Implementing a Capability Machine model into Iris

Aïna Linn Georges Alix Trieu Lars Birkedal

Aarhus University

ageorges@cs.au.dk

January 11, 2020

Introduction

- Capability machines allow for fine grained control over pointer permissions
- Good target for secure compilation
- In particular: we are interested in enforcing certain higher level abstractions such as *local state encapsulation* as *well-bracketed control flow* at the lowest level of the machine
- We need tools to reason about these subtle properties in a language that does not enforce them
- These tools are elaborate and complex: we want to mechanize them, and facilitate the process of using them

Introduction

- Capability machines allow for fine grained control over pointer permissions
- Good target for secure compilation
- In particular: we are interested in enforcing certain higher level abstractions such as *local state encapsulation* as *well-bracketed control flow* at the lowest level of the machine
- We need tools to reason about these subtle properties in a language that does not enforce them
- These tools are elaborate and complex: we want to mechanize them, and facilitate the process of using them

Introduction

- Capability machines allow for fine grained control over pointer permissions
- Good target for secure compilation
- In particular: we are interested in enforcing certain higher level abstractions such as *local state encapsulation* as *well-bracketed control flow* at the lowest level of the machine
- We need tools to reason about these subtle properties in a language that does not enforce them
- These tools are elaborate and complex: we want to mechanize them, and facilitate the process of using them

Introduction

- Capability machines allow for fine grained control over pointer permissions
- Good target for secure compilation
- In particular: we are interested in enforcing certain higher level abstractions such as *local state encapsulation* as *well-bracketed control flow* at the lowest level of the machine
- We need tools to reason about these subtle properties in a language that does not enforce them
- These tools are elaborate and complex: we want to mechanize them, and facilitate the process of using them

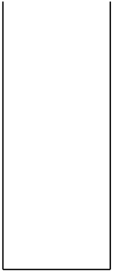
Introduction

- Capability machines allow for fine grained control over pointer permissions
- Good target for secure compilation
- In particular: we are interested in enforcing certain higher level abstractions such as *local state encapsulation* as *well-bracketed control flow* at the lowest level of the machine
- We need tools to reason about these subtle properties in a language that does not enforce them
- These tools are elaborate and complex: we want to mechanize them, and facilitate the process of using them

Capability Machines

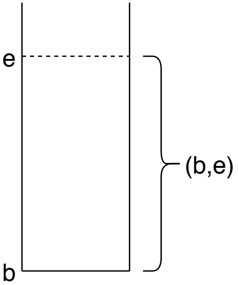
Capability Machine

Capability: An unforgeable token of authority



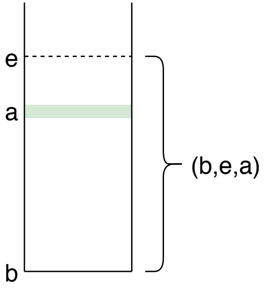
Capability Machine

Capability: An unforgeable token of authority



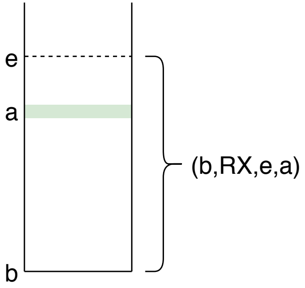
Capability Machine

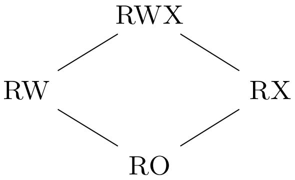
Capability: An unforgeable token of authority



Capability Machine

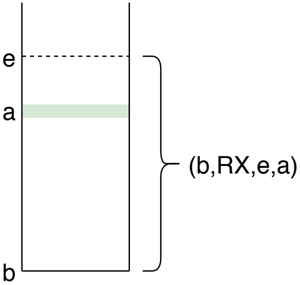
Capability: An unforgeable token of authority

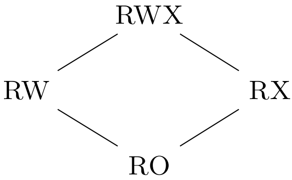




Capability Machine

Capability: An unforgeable token of authority

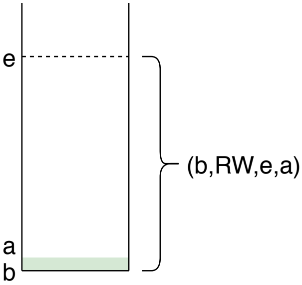




Enforcing Well Bracketed Control Flow using Capabilities

Capability Safety

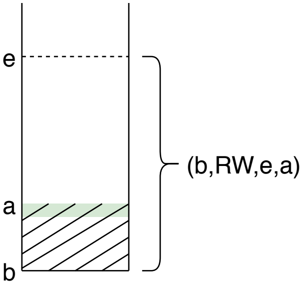
Well Bracketed Control Flow




```
push r_stk 1
scall r
pop r_stk r_1
assert r_1 1
push r_stk 2
scall r
halt
```

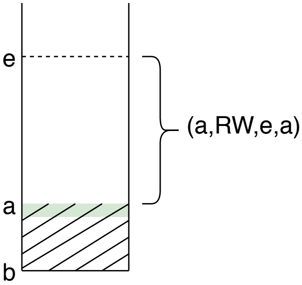
Capability Safety

Well Bracketed Control Flow




```
push r_stk 1
scall r
pop r_stk r_1
assert r_1 1
push r_stk 2
scall r
halt
```

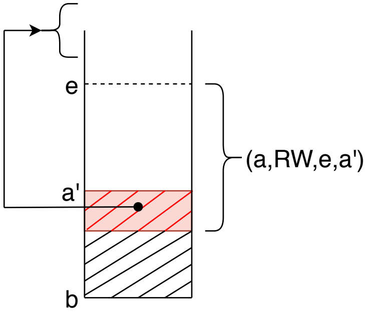
Well Bracketed Control Flow




```
push r_stk 1
scall r
pop r_stk r_1
assert r_1 1
push r_stk 2
scall r
halt
```

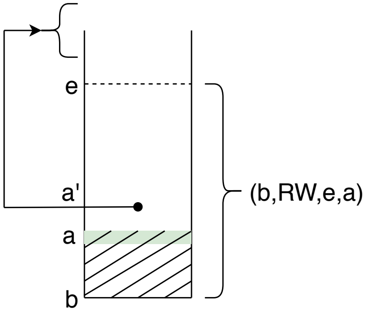
Capability Safety

Well Bracketed Control Flow




```
push r_stk 1
scall r
pop r_stk r_1
assert r_1 1
push r_stk 2
scall r
halt
```

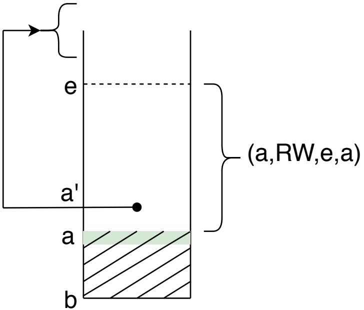
Well Bracketed Control Flow




```
push r_stk 1
scall r
pop r_stk r_1
assert r_1 1
push r_stk 2
scall r
halt
```

Capability Safety

Well Bracketed Control Flow




```
push r_stk 1
scall r
pop r_stk r_1
assert r_1 1
push r_stk 2
scall r
halt
```

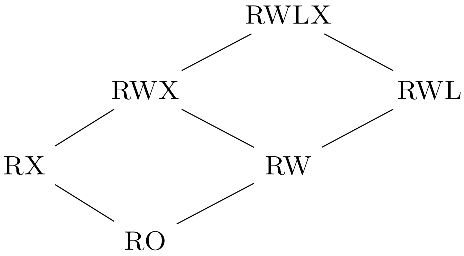
Local Capabilities

Local Capabilities

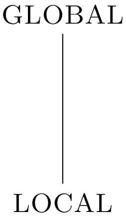
(p,**Local**,b,e,a) (p,**Global**,b,e,a)

Local Capabilities

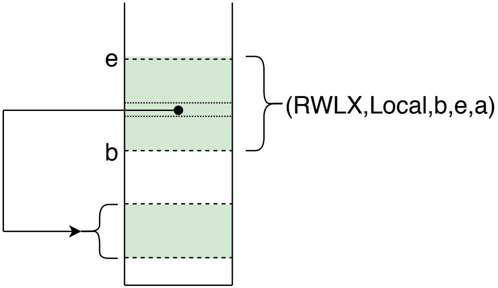
(p,**Local**,b,e,a)



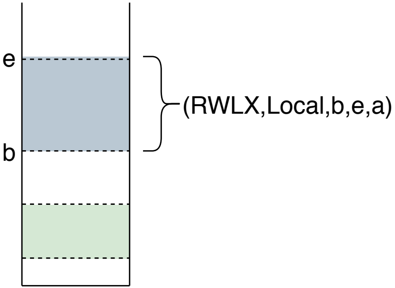
(p,**Global**,b,e,a)



Calling Convention



Calling Convention



Reasoning about Capability Safety

Expressing Capability Safety

- using a Program Logic
- using a logical relation to capture invariants on the type system
- **using a logical relation on an untyped (or uni-typed) language to capture semantic properties of the language**

Expressing Capability Safety

- using a Program Logic
- using a logical relation to capture invariants on the type system
- **using a logical relation on an untyped (or uni-typed) language to capture semantic properties of the language**

Expressing Capability Safety

- using a Program Logic
- using a logical relation to capture invariants on the type system
- using a logical relation on an untyped (or uni-typed) language to capture semantic properties of the language

Expressing Capability Safety

- using a Program Logic
- using a logical relation to capture invariants on the type system
- **using a logical relation on an untyped (or uni-typed) language to capture semantic properties of the language**

Step-indexed Kripke Logical Relation

$$\mathcal{V}(W) \triangleq \{n, (RW, g, b, e, a) | \cdots\} \cup \cdots$$

- World-circularity problem
  - Step indexing
- The world may evolve: we need future world relation
  - Local capabilities are revoked whereas Global capabilities are not, *the relation needs to model this distinction:*

$$\sqsupseteq_{pub} \quad \textit{and} \quad \sqsupseteq_{priv}$$

Step-indexed Kripke Logical Relation

$$\mathcal{V}(W) \triangleq \{n, (RW, g, b, e, a) | \cdots\} \cup \cdots$$

- World-circularity problem
  - Step indexing
- The world may evolve: we need future world relation
  - Local capabilities are revoked whereas Global capabilities are not, *the relation needs to model this distinction:*

$$\sqsupseteq_{pub} \qquad \textit{and} \qquad \sqsupseteq_{priv}$$

Step-indexed Kripke Logical Relation

$$\mathcal{V}(W) \triangleq \{n, (RW, g, b, e, a) | \exists r, W(r) = \iota_{[b,e]}\} \cup \cdots$$

- World-circularity problem
  - Step indexing
- The world may evolve: we need future world relation
  - Local capabilities are revoked whereas Global capabilities are not, *the relation needs to model this distinction:*

$$\sqsupseteq_{pub} \qquad and \qquad \sqsupseteq_{priv}$$

Step-indexed Kripke Logical Relation

$$\mathcal{V}(W) \triangleq \{n, (RW, g, b, e, a) | \exists r, W(r) = \iota_{[b,e]}\} \cup \cdots$$

- World-circularity problem
  - Step indexing
- The world may evolve: we need future world relation
  - Local capabilities are revoked whereas Global capabilities are not, *the relation needs to model this distinction:*

$$\sqsupseteq_{pub} \qquad \textit{and} \qquad \sqsupseteq_{priv}$$

Step-indexed Kripke Logical Relation

$$\mathcal{V}(W) \triangleq \{n, (RW, g, b, e, a) | \exists r, W(r) \overset{n}{=} \iota_{[b,e]}\} \cup \cdots$$

- World-circularity problem
  - Step indexing
- The world may evolve: we need future world relation
  - Local capabilities are revoked whereas Global capabilities are not, *the relation needs to model this distinction:*

$$\sqsupseteq_{pub} \quad \textit{and} \quad \sqsupseteq_{priv}$$

Step-indexed Kripke Logical Relation

$$\mathcal{V}(W) \triangleq \{n, (RW, g, b, e, a) | \exists r, W(r) \stackrel{n}{=} \iota_{[b,e]}\} \cup \cdots$$

- World-circularity problem
  - Step indexing
- The world may evolve: we need future world relation
  - Local capabilities are revoked whereas Global capabilities are not, *the relation needs to model this distinction*:

$$\sqsupseteq_{pub} \qquad \textit{and} \qquad \sqsupseteq_{priv}$$

Step-indexed Kripke Logical Relation

$$\mathcal{V}(W) \triangleq \{n, (RW, g, b, e, a) | \exists r, W(r) \overset{n}{=} \iota_{[b,e]}\} \cup \cdots$$

- World-circularity problem
  - Step indexing
- The world may evolve: we need future world relation
  - Local capabilities are revoked whereas Global capabilities are not, *the relation needs to model this distinction*:

$$\sqsupseteq_{pub} \qquad \textit{and} \qquad \sqsupseteq_{priv}$$

Expressing Capability Safety in Iris - an Iris primer

Iris: Higher-order Concurrent Separation Logic Framework

- Foundational
- Implemented in Coq – equipped with an interactive proof mode
- Framework – embed any language and its operational semantics into Iris
- Comes equipped with:
  - Invariants
  - Ghost state
  - Always and Later Modalities

We can take advantage of Iris' step-indexed model and invariants to mechanize step-indexed Kripke logical relations with recursive worlds in a succinct and elegant way.

Expressing Capability Safety in Iris - an Iris primer

Iris: Higher-order Concurrent Separation Logic Framework

- Foundational
- Implemented in Coq – equipped with an interactive proof mode
- Framework – embed any language and its operational semantics into Iris
- Comes equipped with:
  - Invariants
  - Ghost state
  - Always and Later Modalities

We can take advantage of Iris' step-indexed model and invariants to mechanize step-indexed Kripke logical relations with recursive worlds in a succinct and elegant way.

Expressing Capability Safety in Iris - an Iris primer

Iris: Higher-order Concurrent Separation Logic Framework

- Foundational
- Implemented in Coq – equipped with an interactive proof mode
- Framework – embed any language and its operational semantics into Iris
- Comes equipped with:
  - Invariants
  - Ghost state
  - Always and Later Modalities

We can take advantage of Iris' step-indexed model and invariants to mechanize step-indexed Kripke logical relations with recursive worlds in a succinct and elegant way.

Expressing Capability Safety in Iris - an Iris primer

Iris: Higher-order Concurrent Separation Logic Framework

- Foundational
- Implemented in Coq – equipped with an interactive proof mode
- Framework – embed any language and its operational semantics into Iris
- Comes equipped with:
  - Invariants
  - Ghost state
  - Always and Later Modalities

We can take advantage of Iris' step-indexed model and invariants to mechanize step-indexed Kripke logical relations with recursive worlds in a succinct and elegant way.

Expressing Capability Safety in Iris - an Iris primer

Iris: Higher-order Concurrent Separation Logic Framework

- Foundational
- Implemented in Coq – equipped with an interactive proof mode
- Framework – embed any language and its operational semantics into Iris
- Comes equipped with:
  - Invariants
  - Ghost state
  - Always and Later Modalities

We can take advantage of Iris' step-indexed model and invariants to mechanize step-indexed Kripke logical relations with recursive worlds in a succinct and elegant way.

Expressing Capability Safety in Iris - an Iris primer

Iris: Higher-order Concurrent Separation Logic Framework

- Foundational
- Implemented in Coq – equipped with an interactive proof mode
- Framework – embed any language and its operational semantics into Iris
- Comes equipped with:
  - Invariants
  - Ghost state
  - Always and Later Modalities

We can take advantage of Iris' step-indexed model and invariants to mechanize step-indexed Kripke logical relations with recursive worlds in a succinct and elegant way.

Expressing Capability Safety in Iris - an Iris primer

Iris: Higher-order Concurrent Separation Logic Framework

- Foundational
- Implemented in Coq – equipped with an interactive proof mode
- Framework – embed any language and its operational semantics into Iris
- Comes equipped with:
  - Invariants
  - Ghost state
  - Always and Later Modalities

We can take advantage of Iris' step-indexed model and invariants to mechanize step-indexed Kripke logical relations with recursive worlds in a succinct and elegant way.

Expressing Capability Safety in Iris - an Iris primer

Iris: Higher-order Concurrent Separation Logic Framework

- Foundational
- Implemented in Coq – equipped with an interactive proof mode
- Framework – embed any language and its operational semantics into Iris
- Comes equipped with:
  - Invariants
  - Ghost state
  - Always and Later Modalities

We can take advantage of Iris' step-indexed model and invariants to mechanize step-indexed Kripke logical relations with recursive worlds in a succinct and elegant way.

Expressing Capability Safety in Iris - Challenges

- Region invariants: Iris invariants
- Future world relation: frame preserving updates and world satisfaction
- Step indexing: later modality

Challenges

- Iris was designed with more high level languages in mind, how do we embed a low level machine language into Iris
- Iris abstracts away certain details we want to reason about directly
- There is only one frame preserving update, we need to distinguish between two future world relations

Expressing Capability Safety in Iris - Challenges

- Region invariants: Iris invariants
- Future world relation: frame preserving updates and world satisfaction
- Step indexing: later modality

Challenges

- Iris was designed with more high level languages in mind, how do we embed a low level machine language into Iris
- Iris abstracts away certain details we want to reason about directly
- There is only one frame preserving update, we need to distinguish between two future world relations

Expressing Capability Safety in Iris - Challenges

- Region invariants: Iris invariants
- Future world relation: frame preserving updates and world satisfaction
- Step indexing: later modality

Challenges

- Iris was designed with more high level languages in mind, how do we embed a low level machine language into Iris
- Iris abstracts away certain details we want to reason about directly
- There is only one frame preserving update, we need to distinguish between two future world relations

Expressing Capability Safety in Iris - Challenges

- Region invariants: Iris invariants
- Future world relation: frame preserving updates and world satisfaction
- Step indexing: later modality

Challenges

- Iris was designed with more high level languages in mind, how do we embed a low level machine language into Iris
- Iris abstracts away certain details we want to reason about directly
- There is only one frame preserving update, we need to distinguish between two future world relations

Expressing Capability Safety in Iris

Roadmap

- embed the language into Iris
- define a program logic by proving Hoare Triples
- define the logical relation – using Iris tools to solve the world circularity problem
- prove the fundamental theorem of logical relations
- use the logical relation to prove examples that rely on local state encapsulation and well-bracketed control flow with calls to unknown adversary

Expressing Capability Safety in Iris

Roadmap

- embed the language into Iris
- define a program logic by proving Hoare Triples
- define the logical relation – using Iris tools to solve the world circularity problem
- prove the fundamental theorem of logical relations
- use the logical relation to prove examples that rely on local state encapsulation and well-bracketed control flow with calls to unknown adversary

Expressing Capability Safety in Iris

Roadmap

- embed the language into Iris
- define a program logic by proving Hoare Triples
- define the logical relation – using Iris tools to solve the world circularity problem
- prove the fundamental theorem of logical relations
- use the logical relation to prove examples that rely on local state encapsulation and well-bracketed control flow with calls to unknown adversary

Expressing Capability Safety in Iris

Roadmap

- embed the language into Iris
- define a program logic by proving Hoare Triples
- define the logical relation – using Iris tools to solve the world circularity problem
- prove the fundamental theorem of logical relations
- use the logical relation to prove examples that rely on local state encapsulation and well-bracketed control flow with calls to unknown adversary

Expressing Capability Safety in Iris

Roadmap

- embed the language into Iris
- define a program logic by proving Hoare Triples
- define the logical relation – using Iris tools to solve the world circularity problem
- prove the fundamental theorem of logical relations
- use the logical relation to prove examples that rely on local state encapsulation and well-bracketed control flow with calls to unknown adversary

Roadmap

- embed the language into Iris
- define a program logic by proving Hoare Triples
- define the logical relation – using Iris tools to solve the world circularity problem
- prove the fundamental theorem of logical relations
- use the logical relation to prove examples that rely on local state encapsulation and well-bracketed control flow with calls to unknown adversary

Program Logic

Abstract Instructions

$$(reg, mem) \rightarrow (reg', mem')$$

- Instr Executable
- Instr Halted $\rightarrow$ HaltedV
- Instr Failed $\rightarrow$ FailedV

Abstract Instructions

$$(reg, mem) \rightarrow (reg', mem')$$

- Instr Executable
- Instr Halted $\rightarrow$ HaltedV
- Instr Failed $\rightarrow$ FailedV

Abstract Instructions

$$(reg, mem) \rightarrow (reg', mem')$$

- Instr Executable
- Instr Halted $\rightarrow$ HaltedV
- Instr Failed $\rightarrow$ FailedV

Abstract Instructions

$$(reg, mem) \rightarrow (reg', mem')$$

- Instr Executable
- Instr Halted $\rightarrow$ HaltedV
- Instr Failed $\rightarrow$ FailedV

Abstract Instructions

$$(reg, mem) \rightarrow (reg', mem')$$

- Instr Executable
- Instr Halted $\rightarrow$ HaltedV
- Instr Failed $\rightarrow$ FailedV

A Capability Points-to Predicate

Points-to Predicate with Permissions

$$a \mapsto_a [RWL]w$$

Points-to Predicate with Permissions

$$a \mapsto_a [RWL]w \Rrightarrow a \mapsto_a [RWL]((p, Local), b, e, l)$$

Points-to Predicate with Permissions

$$
\begin{aligned}
a \mapsto_a [RWL]w &\Rrightarrow a \mapsto_a [RWL]((p, Local), b, e, l) \\
&\Rrightarrow a \mapsto_a [RW]((p, Local), b, e, l)
\end{aligned}
$$

Points-to Predicate with Permissions

$$
\begin{aligned}
a \mapsto_a [RWL]w &\Rrightarrow a \mapsto_a [RWL]((p, Local), b, e, l) \\
&\Rrightarrow a \mapsto_a [RW]((p, Local), b, e, l) \\
&\not\Rrightarrow a \mapsto_a [RW]((p', Local), b', e', l')
\end{aligned}
$$

A Unary Logical Relation for Reasoning about Semantic Properties of an Untyped Language

The Value Relation

The Value Relation

A unary logical relation of an un-typed language

$$\mathcal{V} : \mathit{Word} \rightarrow \mathit{iProp}\ \Sigma$$

Challenge: distinguish between Local and Global capabilities:

- At the level of the value relation
- Model revocation

STS: A collection of state transition systems

$$\mathcal{V}((\text{RW}, g), b, e, a) \triangleq \mathop{\Huge *}_{a \in [b,e]} \boxed{\exists w, a \mapsto_a [RW]w * \mathcal{V}(w)}$$

The Value Relation

A unary logical relation of an un-typed language

$$\mathcal{V} : \mathit{Word} \rightarrow \mathit{iProp}\ \Sigma$$

Challenge: distinguish between Local and Global capabilities:

- At the level of the value relation
- Model revocation

STS: A collection of state transition systems

$$\mathcal{V}((\textsc{rw}, g), b, e, a) \triangleq \mathop{\Large\ast}_{a \in [b,e]} \boxed{\exists w, a \mapsto_a [RW] w \ast \mathcal{V}(w)}$$

The Value Relation

A unary logical relation of an un-typed language

$$\mathcal{V} : \mathit{Word} \to \mathit{iProp}\ \Sigma$$

Challenge: distinguish between Local and Global capabilities:

- At the level of the value relation
- Model revocation

STS: A collection of state transition systems

$$\mathcal{V}((\textsc{rw}, g), b, e, a) \triangleq \mathop{\Large *}_{a \in [b,e]} \boxed{\exists w, a \mapsto_a [RW]w * \mathcal{V}(w)}$$

The Value Relation

A unary logical relation of an un-typed language

$$\mathcal{V} : \mathit{Word} \rightarrow \mathit{iProp}\ \Sigma$$

Challenge: distinguish between Local and Global capabilities:

- At the level of the value relation
- Model revocation

STS: A collection of state transition systems

$$\mathcal{V}((\mathrm{RW}, g), b, e, a) \triangleq \mathop{\Huge \ast}_{a \in [b,e]} \boxed{\exists w, a \mapsto_a [RW] w \ast \mathcal{V}(w)}$$

The Value Relation

A unary logical relation of an un-typed language

$$\mathcal{V} : \mathit{Word} \to \mathit{iProp}\ \Sigma$$

Challenge: distinguish between Local and Global capabilities:

- At the level of the value relation
- Model revocation

STS: A collection of state transition systems

$$\mathcal{V}((\textsc{rw}, g), b, e, a) \triangleq \mathop{\scalebox{2}{$\ast$}}_{a \in [b,e]} \boxed{\exists w, a \mapsto_a [RW] w \ast \mathcal{V}(\Sigma)(w)}$$

The Value Relation

A unary logical relation of an un-typed language

$$\mathcal{V} : STS \to \; Word \to iProp\ \Sigma$$

Challenge: distinguish between Local and Global capabilities:

- At the level of the value relation
- Model revocation

STS: A collection of state transition systems

$$\mathcal{V}(\Sigma)((\textsc{rw}, g), b, e, a) \triangleq \mathop{\scalebox{2}{$\ast$}}_{a \in [b,e]} \boxed{\exists w, a \mapsto_a [RW] w * \mathcal{V}(\Sigma)(w)}$$

The Execute Condition

The Execute Condition

$$\text{exec\_cond}(\Sigma)(\text{p,g,b,e}) \triangleq \begin{cases} \forall a \in [b\ \ e], \Sigma' \sqsupseteq_{pub} \Sigma. & \\ \quad \triangleright\ \ \mathcal{E}(\Sigma')(((p,g),b,e,a)) & g = Local \\ & \\ \forall a \in [b\ \ e], \Sigma' \sqsupseteq_{priv} \Sigma. & \\ \quad \triangleright\ \ \mathcal{E}(\Sigma')(((p,g),b,e,a)) & g = Global \end{cases}$$

The Expression Relation

The Expression Relation

$$\begin{aligned}\mathcal{E}(W)(pc) \triangleq \forall r, \mathcal{R}(W)(r) \ * \ &\text{context}(W)(r[\text{PC} := pc]) \\ -\!\!* \ \ &\mathrm{WP}\ \text{Seq (Instr Executable)} \\ &\quad \{v, v = \mathit{HaltedV} \implies \exists W' r', W' \sqsubseteq_{priv} W \\ &\quad * \,\text{context}(W')(r')\}\end{aligned}$$

The Expression Relation

$$
\begin{aligned}
\mathcal{E}(W)(pc) \triangleq \forall r, \mathcal{R}(W)(r) \; * \; &\text{context}(W)(r[\text{PC} := pc]) \\
\mathrel{-\!\!*} \; &\mathrm{WP}\ \text{Seq (Instr Executable)} \\
&\{v, v = HaltedV \implies \exists W' r', W' \sqsubseteq_{priv} W \\
&* \,\text{context}(W')(r')\}
\end{aligned}
$$

$$\text{context}(W)(r) = \; ?$$

The Expression Relation

$$\mathcal{E}(W)(pc) \triangleq \forall r, \mathcal{R}(W)(r) \ * \ \text{context}(W)(r[\text{PC} := pc]) \\ -\!\!* \ \mathrm{WP}\ \text{Seq (Instr Executable)} \\ \{v, v = HaltedV \implies \exists W' r', W' \sqsubseteq_{priv} W \\ * \ \text{context}(W')(r')\}$$

$$\text{context}(W)(r) = \Big(\mathop{\Huge *}_{r_i \mapsto w \in r} r_i \mapsto_r w \Big) \land \text{full\_map } r$$

The Expression Relation

$$\mathcal{E}(W)(pc) \triangleq \forall r, \mathcal{R}(W)(r) \ * \ \text{context}(W)(r[\mathsf{PC} := pc])$$
$$-\!\!* \ \mathrm{WP}\ \mathsf{Seq}\ (\mathsf{Instr\ Executable})$$
$$\{v, v = HaltedV \implies \exists W' r', W' \sqsubseteq_{priv} W$$
$$* \ \text{context}(W')(r')\}$$

$$\text{context}(W)(r) = \Big(\mathop{\Huge *}_{r_i \mapsto w \in r} r_i \mapsto_r w \Big) \land \mathsf{full\_map}\ r$$
$$* \ \mathsf{na\_inv}\ \gamma_{na} \top$$

The Expression Relation

$$\mathcal{E}(W)(pc) \triangleq \forall r, \mathcal{R}(W)(r) \ * \ \text{context}(W)(r[\text{PC} := pc])$$
$$-\!\!* \ \ \mathrm{WP}\ \text{Seq (Instr Executable)}$$
$$\{v, v = HaltedV \implies \exists W' r', W' \sqsubseteq_{priv} W$$
$$* \ \text{context}(W')(r')\}$$

$$\text{context}(W)(r) = \Big(\mathop{\Large *}_{r_i \mapsto w \in r} r_i \mapsto_r w \Big) \wedge \text{full\_map}\ r$$
$$* \ \text{na\_inv}\ \gamma_{na} \top$$
$$* \ \text{sts\_full}\ W$$

The Expression Relation

$$\mathcal{E}(W)(pc) \triangleq \forall r, \mathcal{R}(W)(r) \ * \ \text{context}(W)(r[\text{PC} := pc]) \\ -\!\!* \ \text{WP Seq (Instr Executable)} \\ \{v, v = HaltedV \implies \exists W' r', W' \sqsubseteq_{priv} W \\ * \ \text{context}(W')(r')\}$$

$$\text{context}(W)(r) = \Big(\mathop{\Huge *}_{r_i \mapsto w \in r} r_i \mapsto_r w\Big) \land \text{full\_map } r \\ * \ \text{na\_inv } \gamma_{na} \top \\ * \ \text{sts\_full } W \\ * \ \text{region } W$$

The Fundamental Theorem of Logical Relations

The Fundamental Theorem of logical relations

If we can read a region, and every word in that region is safe, then we can safely execute it

- "If we can read a region" : $p = \mathrm{RX} \vee p = \mathrm{RWX} \vee p = \mathrm{RWLX}$
- "and every word in that region is safe": read_write_cond (p, b, e)
- "then we can safely execute it": $\mathcal{E}(W)(((p, g), b, e, a))$

$$(p = \mathrm{RX} \vee p = \mathrm{RWX} \vee p = \mathrm{RWLX}) \implies$$
$$\text{read\_write\_cond } (p, b, e) \implies \mathcal{E}(W)(((p, g), b, e, a))$$

- "If we can read a region" : $p = \mathrm{RX} \vee p = \mathrm{RWX} \vee p = \mathrm{RWLX}$
- "and every word in that region is safe": read_write_cond (p, b, e)
- "then we can safely execute it": $\mathcal{E}(W)(((p, g), b, e, a))$

$$(p = \mathrm{RX} \vee p = \mathrm{RWX} \vee p = \mathrm{RWLX}) \implies$$
$$\text{read\_write\_cond } (p, b, e) \implies \mathcal{E}(W)(((p, g), b, e, a))$$

- "If we can read a region" : $p = \mathrm{RX} \vee p = \mathrm{RWX} \vee p = \mathrm{RWLX}$
- "and every word in that region is safe": read_write_cond (p, b, e)
- "then we can safely execute it": $\mathcal{E}(W)(((p, g), b, e, a))$

$$(p = \mathrm{RX} \vee p = \mathrm{RWX} \vee p = \mathrm{RWLX}) \implies$$
$$\text{read\_write\_cond } (p, b, e) \implies \mathcal{E}(W)(((p, g), b, e, a))$$

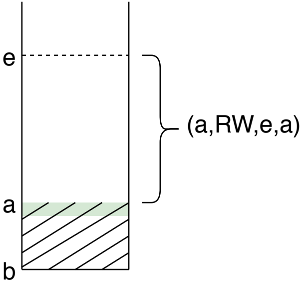
- "If we can read a region" : $p = \mathrm{RX} \vee p = \mathrm{RWX} \vee p = \mathrm{RWLX}$
- "and every word in that region is safe": read_write_cond (p, b, e)
- "then we can safely execute it": $\mathcal{E}(W)(((p, g), b, e, a))$

$$(p = \mathrm{RX} \vee p = \mathrm{RWX} \vee p = \mathrm{RWLX}) \implies$$
$$\text{read\_write\_cond } (p, b, e) \implies \mathcal{E}(W)(((p, g), b, e, a))$$

Reasoning about Unknown Code

Reasoning about Unknown Code

We use the fundamental theorem to reason about calls to an unknown adversary




```
push r_stk 1
scall r
pop r_stk r_1
assert r_1 1
halt
```

$$\begin{aligned}\mathcal{E}(W)(pc) \triangleq \forall r, \mathcal{R}(W)(r) \ * \ \text{context}(W)(r[\text{PC} := pc]) \\ -\!\!* \ \text{WP Seq (Instr Executable)} \\ \{v, v = HaltedV \implies \exists W' r', W' \sqsubseteq_{priv} W \\ * \, \text{context}(W')(r')\}\end{aligned}$$

What's new

What's new: capability machine viewpoint

- Mechanized formalization: currently $\sim 20,000$ lines of code
- A higher level of abstraction

What's new: Iris formalization viewpoint

- Formalization of a machine level language, with no distinction between program and memory
- Distinction between well-bracketed and non well-bracketed calls: using public/private transitions

Conclusion

- Embed a capability machine into Iris
- Define its program logic
- Mechanize a unary logical relation for an untyped capability machine language
- Prove the fundamental theorem of logical relations
- Reason about examples that rely on Local Stack Encapsulation and Well-Bracketed Control Flow with calls to an unknown adversary

References

Lau Skorstengaard, Dominique Devriese, and Lars Birkedal (2018)
Reasoning About a Machine with Local Capabilities
ESOP *Programming Languages and Systems* 475–501.

Derek Dreyer, Georg Neis, Lars Birkedal (2012)
The impact of higher-order state and control effects on local relational reasoning
Journal of Functional Programming 22(4-5) 477–528.

Derek Dreyer, Amal Ahmed, Lars Birkedal (2011)
Logical Step-Indexed Logical Relations
LMCS 7(2:16).