Compositional Secure Compilation against Spectre

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Compositional Secure

Cor

Special thanks to

CISPA
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INFORMATION SECURITY

Contributions & Outline

1. Formal framework for assessing security of Spectre v1 compiler countermeasures

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2. Proofs of security and insecurity of existing Spectre v1 compiler countermeasures

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    - Based on recent secure compilation theory

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   - Preservation of SNI: semantic notion of security

     Guarnieri *et al.* S&P'19

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Speculative Semantics & SNI

$\mathbf{void\ f\ (int\ x)} \mapsto \mathbf{if(x < A.size)\ \{y = B[A[x]]\}}$

run 1: A.size = 16, A[128] = 3

call f 128

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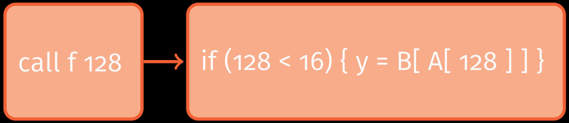

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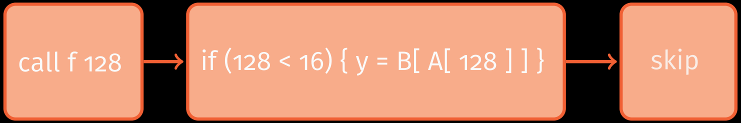

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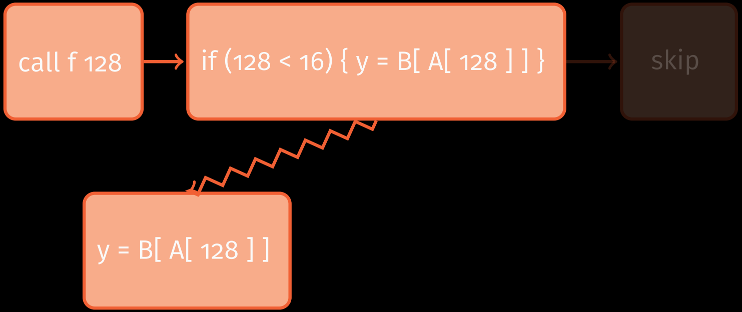

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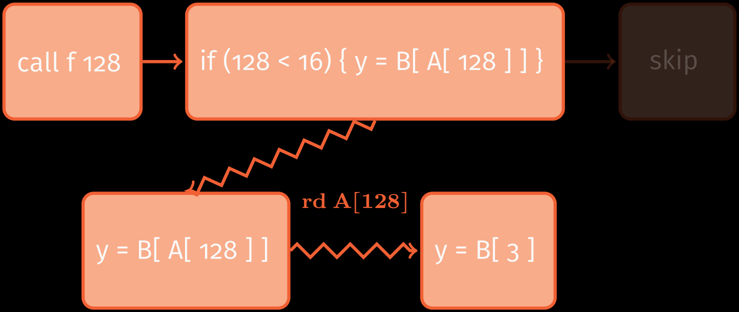

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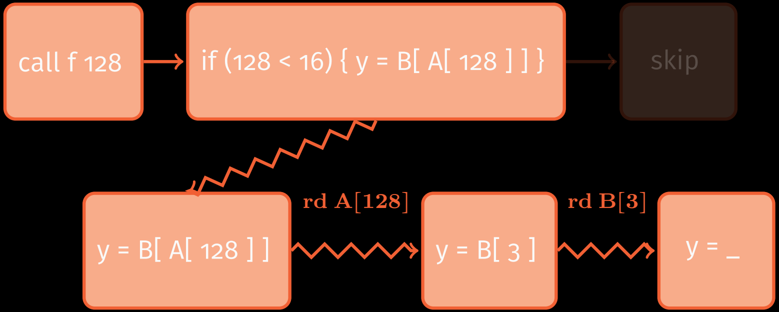

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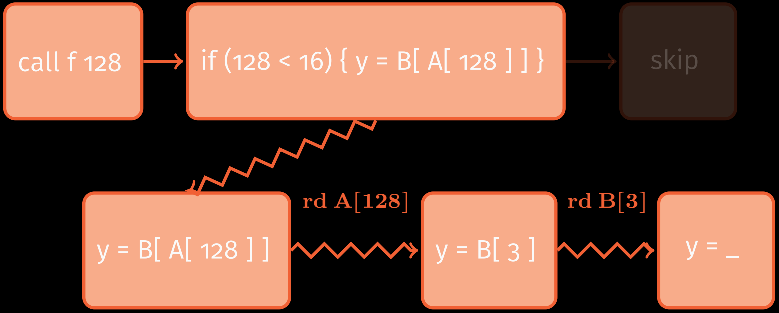

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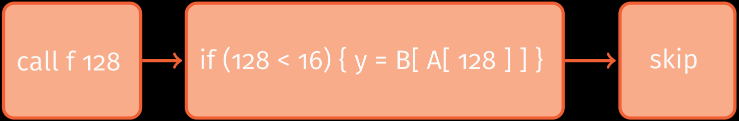

trace 1: $\mathbf{rd\ A[128]}$ $\mathbf{rd\ B[3]}$

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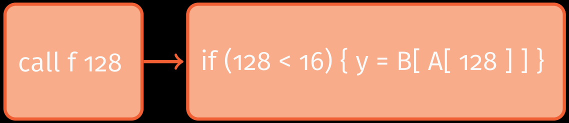
void f (int x) ↦ if(x < A.size) {y = B[A[x]]}

run 1: A.size = 16, A[128] = 3

run 2: A[128] = 7 different H values



call f 128

if (128 < 16) { y = B[A[128]] }

trace 1: **rd A[128]** **rd B[3]**

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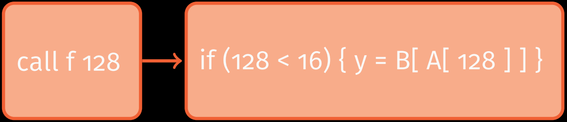

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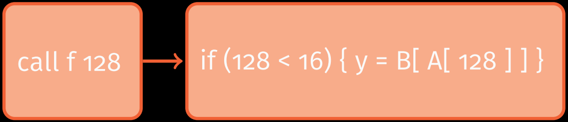

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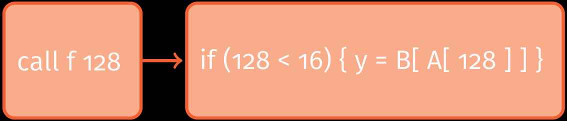

trace 1: $\mathbf{rd\ A[128]}$ $\mathbf{rd\ B[3]}$ different traces

trace 2: $\mathbf{rd\ A[128]}$ $\mathbf{rd\ B[7]}$ $\Rightarrow$ SNI violation

Speculative Semantics & SNI

A program is SNI ($\vdash \mathbf{P} : \mathbf{SNI}$) if, given two runs from low-equivalent states:

- - if the non-speculative traces are low-equivalent
- - then the speculative traces are also low-equivalent

call f

trace 1: $\mathbf{rd}\ \mathbf{A}[128]$ $\mathbf{rd}\ \mathbf{B}[3]$ different traces

trace 2: $\mathbf{rd}\ \mathbf{A}[128]$ $\mathbf{rd}\ \mathbf{B}[7]$ ⇒ SNI violation

Speculative Semantics & SNI

void f (int x) ↦ **if**(**x** < **A**.**size**) {**y** = **B**[**A**[**x**]]}

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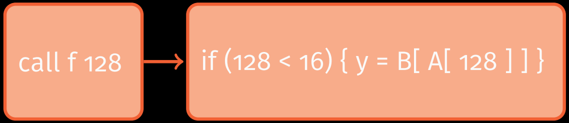

trace 1: **rd A**[**128**] **rd B**[**3**] different traces

trace 2: **rd A**[**128**] **rd B**[**7**] ⇒ SNI violation

Speculative Semantics & SNI

A program attains SNI robustly ($\vdash \mathbf{P} : \mathbf{RSNI}$) if it is $\mathbf{SNI}$ no matter what attacker $\mathbf{A}$ it links against.

$$\forall \mathbf{A}. \vdash \mathbf{A}\left[\mathbf{P}\right] : \mathbf{SNI}$$

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Problems Problems Problems …

Problem: Proving compiler preserves RSNI is hard

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Solution: overapproximate RSNI with a novel property: robust speculative safety (RSS)

Speculative Safety (RSS)

Semantic-Irrelevant Taint Tracking

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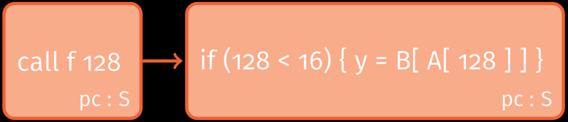
Semantic-Irrelevant Taint Tracking

$\mathbf{void\ f\ (int\ x)} \mapsto \mathbf{if(x < A.size)\ \{y = B[A[x]]\}}$

only 1 run needed: A.size=16, A[128]=3

integrity lattice: $S \subset U \quad S \sqcap U = S \quad U$ does not flow to S



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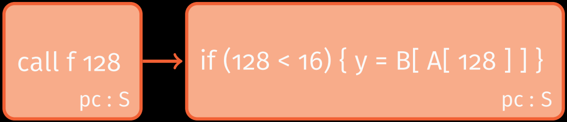

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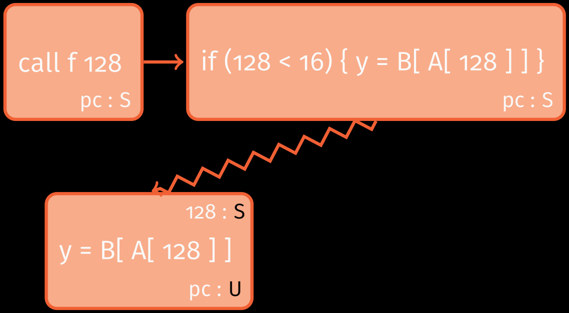

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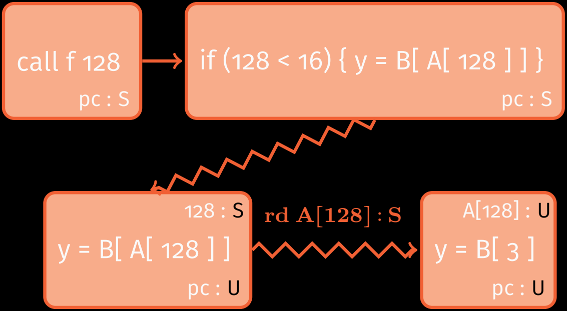

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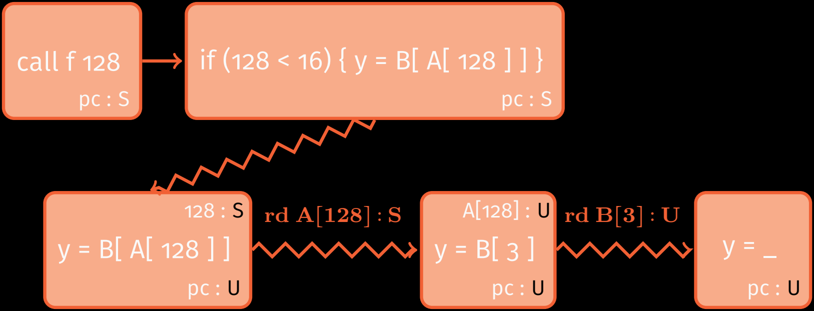

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if (128 < 16) { y = B[A[128]] } pc : S

128 : S y = B[A[128]] pc : U

rd A[128] : S

A[128] : U y = B[3] pc : U

rd B[3] : U

y = _ pc : U

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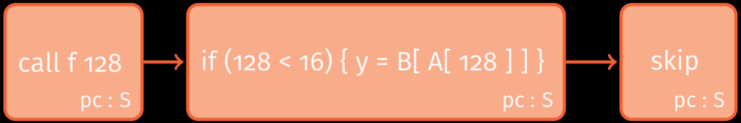

$\mathbf{rd\ A[128] : S}$ $\mathbf{rd\ B[3] : U}$

Speculative Safety (RSS)

Sema

A program is SS ($\vdash \mathbf{P} : \mathbf{SS}$) if its traces do not contain $\mathbf{U}$ actions

A program is SS robustly ($\vdash \mathbf{P} : \mathbf{RSS}$) if it is $\mathbf{SS}$ no matter what attacker $\mathbf{A}$ it links against.

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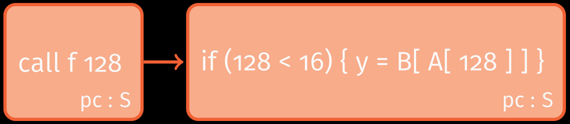

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Robustness & Preserving NI-like Props

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Robustness pros and cons:

- ✓ realistic, (not) lossy, precise attacker + actions awareness
- ✗ coqability, precision, sometimes inefficient

RSS and RSNI

RSS overapproximates RSNI, so:

- in the $\mathbf{target}$: $\forall \mathbf{P}. \vdash \mathbf{P} : \mathbf{RSS} \Rightarrow \vdash \mathbf{P} : \mathbf{RSNI}$

RSS and RSNI

RSS overapproximates RSNI, so:

- in the $\mathbf{target}$: $\forall \mathbf{P}. \vdash \mathbf{P} : \mathbf{RSS} \Rightarrow \vdash \mathbf{P} : \mathbf{RSNI}$
- in the source: $\forall \mathsf{P}. \vdash \mathsf{P} : \mathsf{RSS} \Longleftrightarrow \vdash \mathsf{P} : \mathsf{RSNI}$ (recall, no speculative execution in source)

RSS-Preserving Compiler: RSSC & RSSP

$$\llbracket\cdot\rrbracket : \mathsf{RSSP} \overset{\text{def}}{=} \text{ if } \forall \mathsf{A}.\ \vdash \mathsf{A}\left[\mathsf{P}\right] : \mathsf{RSS} \text{ and } \mathsf{RSS} \sim \mathbf{RSS}$$

$$\text{then } \forall \mathbf{A}.\ \vdash \mathbf{A}\left[\llbracket\mathsf{P}\rrbracket\right] : \mathbf{RSS}$$

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$\approx =$ same traces, plus $\mathbf{S}$ actions in $\mathbf{m}$

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- $\forall A$: explicit attacker model (robustness)
- Proof: RSSC & RSSP are equivalent

  RSSC : clear security guarantees

  RSSP : simpler proofs

RSS-Preserving Compiler: RSSC **&** RSSP

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Danger

of: RSSC & RSSP are equivalent

RSSC : clear security guarantees

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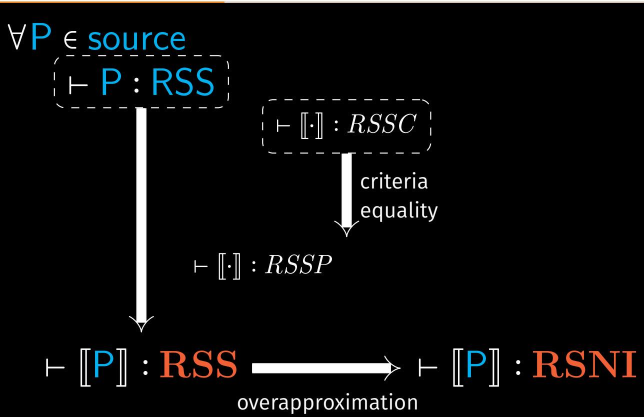
Secure Compilation Framework for Spectre

$$\begin{tikzcd}
\forall P \in \text{source} & & \\
\boxed{\vdash P : \mathrm{RSS}} \arrow[dd] & \boxed{\vdash [\![\cdot]\!] : RSSC} \arrow[d, "\text{criteria equality}"] & \\
& \vdash [\![\cdot]\!] : RSSP & \\
\vdash [\![P]\!] : \mathbf{RSS} \arrow[rr, "\text{overapproximation}"'] & & \vdash [\![P]\!] : \mathbf{RSNI}
\end{tikzcd}$$

Secure Compilation Framework for Spectre



$\forall P \in$ source

$\vdash P : \mathsf{RSS}$

$\vdash [\![\cdot]\!] : RSSC$

criteria equality

$\vdash [\![\cdot]\!] : RSSP$

$\vdash [\![P]\!] : \mathbf{RSS} \longrightarrow \vdash [\![P]\!] : \mathbf{RSNI}$

overapproximation

- all source programs are trivially RSS

Secure Compilation Framework for Spectre

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 & \, & \\
 & \vdash [\![\cdot]\!] : \mathit{RSSP} & \\
\vdash [\![\mathsf{P}]\!] : \mathbf{RSS} \arrow[rr, "\text{overapproximation}"'] & & \vdash [\![\mathsf{P}]\!] : \mathbf{RSNI}
\end{tikzcd}$$

- all source programs are trivially RSS
- to show security: simply prove RSSC

Preservation or Enforcement?

Is it still preservation if the property is trivial in source?

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Enforcement cannot work for classes (more on this later)

Security Spectrum

- 2 notions of RSS and RSNI (thus 2 $\mathbf{target}$s):
    - strong(+): no speculative leaks

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```
void get (int y)
  if (y < size) then
    temp = B[A[y]*512]
```

Violates + and -

```
void get (int y)
  x = A[y];
  if (y < size) then
    temp = B[x];
```

Violates +, Satisfies -

RSSC **for** `lfence`

$\mathsf{void\ f(int\ x)} \mapsto \mathsf{if}(\mathsf{x} < \mathsf{A.size})\{\mathsf{y} = \mathsf{B}[\mathsf{A}[\mathsf{x}]]\}$ // A.size=16, A[128]=3

$[\![\cdot]\!] = \mathbf{void\ f(int\ x)} \mapsto \mathbf{if(x < A.size)\{lfence; y = B[A[x]]\}}$

call f 128

pc : S

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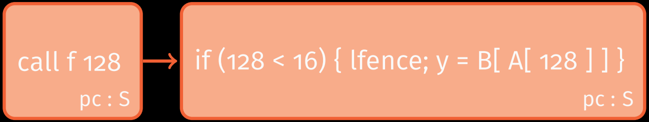

call f 128

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if (128 < 16) { lfence; y = B[A[128]] }

pc : S

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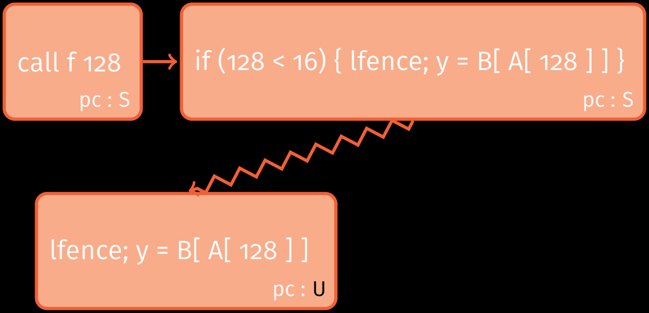

call f 128

pc : S

if (128 < 16) { lfence; y = B[A[128]] }

pc : S

lfence; y = B[A[128]]

pc : U

RSSC **for** `lfence`

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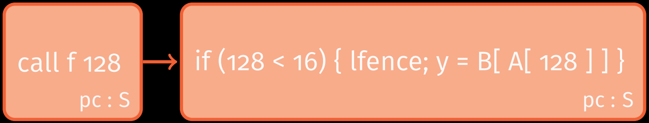

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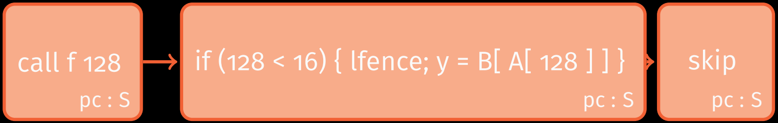

RSSC **for** SLH

$\mathsf{void\ f(int\ x)} \mapsto \mathsf{if(x < A.size)\{y = B[A[x]]\}}$ // A.size=16, A[128]=3

$[\![\cdot]\!] = \mathbf{void\ f(int\ x) \mapsto if(x < A.size)\{y = B[mask(A[x])]\}}$

call f 128

pc : S

RSSC for SLH

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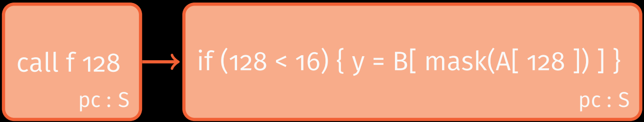

RSSC **for** SLH

void f(int x) $\mapsto$ if(x < A.size){y = B[A[x]]}   // A.size=16, A[128]=3

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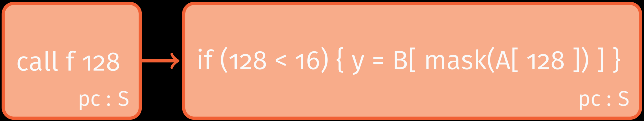

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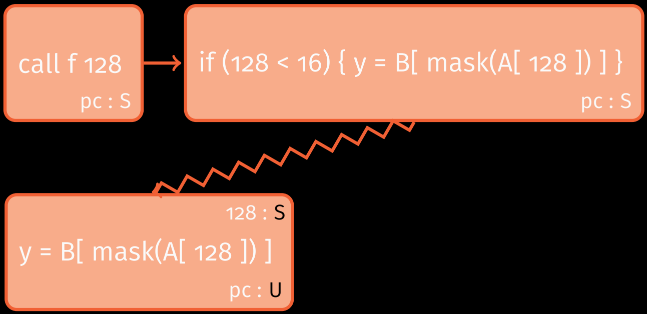

call f 128

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pc : S

128 : S

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pc : U

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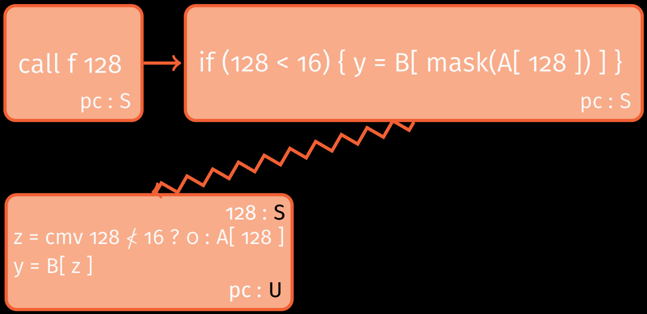

call f 128

pc : S

if (128 < 16) { y = B[mask(A[128])] }

pc : S

128 : S

z = cmv 128 $\not<$ 16 ? 0 : A[128]

y = B[z]

pc : U

RSSC for SLH

void f(int x) ↦ if(x < A.size){y = B[A[x]]}   // A.size=16, A[128]=3

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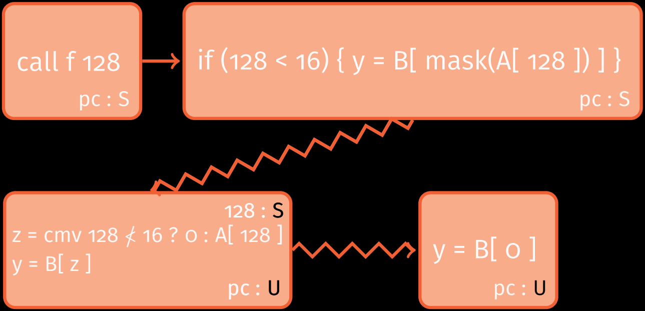
call f 128
pc : S
if (128 < 16) { y = B[mask(A[128])] }
pc : S
128 : S
z = cmv 128 ≮ 16 ? 0 : A[128]
y = B[z]
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y = B[0]
pc : U

RSSC for SLH

void f(int x) ↦ if(x < A.size){y = B[A[x]]}   // A.size=16, A[128]=3

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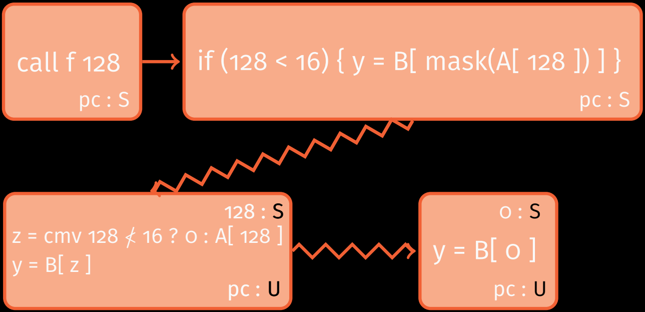

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pc : S

128 : S
z = cmv 128 $\nless$ 16 ? 0 : A[128]
y = B[z]
pc : U

0 : S
y = B[0]
pc : U

RSSC for SLH

void f(int x) ↦ if(x < A.size){y = B[A[x]]}   // A.size=16, A[128]=3

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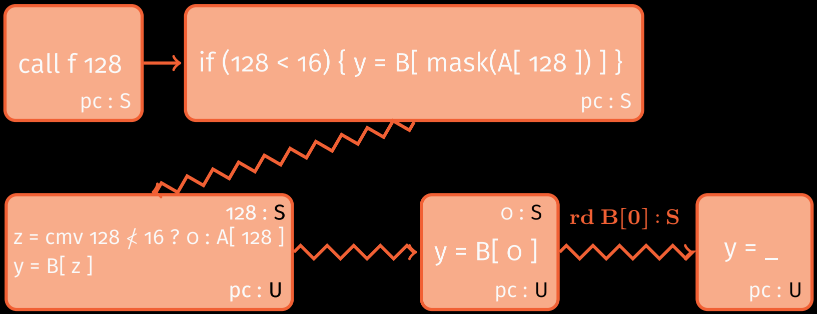


RSSC for SLH

SLH preserves RSS- (and thus RSNI-) but not RSS+ (and thus not RSNI+)

Framework benefits: fine-grained analysis of countermeasures security

vo …28]=3

$[\![\cdot]\!]$ =

call f

pc : S

pc : S

pc : S

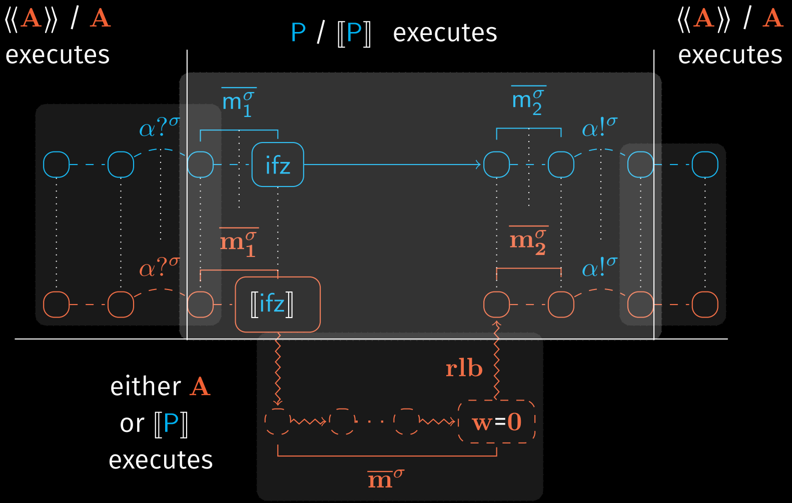
$\mathbf{rd\ B[0] : S}$

Insecurity Results

- MSVC is Insecure
- Non-interprocedural SLH is insecure

Both omit speculation barriers

Proofs Insight


$\langle\!\langle \mathbf{A} \rangle\!\rangle$ / $\mathbf{A}$ executes
P / ⟦P⟧ executes
$\langle\!\langle \mathbf{A} \rangle\!\rangle$ / $\mathbf{A}$ executes
$\overline{m_1^\sigma}$
$\overline{m_2^\sigma}$
$\alpha?^\sigma$
$\alpha!^\sigma$
ifz
$\overline{\mathbf{m}_1^\sigma}$
$\overline{\mathbf{m}_2^\sigma}$
$\alpha?^\sigma$
$\alpha!^\sigma$
⟦ifz⟧
rlb
either $\mathbf{A}$ or ⟦P⟧ executes
w=0
$\overline{\mathbf{m}^\sigma}$

Beyond V1 Protection

- $RSSP$ with V1 trace model = $RSSP_1$

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Beyond V1 Protection

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Beyond V1 Protection

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- take $[\![\cdot]\!]^{\mathbf{T}}_{\mathbf{T}}$ that produces V4-secure code

- if $\vdash [\![\cdot]\!]^{\mathsf{S}}_{\mathbf{T}} : RSSP_1$
- and $\vdash [\![\cdot]\!]^{\mathbf{T}}_{\mathbf{T}} : RSSP_4$
- what do we know about $\vdash \left[\!\!\left[[\![\cdot]\!]^{\mathsf{S}}_{\mathbf{T}} \right]\!\!\right]^{\mathbf{T}}_{\mathbf{T}} :?$

Composition Results

- “Unknown” (but expected(?)):

$$
\begin{aligned}
\text{if} \quad & \vdash [\![\cdot]\!]^{\mathsf{S}}_{\mathsf{I}} : X && (RSSP_1) \\
\text{and} \quad & \vdash [\![\cdot]\!]^{\mathsf{I}}_{\mathbf{T}} : Y && (RSSP_4) \\
\text{then} \quad & \vdash \left[\!\!\left[[\![\cdot]\!]^{\mathsf{S}}_{\mathsf{I}} \right]\!\!\right]^{\mathsf{I}}_{\mathbf{T}} : X \cap Y &&
\end{aligned}
$$

Composition Results

- “Unknown” (but expected(?)):

$$\begin{aligned} \text{if} \quad & \vdash [\![\cdot]\!]^{\mathsf{S}}_{\mathsf{I}} : X && (RSSP_1) \\ \text{and} \quad & \vdash [\![\cdot]\!]^{\mathsf{I}}_{\mathbf{T}} : Y && (RSSP_4) \\ \text{then} \quad & \vdash \left[\!\!\left[[\![\cdot]\!]^{\mathsf{S}}_{\mathsf{I}} \right]\!\!\right]^{\mathsf{I}}_{\mathbf{T}} : X \cap Y \end{aligned}$$

- problem:

$$RSSP_1 \cap RSSP_4 \neq RSSP_1 \cup RSSP_4$$

Proposed Solution (wip)

Instrumentations:

- preserve some [class of] (hyper)property $\mathbf{X}$
- enforce a specific (hyper)property $\mathbf{Y}$

$$\vdash [\![\cdot]\!] \succ_{\mathbf{X}} \mathbf{Y}$$

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Proposed Solution (wip)

Instrumentations:

- preserve some [class of] (hyper)property $\mathbf{X}$
- enforce a specific (hyper)property $\mathbf{Y}$

cannot enforce classes

$$\vdash [\![\cdot]\!] \succ_{\mathbf{X}} \mathbf{Y}$$

Instrumentations for Spectre (wip)

if $\vdash \llbracket \cdot \rrbracket^{S}_{I} : RSSP_1$

and $\vdash \llbracket \cdot \rrbracket^{I}_{\mathbf{T}} \succ_{RSSP_1} RSSP_4$

then $\vdash \left\llbracket \llbracket \cdot \rrbracket^{S}_{I} \right\rrbracket^{I}_{\mathbf{T}} : RSSP_1 \cup RSSP_4$

More Generally (wip)

- some optimisation passes may not preserve some property X (specific, not class)

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- we need later passes to enforce X
- interesting (unknown(?)) metatheory, very interesting application

Questions?