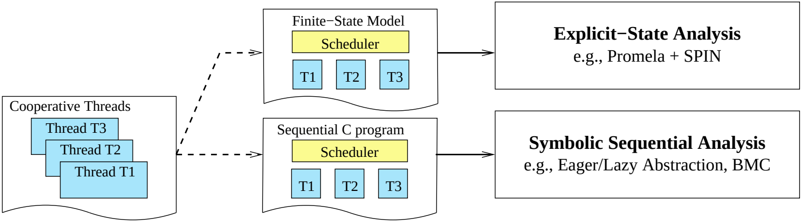

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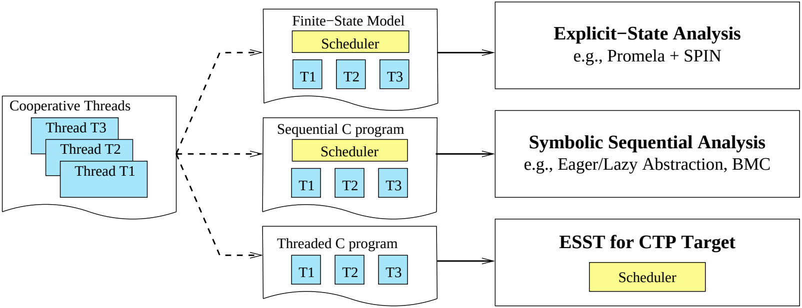
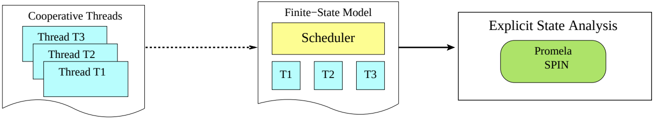


Finite-Model for Cooperative Threaded Programs

Translate cooperative threads into a Finite-State Model

- e.g. Promela [Hol05]



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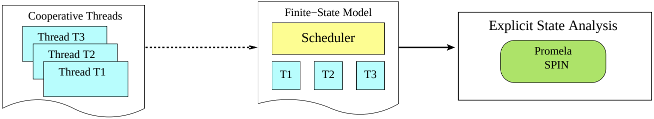

Analysis can be done with Explicit State Model Checker

- e.g, SPIN Model Checker [Hol05]

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  - Thread suspension as function thread_suspend()
    - Implementation varies from the encodings

```
wait(...);  ⟹      thread_state = WAITING;
                    thread_pc = NEXT_LOC;
                    global = local;
                    thread_suspend();
                  NEXT_LOC_LABEL:
                    local = global;
```

```
inline thread_body() {
  if
   :: (thread_pc == NEXT_LOC) ->
                    goto NEXT_LOC_LABEL;
   :: ...
   :: else -> skip;
  fi
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```

[CCNR11, CNR13] shows finite-model for SystemC designs

Encoding of primitive functions

Channel update

```
#define ITE(C,T,E) { if ::C -> T; ::else -> E; fi }

inline p_to_c_update() {
 ITE(p_to_c_new != p_to_c_old,
     p_to_c_old = p_to_c_new; e_p_to_c = NOTIFIED_DELTA, skip)
}
```

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```

Event Notification

```
bool p_write_notified, p_read_notified, c_read_and_ack_notified;

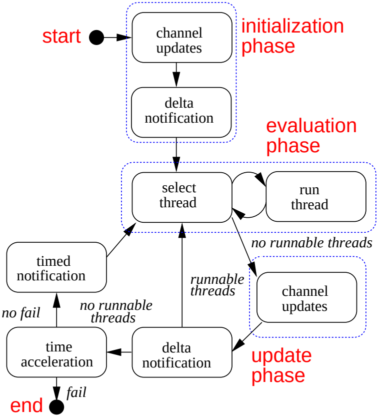
inline is_p_write_notified(notified) {
  ITE(((p_write_pc == wait_1 && e_p_write_state == NOTIFIED) ||
       (p_write_pc == wait_2 && e_state         == NOTIFIED)),
       notified = true, notified = false);
}

inline notify_threads() {
  is_p_write_notified(p_write_notified);
  ITE(p_write_notified, p_write_state = RUNNABLE, skip);
  is_p_read_notified(p_read_notified);
  ITE(p_read_notified, p_read_state = RUNNABLE, skip);
  is_c_read_and_ack_notified(c_read_and_ack_notified);
  ITE(c_read_and_ack_notified, c_read_and_ack_state = RUNNABLE, skip);
}

inline e_notify() {
  e_state = NOTIFIED; notify_threads(); e_state = NONE;
}
```

Encoding of the scheduler

For SystemC



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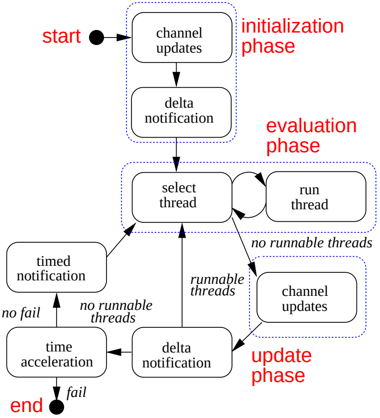


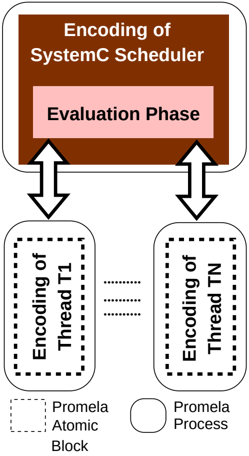

```
proctype Scheduler() {
 bool runnable, accelerated;
 channel_updates();
 delta_notification();
start_DeltaCycle:
 exists_runnable_threads(runnable);
 ITE(!runnable,goto TimedNotification,skip);
 evaluation_phase();
 channel_updates();
progress_DeltaCycle:
 delta_notification();
 ITE(runnable,goto start_DeltaCycle,skip);
TimedNotification:
 time_acceleration(accelerated);
 ITE(accelerated,goto SchedulerExit,skip);
 timed_notification();
 goto start_DeltaCycle;
SchedulerExit:
}
```

Finite-Model for Cooperative Threaded Programs (II)

- Encode threads and thread suspension/resume depending on the encoding of the synchronization thread-scheduler
  - Thread-To-Process
  - Thread-To-Atomic-Block
  - One-Atomic-Block

Thread-To-Process Encoding

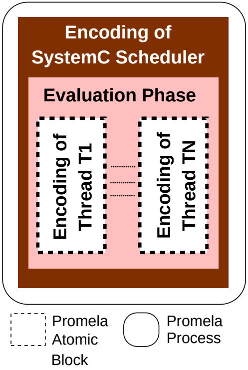
Threads and scheduler as separate processes, synchronization scheduler-threads through token exchange on a rendezvous channel




```
inline thread_suspend () {thread_chan!TK;
                          thread_chan?TK;}
active proctype thread_1() {
 thread_1_entry:
  atomic { thread_1_chan?TK; thread_1_body(); }
 thread_1_exit:
  goto thread_1_entry;
}
inline evaluation_phase() {
 do
  :: thread_1_state == RUNNABLE ->
     thread_1_state = RUNNING;
     thread_1_chan!TK; thread_1_chan?TK;
  ...
  :: thread_N_state == RUNNABLE ->
     thread_N_state = RUNNING;
     thread_N_chan!TK; thread_N_chan?TK;
  :: else -> break;
 od;
}
```

Thread-To-Atomic-Block Encoding

Threads and scheduler embedded in a unique process, thread suspension through jump to the exit location, no need of the rendezvous channel. Each thread body enclosed in an atomic block

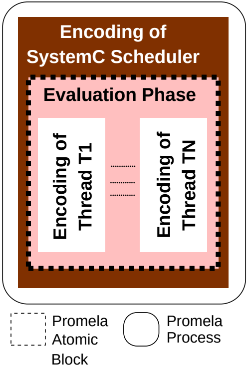



```
inline thread_1() {
  atomic {  thread_1_body();  }
 thread_1_exit:
  skip;
}

inline evaluation_phase() {
 do
   :: thread_1_state == RUNNABLE ->
       thread_1_state = RUNNING;  thread_1();
   ...
   :: thread_N_state == RUNNABLE ->
       thread_N__state = RUNNING;  thread_N();
   :: else -> break;
 od;
}
```

One-Atomic-Block Encoding

Derived from Thread-To-Atomic-Block enclosing whole evaluation phase into an atomic block



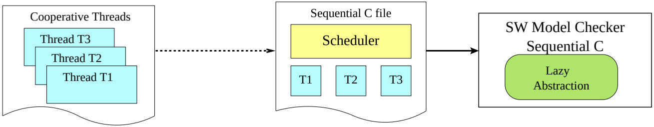

```
proctype scheduler() {
  ...
  atomic {
    evaluation_phase();
  }
  ...
}
```

Limitations of Finite State Model for CTPs

- Under-approximation
  - There might be different inputs for which the property is violated
- Partial Order Reduction (POR) within model checker can be ineffective
  - POR should be carried out at the level of the Scheduler
  - Explicit state model checkers (e.g. SPIN) do POR at process level
  - Useful domain information lost in the encoding
- State explosion

Symbolic Model Checking of Sequential Software

Translate cooperative threads into sequential C program



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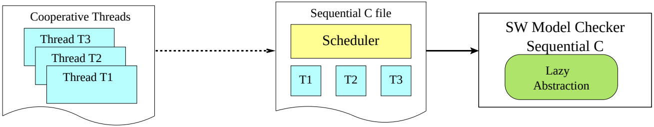

Analysis can be based on:

- Bounded Model Checking [CKL04]
- Lazy Predicate Abstraction [HJMS02]
- Lazy Abstraction with Interpolants [McM06]

Sequentializing Cooperative Threads

- Encode each thread as a function

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```
void thread() {
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- Encode thread communication primitives opening their definition
- Encode `Scheduler` as a function:
  - Must allow for exploring all possible thread interleavings:

```
while ( exists_runnable_thread() ) {
  if ( thread_i_state == RUNNABLE && nondet() )
    thread_i();
  ...
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[CMNR10, CNR13] shows sequentialization for SystemC

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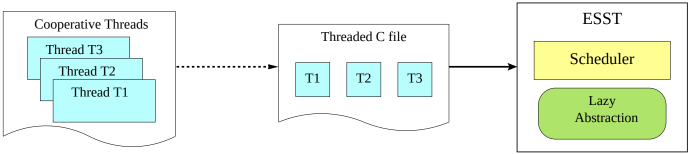
  - Lazy abstraction with interpolants
    - Slow convergence
    - Large interpolants

Model Checking with ESST

Explicit-Scheduler Symbolic-Thread (ESST) algorithm



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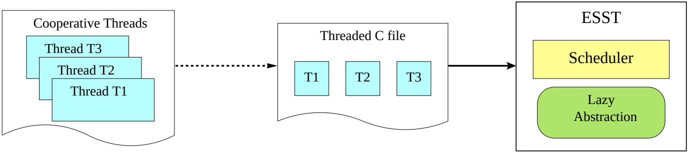

In a nutshell . . .

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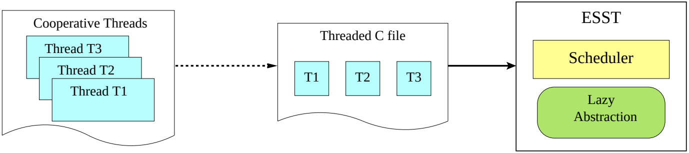

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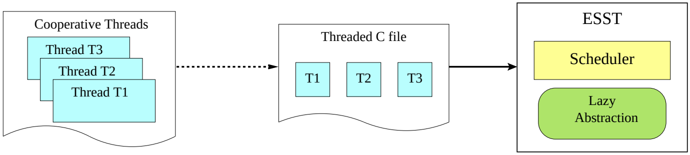

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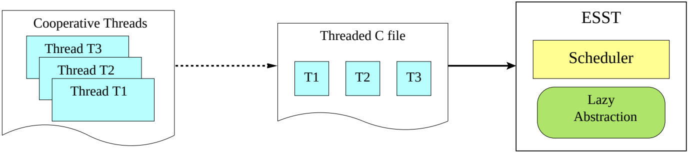
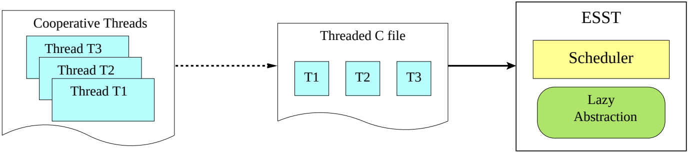


In a nutshell . . .

- Analyze threads symbolically using lazy predicate abstraction.
- Analyze scheduler using explicit-state techniques:
  - Keep track of the scheduler states explicitly

Model Checking with ESST

Explicit-Scheduler Symbolic-Thread (ESST) algorithm



In a nutshell . . .

- Analyze threads symbolically using lazy predicate abstraction.
- Analyze scheduler using explicit-state techniques:
  - Keep track of the scheduler states explicitly
- Scheduler is part of the model-checking algorithm

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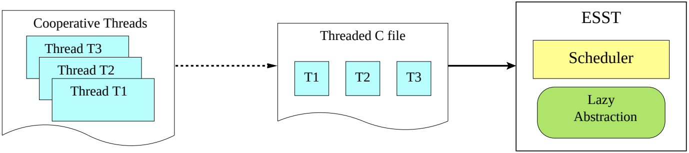

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[CMNR10, CNR13] shows ESST for SystemC, [CNR12a] for FairThreads

Abstract Reachability Forest (ARF)

- An abstract reachability forest (ARF) consists of connected abstract reachability trees ART’s
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  - Each ART is obtained by unwinding the CFG of running thread
- An ARF node with N threads:

$$(\langle l_1, \varphi_1 \rangle, \ldots, \langle l_N, \varphi_N \rangle, \varphi, S)$$

  - $\langle l_i, \varphi_i \rangle$ where l_i CFG location and φ_i region of thread i
  - φ is global region (e.g., for shared variables)
  - S is scheduler state: mapping from variables to values

Primitive Executor

- Primitive executor

$$\textsc{SExec} : \mathit{SchedulerState} \times \mathit{PrimitiveCall} \to \mathit{SchedulerState}$$

Example:

$S' = \textsc{SExec}(S, \texttt{wait\_event(e)})$, such that

$$S' = S[t_{state} \mapsto \mathit{WAITING}, t_{event} \mapsto \mathrm{e}]$$

Scheduler

- Scheduler

$$\textsc{Sched} : \mathit{SchedulerState} \rightarrow \mathcal{P}(\mathit{SchedulerState})$$

$\{S_1, \ldots, S_m\} = \textsc{Sched}(S)$

  - No running thread in S
  - Each S_i for $i = 1, \ldots, m$ has exactly one running thread

ESST Algorithm: ARF Construction

Computing successor nodes involves:

- Computing abstract strongest post-condition *SP*
- Executing primitive functions
- Running the scheduler

ESST Algorithm: ARF Analysis

On-the-fly construction of an ARF with CEGAR

1. Pick an ARF node

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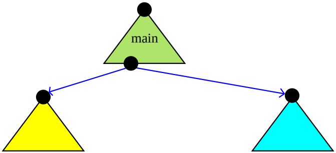

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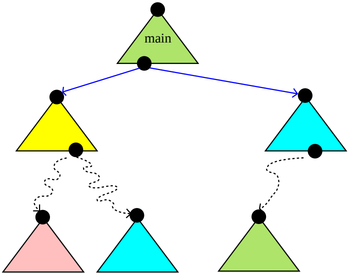

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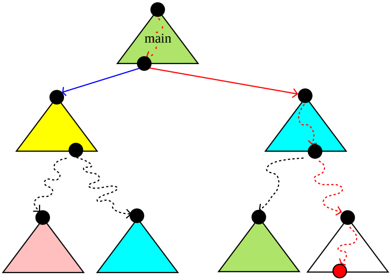

ESST Algorithm: ARF Analysis

On-the-fly construction of an ARF with CEGAR

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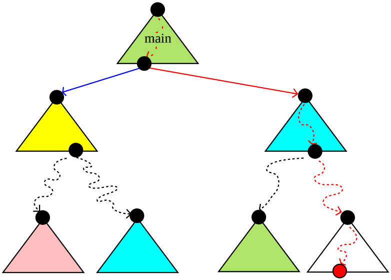

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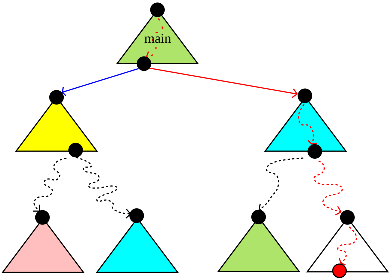

ESST Algorithm: ARF Analysis

On-the-fly construction of an ARF with CEGAR

1. Pick an ARF node
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3. If reach the error location: analyze path
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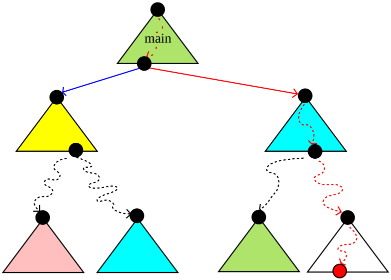
   - If path is spurious:
     - Discover predicates to refine abstraction



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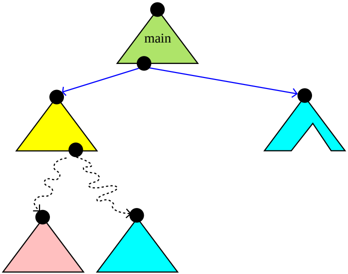
     - Undo part of ARF



ESST Algorithm: ARF Analysis

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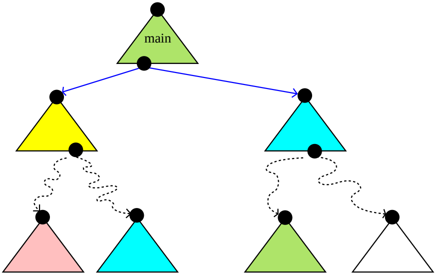

ESST Algorithm: ARF Analysis

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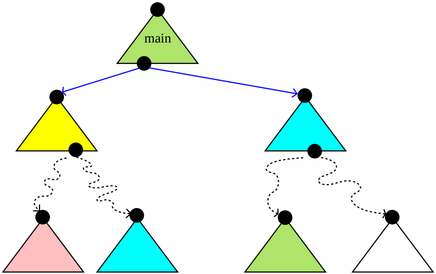
4. ARF is safe $\Rightarrow$ program is safe



ESST Algorithm: ARF Construction (Rule 1)

Thread i is the running thread in S, and op in the CFA edge (l_i, op, l'_i) is not a primitive function call

$$(\langle l_1, \varphi_1 \rangle, \quad \ldots \quad \langle l_i, \varphi_i \rangle, \quad \ldots \quad \langle l_n, \varphi_n \rangle, \quad \varphi, \quad S)$$

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$$
\begin{array}{ccccccc}
(\langle l_1, \varphi_1 \rangle, & \ldots & \langle l_i, \varphi_i \rangle, & \ldots & \langle l_n, \varphi_n \rangle, & \varphi, & S) \\
 & & \Big\downarrow SP^{\pi_i}_{op}(\psi_i) & & & & \\
 & & \langle l_i', \varphi_i' \rangle, & & & &
\end{array}
$$

- $\psi_i \Leftrightarrow \varphi_i \wedge \varphi$

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(\langle l_1, \varphi_1 \rangle, & \ldots & \langle l_i, \varphi_i \rangle, & \ldots & \langle l_n, \varphi_n \rangle, & \varphi, & S) \\
\downarrow SP^{\pi_1}_{\text{HAVOC}(op)}(\psi_1) & & \downarrow SP^{\pi_i}_{op}(\psi_i) & & \downarrow SP^{\pi_n}_{\text{HAVOC}(op)}(\psi_n) & \downarrow SP^{\pi}_{op}(\varphi) & \\
(\langle l_1, \varphi'_1 \rangle, & \ldots & \langle l'_i, \varphi'_i \rangle, & \ldots & \langle l_n, \varphi'_n \rangle, & \varphi', &
\end{array}
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- $\psi_i \Leftrightarrow \varphi_i \wedge \varphi$
- Havoc HAVOC $(g := e) = (g := f)$
  - g is a global variable
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\begin{tikzcd}
(\langle l_1, \varphi_1 \rangle, \arrow[d, "SP^{\pi_1}_{\textsc{havoc}(op)}(\psi_1)"] & \ldots & \langle l_i, \varphi_i \rangle, \arrow[d, "SP^{\pi_i}_{op}(\psi_i)"] & \ldots & \langle l_n, \varphi_n \rangle, \arrow[d, "SP^{\pi_n}_{\textsc{havoc}(op)}(\psi_n)"] & \varphi, \arrow[d, "SP^{\pi}_{op}(\varphi)"] & S) \arrow[d] \\
(\langle l_1, \varphi'_1 \rangle, & \ldots & \langle l'_i, \varphi'_i \rangle, & \ldots & \langle l_n, \varphi'_n \rangle, & \varphi', & S)
\end{tikzcd}
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ESST Algorithm: ARF Construction (Rule 2)

Thread i is the running thread in S, and op in the CFA edge (l_i, op, l_i') is ~~not~~ a primitive function call.

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$$\begin{array}{ccccccc} (\langle l_1,\varphi_1\rangle, & \ldots & \langle l_i,\varphi_i\rangle, & \ldots & \langle l_n,\varphi_n\rangle, & \varphi, & S) \\ \downarrow & & \downarrow & & \downarrow & \downarrow & \\ (\langle l_1,\varphi_1\rangle, & \ldots & \langle l'_i,\varphi_i\rangle, & \ldots & \langle l_n,\varphi_n\rangle, & \varphi, & \end{array}$$

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\begin{array}{cccccccc}
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\downarrow & & \downarrow & & \downarrow & \downarrow & \downarrow & \textsc{Sexec}(S, op) \\
(\langle l_1, \varphi_1 \rangle, & \ldots & \langle l'_i, \varphi_i \rangle, & \ldots & \langle l_n, \varphi_n \rangle, & \varphi, & S') &
\end{array}
$$

ESST Algorithm: ARF Construction (Rule 3)

No running thread in S

$$(\ldots, S)$$

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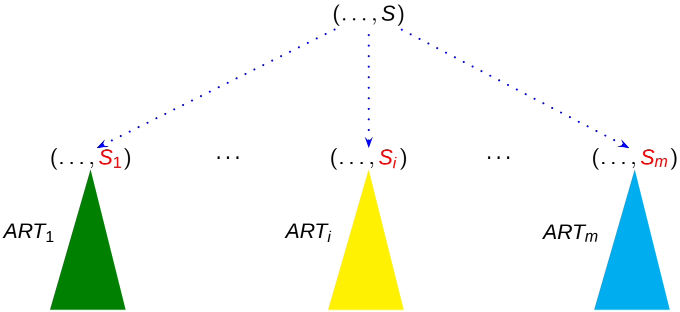
$$(\ldots, S_1) \qquad \cdots \qquad (\ldots, S_i) \qquad \cdots \qquad (\ldots, S_m)$$

- $\{S_1, \ldots, S_m\} = \textsc{Sched}(S)$

ESST Algorithm: ARF Construction (Rule 3)

No running thread in S



- $\{S_1, \ldots, S_m\} = \textsc{Sched}(S)$
- $(\ldots, S) \dashrightarrow (\ldots, S_i)$ is ARF connector

ESST Algorithm: Coverage

- Coverage check

$$(\langle l_1, \varphi_1 \rangle, \quad \ldots \quad \langle l_i, \varphi_i \rangle, \quad \ldots \quad \langle l_n, \varphi_n \rangle, \qquad \varphi, \qquad S)$$

$$(\langle l_1, \varphi'_1 \rangle, \quad \ldots \quad \langle l_i, \varphi'_i \rangle, \quad \ldots \quad \langle l_n, \varphi'_n \rangle, \qquad \varphi', \qquad S')$$

ESST Algorithm: Coverage

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\begin{array}{ccccccc}
(\langle l_1, \varphi_1 \rangle, & \ldots & \langle l_i, \varphi_i \rangle, & \ldots & \langle l_n, \varphi_n \rangle, & \varphi, & S) \\
\Big\downarrow \text{covered} & & \Big\downarrow \text{covered} & & \Big\downarrow \text{covered} & \Big\downarrow \models & \Big\downarrow = \\
(\langle l_1, \varphi'_1 \rangle, & \ldots & \langle l_i, \varphi'_i \rangle, & \ldots & \langle l_n, \varphi'_n \rangle, & \varphi', & S')
\end{array}
$$

ESST Algorithm: Feasibility Check

- Feasibility check

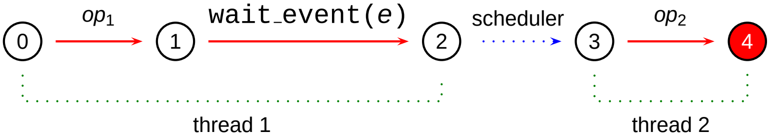
ARF Path π

$$0 \xrightarrow{op_1} 1 \xrightarrow{\texttt{wait\_event}(e)} 2 \xrightarrow{\text{scheduler}} 3 \xrightarrow{op_2} 4$$

ESST Algorithm: Feasibility Check

- Feasibility check

ARF Path π



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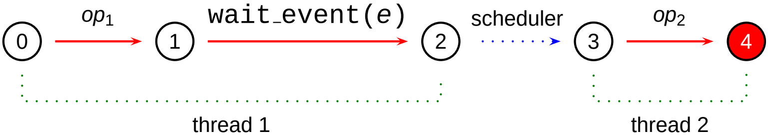
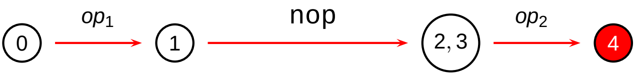


ARF path π'



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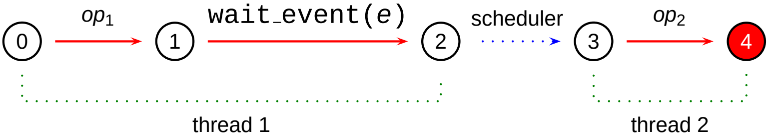

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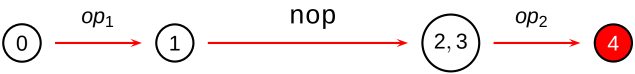

π is feasible iff so is π'

Correctness of ESST

Theorem

Let P be a threaded sequential program. For every terminating execution of $\mathrm{ESST}(P)$*, we have the following properties:*

1. *If* $\mathrm{ESST}(P)$ *returns a feasible counter-example path* $\hat{\rho}$*, then we have* $\gamma \xrightarrow{\hat{\rho}} \gamma'$ *for an initial configuration* γ *and an error configuration* γ' *of* P
2. *If* $\mathrm{ESST}(P)$ *returns a safe ARF* $\mathcal{F}$*, then for every configuration* $\gamma \in \mathit{Reach}(P)$*, there is an ARF node* $\eta \in \mathit{Nodes}(\mathcal{F})$ *such that* $\gamma \models \eta$

Limitations of ESST for CTPs

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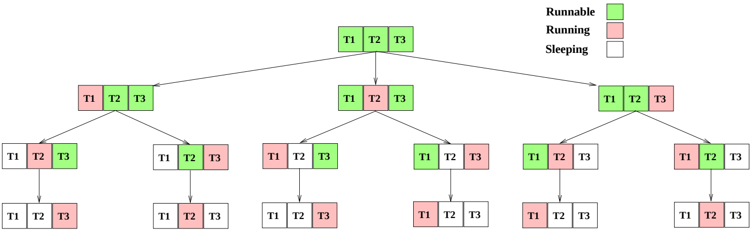
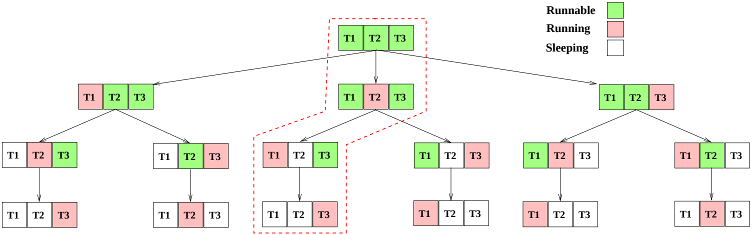


Given n threads: $n!$ interleavings, at least 2^n abstract states

Limitations of ESST for CTPs



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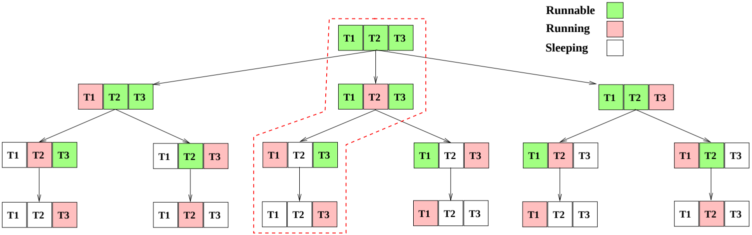
Impacts on ESST:

Limitations of ESST for CTPs



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Impacts on ESST:

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  - Expensive abstract post image computations

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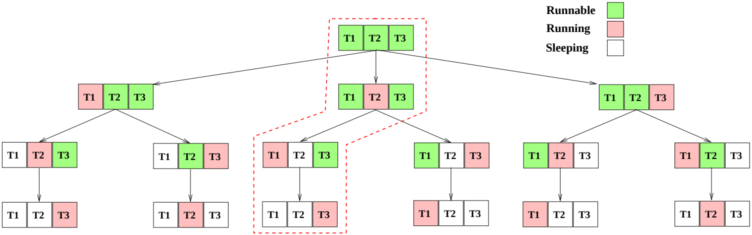

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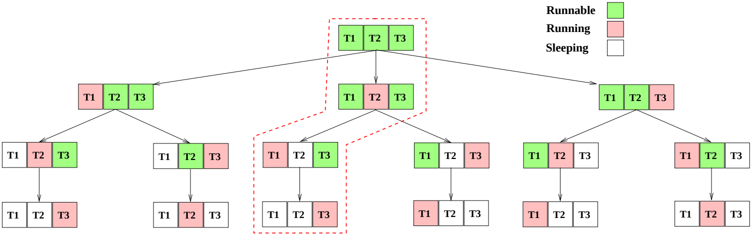

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$\Rightarrow$ Degrade performace of ESST + State explosion

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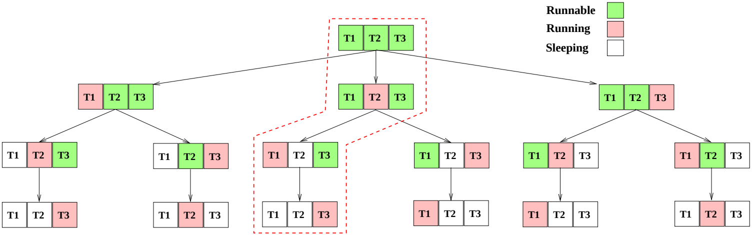

Given *n* threads: *n*! interleavings, at least 2^n abstract states

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⇒ Degrade performace of ESST + State explosion

- Apply partial-order reduction to ESST [CNR11]
  - Allow ESST to explore only representative interleavings

Partial-Order Reduction (POR)

Idea of POR

Exploit independence and commutativity of transitions

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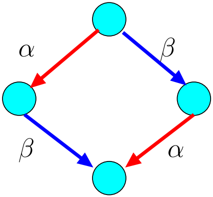
Exploit independence and commutativity of transitions

Two transitions are independent if

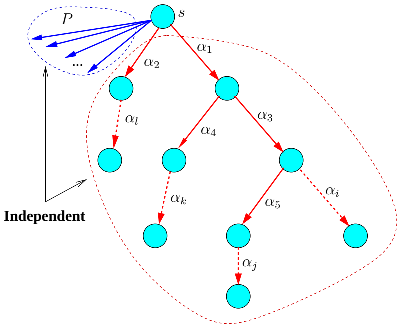
1. they neither disable nor enable each other
2. they commute



Persistent Set

Persistent Set

A set P of transitions is persistent in a state s if the transitions are independent of every $\alpha_i \notin P$ reachable from s



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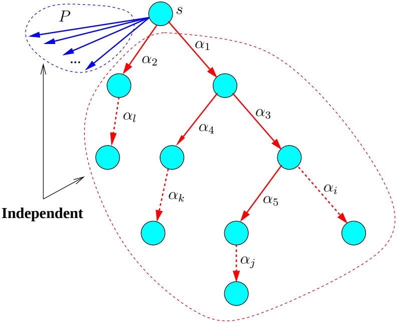
A set P of transitions is persistent in a state s if the transitions are independent of every $\alpha_i \notin P$ reachable from s

$\Rightarrow$ One only needs to explore P



Requirements for Verifying Safety Properties

1. Successor-state condition: persistent set *P* in state *s* is empty iff no enabled transitions in *s*

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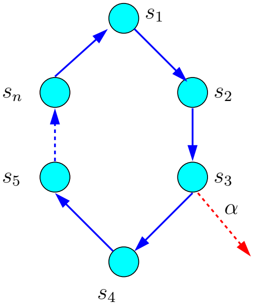
2. Cycle condition: disallow



α is enabled in s_i but not in the persistent sets of $s_1, \ldots, s_n$

Identifying Atomic Blocks

An atomic block correspond to a non-interleaved transition

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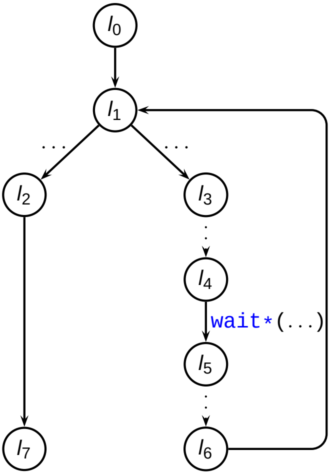

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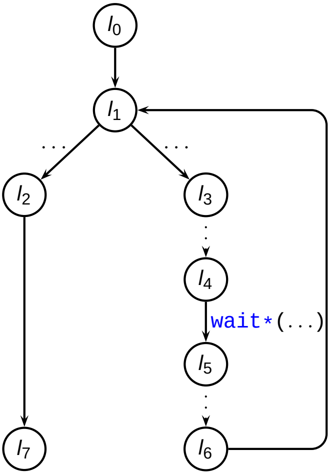

Fragment between two wait*(...)

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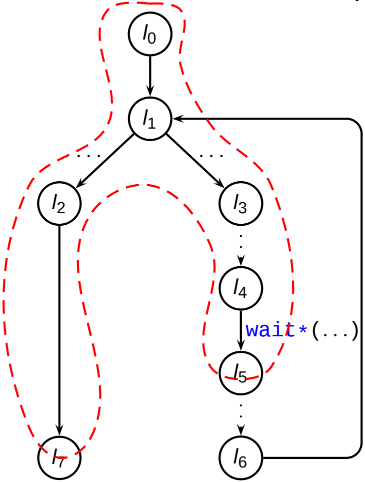

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Identify an atomic block by its entry:

1. Entry: l_o, Exit: l_5, l_7

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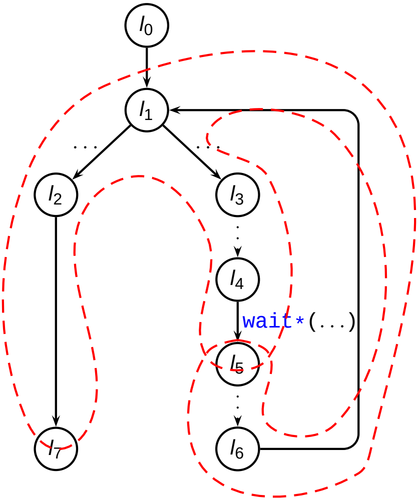

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Atomic Block (In)dependence

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The Function PERSISTENT

Compute persistent scheduler states:

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Extension of ESST Rule: Persistent Set

No running thread in S

$$N = (\ldots, S)$$

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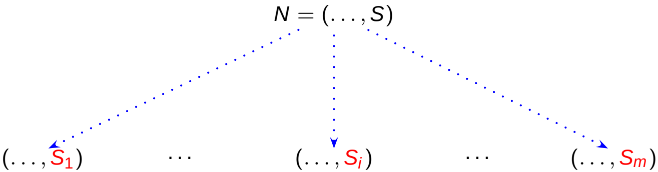

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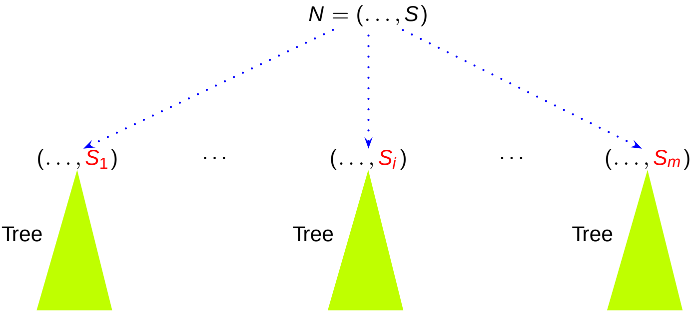

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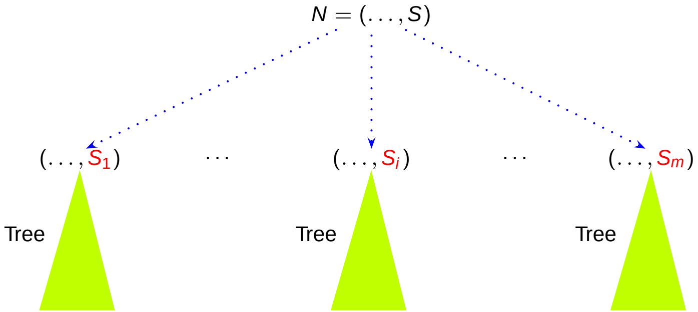

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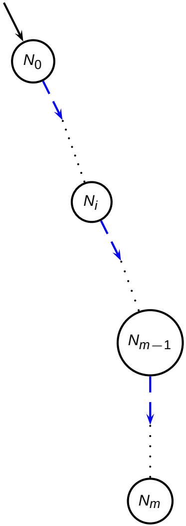

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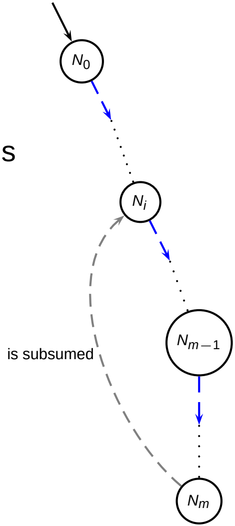

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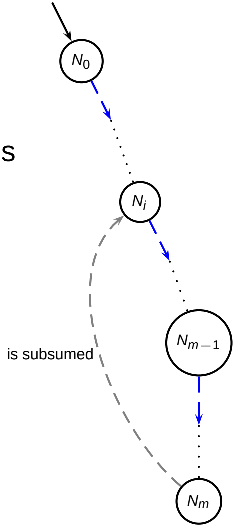

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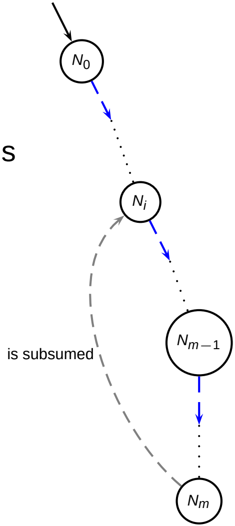

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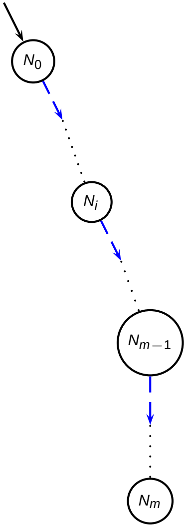

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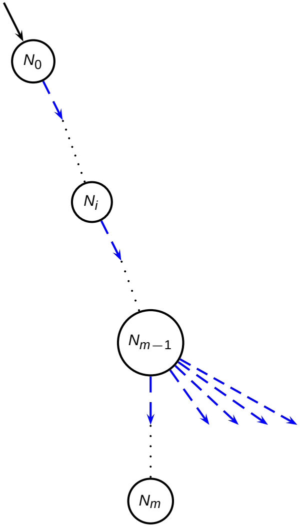

Correctness of ESST+POR

Theorem

Let P be a threaded sequential program. For every terminating executions of $\mathrm{ESST}(P)$ *and* $\mathrm{ESST}_{\mathrm{POR}}(P)$*, we have that* $\mathrm{ESST}(P)$ *reports safe iff so does* $\mathrm{ESST}_{\mathrm{POR}}(P)$*.*

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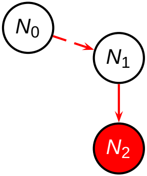

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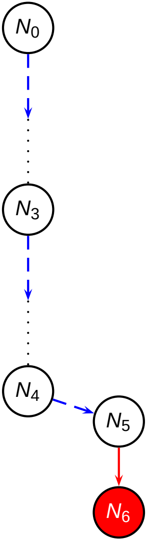

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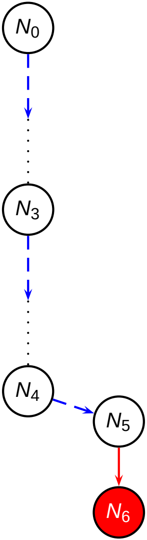

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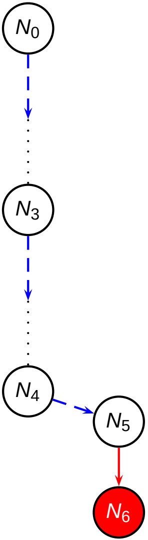

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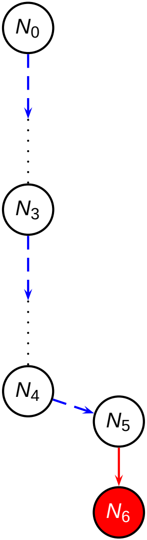

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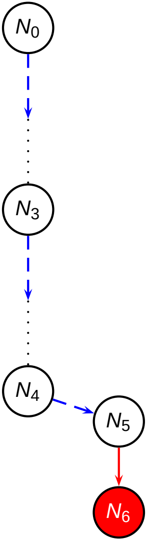

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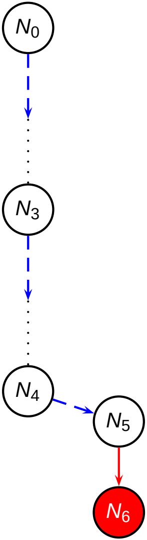
$\Rightarrow$ Degrade performance of ESST
  - Experimental evaluation does not show this behavior

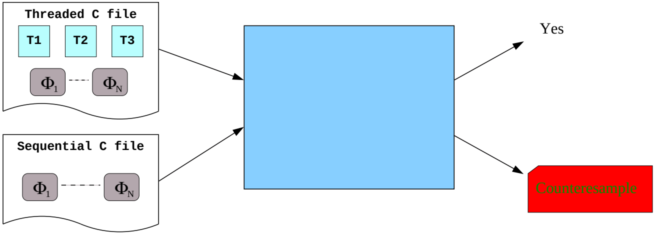


Outline

- Cooperative Threaded Programs (CTPs)
- Background
  - Safe Sequential Programs
  - Model Checking of Sequential Programs
    - Finite Model for Sequential Programs
    - Symbolic Model Checking of Sequential Programs
- Approaches to Model Checking of CTPs
  - Finite-Model for Cooperative Threaded Programs
  - Symbolic Model Checking of Sequential Software
  - Explicit Scheduler and Symbolic Threads (ESST)
- The Kratos Software Model Checker
- Experimental Results
- Related Work
- Conclusions

KRATOS: Overview

- KRATOS is a software model checker for sequential and threaded programs with cooperative scheduler



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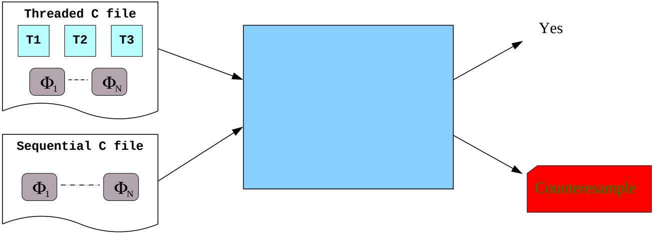

- KRATOS verifies safety properties in the form of program assertion

KRATOS: Overview (II)

- Analyses for sequential programs:
  - Sequential analysis:
    - Lazy abstraction [HJMS02]
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    - Property Driven Reachability for Software [CG12]
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Typically SW model checkers stops once they find a violated assertion, and returns a counterexample

- For finding all violated assertions: one assertion at a time in the program under analysis

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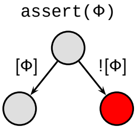

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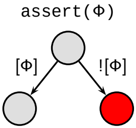
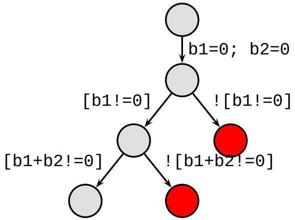


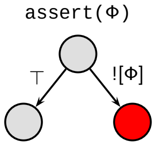

```
int b1=0, b2=0;
assert(b1 != 0);
assert(b1+b2 != 0);
```

2nd assertion cannot be violated: it is blocked by the 1st one



Software Model Checking of Multiple Assertions (II)

- Modify the interpretation of `assert` to enable handling of multiple assertions and produce a counterexample for all violated assertions
  - Interpret assertions-as-properties



- Extend SW model checking via lazy-predicate abstraction to deal with multiple assertions
  - Two search techniques
    - All-in-one-go
    - One-at-a-time
  - Both interpret assertion as properties

SW MC Multiple Assertions: All-In-One-Go

- When an assertion violation reached, the assertion is disabled, and the search continues for other possible violations of other assertions
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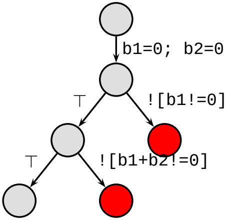

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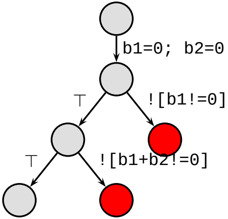

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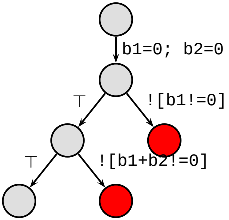

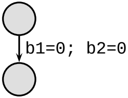

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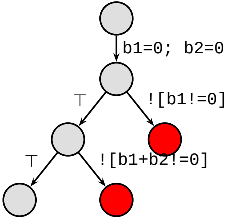

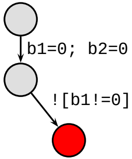

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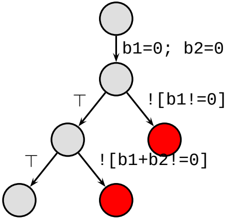

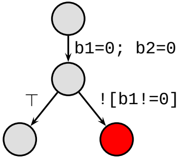

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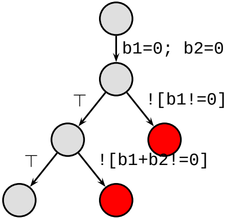

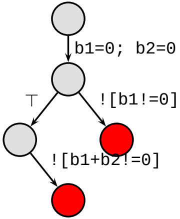

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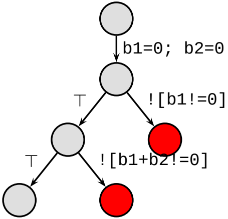

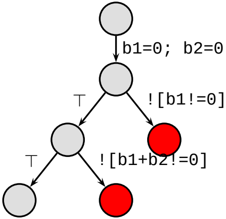

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- One assertion at a time is checked
  - Disabling other assertions

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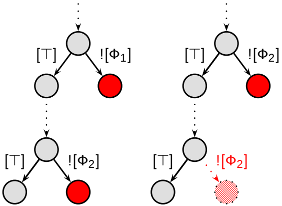
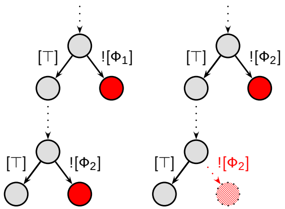


SW MC Multiple Assertions: One-At-A-Time

- One assertion at a time is checked
  - Disabling other assertions
- ART/ARF used for checking one assertion re-used for proving the others

...
assert(Φ_1);
...
assert(Φ_2);
...



SW MC Multiple Assertions: One-At-A-Time

- One assertion at a time is checked
  - Disabling other assertions
- ART/ARF used for checking one assertion re-used for proving the others
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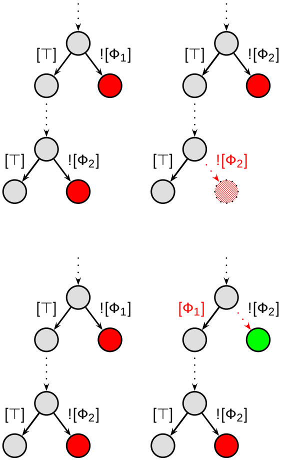

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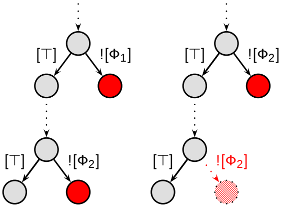

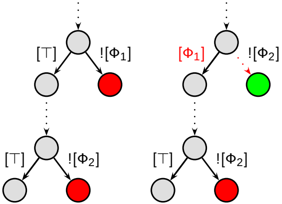

- Enables for several optimizations
  - On-the-fly slicing with respect to the checked assertion
  - Partitioning the predicates used to prove each assertion
  - Collecting loop invariants from the constructed ART/ARF to be used to possibly strengthen the successive searches

Architecture of KRATOS

- Front-end:
  - Parser and Type checker
  - CFG encoder: single-block, basic-block and large-block [BCG+09] encodings
  - Optimization: constant propagation, dead-code elimination, cone-of-influence reduction

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- Backend: NUSMV and MATHSAT
  - Advanced techniques for boolean predicate abstraction
  - Entailment checks in abstract state coverage
  - Feasibility checks of counter-examples (via SMT)

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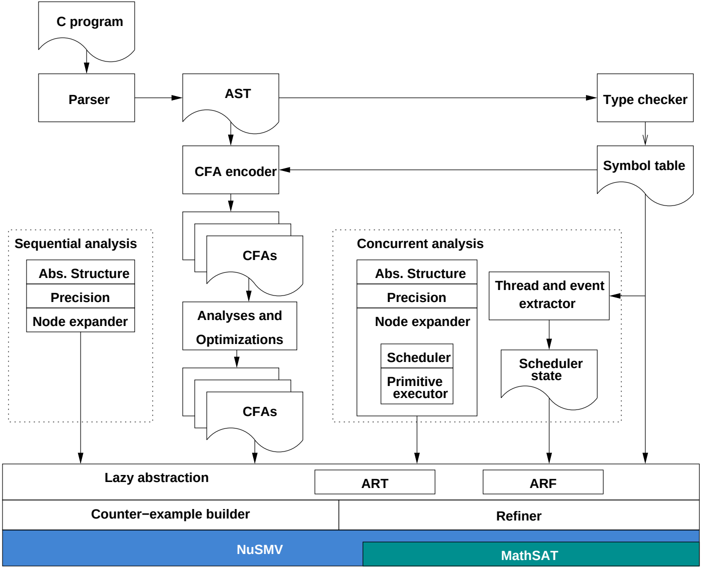

KRATOS: Availability

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Outline

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- Resource limit: time limit 1000s, memory limit 2GB

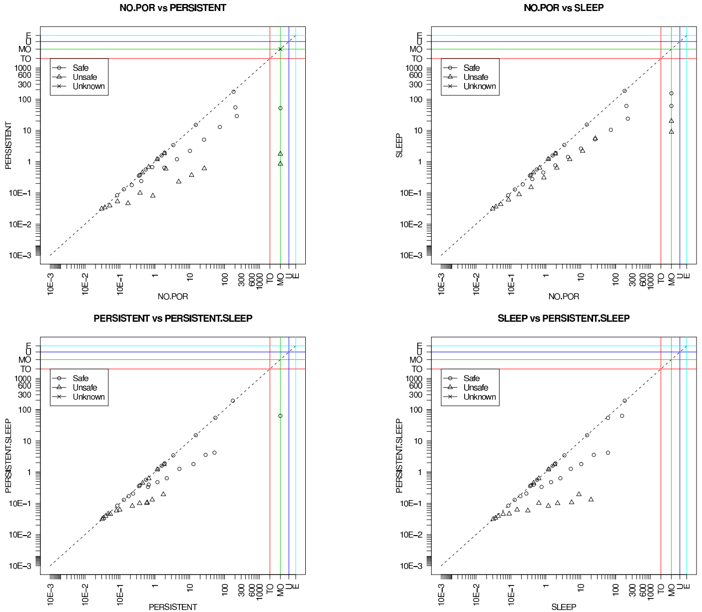
SystemC Benchmarks

Benchmarks	V	Finite-State Models			Sequentialization							Threaded
		PROMELA +SPIN			Eager	Lazy PA			Lazy AWI		BMC	ESST
		T2P	T2AB	1AB	SATABS	BLAST	CPACHECKER	KRATOS	WOLVERINE	KRATOS	CBMC	
bist-cell	S	-	-	-	31.740	5.300	7.340	0.400	T.O.	**0.300**	-	1.390
kundu-bug-1	U	**0.001**	0.010	**0.001**	33.730	105.850	24.310	25.000	205.370	25.590	1.080	0.590
kundu-bug-2	U	**0.001**	**0.001**	**0.001**	79.160	Err	17.710	0.890	580.990	11.200	2.450	0.500
kundu	S	-	-	-	96.460	Err	35.620	151.490	T.O.	T.O.	-	**1.090**
mem-slave-tlm.1	S	-	-	-	69.150	80.360	120.060	139.790	78.920	40.590	-	**3.500**
mem-slave-tlm.3	S	-	-	-	385.410	745.690	M.O.	T.O.	470.890	596.250	-	**42.690**
mem-slave-tlm.5	S	-	-	-	T.O.	Err	T.O.	T.O.	T.O.	T.O.	-	**280.260**
mem-slave-tlm-bug.1	U	**0.001**	**0.001**	**0.001**	83.140	84.420	42.190	13.800	90.710	27.790	53.750	2.600
mem-slave-tlm-bug.3	U	0.010	**0.001**	**0.001**	719.070	763.640	M.O.	T.O.	505.100	687.150	55.850*	33.390
mem-slave-tlm-bug.5	U	**0.001**	**0.001**	0.010	T.O.	Err	M.O.	T.O.	T.O.	T.O.	56.890*	207.970
mem-slave-tlm-bug2.1	U	**0.001**	**0.001**	**0.001**	75.610	82.070	33.160	2.790	85.830	18.000	54.770	1.400
mem-slave-tlm-bug2.3	U	0.150	**0.130**	0.300	391.900	T.O.	71.680	18.390	T.O.	401.870	56.400*	12.290
mem-slave-tlm-bug2.5	U	21.000	**17.000**	43.300	T.O.	Err	158.580	85.090	T.O.	T.O.	58.960*	40.490
pc-sfifo-1	S	-	-	-	3.490	20.350	16.960	3.300	13.690	3.590	-	**0.300**
pc-sfifo-2	S	-	-	-	4.810	34.650	25.820	8.400	32.430	25.590	-	**0.500**
pipeline-bug	U	**0.001**	**0.001**	**0.001**	737.320	T.O.	54.840	13.600	T.O.	103.290	-	6.400
pipeline	S	-	-	-	T.O.	T.O.	**67.630**	T.O.	T.O.	T.O.	-	81.790
token-ring.1	S	-	-	-	9.970	6.360	11.940	4.300	49.880	3.500	-	**0.100**
token-ring.5	S	-	-	-	814.160	T.O.	M.O.	T.O.	T.O.	T.O.	-	**0.400**
token-ring.9	S	-	-	-	T.O.	T.O.	M.O.	T.O.	T.O.	T.O.	-	**1.100**
token-ring.13	S	-	-	-	T.O.	M.O.	M.O.	T.O.	T.O.	T.O.	290.450	**4.500**
token-ring-bug.1	U	**0.001**	**0.001**	**0.001**	5.460	3.300	14.870	1.500	T.O.	2.590	1.620	**0.001**
token-ring-bug.5	U	**0.001**	**0.001**	**0.001**	748.250	T.O.	M.O.	T.O.	T.O.	T.O.	15.060	0.100
token-ring-bug.9	U	**0.001**	**0.001**	**0.001**	T.O.	T.O.	M.O.	T.O.	T.O.	T.O.	95.460	0.300
token-ring-bug.13	U	**0.001**	**0.001**	**0.001**	T.O.	M.O.	M.O.	T.O.	T.O.	T.O.	288.940	1.790
token-ring-bug2.1	U	0.010	**0.001**	4.100	5.940	2.480	13.980	2.000	T.O.	1.500	1.090	**0.001**
token-ring-bug2.5	U	T.O.	T.O.	T.O.	819.060	T.O.	M.O.	T.O.	T.O.	T.O.	15.370	**0.100**
token-ring-bug2.9	U	M.O.	M.O.	T.O.	T.O.	T.O.	M.O.	T.O.	T.O.	T.O.	97.980	**0.390**
token-ring-bug2.13	U	M.O.	M.O.	T.O.	T.O.	M.O.	M.O.	T.O.	T.O.	T.O.	312.380	**2.700**
toy-bug-1	U	5.550	5.340	4.560	23.570	241.240	45.650	10.200	T.O.	T.O.	1.430	**0.490**
toy-bug-2	U	5.690	5.290	4.560	19.560	144.610	44.810	3.890	T.O.	T.O.	1.410	**0.200**
toy	S	-	-	-	22.150	Err	195.620	T.O.	T.O.	T.O.	-	**1.800**
transmitter.1	U	**0.001**	**0.001**	**0.001**	2.280	1.190	17.060	1.090	T.O.	0.800	0.430	**0.001**
transmitter.5	U	**0.001**	**0.001**	**0.001**	224.070	T.O.	353.480	409.670	T.O.	T.O.	10.080	**0.001**
transmitter.9	U	**0.001**	0.010	**0.001**	T.O.	T.O.	M.O.	T.O.	T.O.	T.O.	74.420	0.100
transmitter.13	U	**0.001**	**0.001**	**0.001**	T.O.	T.O.	T.O.	T.O.	T.O.	T.O.	259.060	0.090

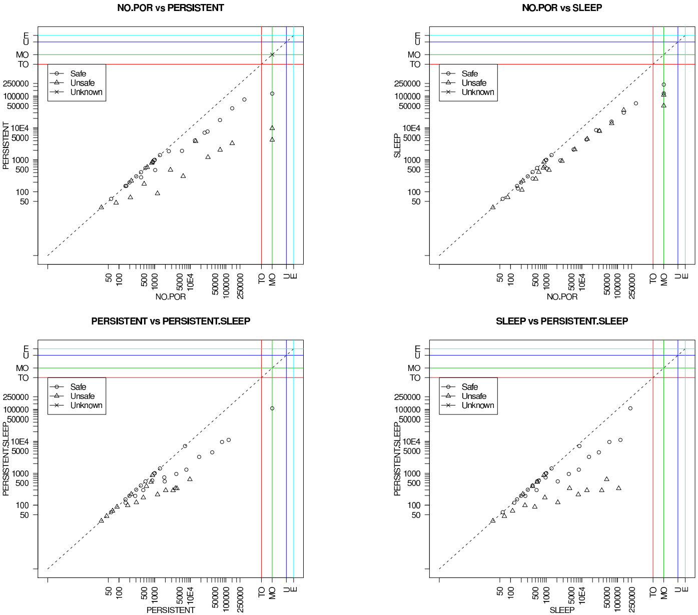
FairThreads Benchmarks

Name	V	SatAbs	CpaChecker	Kratos Seq	CBMC	Kratos ESST
fact1	S	9.07	14.26	2.90	-	**0.01**
fact1-bug	U	22.18	8.06	0.39	15.09	**0.01**
fact1-mod	S	4.41	8.18	0.50	-	**0.40**
fact2	S	69.05	17.25	15.40	-	**0.01**
gear-box	S	T.O	T.O	T.O	-	T.O
ft-pc-sfifo1	S	57.08	56.56	44.49	-	**0.30**
ft-pc-sfifo2	S	715.31	T.O	T.O	-	**0.39**
ft-token-ring.3	S	115.66	T.O	T.O	-	**0.48**
ft-token-ring.4	S	448.86	T.O	T.O	-	**5.20**
ft-token-ring.5	S	T.O	T.O	T.O	-	**213.37**
ft-token-ring.6	S	T.O	T.O	T.O	-	T.O
ft-token-ring.7	S	T.O	T.O	T.O	-	T.O
ft-token-ring.8	S	T.O	T.O	T.O	-	T.O
ft-token-ring.9	S	T.O	T.O	T.O	-	T.O
ft-token-ring.10	S	T.O	T.O	T.O	-	T.O
ft-token-ring-bug.3	U	111.10	T.O	T.O	158.76	**0.10**
ft-token-ring-bug.4	U	306.41	T.O	T.O	*407.36	**1.70**
ft-token-ring-bug.5	U	860.29	T.O	T.O	*751.44	**66.09**
ft-token-ring-bug.6	U	T.O	T.O	T.O	T.O	T.O
ft-token-ring-bug.7	U	T.O	T.O	T.O	T.O	T.O
ft-token-ring-bug.8	U	T.O	T.O	T.O	T.O	T.O
ft-token-ring-bug.9	U	T.O	T.O	T.O	T.O	T.O
ft-token-ring-bug.10	U	T.O	T.O	T.O	T.O	T.O

ESST vs ESST+POR: Run time



ESST vs ESST+POR: Explored abstract states



Industrial Benchmarks from Ansaldo STS

Embedded Software from Logica di Sicurezza (LDS) a generic subsystem of ERTMS developed by Ansaldo STS

- An LDS specification
  - An entity description of the physical and logical entities
  - A configuration describing a particular physical layout
- LDS is specified in VELOS
  - Structured programming language with a C++ like syntax developed by Ansaldo STS
    - Classes for representing Components, Points, EOAs,. . .
    - Member variables represent the state of the entity
    - Member functions represent actions to modify member variables

All properties	BLAST	SATABS	CPACHECKER	CBMC	KRATOS
Solved	0	0	8	20	53
Safe	0	0	8	-	33
Unsafe	0	0	0	20	20
Time out	2	52	0	0	0
Memory out	43	0	45	0	0
Total time	-	-	17m:7s	2h:41m:22s	**28m:46s**
Max space	-	-	8.4Gb	728.1Mb	**5.2Gb**

Results presented at [CCL+12]

Outline

Related Work

- Sequential Software
  - Many software model checker for sequential software (in C)
    - CPACHECKER [BK11], BLAST [BHJM07], IMPACT [McM06], WOLVERINE [WKM12], LLBMC [FMS13] UFO [AGL+13], SATABS [CKSY05], CBMC [CKL04], . . .
  - Growing interest:
    - Software Model Checking competition `http://sv-comp.sosy-lab.org/2014/`
- Cooperative Threaded Programs
  - SystemC via reduction to NUSMV [Moy05, MMMC05], and to PROMELA [TCMM07, MJM10]
  - SystemC via reduction to software model checking [KS05]
  - SystemC via reduction to Timed Automata [HFG08]
  - SystemC via reduction to CADP [GHPS09]
  - FairThreads via reduction to SIGNAL [JBGT10]
  - OSEK/VDX via reduction to timed automata [WH08]
  - SPECC via CEGAR with NUSMV [CJK07]

Outline

Conclusions

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  - Finite-model encoding and analysis with SPIN
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Future Work

- Semi-Symbolic-Scheduler/Symbolic-Threads (S3ST)
  - Non-constant arguments to primitive function calls
    - Preliminary results for SystemC are positive and encouraging [CNR12b]
- Find safety regions of parametric designs exploiting S3ST
- Apply ESST paradigm to other specification languages and application domains
  - PLC, Automotive, Robotics, etc.

Questions?

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