Automated Analysis of Weak Memory Models

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MSc Candidate

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Task statement

- Improve the proof-of-concept memory model-aware analysis tool `Porthos` [2] by extending support for the input language.

Task specification

- Study the general framework for memory model-aware analysis of concurrent programs [1];
- Review existing tools for memory model-aware analysis;
- Develop a *C compiler infrastructure* as a part of an abstract interpretation engine for the new tool `PorthosC`;
- Improve the SMT-encoding scheme for an *arbitrary control-flow*;
- Enhance performance, extensibility, reliability and maintainability of the tool.

Verification of concurrent software

Motivating example: Write-write reordering (compiler relaxations)

{ x=0; y=0; }	
P	Q
$p_0: \quad x \leftarrow 1$	$q_0: \quad y \leftarrow 1$
$p_1: \quad r_p \leftarrow y$	$q_1: \quad r_q \leftarrow x$
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Single thread
(no concurrency)

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

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Sequential Consistency
(classical concurrency)

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

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

$p_0, q_0, p_1, q_1 \quad (1; 1)$

$p_0, q_0, q_1, p_1 \quad (1; 1)$

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Total Store Order
(e.g., x86)

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

Motivating example: Store buffering (hardware relaxations)

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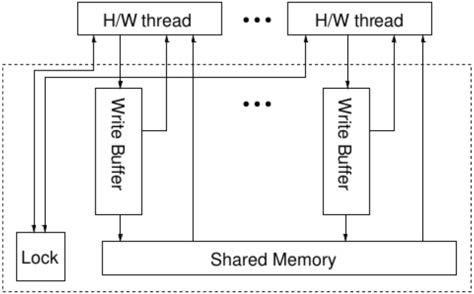

Figure: An x86-TSO abstract machine [4]

Verification of concurrent software

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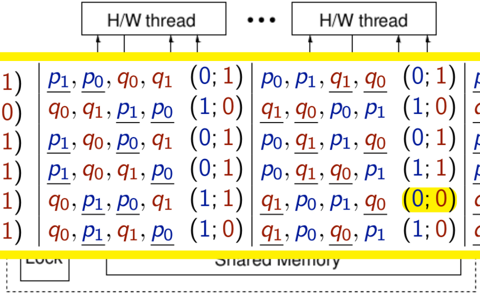

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Weak memory model-aware analysis

Event-based program representation

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

Weak memory model-aware analysis

Testing candidate executions

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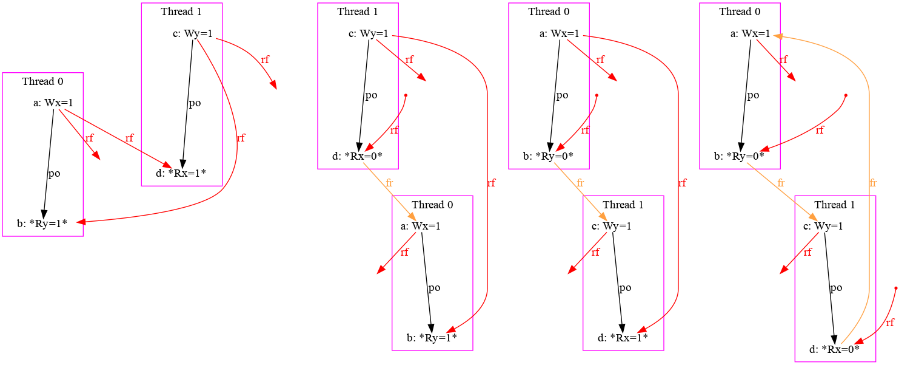

Figure: The four candidate executions allowed under x86-TSO

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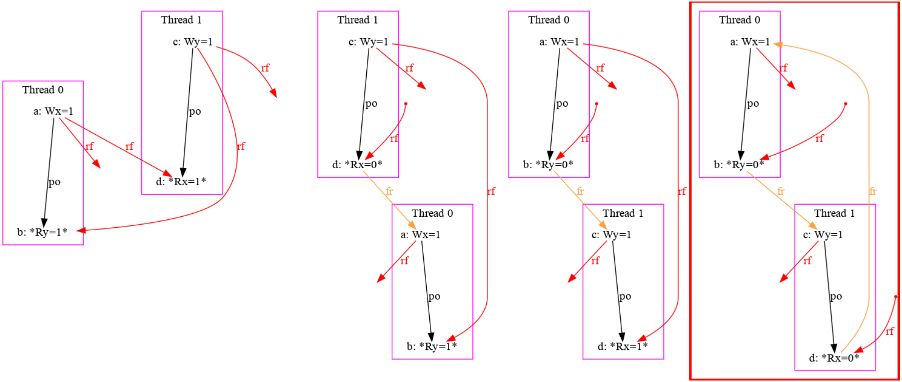
SC model:

...

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

`acyclic(fr ∪ po)`



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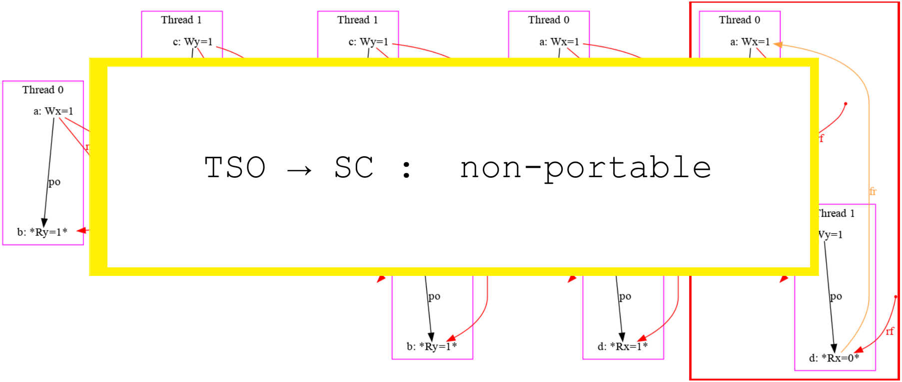

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Portability analysis

The Porthos tool

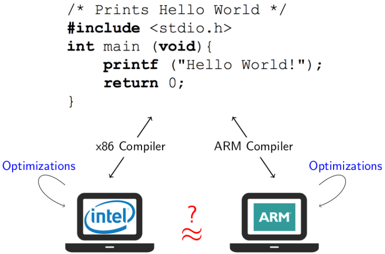

Figure: The illustration of the portability problem [3]

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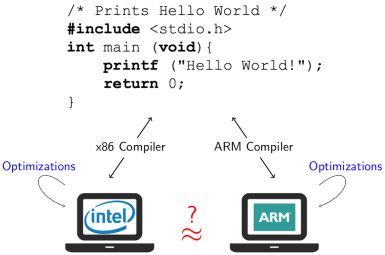

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Definition (Portability [2])

The program P is portable from the source memory model $\mathcal{M}_\mathcal{S}$ to the target model $\mathcal{M}_\mathcal{T}$ if $cons_{\mathcal{M}_\mathcal{T}}(P) \subseteq cons_{\mathcal{M}_\mathcal{S}}(P)$

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

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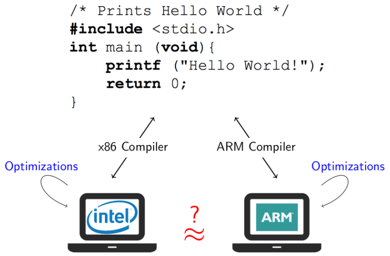

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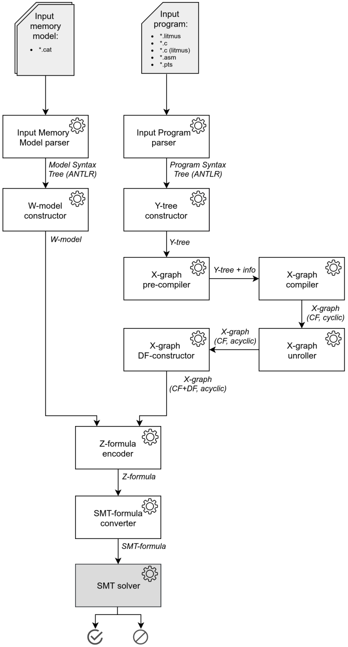
PorthosC: Architecture

Main components

- The enhanced version of Porthos, that is able to analyse C programs, has got a new name *PorthosC*.



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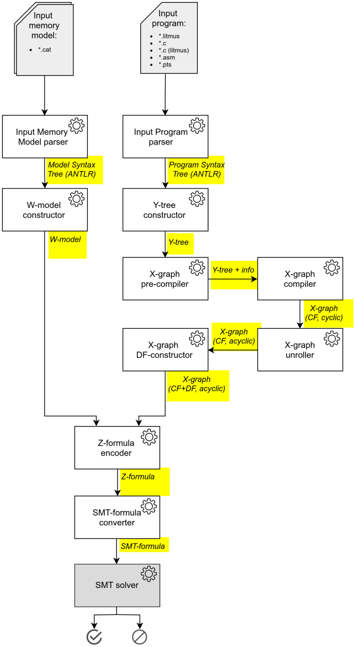

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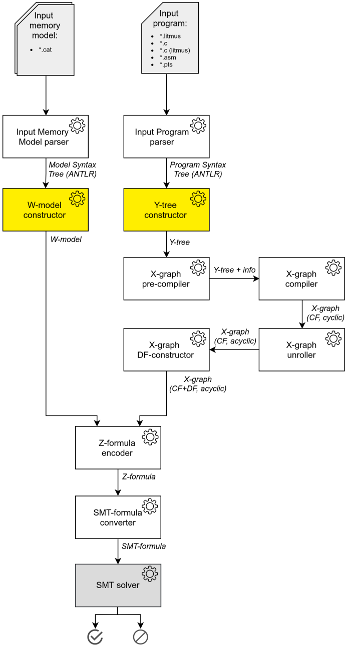

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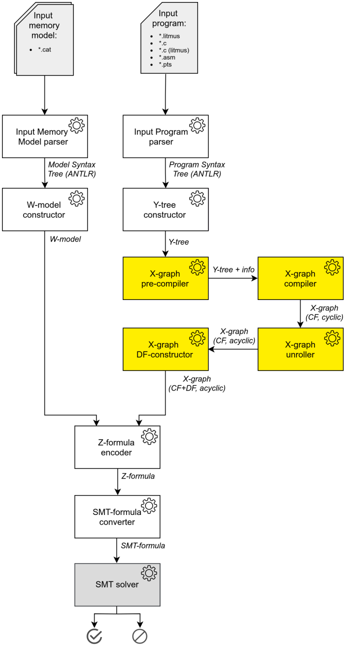

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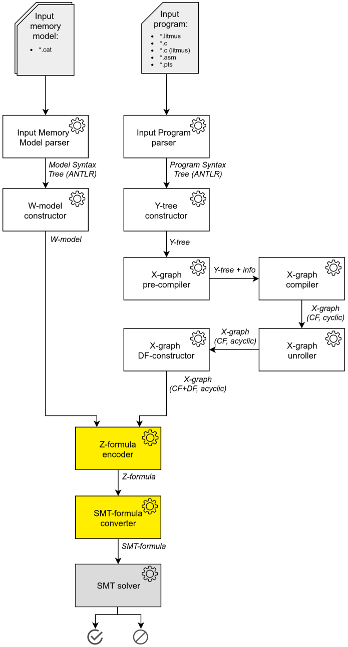

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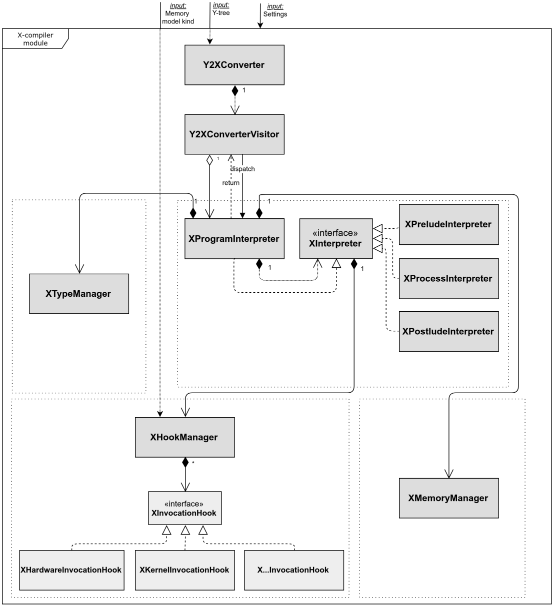
Abstract interpretation module

- The abstract interpretation module is an essential part of the compiler of C code into the event-flow graph representation (`X-graph`).



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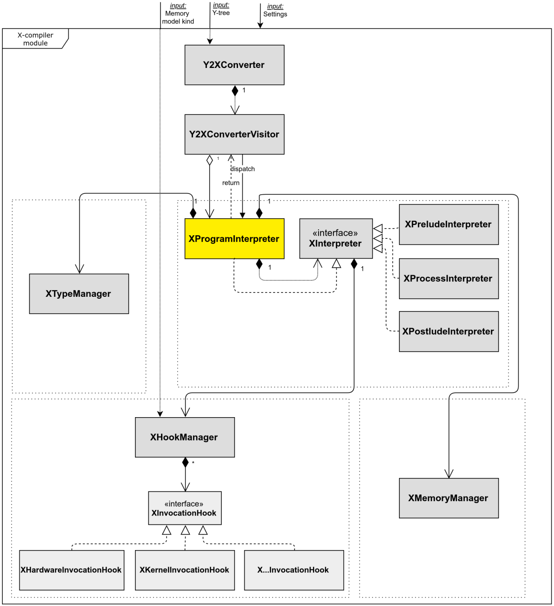

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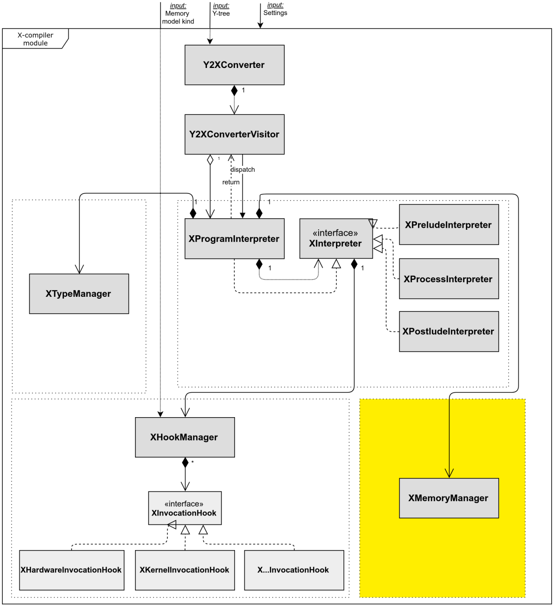

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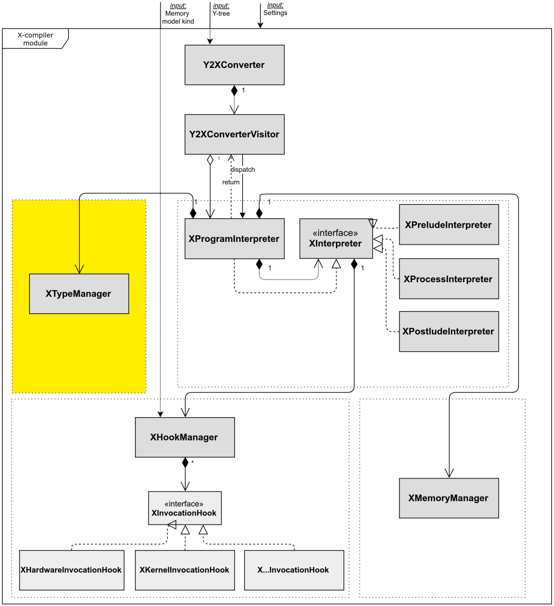

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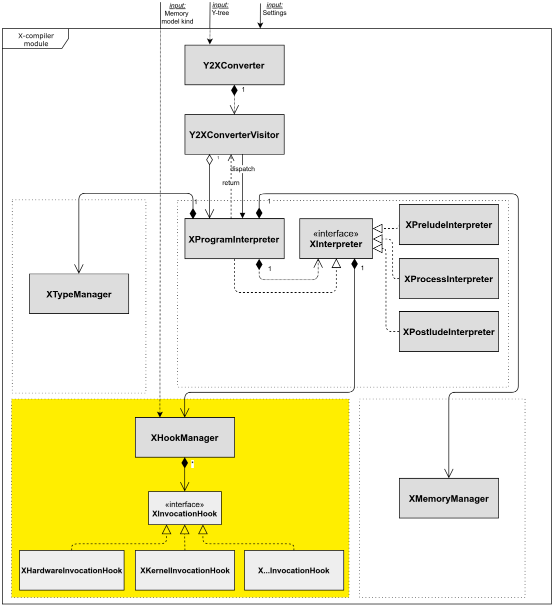

Porthos v1: The input language

```
{ x, y }

thread t0 {
    r0 <- 1;
    r1 <- (2 + r0) * 3;
    y := r2;
    while (r0 > 4) {
      r0 <:- x;
      r1 <- (r0 + 5);
      x.store(_rx, r1);
      y = x.load(_rx)
    };
}

exists x = 1, y = 2, 0:r1 = 3,
```

Figure: A program example in the Porthos v1 input language

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```
...

⟨instr⟩
  : ⟨atom⟩
  | '{' ⟨instr⟩ '}'
  | ⟨instr⟩ ';' ⟨instr⟩
  | 'while' '(' ⟨bool-expr⟩ ')' ⟨instr⟩
  | 'if' ⟨bool-expr⟩ '{' ⟨instr⟩ '}' ⟨instr⟩
  ;

⟨atom⟩
  : ⟨reg⟩ '<-' ⟨expression⟩
  | ⟨reg⟩ '<:-' ⟨loc⟩
  | ⟨loc⟩ ':=' ⟨reg⟩
  | ⟨reg⟩ '=' ⟨loc⟩ '.' 'store' '(' ⟨atomic⟩ ',' ⟨reg⟩ ')'
  | ⟨reg⟩ '=' ⟨loc⟩ '.' 'load' '(' ⟨atomic⟩ ')'
  | ('mfence' | 'sync' | 'lwsync' | 'isync')
  ;

...
```

Figure: A sketch of the Porthos v1 input language grammar

Porthos v1: The input language

Static syntactic determination of the variables kind

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  | ‘if’ ⟨bool-expr⟩ ‘{’ ⟨instr⟩ ‘}’ ⟨instr⟩
  ;

⟨atom⟩
  : ⟨reg⟩ ‘<-’ ⟨expression⟩
  | ⟨reg⟩ ‘<:-’ ⟨loc⟩
  | ⟨loc⟩ ‘:=’ ⟨reg⟩
  | ⟨reg⟩ ‘=’ ⟨loc⟩ ‘.’ ‘store’ ‘(’ ⟨atomic⟩ ‘,’ ⟨reg⟩ ‘)’
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...
```

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Porthos v1: The input language

Lack of support for functions invocations

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  | ‘{’ ⟨instr⟩ ‘}’
  | ⟨instr⟩ ‘;’ ⟨instr⟩
  | ‘while’ ‘(’ ⟨bool-expr⟩ ‘)’ ⟨instr⟩
  | ‘if’ ⟨bool-expr⟩ ‘{’ ⟨instr⟩ ‘}’ ⟨instr⟩
  ;

⟨atom⟩
  : ⟨reg⟩ ‘<-’ ⟨expression⟩
  | ⟨reg⟩ ‘<:-’ ⟨loc⟩
  | ⟨loc⟩ ‘:=’ ⟨reg⟩
  | ⟨reg⟩ ‘=’ ⟨loc⟩ ‘.’ ‘store’ ‘(’ ⟨atomic⟩ ‘,’ ⟨reg⟩ ‘)’
  | ⟨reg⟩ ‘=’ ⟨loc⟩ ‘.’ ‘load’ ‘(’ ⟨atomic⟩ ‘)’
  | (‘mfence’ | ‘sync’ | ‘lwsync’ | ‘isync’)
  ;

...
```

Figure: A sketch of the Porthos v1 input language grammar

Porthos v1: The input language

Lack of support for unconditional jumps

```
{ x, y }

thread t0 {
    r0 <- 1;
    r1 <- (2 + r0) * 3;
    y := r2;
    while (r0 > 4) {
      r0 <:- x;
      r1 <- (r0 + 5);
      x.store(_rx, r1);
      y = x.load(_rx)
    };
}

exists x = 1, y = 2, 0:r1 = 3,
```

Figure: A program example in the Porthos v1 input language

```
...

⟨instr⟩
  : ⟨atom⟩
  | ‘{’ ⟨instr⟩ ‘}’
  | ⟨instr⟩ ‘;’ ⟨instr⟩
  | ‘while’ ‘(’ ⟨bool-expr⟩ ‘)’ ⟨instr⟩
  | ‘if’ ⟨bool-expr⟩ ‘{’ ⟨instr⟩ ‘}’ ⟨instr⟩
  ;

⟨atom⟩
  : ⟨reg⟩ ‘<-’ ⟨expression⟩
  | ⟨reg⟩ ‘<:-’ ⟨loc⟩
  | ⟨loc⟩ ‘:=’ ⟨reg⟩
  | ⟨reg⟩ ‘=’ ⟨loc⟩ ‘.’ ‘store’ ‘(’ ⟨atomic⟩ ‘,’ ⟨reg⟩ ‘)’
  | ⟨reg⟩ ‘=’ ⟨loc⟩ ‘.’ ‘load’ ‘(’ ⟨atomic⟩ ‘)’
  | (‘mfence’ | ‘sync’ | ‘lwsync’ | ‘isync’)
  ;

...
```

Figure: A sketch of the Porthos v1 input language grammar

PorthosC: The input language

```
{ int *x = 1; }

extern int z;

void thread_0(int &x, int &y) {
  L0: x = 0;
  int r;
  while (x * (5 + 4 / 2) % 3 == 1) {
    if (x != 0)
      goto L0;
    if (y > 6)
      continue;
    else if (++y > 7) {
      r = r + 10;
      break;
    }
    else
      goto L1;
    r = 11;
  }
  y = x.load(_rx) + 1;
  L1: x.store(_rx, r);
}

exists (y == x + 1 && thread_0:r > 21)
```

Figure: A program example in C

PorthosC: The input language

```
{ int *x = 1; }

extern int z;

void thread_0(int &x, int &y) {
  L0: x = 0;
  int r;
  while (x * (5 + 4 / 2) % 3 == 1) {
    if (x != 0)
      goto L0;
    if (y > 6)
      continue;
    else if (++y > 7) {
      r = r + 10;
      break;
    }
    else
      goto L1;
    r = 11;
  }
  y = x.load(_rx) + 1;
  L1: x.store(_rx, r);
}

exists (y == x + 1 && thread_0:r > 21)
```

Figure: A program example in C

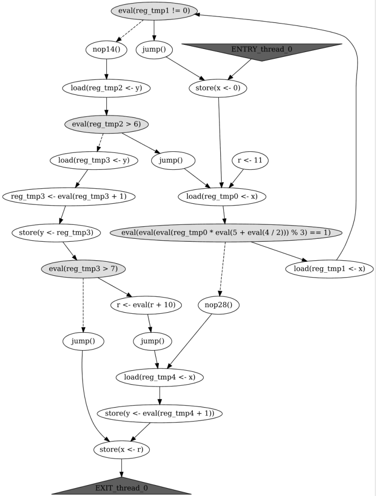


Figure: The compiled event-flow graph

PorthosC: The input language

Pre-compilation phase for the syntactic determination of the variables kind

```
{ int *x = 1; }

extern int z;

void thread_0(int &x, int &y) {
  L0: x = 0;
  int r;
  while (x * (5 + 4 / 2) % 3 == 1) {
    if (x != 0)
      goto L0;
    if (y > 6)
      continue;
    else if (++y > 7) {
      r = r + 10;
      break;
    }
    else
      goto L1;
    r = 11;
  }
  y = x.load(_rx) + 1;
  L1: x.store(_rx, r);
}

exists (y == x + 1 && thread_0:r > 21)
```

Figure: A program example in C

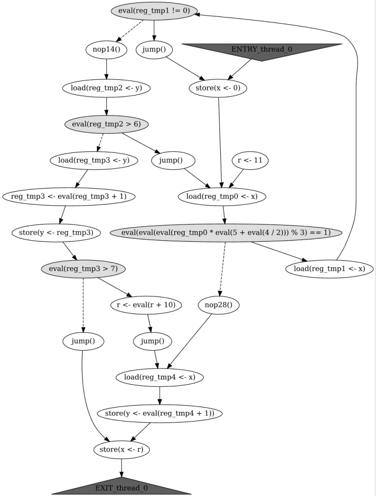


Figure: The compiled event-flow graph

PorthosC: The input language

Support for functions invocations: The invocation hooking mechanism

```
{ int *x = 1; }

extern int z;

void thread_0(int &x, int &y) {
  L0: x = 0;
  int r;
  while (x * (5 + 4 / 2) % 3 == 1) {
    if (x != 0)
      goto L0;
    if (y > 6)
      continue;
    else if (++y > 7) {
      r = r + 10;
      break;
    }
    else
      goto L1;
    r = 11;
  }
  y = x.load(_rx) + 1;
  L1: x.store(_rx, r);
}

exists (y == x + 1 && thread_0:r > 21)
```

Figure: A program example in C

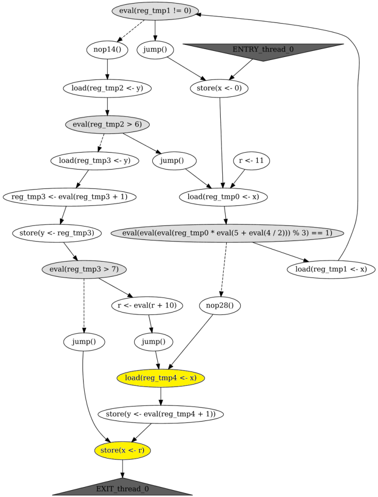


Figure: The compiled event-flow graph

PorthosC: The input language

Support for an arbitrary control-flow

```
{ int *x = 1; }

extern int z;

void thread_0(int &x, int &y) {
  L0: x = 0;
  int r;
  while (x * (5 + 4 / 2) % 3 == 1) {
    if (x != 0)
      goto L0;
    if (y > 6)
      continue;
    else if (++y > 7) {
      r = r + 10;
      break;
    }
    else
      goto L1;
    r = 11;
  }
  y = x.load(_rx) + 1;;
  L1: x.store(_rx, r);
}

exists (y == x + 1 && thread_0:r > 21)
```

Figure: A program example in C

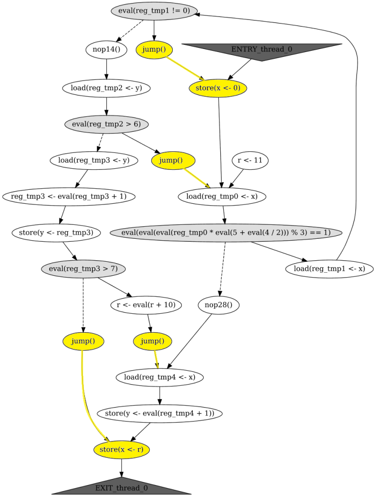
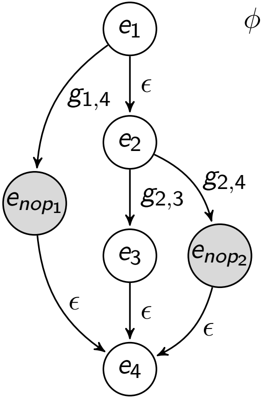


Figure: The compiled event-flow graph

PorthosC: The new control-flow encoding scheme



$$
\begin{aligned}
\phi_{CF} = {} & [\mathbf{x}(e_2) \Rightarrow \mathbf{x}(e_1)] \\
& \wedge [\mathbf{x}(e_3) \Rightarrow \mathbf{x}(e_2)] \\
& \wedge [\mathbf{x}(e_{nop_1}) \Rightarrow \mathbf{x}(e_1)] \\
& \wedge [\mathbf{x}(e_{nop_2}) \Rightarrow \mathbf{x}(e_2)] \\
& \wedge [\mathbf{x}(e_4) \Rightarrow (\mathbf{x}(e_{nop_1}) \vee \mathbf{x}(e_3) \vee \mathbf{x}(e_{nop_2}))] \\
& \wedge [\mathbf{x}(e_{nop_1}) \wedge \mathbf{x}(e_1) \Rightarrow g_{1,4}] \\
& \wedge [(\mathbf{x}(e_3) \wedge \mathbf{x}(e_2)) \Rightarrow g_{2,3}] \\
& \wedge [(\mathbf{x}(e_{nop_2}) \wedge \mathbf{x}(e_2)) \Rightarrow g_{2,4}] \\
& \wedge \neg[\mathbf{x}(e_2) \wedge \mathbf{x}(e_{nop_1})] \\
& \wedge \neg[\mathbf{x}(e_3) \wedge \mathbf{x}(e_{nop_2})]
\end{aligned}
$$

Figure: Example of encoding for the control-flow of the event-flow graph

PorthosC: The new DFS-based X-graph unrolling scheme

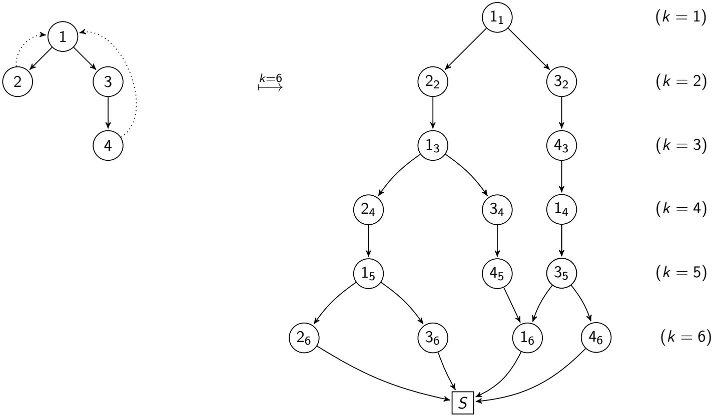


Figure: Example of the flow graph unrolling up to bound $k = 6$

Evaluation

The new unrolling scheme

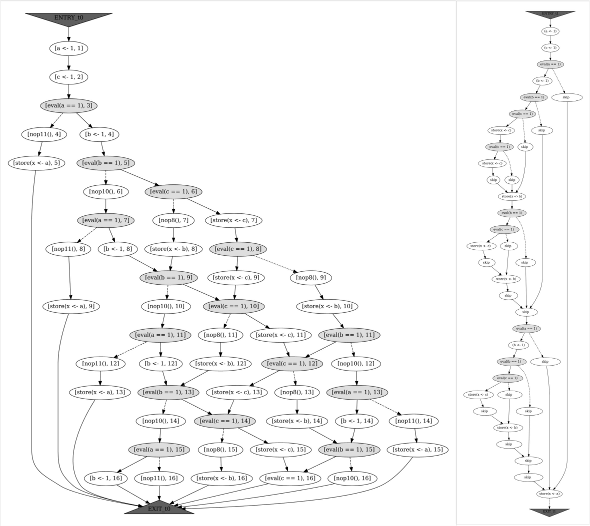
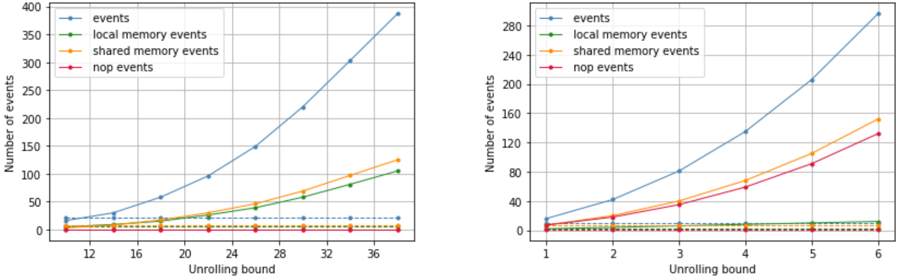


Figure: Illustration of differences in unrolling schemes of `PorthosC` (left) and `Porthos v1` (right)

Evaluation

Overhead of the new unrolling scheme: Number of events

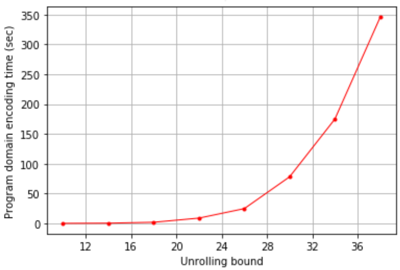


(a) The graph unrolled by `PorthosC` (b) The graph unrolled by `Porthos v1`

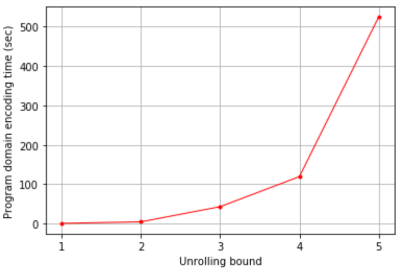
Figure: Dependency of unrolled events number on the unrolling bound k

Evaluation

Overhead of the new unrolling scheme: Execution time



(a) Program domain encoding time of the graph unrolled by `PorthosC`



(b) Program domain encoding time of the graph unrolled by `PorthosC`

Figure: Dependency of program domain encoding time (in seconds) on the unrolling bound

Summary

- The result of the work is the generalised framework for memory model-aware analysis `PorthosC`;
  - The *input language* has been extended to a higher subset of C language (including unconditional control-flow jumps);
  - The old *architecture* of `Porthos` has been revised and redesigned for `PorthosC`;
  - The *new unrolling scheme* produces complete state space of the analysing program within the user-defined bound k, though the encoding time growth rapidly (exponentially) as the unrolling bound grows;
  - The *invocation hooking mechanism* is an important part of the abstract interpretation engine, that serves as a knowledge base for the program domain and increases the extensibility of the tool.

Directions for future work

- Extending the *knowledge base* of domain-specific functions to model synchronisation primitives;
- Supporting *new input languages* (e.g., different assembly languages);
- Supporting *complex data types* (s.a. arrays, pointers, structures, etc.);
- Adding the *inter-procedural analysis mode*;
- Handling the *state explosion problem* (with standard model-checking techniques adjusted by the information about the weak memory model of the execution environment).

Thank you for attention

Bibliography I

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