Verification of Spectre Mitigations using Hypersimulations

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UNIVERSITÄT
DES
SAARLANDES

Spectre

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if (i < A.size && i > 0) {
        int x = A[i];
        int y = B[x * 256];
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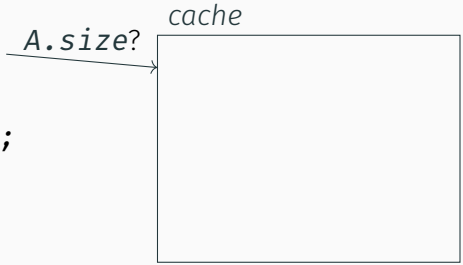

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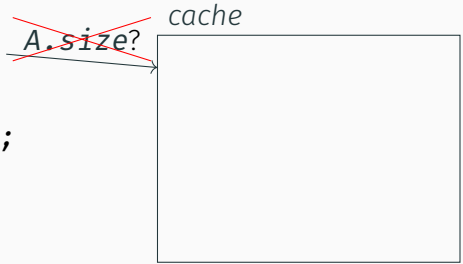

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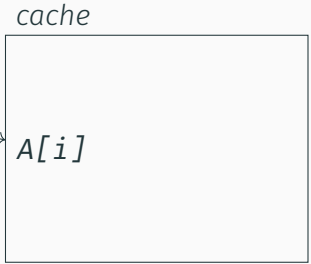

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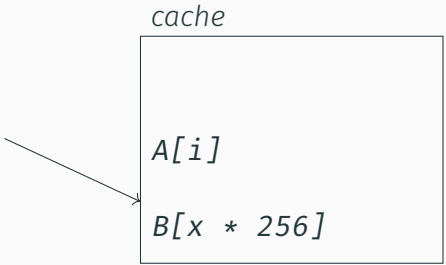

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$\Longrightarrow$ costly, can only protect future hardware

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    - SPECTECTOR: symbolic execution

Spectre Mitigations

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    - Speculative Load Hardening: additional data dependencies
    - MSVC: Fence instructions, pattern-based

Contributions

- Method of verifying compiler-based spectre mitigations

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- Incompatibility between speculative load hardening and always-mispredict semantics
- Design and verify a mitigation that could not be verified previously
- All work formalized in the Coq Proof Assistant

Verifying Spectre Mitigations: Speculative Noninterference [Guarnieri et al., 2018]

Noninterference

Same public inputs $\Longrightarrow$ Same observations

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Speculative Noninterference

Same observations under nonspeculative execution $\Longrightarrow$ Same observations under speculative execution

Patrignani and Guarnieri [2021]: Verifying Mitigations Using Speculative Safety

Applying a mitigation: Compilation

Language without speculative execution $\longrightarrow$ Language with speculative execution

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Patrignani and Guarnieri [2021]: Verifying Mitigations Using Speculative Safety

Applying a mitigation: Compilation

Language without speculative execution $\longrightarrow$ Language with speculative execution

- Without speculation, speculative noninterference is always satisfied
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- Approximate using speculative safety

Patrignani and Guarnieri [2021]: Verifying Mitigations Using Speculative Safety

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  - not all mitigations can be verified
- Our approach does not have these limitations

Verifying Spectre Mitigations: Preservation of Leakage Equivalence

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\begin{tikzcd}
\text{Source Speculative Noninterference} \arrow[r, Leftrightarrow] \arrow[d, Rightarrow, color=red] & \text{Source Property} \arrow[d, Rightarrow] \\
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Same observations under nonspeculative execution of source program $\Longrightarrow$ Same observations under speculative execution of mitigated program

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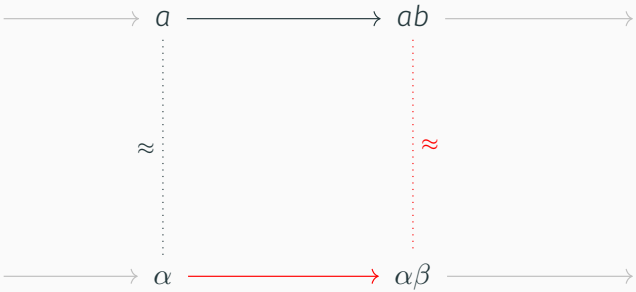
Target Leakage Equivalence

Speculative Noninterference

Leakage equivalence under nonspeculative execution of source program $\Longrightarrow$ Leakage Equivalence under speculative execution of mitigated program

Preservation of Hyperproperties: Constant-Time Simulations [Barthe et al., 2018]



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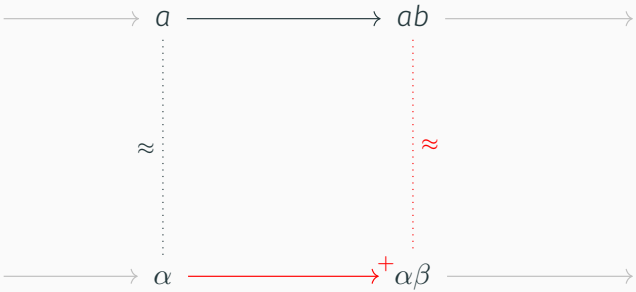

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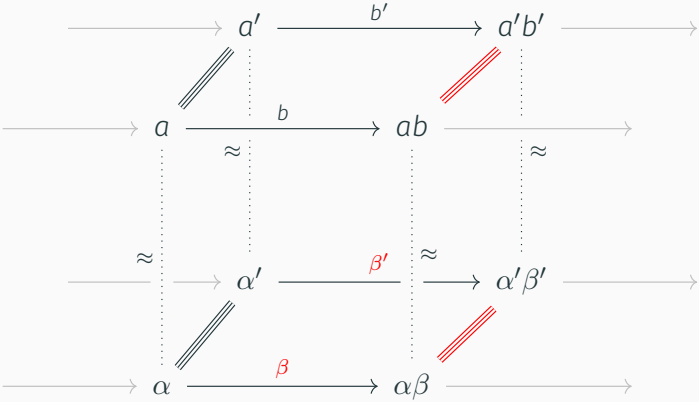

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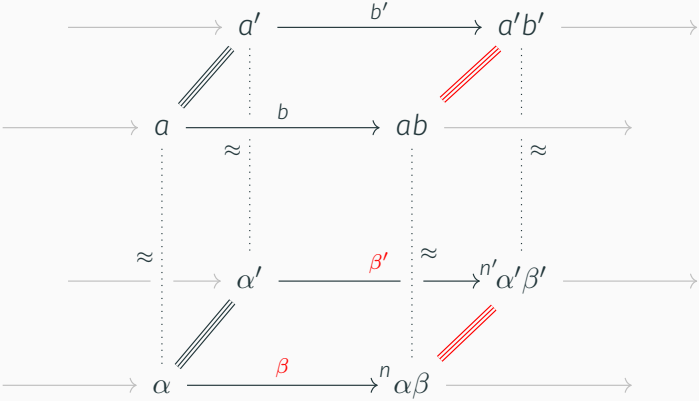

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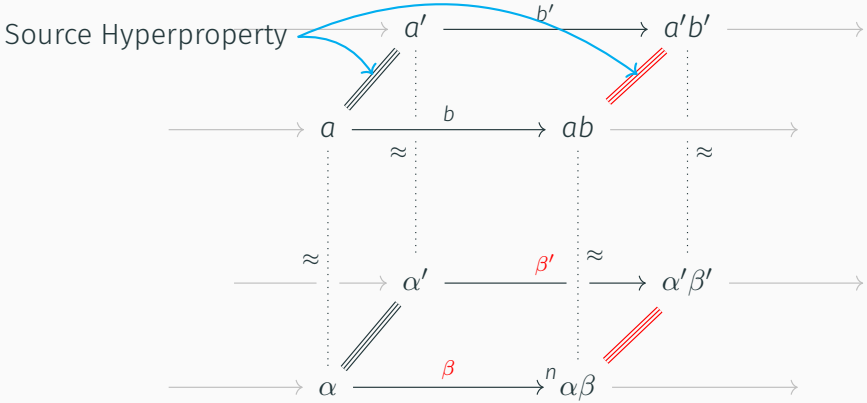

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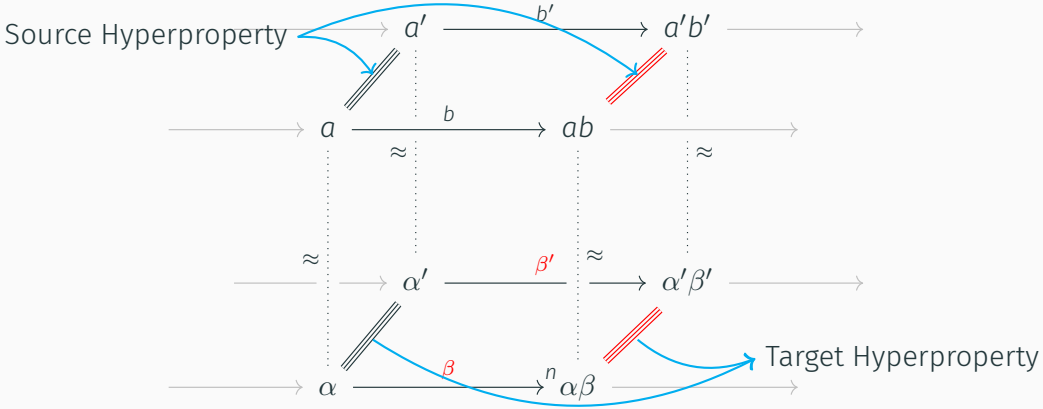
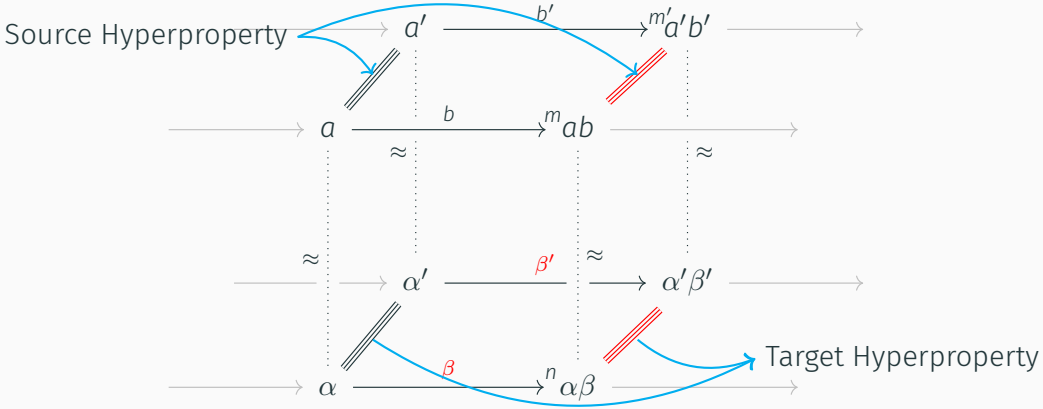


Preservation of Hyperproperties: Hyper-Simulations [Rosemann, 2023]



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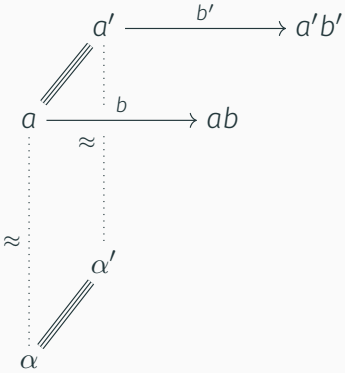

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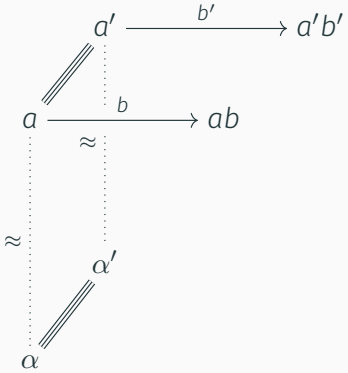

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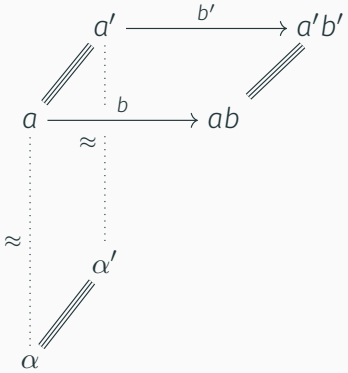

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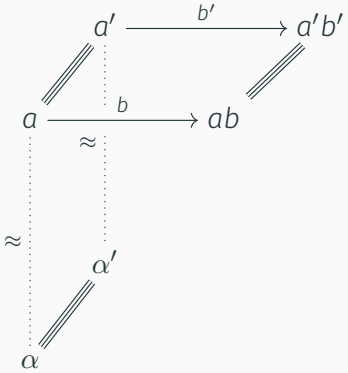

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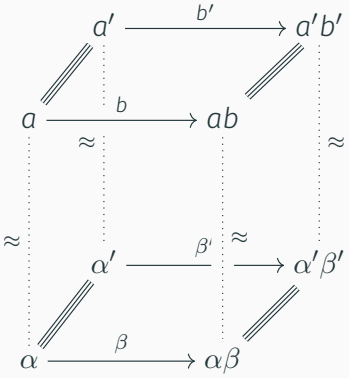

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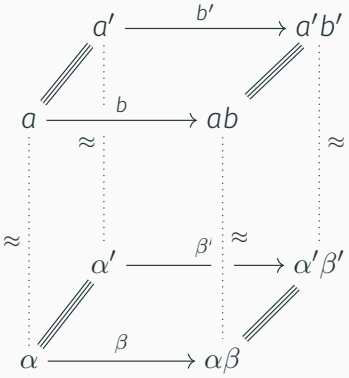

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- Prove that target relation is satisfied after hyper-step
- Conclude that target traces are leakage equivalent

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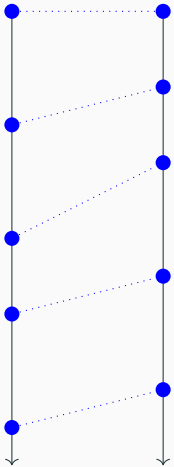
- From hypersimulation: target relation *always holds at some future point*



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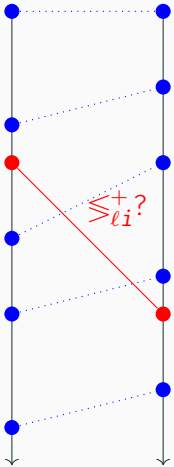

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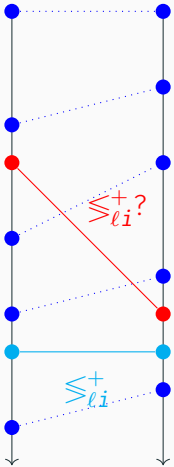

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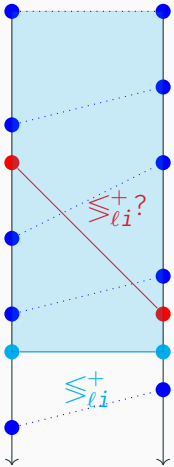

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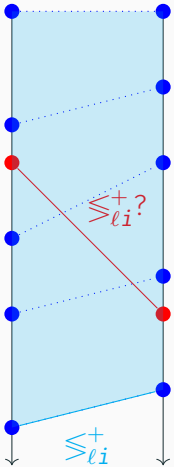
- Target relation implies $\lesssim^{+}_{\ell i}$
  $\implies$ $\lesssim^{+}_{\ell i}$ must hold everywhere



Modelling Speculative Execution: Toy Language

$$
\begin{aligned}
Expr \ni e ::= \; & n && n \in \mathbb{N} \\
\mid \; & x && x \text{ is a variable name} \\
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\begin{aligned}
\mathit{Stmt} \ni s ::= {} & \texttt{skip} && \mid x := e \\
\mid {} & \texttt{fence} && \mid \texttt{if}\ e\ \texttt{then}\ p_1\ \texttt{else}\ p_2\ \texttt{end} \\
\mid {} & \texttt{read}\ [e]\ x && \mid \texttt{while}\ e\ \texttt{do}\ p_1\ \texttt{finally}\ p_2\ \texttt{end} \\
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- Speculation window determines how long to follow mispredicted paths
- Always-Mispredict semantics [Guarnieri et al., 2018] captures all possible combinations of branch predictions

Modelling Speculative Execution: Speculative Semantics

$$\left\langle \bot \mid [x \mapsto -1] \mid [-1 \mapsto 42] \mid \begin{array}{l} \texttt{if}\ x > 0 \\ \texttt{then}\ \texttt{if}\ x < 10 \\ \qquad \texttt{then}\ \texttt{read}\ [x]\ y \\ \qquad \texttt{else}\ \texttt{fence} \\ \qquad \texttt{end} \\ \texttt{else}\ \texttt{skip} \\ \texttt{end} \end{array} \right\rangle$$

Modelling Speculative Execution: Speculative Semantics

$$\frac{\text{no-rollback}(n) \qquad [\![b]\!]_{\mathcal{V}} = 0}{\begin{array}{l}\langle n \mid \mathcal{V} \mid \mathcal{H} \mid \texttt{if}\ b\ \texttt{then}\ p_1\ \texttt{else}\ p_2\ \texttt{end}; p\rangle :: S \\ \rightarrow_{\text{sp}} \langle \text{wndw}(n) \mid \mathcal{V} \mid \mathcal{H} \mid p_1 \mathbin{+\!\!+} p\rangle :: \langle \text{decr}(n) \mid \mathcal{V} \mid \mathcal{H} \mid p_2 \mathbin{+\!\!+} p\rangle :: S\end{array}} \ \textsc{AMIfFalse}$$

$$\left\langle \bot \mid [x \mapsto -1] \mid [-1 \mapsto 42] \mid \begin{array}{l}\texttt{if}\ x > 0 \\ \texttt{then}\ \texttt{if}\ x < 10 \\ \qquad \texttt{then}\ \texttt{read}\ [x]\ y \\ \qquad \texttt{else}\ \texttt{fence} \\ \qquad \texttt{end} \\ \texttt{else}\ \texttt{skip} \\ \texttt{end}\end{array} \right\rangle$$

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```
if x > 0
then if x < 10
     then read [x] y
     else fence
     end
else skip
end
```

$$\left\langle 16 \mid [x \mapsto -1] \mid [-1 \mapsto 42] \mid \begin{array}{l} \texttt{if}\ x < 10 \\ \texttt{then read}\ [x]\ y \\ \texttt{else fence end} \end{array} \right\rangle$$

$$\langle \bot \mid [x \mapsto -1] \mid [-1 \mapsto 42] \mid \texttt{skip}\rangle$$

Modelling Speculative Execution: Speculative Semantics

```
if x > 0
then if x < 10
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     else fence
     end
else skip
end
```

$$\langle 15 \mid [x \mapsto -1] \mid [-1 \mapsto 42] \mid \mathtt{read}\ [x]\ y \rangle$$

$$\langle 15 \mid [x \mapsto -1] \mid [-1 \mapsto 42] \mid \mathtt{fence} \rangle$$

$$\langle \bot \mid [x \mapsto -1] \mid [-1 \mapsto 42] \mid \mathtt{skip} \rangle$$

Modelling Speculative Execution: Speculative Semantics

```
if x > 0
then if x < 10
     then read [x] y
     else fence
     end
else skip
end
```

$$\langle 14 \mid [x \mapsto -1, y \mapsto 42] \mid [-1 \mapsto 42] \mid [] \rangle$$

$$\langle 15 \mid [x \mapsto -1] \mid [-1 \mapsto 42] \mid \texttt{fence} \rangle$$

$$\langle \bot \mid [x \mapsto -1] \mid [-1 \mapsto 42] \mid \texttt{skip} \rangle$$

Modelling Speculative Execution: Speculative Semantics

```
if x > 0
then if x < 10
     then read [x] y
     else fence
     end
else skip
end
```

$$\langle 15 \mid [x \mapsto -1] \mid [-1 \mapsto 42] \mid \texttt{fence} \rangle$$

$$\langle \bot \mid [x \mapsto -1] \mid [-1 \mapsto 42] \mid \texttt{skip} \rangle$$

Modelling Speculative Execution: Speculative Semantics

```
if x > 0
then if x < 10
     then read [x] y
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     end
else skip
end
```

$$\langle 0 \mid [x \mapsto -1] \mid [-1 \mapsto 42] \mid [] \rangle$$

$$\langle \bot \mid [x \mapsto -1] \mid [-1 \mapsto 42] \mid \mathit{skip} \rangle$$

Modelling Speculative Execution: Speculative Semantics

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if x > 0
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Modelling Speculative Execution: Speculative Semantics

```
if x > 0
then if x < 10
     then read [x] y
     else fence
     end
else skip
end
```

$$\langle \bot \mid [x \mapsto -1] \mid [-1 \mapsto 42] \mid [] \rangle$$

Modelling Side-Channel Vulnerabilities: Leakage Models

Leakage models: functions from sequences of states to sequences of observations

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$$\begin{tikzcd}
\langle \mathcal{V} \mid \mathcal{H} \mid \texttt{while}\ldots\rangle \arrow[r] & \langle \mathcal{V} \mid \mathcal{H} \mid \texttt{if}\ldots\rangle \arrow[r] \arrow[d] & \langle \mathcal{V} \mid \mathcal{H} \mid \texttt{read}\ldots\rangle \arrow[r] \arrow[d] & \langle \mathcal{V} \mid \mathcal{H} \mid \texttt{write}\ldots\rangle \arrow[r] \arrow[d] & \cdots \\
 & \text{branch } \top \arrow[r] & \text{read } \mathit{addr} \arrow[r] & \text{write } \mathit{addr} \arrow[r] & \cdots
\end{tikzcd}$$

ℓ_{ct} control flow, memory accesses

Modelling Side-Channel Vulnerabilities: Leakage Models

Leakage models: functions from sequences of states to sequences of observations

$$\begin{tikzcd}
\langle \mathcal{V} \mid \mathcal{H} \mid \texttt{while}\ldots\rangle \arrow[r] \arrow[d] & \langle \mathcal{V} \mid \mathcal{H} \mid \texttt{if}\ldots\rangle \arrow[r] & \langle \mathcal{V} \mid \mathcal{H} \mid \texttt{read}\ldots\rangle \arrow[r] \arrow[d] & \langle \mathcal{V} \mid \mathcal{H} \mid \texttt{write}\ldots\rangle \arrow[r] \arrow[d] & \cdots \\
\text{loop} \arrow[rr] & & \text{read } \mathit{addr} \arrow[r] & \text{write } \mathit{addr} \arrow[r] & \cdots
\end{tikzcd}$$

ℓ_{ct} control flow, memory accesses

ℓ_{lm} loop headers, memory accesses

Modelling Side-Channel Vulnerabilities: Leakage Models

Leakage models: functions from sequences of states to sequences of observations

$$\langle \mathcal{V} \mid \mathcal{H} \mid \texttt{while}\ldots\rangle \to \langle \mathcal{V} \mid \mathcal{H} \mid \texttt{if}\ldots\rangle \to \langle \mathcal{V} \mid \mathcal{H} \mid \texttt{read}\ldots\rangle \to \langle \mathcal{V} \mid \mathcal{H} \mid \texttt{write}\ldots\rangle \to \cdots$$

$$\longrightarrow \qquad \longrightarrow \text{read } \mathit{addr} \longrightarrow \text{write } \mathit{addr} \longrightarrow \cdots$$

ℓ_{ct} control flow, memory accesses

ℓ_{lm} loop headers, memory accesses

ℓ_{mem} only memory accesses

Verifying Intel's Mitigation

Mitigation proposed by Intel [Intel, 2018, 2021]:
Insertion of Fence instructions after every branch

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$$
\begin{aligned}
(\!|\texttt{if}\ b\ \texttt{then}\ p_1\ \texttt{else}\ p_2\ \texttt{end}; p|\!)_{\text{fence}} &= \texttt{if}\ b\ \texttt{then fence}; (\!|p_1|\!)_{\text{fence}} \\
&\quad \texttt{else fence}; (\!|p_2|\!)_{\text{fence}}\ \texttt{end}; (\!|p|\!)_{\text{fence}} \\
(\!|\texttt{while}\ b\ \texttt{do}\ p_1\ \texttt{finally}\ p_2\ \texttt{end}; p|\!)_{\text{fence}} &= \texttt{while}\ b\ \texttt{do fence}; (\!|p_1|\!)_{\text{fence}} \\
&\quad \texttt{finally fence}; (\!|p_2|\!)_{\text{fence}}\ \texttt{end}; (\!|p|\!)_{\text{fence}} \\
(\!|s; p|\!)_{\text{fence}} &= s; (\!|p|\!)_{\text{fence}} \qquad \text{otherwise} \\
(\!|[]|\!)_{\text{fence}} &= []
\end{aligned}
$$

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$(\!|\cdot|\!)_{\mathsf{fence}}$ is proven secure under

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  (*new result*)

Verifying Intel's Mitigation

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- ℓ_{lm} Leakage model including loop headers, but not all control flow
  (*new result*)
- ℓ_{mem} Leakage model without any control flow
  (*new result*)

Issues with Speculative Load Hardening

Speculative Load Hardening [Carruth, 2018]:
Protect memory access with artificial data dependencies

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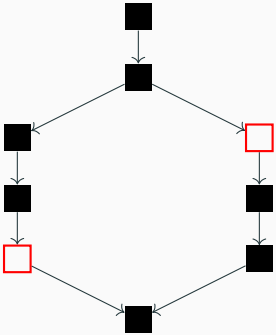
  - data dependency on branch conditions
  - detects speculative execution
- Memory accesses compute address using special register
  - original address during nonspeculative execution
  - known safe address during speculative execution

Issues with Speculative Load Hardening



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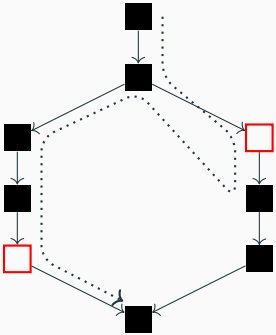
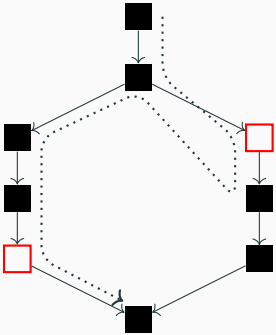
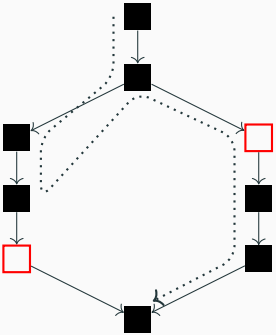


Issues with Speculative Load Hardening





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- Always-Mispredict semantics do not model this
- More accurate semantics *with vendor guarantees* needed

Relaxed Insertion of Fences

$$\texttt{read}\ [1]\ x;\ \texttt{if}\ x \geq 0\ \texttt{then}\ \texttt{read}\ [x]\ y\ \texttt{else}\ \texttt{read}\ [x]\ y\ \texttt{end};\ \texttt{write}\ [1]\ y$$

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Relaxed insertion of fences:

- At every branch, check the sequence of `read` and `write` instructions
- Insert a `fence` instruction if the sequences are different

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Relaxed insertion of fences:

- At every branch, check the sequence of `read` and `write` instructions
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→ Proof-of-concept implementation has some additional restrictions

Relaxed Insertion of Fences

- Mitigated code may not be speculatively safe

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$\Longrightarrow$ reasonable mitigations that were not covered before

Further Work

Patrignani and Guarnieri [2021] support

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- function calls

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Patrignani and Guarnieri [2021] support

- function calls
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Other applications:

- semantics closer to actual hardware
- semantics for different spectre variations [Fabian et al., 2022]
- more precise semantics based on hardware guarantees

Conclusion

Our approach

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- confirms prior work [Patrignani and Guarnieri, 2021]

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Our approach

- confirms prior work [Patrignani and Guarnieri, 2021]
- enables reasoning about more leakage models
  - control flow does not need to be included
- verifies mitigations that could not be verified before
  - such mitigations are reasonable, not contrived examples

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Julian Rosemann. Private communications, not yet released. All relevant proofs are included in the Coq development, 2023.

Nonspeculative Semantics i

$$\frac{}{\langle \mathcal{V} \mid \mathcal{H} \mid \texttt{skip}; p\rangle \to_{\mathsf{ns}} \langle \mathcal{V} \mid \mathcal{H} \mid p\rangle}\ \textsc{Skip}$$

$$\frac{}{\langle \mathcal{V} \mid \mathcal{H} \mid \texttt{fence}; p\rangle \to_{\mathsf{ns}} \langle \mathcal{V} \mid \mathcal{H} \mid p\rangle}\ \textsc{Fence}$$

$$\frac{[\![e]\!]_{\mathcal{V}} = v}{\langle \mathcal{V} \mid \mathcal{H} \mid x := e; p\rangle \to_{\mathsf{ns}} \langle \mathcal{V}[x \mapsto v] \mid \mathcal{H} \mid p\rangle}\ \textsc{Assign}$$

$$\frac{[\![a]\!]_{\mathcal{V}} = a' \qquad \mathcal{H}(a') = v}{\langle \mathcal{V} \mid \mathcal{H} \mid \texttt{read}\,[a]\,x; p\rangle \to_{\mathsf{ns}} \langle \mathcal{V}[x \mapsto v] \mid \mathcal{H} \mid p\rangle}\ \textsc{Read}$$

$$\frac{[\![a]\!]_{\mathcal{V}} = a' \qquad \mathcal{V}(x) = v}{\langle \mathcal{V} \mid \mathcal{H} \mid \texttt{write}\,[a]\,x; p\rangle \to_{\mathsf{ns}} \langle \mathcal{V} \mid \mathcal{H}[a' \mapsto v] \mid p\rangle}\ \textsc{Write}$$

Nonspeculative Semantics ii

$$\frac{[\![b]\!]_{\mathcal{V}} \neq 0}{\langle \mathcal{V} \mid \mathcal{H} \mid \texttt{if}\ b\ \texttt{then}\ p_1\ \texttt{else}\ p_2\ \texttt{end}; p\rangle \to_{\mathrm{ns}} \langle \mathcal{V} \mid \mathcal{H} \mid p_1 +\!\!+ p\rangle}\ \textsc{IfTrue}$$

$$\frac{[\![b]\!]_{\mathcal{V}} = 0}{\langle \mathcal{V} \mid \mathcal{H} \mid \texttt{if}\ b\ \texttt{then}\ p_1\ \texttt{else}\ p_2\ \texttt{end}; p\rangle \to_{\mathrm{ns}} \langle \mathcal{V} \mid \mathcal{H} \mid p_2 +\!\!+ p\rangle}\ \textsc{IfFalse}$$

$$\frac{}{\begin{array}{c}\langle \mathcal{V} \mid \mathcal{H} \mid \texttt{while}\ b\ \texttt{do}\ p_1\ \texttt{finally}\ p_2\ \texttt{end}; p\rangle \\ \to_{\mathrm{ns}} \langle \mathcal{V} \mid \mathcal{H} \mid \texttt{if}\ b\ \texttt{then}\ (p_1 +\!\!+ \texttt{while}\ b\ \texttt{do}\ p_1\ \texttt{finally}\ p_2\ \texttt{end})\ \texttt{else}\ p_2\ \texttt{end}; p\rangle\end{array}}\ \textsc{While}$$

$$\frac{}{\langle \mathcal{V} \mid \mathcal{H} \mid [\,]\rangle \to_{\mathrm{ns}} \langle \mathcal{V} \mid \mathcal{H} \mid [\,]\rangle}\ \textsc{Term}$$

Speculative Semantics i

$$\text{decr}(n) := \begin{cases} \bot & \text{if } n = \bot \\ n - 1 & \text{otherwise} \end{cases} \qquad \text{wndw}(n) := \begin{cases} \omega & \text{if } n = \bot \\ n - 1 & \text{otherwise} \end{cases}$$

$$\text{no-rollback}(n) := n > 0 \vee n = \bot \qquad \text{zero-out}(n) := \begin{cases} \bot & \text{if } n = \bot \\ 0 & \text{otherwise} \end{cases}$$

$$\frac{\text{no-rollback}(n)}{\langle n \mid \mathcal{V} \mid \mathcal{H} \mid \texttt{skip}; p\rangle :: S \rightarrow_{\text{sp}} \langle \text{decr}(n) \mid \mathcal{V} \mid \mathcal{H} \mid p\rangle :: S}\ \text{AMSkip}$$

Speculative Semantics ii

$$\frac{\text{no-rollback}(n)}{\langle n \mid \mathcal{V} \mid \mathcal{H} \mid \texttt{fence}; p\rangle :: S \rightarrow_{\text{sp}} \langle \text{zero-out}(n) \mid \mathcal{V} \mid \mathcal{H} \mid p\rangle :: S} \ \textsc{AMFence}$$

$$\frac{\text{no-rollback}(n) \qquad [\![e]\!]_{\mathcal{V}} = v}{\langle n \mid \mathcal{V} \mid \mathcal{H} \mid x := e; p\rangle :: S \rightarrow_{\text{sp}} \langle \text{decr}(n) \mid \mathcal{V}[x \mapsto v] \mid \mathcal{H} \mid p\rangle :: S} \ \textsc{AMAssign}$$

$$\frac{\text{no-rollback}(n) \qquad [\![a]\!]_{\mathcal{V}} = a' \qquad \mathcal{H}(a') = v}{\langle n \mid \mathcal{V} \mid \mathcal{H} \mid \texttt{read}\ [a]\ x; p\rangle :: S \rightarrow_{\text{sp}} \langle \text{decr}(n) \mid \mathcal{V}[x \mapsto v] \mid \mathcal{H} \mid p\rangle :: S} \ \textsc{AMRead}$$

$$\frac{\text{no-rollback}(n) \qquad [\![a]\!]_{\mathcal{V}} = a' \qquad \mathcal{V}(x) = v}{\langle n \mid \mathcal{V} \mid \mathcal{H} \mid \texttt{write}\ [a]\ x; p\rangle :: S \rightarrow_{\text{sp}} \langle \text{decr}(n) \mid \mathcal{V} \mid \mathcal{H}[a' \mapsto v] \mid p\rangle :: S} \ \textsc{AMWrite}$$

Speculative Semantics iii

$$\frac{\text{no-rollback}(n)}{\begin{array}{c}\langle n \mid \mathcal{V} \mid \mathcal{H} \mid \texttt{while}\ e\ \texttt{do}\ p_1\ \texttt{finally}\ p_2\ \texttt{end};\rangle :: S \\ \rightarrow_{\text{sp}} \langle \text{decr}(n) \mid \mathcal{V} \mid \mathcal{H} \mid \texttt{if}\ e\ \texttt{then}\ (p_1 +\!\!+ [\texttt{while}\ e\ \texttt{do}\ p_1\ \texttt{finally}\ p_2\ \texttt{end}])\ \texttt{else}\ p_2\ \texttt{end}; p\rangle \\ :: S\end{array}}\ \textsc{AMWhile}$$

$$\frac{\text{no-rollback}(n) \qquad [\![b]\!]_{\mathcal{V}} \neq 0}{\begin{array}{c}\langle n \mid \mathcal{V} \mid \mathcal{H} \mid \texttt{if}\ b\ \texttt{then}\ p_1\ \texttt{else}\ p_2\ \texttt{end}; p\rangle :: S \\ \rightarrow_{\text{sp}} \langle \text{wndw}(n) \mid \mathcal{V} \mid \mathcal{H} \mid p_2 +\!\!+ p\rangle :: \langle \text{decr}(n) \mid \mathcal{V} \mid \mathcal{H} \mid p_1 +\!\!+ p\rangle :: S\end{array}}\ \textsc{AMIfTrue}$$

Speculative Semantics iv

$$\frac{\text{no-rollback}(n) \qquad [\![b]\!]_{\mathcal{V}} = 0}{\begin{array}{c}\langle n \mid \mathcal{V} \mid \mathcal{H} \mid \texttt{if}\ b\ \texttt{then}\ p_1\ \texttt{else}\ p_2\ \texttt{end}; p\rangle :: S \\ \rightarrow_{\text{sp}} \langle \text{wndw}(n) \mid \mathcal{V} \mid \mathcal{H} \mid p_1 +\!\!+ p\rangle :: \langle \text{decr}(n) \mid \mathcal{V} \mid \mathcal{H} \mid p_2 +\!\!+ p\rangle :: S\end{array}}\ \textsc{AMIfFalse}$$

$$\frac{}{\langle 0 \mid \mathcal{V} \mid \mathcal{H} \mid p\rangle :: S \rightarrow_{\text{sp}} S}\ \textsc{AMRollback} \qquad \frac{n \neq \bot \wedge n > 0}{\langle n \mid \mathcal{V} \mid \mathcal{H} \mid []\rangle :: S \rightarrow_{\text{sp}} S}\ \textsc{AMRollbackT}$$

$$\frac{}{\langle \bot \mid \mathcal{V} \mid \mathcal{H} \mid []\rangle :: S \rightarrow_{\text{sp}} \langle \bot \mid \mathcal{V} \mid \mathcal{H} \mid []\rangle :: S}\ \textsc{AMTerm} \qquad \frac{}{[] \rightarrow_{\text{sp}} []}\ \textsc{AMTerm'}$$

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Extend the semantics with taint tracking (Safe / Unsafe)

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Speculating? + Secret Data?

Observation Taint

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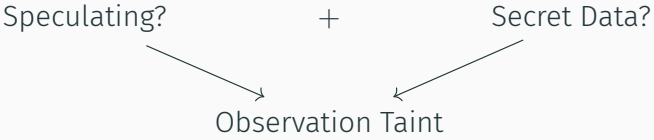

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Speculative safety implies speculative noninterference

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- Our approach does not have these limitations

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