Automated Analysis of Weak Memory Models

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Outline

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Problem statement (Цель работы)

To rework the proof-of-concept memory model-aware analysis tool `Porthos` [3] by:

- extending the C-like input language,
- revising its architecture and
- re-implementing the tool in order to enhance performance, extensibility, reliability and maintainability

Task specification (Задачи работы)

- Study the general framework for memory model-aware analysis of concurrent programs [1];
- Review existing tools for memory model-aware analysis;
- Investigate existing architecture of `Porthos`, its strengths and weaknesses;
- Design a new architecture for `PorthosC` that *allow to* easily support the C input language, be robust, transparent, efficient and extensible.

Verification of concurrent software

Example: Write-write reordering (compiler relaxations)

{ x=0; y=0; }	
P	Q
p_0 : $x \leftarrow 1$	q_0 : $y \leftarrow 1$
p_1 : $r_p \leftarrow y$	q_1 : $r_q \leftarrow x$

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SC

p_0, p_1, q_0, q_1 $(0;1)$

q_0, q_1, p_0, p_1 $(1;0)$

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TSO

$\underline{p_1}, \underline{p_0}, q_0, q_1$	$(0;1)$	$p_0, p_1, \underline{q_1}, \underline{q_0}$	$(0;1)$	$\underline{p_1}, \underline{p_0}, \underline{q_1}, \underline{q_0}$	$(0;1)$
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Verification of concurrent software

Example: Store buffering (hardware relaxations)

{ x=0; y=0; }	
P	Q
p_0 : $x \leftarrow 1$	q_0 : $y \leftarrow 1$
p_1 : $r_p \leftarrow y$	q_1 : $r_q \leftarrow x$

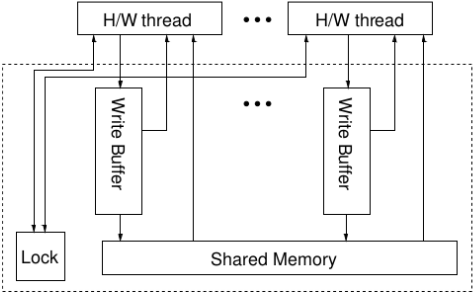

Figure: An x86-TSO abstract machine [4]

The weak memory model

Axiomatic semantics: The definition

- **Event** $\in \mathbb{E}$, a low-level primitive operation:
  - *memory event* $\in \mathbb{M} = \mathbb{R} \cup \mathbb{W}$: access to a local/shared memory,
  - *computational event* $\in \mathbb{C}$: computation over local memory, and
  - *barrier event* $\in \mathbb{B}$: synchronisation fences;
- **Relation** $\subseteq \mathbb{E} \times \mathbb{E}$:
  - *basic relations*:
    - *program-order* relation po $\subseteq \mathbb{E} \times \mathbb{E}$: (control-flow),
    - *read-from* relation `rf` $\subseteq \mathbb{W} \times \mathbb{R}$: (data-flow), and
    - *coherence-order* relation co $\subseteq \mathbb{W} \times \mathbb{W}$: (data-flow);
  - *derived relations*:
    - *union* `r1 | r2`,
    - *sequence* `r1 ; r2`,
    - *transitive closure* `r+`,
    - $\cdots$;
- **Assertion** over relations or sets of events:
  - *acyclicity*, *irreflexivity* or *emptiness*

The weak memory model

Testing the candidate executions

{ x=0; y=0; }	
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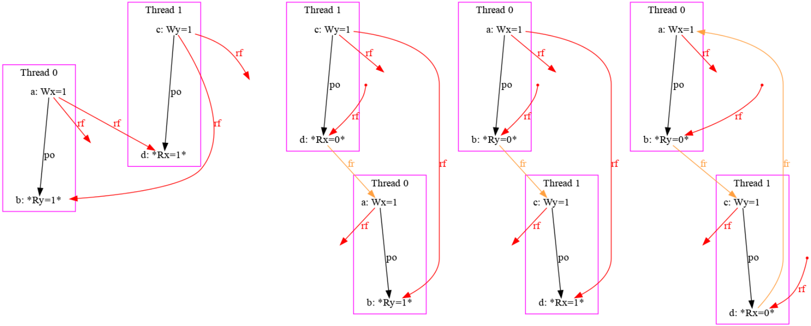

Figure: The four candidate executions allowed under x86-TSO

The weak memory model

Testing the candidate executions

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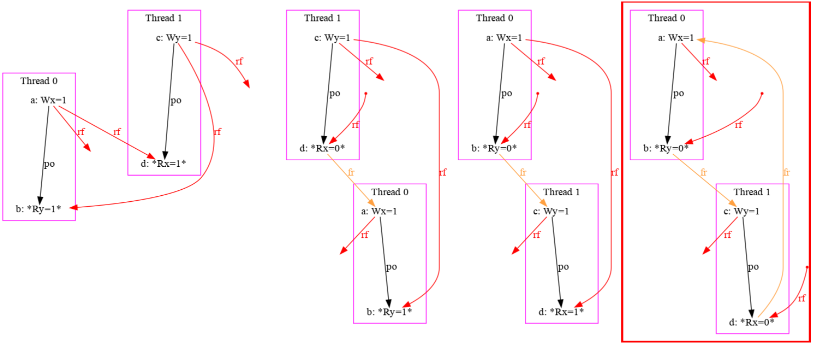
SC model:

```
...
fr = (rf^-1; co)
acyclic(fr ∪ po)
```



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Tools for memory model-aware analysis

- `diy` tool suite:
  - `diy`, `diycross` and `diyone`, litmus tests generators,
  - `litmus`, a litmus test concrete executor, and
  - `herd`, a weak memory model simulator;
- the stateless model checkers (`CHESS`, `Nidhugg`);
- the tool for automated synthesis of the synchronisation primitives `musketeer`;
- the instrumenting compiler `goto-cc` which is a part of `CBMC` model checker;
- the tool `Porthos` for analysing the portability of the C programs;
- and others.

Portability analysis

The `Porthos` tool

- Let the function $cons_{\mathcal{M}}(P)$ calculate the set of executions of program P consistent under the memory model $\mathcal{M}$.

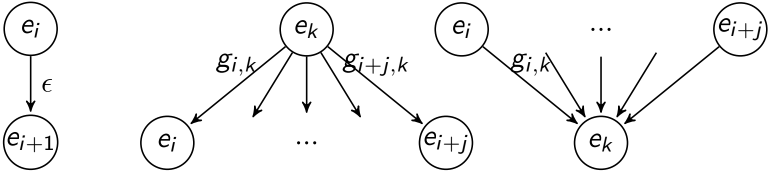
Definition (Portability [3])

Let $\mathcal{M}_{\mathcal{S}}$, $\mathcal{M}_{\mathcal{T}}$ be two weak memory models. The program P is portable from $\mathcal{M}_{\mathcal{S}}$ to $\mathcal{M}_{\mathcal{T}}$ if $cons_{\mathcal{M}_{\mathcal{T}}}(P) \subseteq cons_{\mathcal{M}_{\mathcal{S}}}(P)$

- Portability as an SMT-based bounded reachability problem: $\phi = \phi_{CF} \wedge \phi_{DF} \wedge \phi_{\mathcal{M}_{\mathcal{T}}} \wedge \phi_{\neg\mathcal{M}_{\mathcal{S}}}$
- $\mathtt{SAT}(\phi) \implies$ the portability bug

Encoding for the control-flow

- Porthos v1 used another encoding scheme, where the high-level instructions were represented in the SMT-formula by separate variables: $\phi_{CF}(i_2; i_3) = (cf_{i_1} \Leftrightarrow (cf_{i_2} \wedge cf_{i_3})) \wedge \phi_{CF}(i_2) \wedge \phi_{CF}(i_3)$.
- In PorthosC, the high-level AST firstly is compiled into the *event-flow graph* with events as nodes and relations as edges.
- All edges are labelled by *guards*, local-memory computations (ϵ denotes an empty guard).



(a) The sequence (b) Conditional branching (c) Branch merging

Figure: Possible mutual arrangements of events in a control-flow graph

Encoding for the control-flow

- Let $\mathbf{x} : \mathbb{E} \rightarrow \{0, 1\}$ be the predicate that signifies the fact that the event has been executed.
- The control-flow of the program is encoded as following:

$$\phi_{CF_{seq}} = \mathbf{x}(e_{i+1}) \Rightarrow \mathbf{x}(e_i)$$

$$\begin{aligned}\phi_{CF_{br}} = \; & [\mathbf{x}(e_i) \Rightarrow \mathbf{x}(e_k)] \wedge \cdots \wedge [\mathbf{x}(e_{i+j}) \Rightarrow \mathbf{x}(e_k)] \\ & \wedge [\mathbf{x}(e_i) \wedge \mathbf{x}(e_k) \Rightarrow g_{i,k}] \wedge \cdots \wedge [\mathbf{x}(e_{i+j}) \wedge \mathbf{x}(e_k) \Rightarrow g_{i+j,k}] \\ & \wedge \cdots \\ & \wedge \Big(\bigvee_{e_l \in \, \mathtt{succ}(e_m)} \; \bigvee_{\substack{e_n \in \, \mathtt{succ}(e_k) \\ e_n \neq e_m}} \neg[\mathbf{x}(e_m) \wedge \mathbf{x}(e_n)] \Big)\end{aligned}$$

$$\phi_{CF_{mer}} = \mathbf{x}(e_k) \Rightarrow \Big(\bigvee_{e_p \in \, \mathtt{pred}(e_k)} \mathbf{x}(e_p) \Big)$$

Encoding for the data-flow

- SSA-indices are computed as following:
  - any access to a shared variable (both read and write) increments its SSA-index;
  - only writes to a local variable increment its SSA-index (reads preserve indices);
  - no access to a constant variable or computed (evaluated) expression changes their SSA-index.

The data-flow of an event is encoded as following:

$$\begin{aligned}
\phi_{DF_{e=\mathtt{load}(r \leftarrow l)}} &= [\mathbf{x}(e) \Rightarrow (r_{i+1} = l_{i+1})] \\
\phi_{DF_{e=\mathtt{store}(l \leftarrow r)}} &= [\mathbf{x}(e) \Rightarrow (l_{i+1} = r_i)] \\
\phi_{DF_{e=\mathtt{eval}(\cdot)}} &= [\mathbf{x}(e) \Rightarrow \mathbf{v}(e)] \\
\phi_{DF_{mem}}(e_1, e_2) &= [\mathtt{rf}(e_1, e_2) \Rightarrow (l_i = l_j)]
\end{aligned}$$

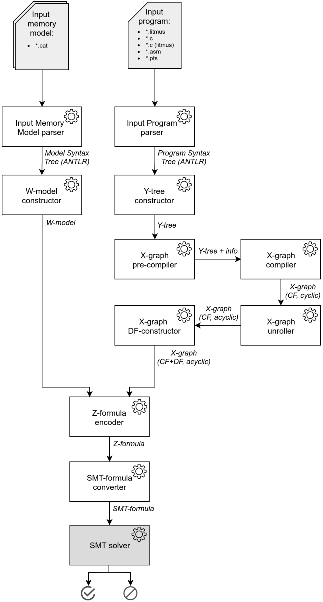
Outline

The input language

The input language parser used by `Porthos` suffered from several disadvantages:

- it contained the parser code inlined directly into the grammar (hardly maintainable);
- the semantics of operations and kinds of variables (global or shared) were determined syntactically (4 different types of assignment:'=', ':=', '<−' and '<:−', each for different kinds of arguments);
- restricted syntax for expressions.
- In contrast, `PorthosC` uses the full C language grammar of proposed in the C11 standard [2] and the visitor that converts the ANTLR grammar to the AST (`Y-tree`).

Architecture



The X-graph internal representation

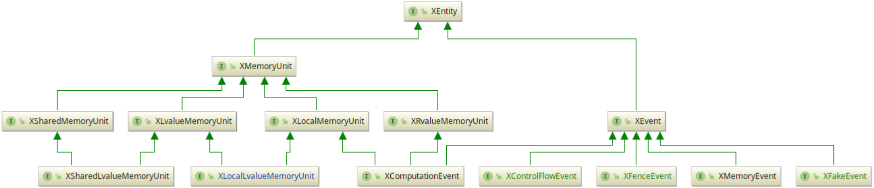


Figure: The inheritance tree of main X-graph interfaces

The X-graph compiler

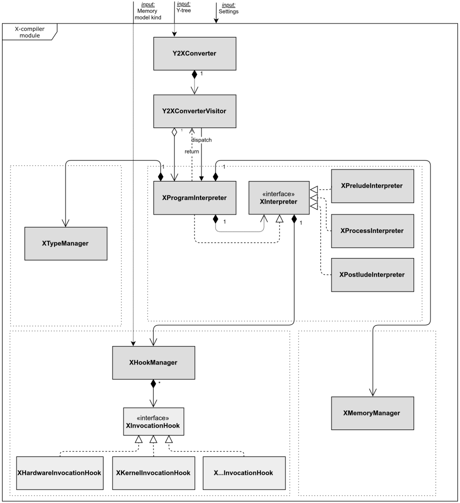


Figure: Main components of the X-compilation processing unit

X-graph unrolling

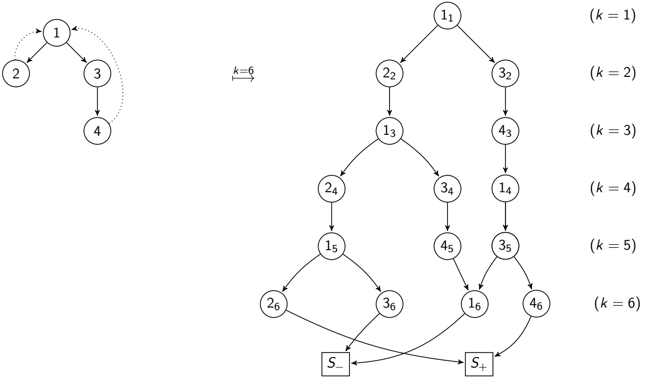


Figure: Example of the flow graph unrolling up to bound $k = 6$

Outline

Evaluation

[to be done]

Summary

- The general framework for memory model-aware analysis was implemented in `PorthosC`;
- The input language has been extended;
- The old architecture of `Porthos` has been analysed and considered while designing the new architecture for `PorthosC`;
- to be done: more

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