Exorcising Spectres with Secure Compilers

(wip)

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Talk Outline

Slides courtesy of M.G.

Foundations of Secure Compilation

Exorcism via RSC

Spectre v1

Slides courtesy of M.G.

Speculative execution + branch prediction

Size of array **A**

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if (x < A_size)
    y = B[A[x]]
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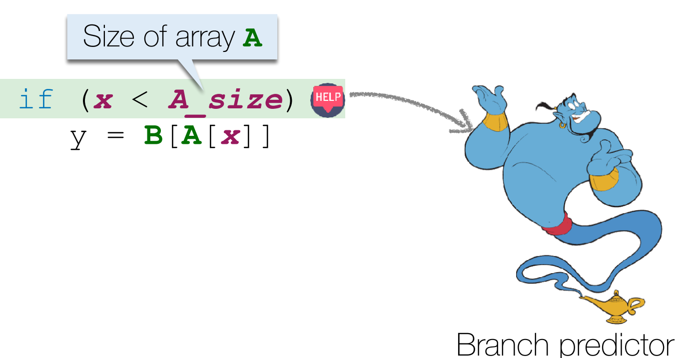

Speculative execution + branch prediction

Prediction based on ***branch history*** & ***program structure***

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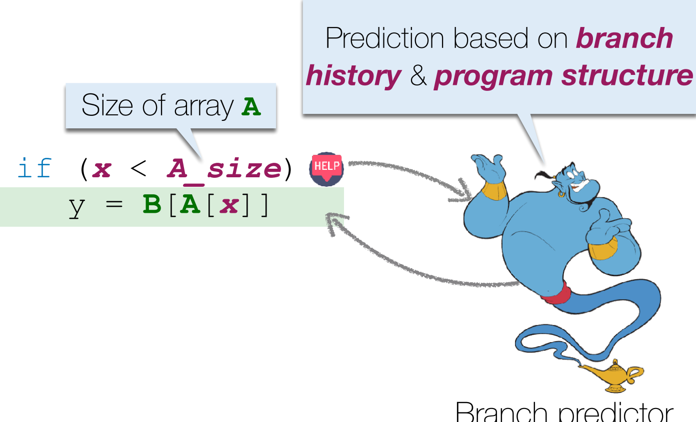
HELP

Branch predictor

Speculative execution + branch prediction



Speculative execution + branch prediction

Prediction based on ***branch history*** & ***program structure***

Size of array **A**

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Wrong predicton? ***Rollback changes***!

- ✔ Architectural (ISA) state
- ✖ Microarchitectural state

Branch predictor

Spectre V1

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void f(int x)
  if (x < A_size)
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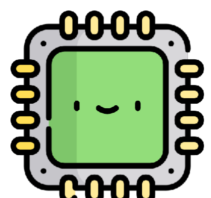

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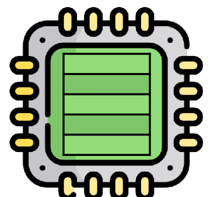

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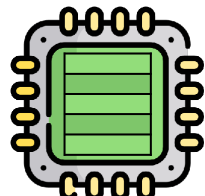

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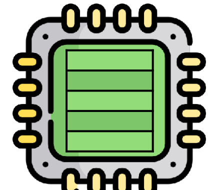

Spectre V1

A_size=16

B B[0] B[1] ...

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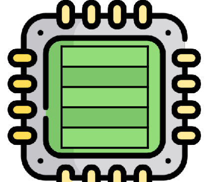

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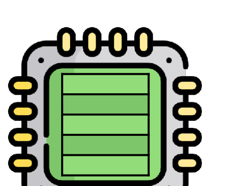

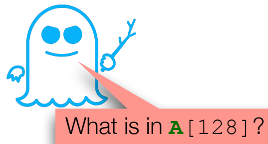

What is in A[128]?

Spectre V1

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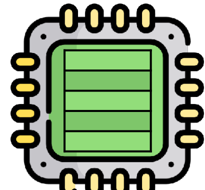

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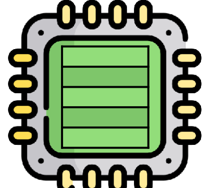

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What is in A[128]?

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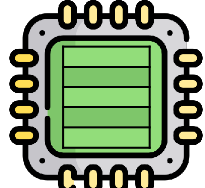

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What is in A[128]?

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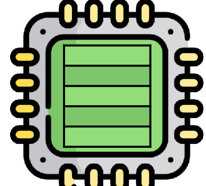

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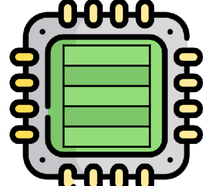

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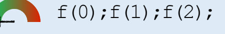

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Spectre V1

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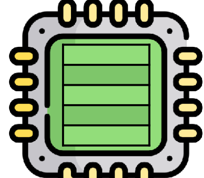

What is in A[128]?

1) Training f(0);f(1);f(2); …

2) Prepare cache

Spectre V1

`A_size`=16

B: B[0] B[1] ...

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What is in `A[128]`?

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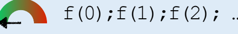

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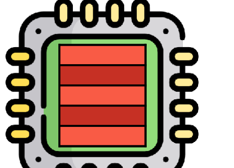

Spectre V1

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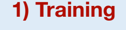

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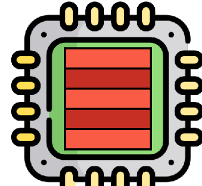

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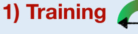

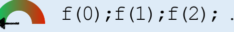

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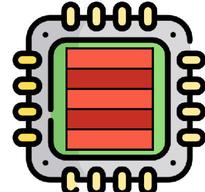

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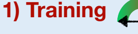
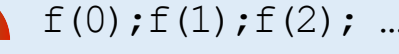

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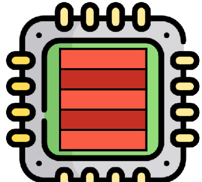

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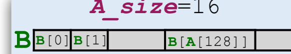


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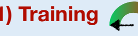

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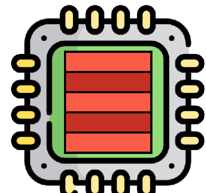

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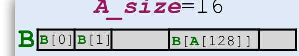


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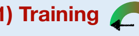
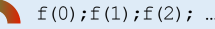
1) Training  

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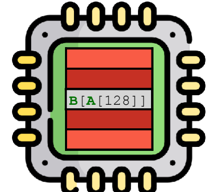

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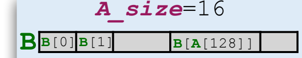
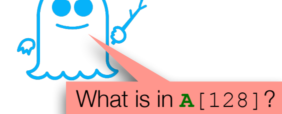
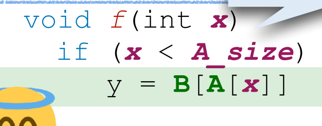
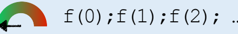






1) Training 

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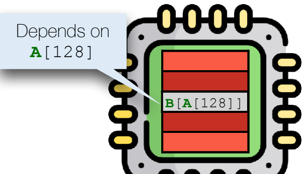

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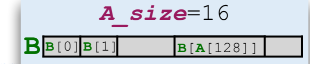

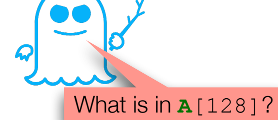

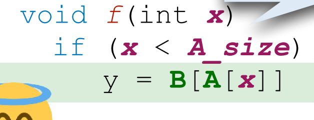

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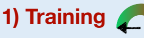
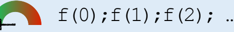
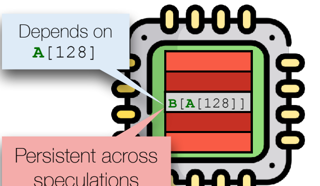
1) Training   `f(0);f(1);f(2); …`

2) Prepare cache

3) Run with `x = 128`



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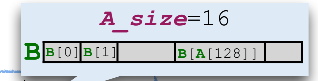

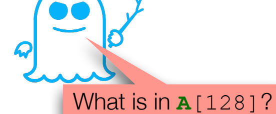

What is in A[128]?

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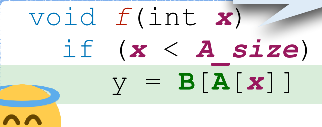
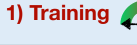


Depends on A[128]

B[A[128]]

Persistent across speculations

1) Training  f(0);f(1);f(2); …

2) Prepare cache

3) Run with x = 128

4) Extract from cache

Compiler-level countermeasures

Compiler-level countermeasures

For ***Spectre V1***

Injecting speculation barriers

```
if (x < A_size)
    y = B[A[x]]
```

```
if (x < A_size)
   lfence
   y = B[A[x]]
```

- In x86, ***LFENCE*** act as ***speculation barrier***
- Compiler injects LFENCE after each branch instruction
    - Microsoft Visual C++
    - Intel ICC
- Effectively ***stop speculative execution***!

Speculative load-hardening (SLH)

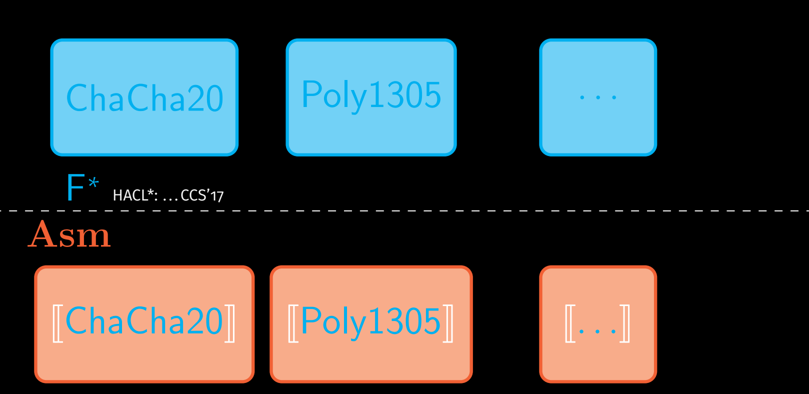
```
if (x < A_size)
    y = B[A[x]]
```

```
if (x < A_size)
    y = B[mask(A[x])]
```

- Injects ***data dependencies*** and ***masking operations***
    - Combines ***conditional moves*** and ***binary operations***
- Stops ***speculative leaks***
- Does not block speculative execution!
- Implemented in Clang

Foundations of Secure Compilation

Secure Compilation Goals



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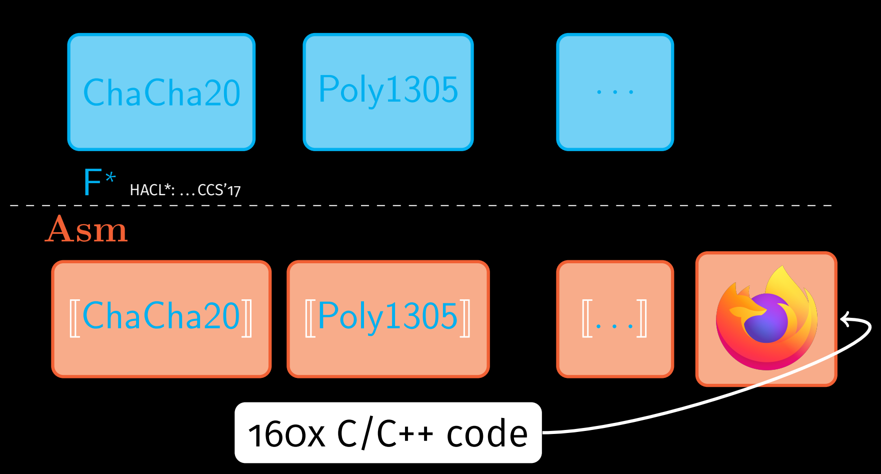

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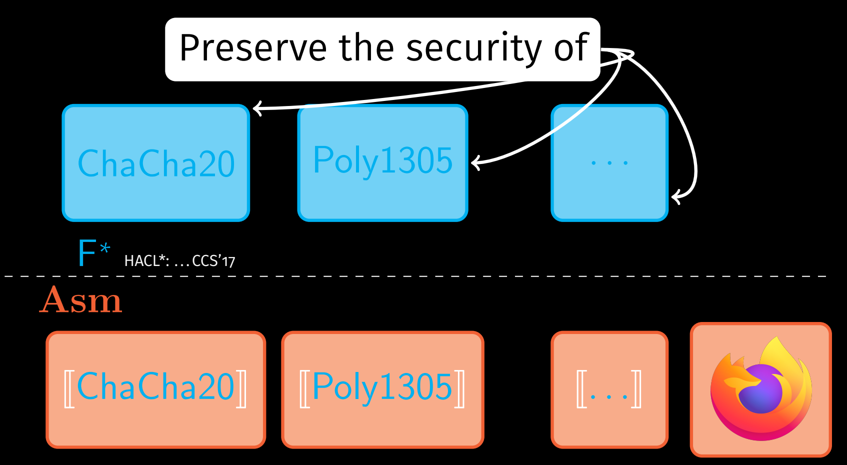

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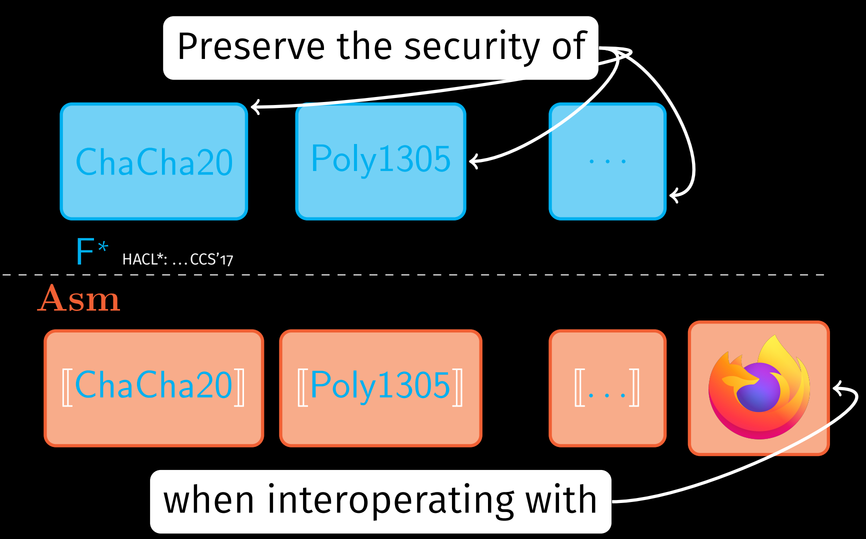

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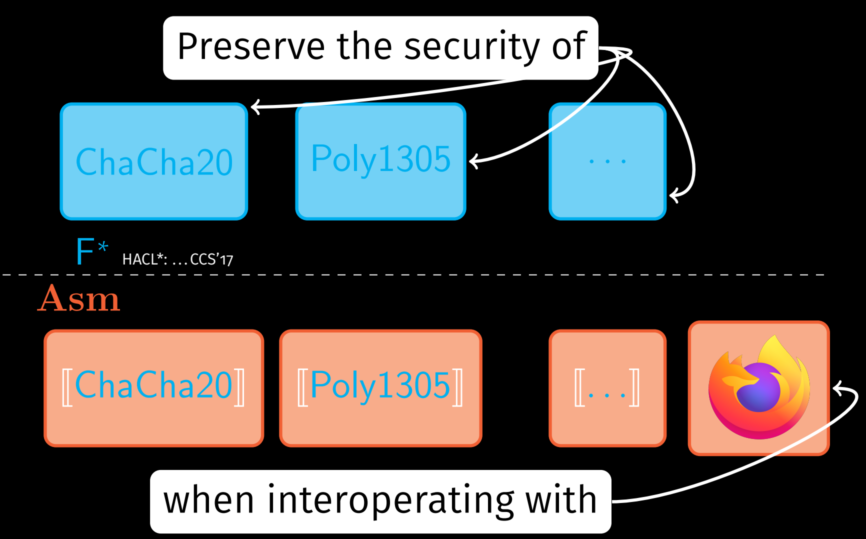

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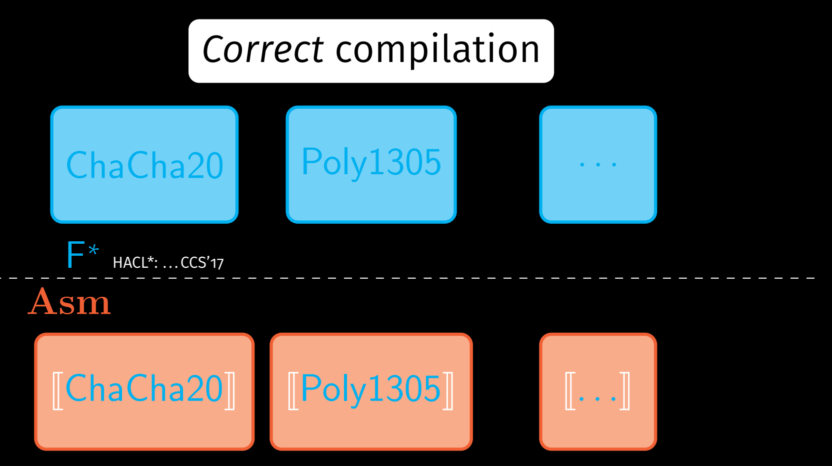

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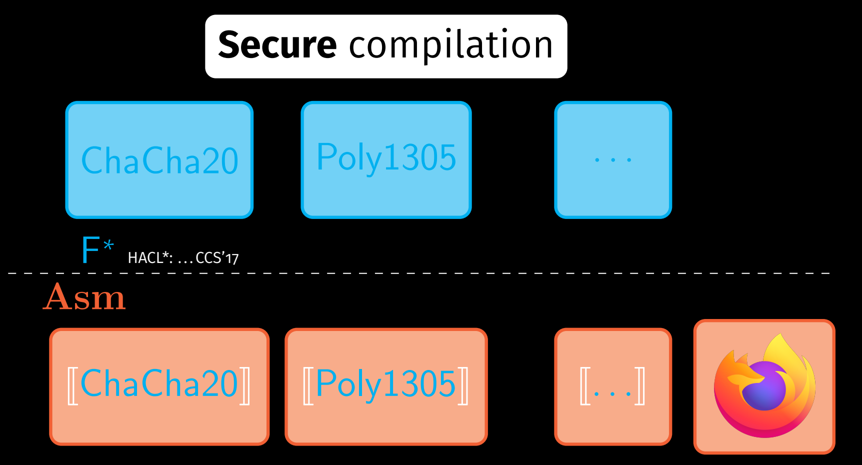
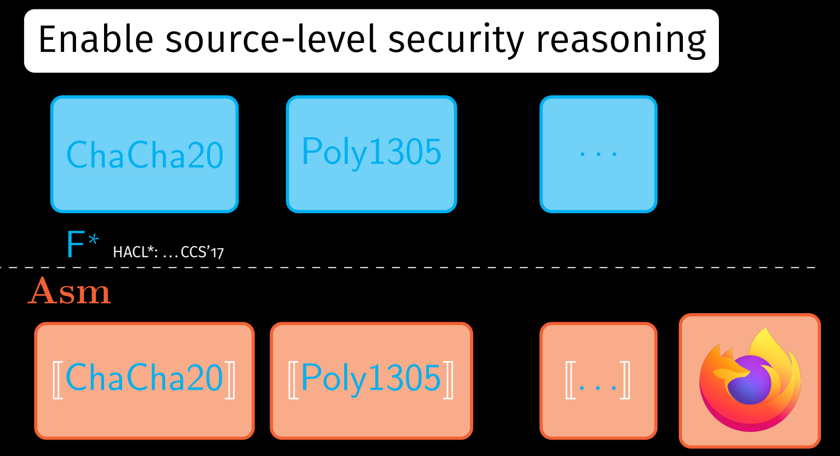
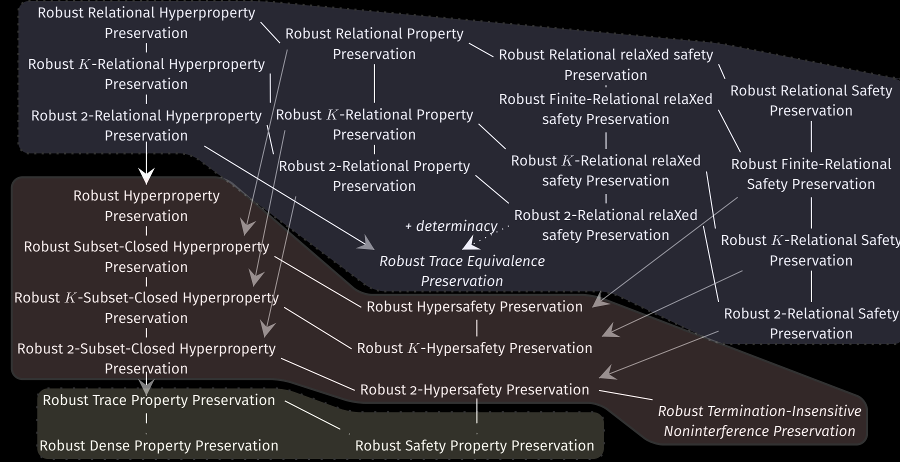


Secure Compilation Goals



Robust Compilation Criteria "Journey Beyond Full Abstraction …" CSF'19



Robust Compilation Criteria "Journey Beyond Full Abstraction ..." CSF'19

Relational Hyperproperties

Robust Relational Hyperproperty Preservation

Robust K-Relational Hyperproperty Preservation

Robust 2-Relational Hyperproperty Preservation

Robust Relational Property Preservation

Robust K-Relational Property Preservation

Robust 2-Relational Property Preservation

Robust Relational relaXed safety Preservation

Robust Finite-Relational relaXed safety Preservation

Robust K-Relational relaXed safety Preservation

Robust 2-Relational relaXed safety Preservation

Robust Relational Safety Preservation

Robust Finite-Relational Safety Preservation

Robust K-Relational Safety Preservation

Robust 2-Relational Safety Preservation

+ *determinacy*

Robust Trace Equivalence Preservation

Hyperproperties

Robust Hyperproperty Preservation

Robust Subset-Closed Hyperproperty Preservation

Robust K-Subset-Closed Hyperproperty Preservation

Robust 2-Subset-Closed Hyperproperty Preservation

Robust Hypersafety Preservation

Robust K-Hypersafety Preservation

Robust 2-Hypersafety Preservation

Robust Termination-Insensitive Noninterference Preservation

Trace Properties

Robust Trace Property Preservation

Robust Dense Property Preservation

Robust Safety Property Preservation

Exorcism via RSC

Goal

1. formalise `lfence` & `SLH` compilers

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4. adapt RSC to preserve SS: RSSC

Goal

1. formalise `lfence` & `SLH` compilers
2. $\mathbf{T}$ must capture speculative execution ($\rightsquigarrow$)
3. need a safety property capturing vulnerability to Spectre v1: SS
4. adapt RSC to preserve SS: RSSC
5. prove the compilers attain RSSC

Goal Up Next

2. $\mathbf{T}$ must capture speculative execution ($\rightsquigarrow$)
3. need a safety property capturing vulnerability to Spectre v1: SS
4. adapt RSC to preserve SS: RSSC

Speculative Semantics 101 "Spectector …" S&P'20

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

call f 128

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y = B[A[128]] —rdA[128]→ y = B[3] —rdB[3]→ y = _

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$\mathbf{rdA[128]}$ $\mathbf{rdB[3]}$

Speculative Safety (SS): Taint Tracking

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

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

call f 128
pc : S

Speculative Safety (SS): Taint Tracking

```
void f (int x) ↦ if (x < A.size) { y = B[ A[ x ] ] }        // A.size=16, A[128]=3
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$\mathbf{rdA[128] : S}$

A[128] : U
y = B[3]
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→

skip
pc : S

$\mathbf{rdA[128] : S}$ $\mathbf{rdB[3] : U}$

SS-Preserving Compiler: RSSC & RSSP

$$[\![\cdot]\!] : \mathsf{RSSP} \stackrel{\text{def}}{=} \text{ if } \forall \mathsf{A}.\mathsf{A}\left[\mathsf{P}\right] : SS \text{ then } \forall \mathbf{A}.\mathbf{A}\left[[\![\mathsf{P}]\!]\right] : SS$$

SS-Preserving Compiler: RSSC & RSSP

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$$[\![\cdot]\!] : \text{RSSC} \overset{\text{def}}{=} \text{ if } \forall \mathbf{A}. \mathbf{A}[[\![P]\!]] \rightsquigarrow \mathbf{t} \text{ then } \exists A. A[P] \rightsquigarrow t \approx \mathbf{t}$$

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

SS-Preserving Compiler: RSSC & RSSP

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$\mathcal{SS}$-Preserving Compiler: RSSC & RSSP

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- RSSC & RSSP are equivalent
- `lfence` : RSSC because it has no speculation ($\mathbf{pc}$: $\mathbf{S}$ always)
- `SLH` : RSSC because masking taints as $\mathbf{S}$

RSSC for `lfence`

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

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

call f 128

pc : S

RSSC for `lfence`

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call f 128
pc : S

→

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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call f 128
pc : S

→

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

→

skip
pc : S

RSSC for SLH

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

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

call f 128

pc : S

RSSC for SLH

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call f 128
pc : S

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

128 : S
y = B[mask(A[128])]
pc : U

RSSC **for** SLH

$\texttt{void f(int x)} \mapsto \texttt{if(x < A.size)\{y = B[A[x]]\}}$ // 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 $\nless$ 16 ? 0 : A[128]
y = B[z]
pc : U

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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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

y = B[0]
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RSSC **for** SLH

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

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

rd B[0] : S

y = _
pc : U

RSSC **for** SLH

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

call f 128 → if (128 < 16) { y = B[mask(A[128])] } → skip

pc : S | pc : S | pc : S

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

Questions?