Implementing a Capability Machine model into Iris

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October 25, 2019

Overview

Layers of Abstraction

Programming Languages

Assembly Language

Machine Code

. . .

Layers of Abstraction

Programming Languages

- Local State Encapsulation

Assembly Language

Machine Code

...

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- Well Bracketed Control Flow

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- Programs lie in Memory, Program Counter, ...

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- Programs lie in Memory, Program Counter, ...
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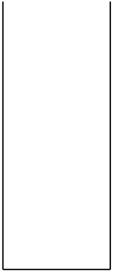
Machine Code

- Instruction Decoding, Cache, etc.

. . .

Capability Machine

Capability: An unforgeable token of authority



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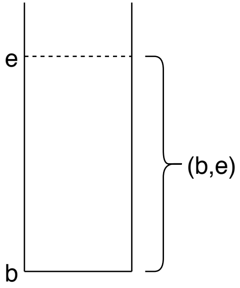

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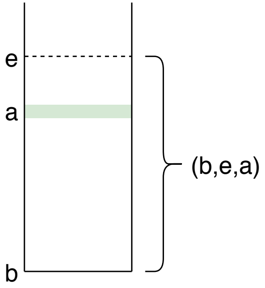

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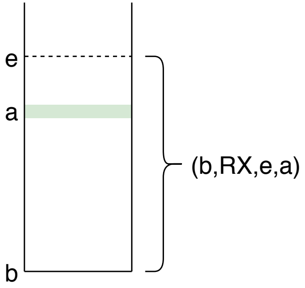
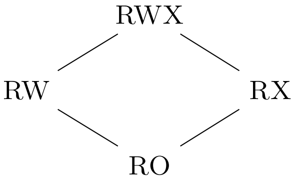
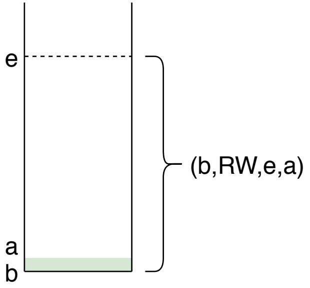




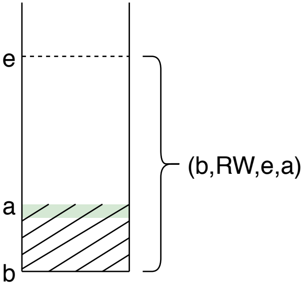
Capability Safety

Local State Encapsulation




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

Local State Encapsulation

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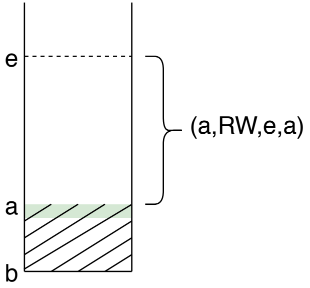


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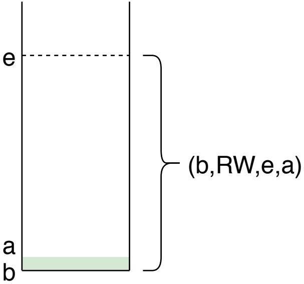
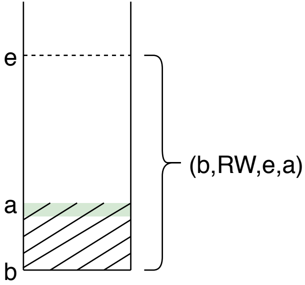
Well Bracketed Control Flow




```
push r_stk 1
scall r ([r])
pop r_stk r_1
assert r_1 1
push r_stk 2
scall r
halt
```

Capability Safety

Well Bracketed Control Flow

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Capability Safety

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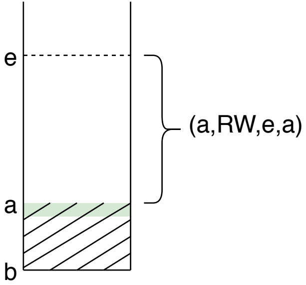


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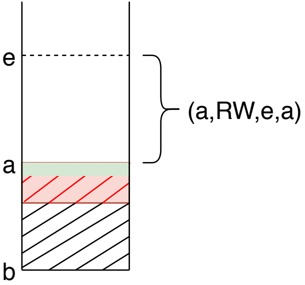


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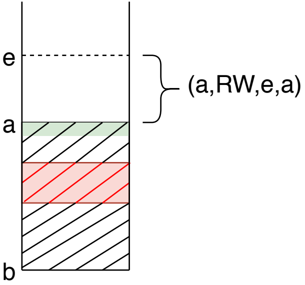


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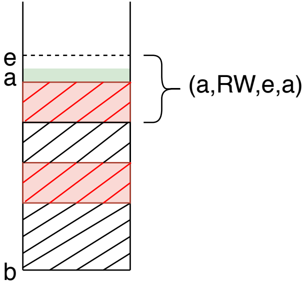


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(p,**Local**,b,e,a) (p,**Global**,b,e,a)

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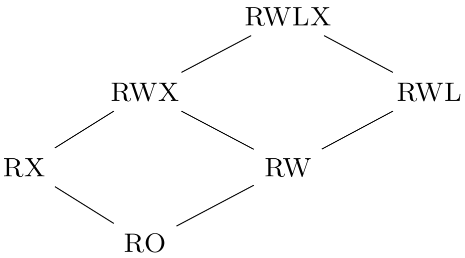

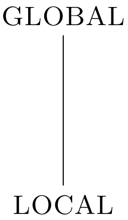

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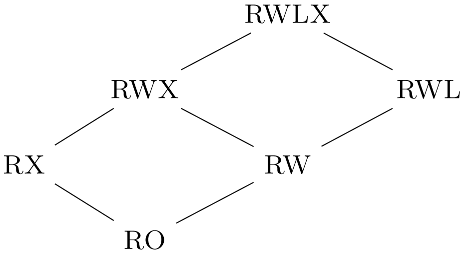

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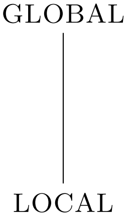

not well-bracketed

Expressing Capability Safety

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  4. prove the fundamental theorem of logical relations

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  1. embed the language into Iris
  2. define a program logic by proving Hoare Triples
  3. define the logical relation
  4. prove the fundamental theorem of logical relations
  5. use the logical relation to prove examples that rely on LSE and WBCF with calls to unknown adversary

Abstract Instructions

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

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- Instr Executable

Abstract Instructions

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

- Instr Executable
- Instr Halted

Abstract Instructions

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

- Instr Executable
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Abstract Instructions

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

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

Hoare Triples of the Program Logic: Success

$$
\begin{aligned}
& \quad decode(w) = \text{Load dst src} \\
& \quad \wedge \text{ isCorrectPC } ((p_{pc}, g_{pc}), b_{pc}, e_{pc}, a_{pc}) \\
& \quad \wedge \text{ readAllowed } p_{src} \ \wedge \ \text{withinBounds } (b_{src}, e_{src}, a_{src}) \\
& \quad \wedge \ p_{pc} \sqsubseteq p'_{pc} \ \wedge \ p_{src} \sqsubseteq p'_{src} \\
& \{\{\{ \text{ PC} \mapsto_r ((p_{pc}, g_{pc}), b_{pc}, e_{pc}, a_{pc}) * a_{pc} \mapsto_a [p'_{pc}]w \\
& \quad * \, dst \mapsto_r w_{dst} * src \mapsto_r ((p_{src}, g_{src}), b_{src}, e_{src}, a_{src}) \\
& \quad * \, a_{src} \mapsto_a [p'_{src}] w_{src} \}\}\} \\
& \quad \text{Instr Executable} \\
& \{\{\{ \ \}\}\}
\end{aligned}
$$

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\{\{\{\ \text{PC} \mapsto_r ((p_{pc}, g_{pc}), b_{pc}, e_{pc}, a_{pc} + 1)\}\}\}
\end{array}
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& \quad \text{Instr Executable} \\
\{\{\{ & \ \text{PC} \mapsto_r ((p_{pc}, g_{pc}), b_{pc}, e_{pc}, a_{pc} + 1) * a_{pc} \mapsto_a [p'_{pc}]w \}\}\}
\end{aligned}
$$

Hoare Triples of the Program Logic: Success

$$
\begin{aligned}
& \quad decode(w) = \text{Load dst src} \\
& \land \ \text{isCorrectPC} \ ((p_{pc}, g_{pc}), b_{pc}, e_{pc}, a_{pc}) \\
& \land \ \text{readAllowed} \ p_{src} \ \land \ \text{withinBounds} \ (b_{src}, e_{src}, a_{src}) \\
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\end{aligned}
$$

Points to Predicate with Permissions

$$a \mapsto_a [RWL]w$$

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

Points to Predicate with Permissions

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

Points to Predicate with Permissions

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

Hoare Triples of the Program Logic: Failure

$$
\begin{array}{l}
\quad decode(w) = \text{Load dst src} \\
\quad \wedge \ \text{isCorrectPC} \ ((p_{pc}, g_{pc}), b_{pc}, e_{pc}, a_{pc}) \\
\quad \wedge \ \neg\text{readAllowed} \ p_{src} \ \vee \ \neg\text{withinBounds} \ (b_{src}, e_{src}, a_{src}) \\
\quad \wedge \ p_{pc} \sqsubseteq p'_{pc} \\
\{\{\{ \ \text{PC} \mapsto_r ((p_{pc}, g_{pc}), b_{pc}, e_{pc}, a_{pc}) * a_{pc} \mapsto_a [p'_{pc}]w \\
\quad * \ src \mapsto_r ((p_{src}, g_{src}), b_{src}, e_{src}, a_{src})\}\}\} \\
\quad \text{Instr Executable} \\
\{\{\{ \ \text{FailedV}, \top\}\}\}
\end{array}
$$

The Value Relation

A unary logical relation of an un-typed language

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

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A unary logical relation of an un-typed language

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- Reasoning about local state: World
  A collection of state transition systems

The Value Relation

A unary logical relation of an un-typed language

$$\mathcal{V} : \textcolor{red}{World} \to \ Word \to iProp\ \Sigma$$

- Reasoning about local state: World
  A collection of state transition systems

$$\mathcal{V}(W)(z) \triangleq \exists z' \in \mathbb{Z}. z = z'$$

$$\mathcal{V}(W)(((\text{RO}, g), b, e, a)) \triangleq \exists\ p', \text{RO} \sqsubseteq p' * \text{read\_write\_cond(p',b,e)}$$

$$\mathcal{V}(W)(((\text{RX}, g), b, e, a)) \triangleq \exists\ p', \text{RX} \sqsubseteq p' * \text{read\_write\_cond(p',b,e)}$$

$$* \ \square \ \text{exec\_cond(W)(p,g,b,e)}$$

The Execute Condition

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

The Expression Relation

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

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

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

The Expression Relation

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&\quad * \ \mathsf{context}(W')(r')\}
\end{aligned}
$$

$$
\mathsf{context}(W)(r) = \left(\mathop{\Large *}_{r_i \mapsto w \in r} r_i \mapsto_r w \right) \land \mathsf{full\_map}\ r
$$

The Expression Relation

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$$* \ \text{na\_inv } \gamma_{na} \top$$

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$$* \ \mathsf{na\_inv}\ \gamma_{na} \top$$
$$* \ \mathsf{sts\_full}\ W$$

The Expression Relation

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

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

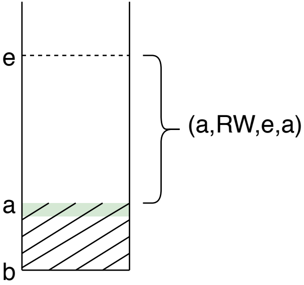
The Fundamental Theorem of Logical Relations

If we can read a region, and that region is safe, we can safely execute it

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

Capability Safety

We use the FTLR to reason about calls to an unknown adversary




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

Conclusion

- Embedding of a Capability Machine into Iris
- The Program Logic
- A unary Logical Relation for an Untyped Capability Machine Language
- 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

John Smith (2012)
Title of the publication
Journal Name 12(3), 45 – 678.