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` [**Porthos17a**] 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 [**alglave2010shared**];
- 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.

Outline

Verification of Concurrent Software

Example: Write-write reordering (compiler relaxations)

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

Verification of Concurrent Software

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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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SC		TSO					
p_0, p_1, q_0, q_1	$(0;1)$	$\underline{p_1}, \underline{p_0}, q_0, q_1$	$(0;1)$	$p_0, p_1, \underline{q_1}, \underline{q_0}$	$(0;1)$	$\underline{p_1}, \underline{p_0}, \underline{q_1}, \underline{q_0}$	$(0;1)$
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Verification of Concurrent Software

Example: Store buffering (by hardware)

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

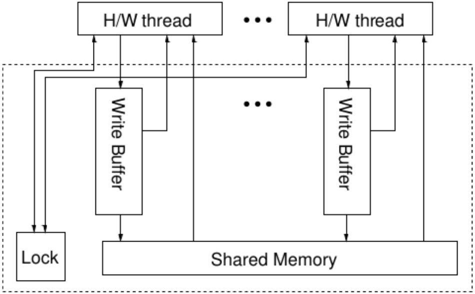

Figure: An x86-TSO abstract machine [**sewell2010x86**]

Weak Memory Model

Axiomatic semantics

- **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 $\mathtt{po} \subseteq \mathbb{E} \times \mathbb{E}$: (control-flow),
    - *read-from* relation $\mathtt{rf} \subseteq \mathbb{W} \times \mathbb{R}$: (data-flow), and
    - *coherence-order* relation $\mathtt{co} \subseteq \mathbb{W} \times \mathbb{W}$: (data-flow);
  - *derived relations*:
    - *union* $\mathtt{r1} \mid \mathtt{r2}$,
    - *sequence* $\mathtt{r1}\ ;\ \mathtt{r2}$,
    - *transitive closure* $\mathtt{r+}$,
    - $\cdots$;
- **Assertion** over relations or sets of events:
  - *acyclicity*, *irreflexivity* or *emptiness*

Weak Memory Model

Example: Store buffering (hardware relaxations)

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P	Q
p_0 : $x \leftarrow 1$	q_0 : $y \leftarrow 1$
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SC model:

...

`fr = (rf^-1; co)`

`acyclic(fr ∪ po)`

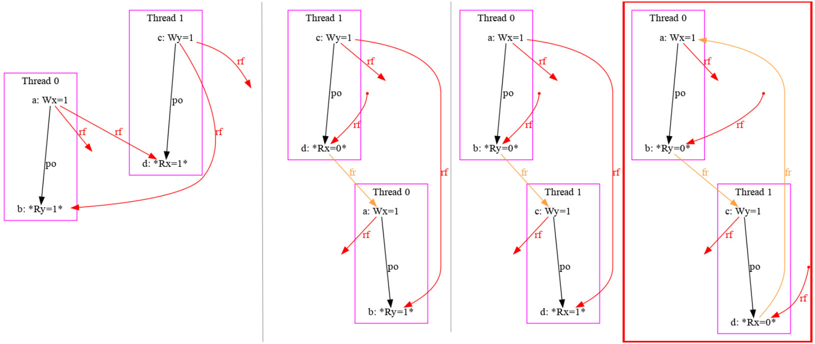


Figure: The four candidate executions allowed under x86-TSO

Outline

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 [**Porthos17a**])

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

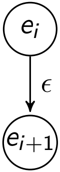
Outline

Encoding for the control-flow

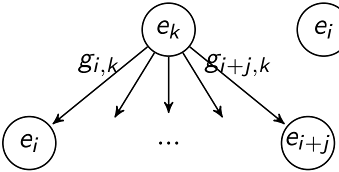
- In `Porthos`, the high-level instructions were represented in the SMT-formula by separate variables.
- For example, the sequential instruction $i_1 = i_2; i_3$ was encoded as $\phi_{CF}(i_2; i_3) = (cf_{i_1} \Leftrightarrow (cf_{i_2} \wedge cf_{i_3})) \wedge \phi_{CF}(i_2) \wedge \phi_{CF}(i_3)$,

Encoding for the control-flow

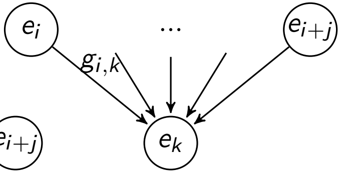
- The new encoding scheme of `PorthosC` follows [**heljanko2008unfoldings**] in general.
- The high-level AST is compiled into the *event-flow graph*, where edges (transitions) are labelled by the *guard* (ϵ is an empty guard).



(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

The control-flow is encoded as following:

$$
\begin{aligned}
\phi_{CF_{seq}} = \;& \mathbf{x}(e_{i+1}) \Rightarrow \mathbf{x}(e_i) \\
\phi_{CF_{br}} = \;& [\mathbf{x}(e_i) \Rightarrow \mathbf{x}(e_k)] \;\wedge\; \cdots \;\wedge\; [\mathbf{x}(e_{i+j}) \Rightarrow \mathbf{x}(e_k)] \\
& \wedge [\mathbf{x}(e_i) \wedge \mathbf{x}(e_k) \Rightarrow g_{i,k}] \;\wedge\; \cdots \;\wedge\; [\mathbf{x}(e_{i+j}) \wedge \mathbf{x}(e_k) \Rightarrow g_{i+j,k}] \\
& \wedge \cdots \\
& \wedge \Big(\bigvee_{e_l \in \, \texttt{succ}(e_m)} \; \bigvee_{\substack{e_n \in \, \texttt{succ}(e_k) \\ e_n \neq e_m}} \neg[\mathbf{x}(e_m) \wedge \mathbf{x}(e_n)] \Big) \\
\phi_{CF_{mer}} = \;& \mathbf{x}(e_k) \Rightarrow \Big(\bigvee_{e_p \in \, \texttt{pred}(e_k)} \mathbf{x}(e_p) \Big)
\end{aligned}
$$

Encoding for the data-flow

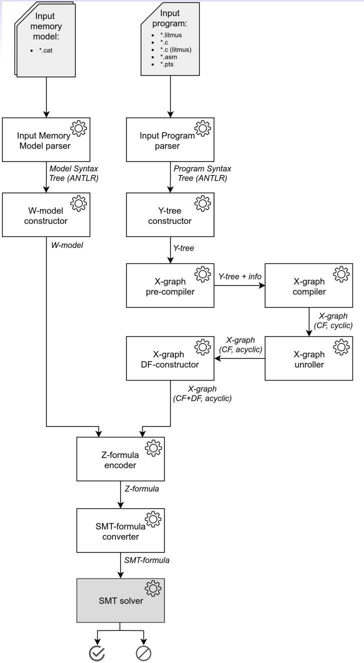
- SSA-indices are computed as following:
  - any access to a shared variable (both read and write) increments its SSA-index;
  - only writes to a local variable increment its SSA-index (reads preserve indices);
  - no access to a constant variable or computed (evaluated) expression changes their SSA-index.

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

Architecture



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 [**jtc2011sc22**] and the visitor that converts the ANTLR grammar to the AST (`Y-tree`).

The X-graph

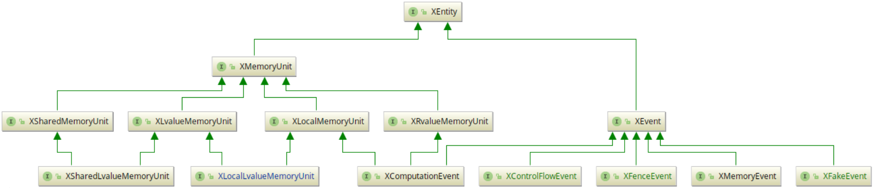


Figure: The inheritance tree of main X-graph interfaces

The X-graph compiler

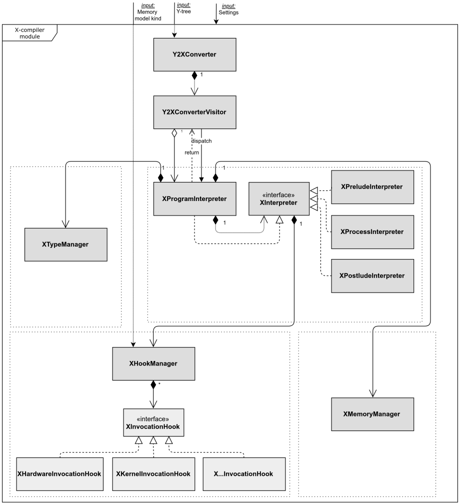


Figure: Main components of the X-compilation processing unit

X-graph unrolling

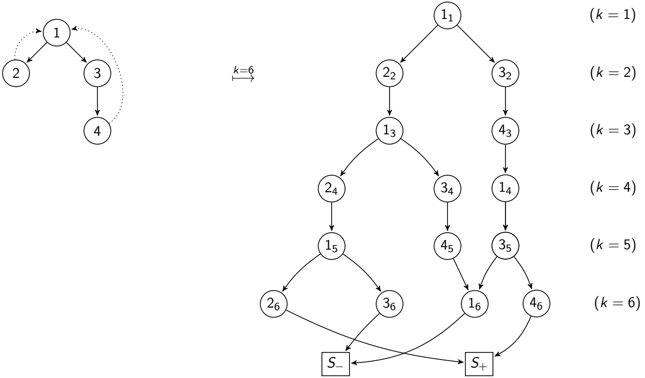


Figure: Example of the flow graph unrolling up to bound $k = 6$

Summary

- The first main message of your talk in one or two lines.
- The second main message of your talk in one or two lines.
- Perhaps a third message, but not more than that.

- Outlook
  - Something you haven't solved.
  - Something else you haven't solved.

Bibliography I