Foundations and Applications of Secure Compilation (includes wip)

Marco Patrignani[1,2]

20th March 2020

1 Stanford University 2 CISPA Helmholtz Center for Information Security

Talk Outline

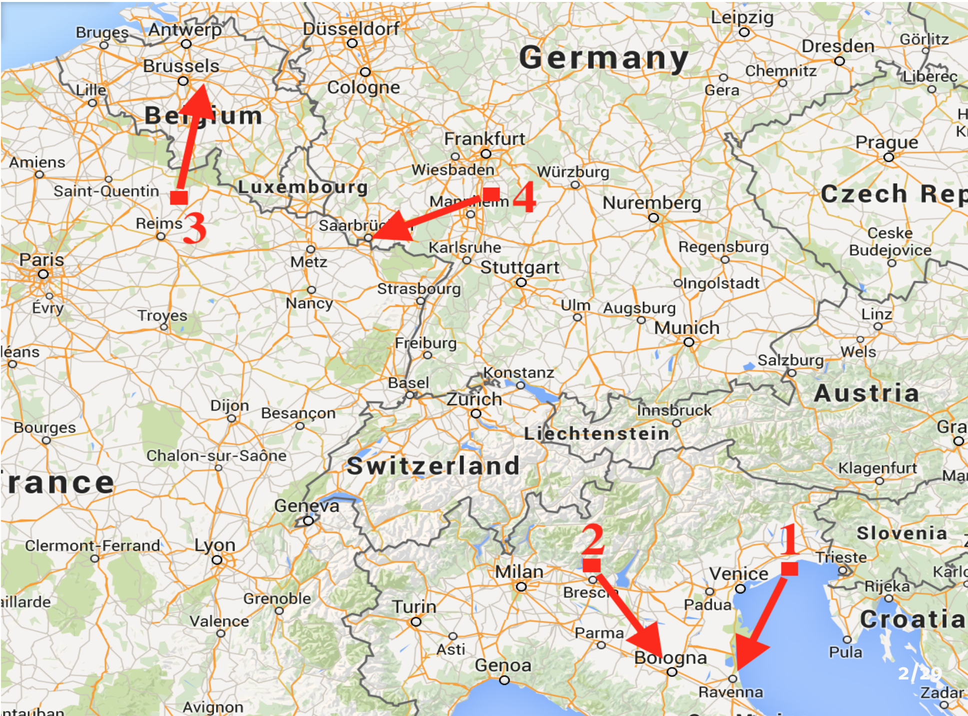
Who Am I ?

Foundations of Secure Compilation

Exorcising Spectres with Secure Compilers WIP

Future Outlook

Who Am I ?



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Reims
3
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Karlsruhe
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Special Thanks to:

(wrt the contents of this talk)

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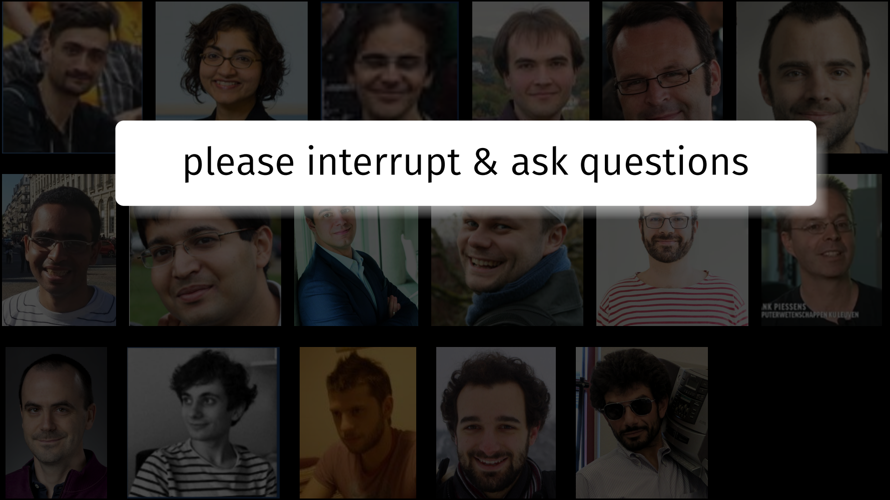

please interrupt & ask questions

Foundations of Secure Compilation

Programming Languages: Pros and Problems

Good PLs (, , , , …) provide:

- helpful abstractions to write secure code

Programming Languages: Pros and Problems

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but

- when compiled ($[\![\cdot]\!]$) and linked with adversarial target code

Programming Languages: Pros and Problems

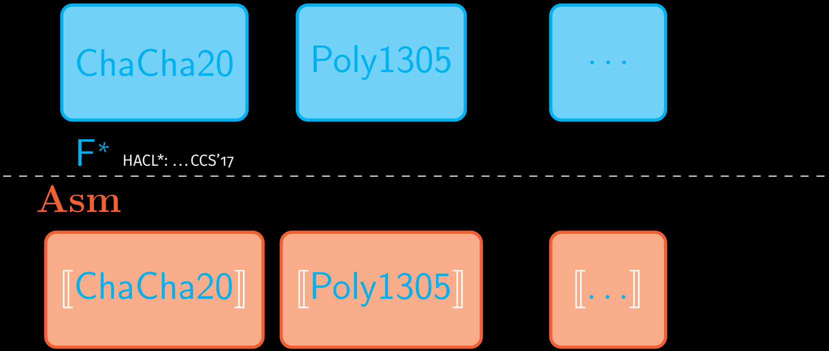
Good PLs (, TypeScript, , , …) provide:

- helpful abstractions to write secure code

but

- when compiled ($[\![\cdot]\!]$) and linked with adversarial target code
- these abstractions are NOT enforced

Secure Compilation: Example



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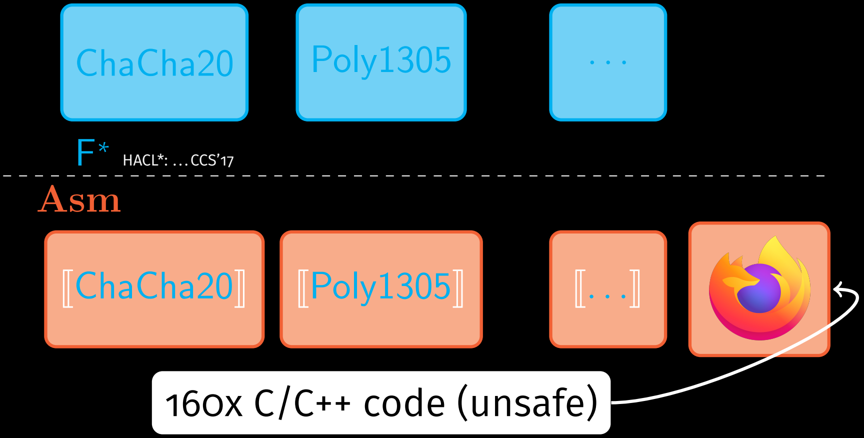

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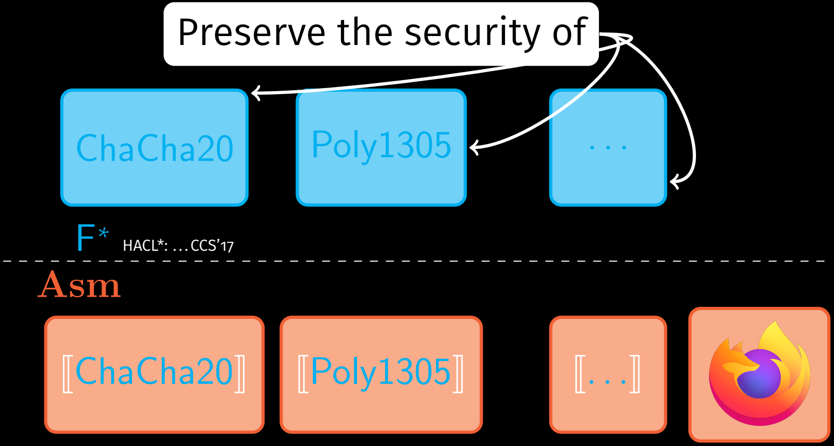

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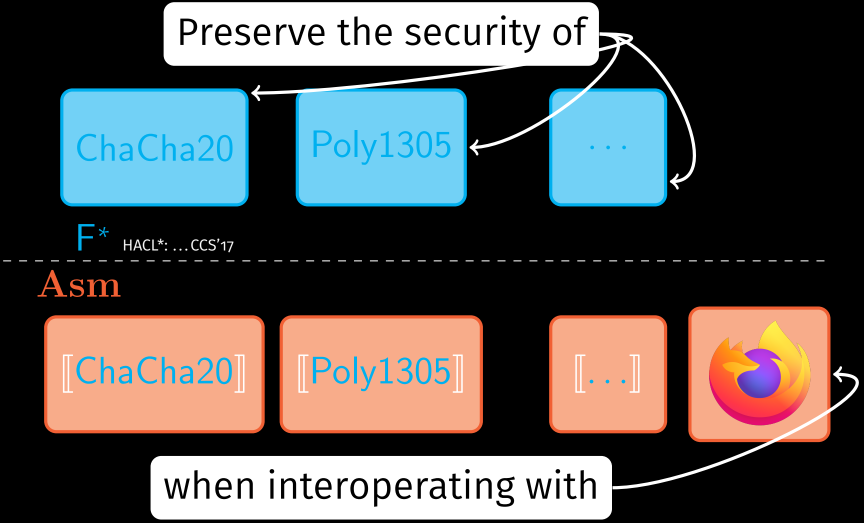

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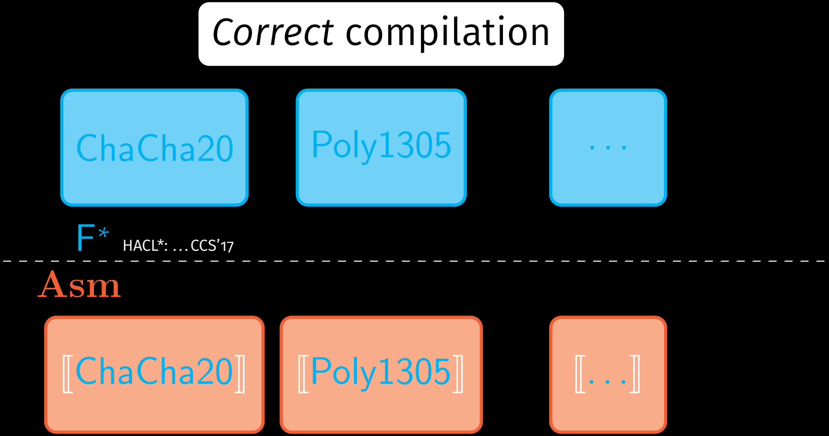

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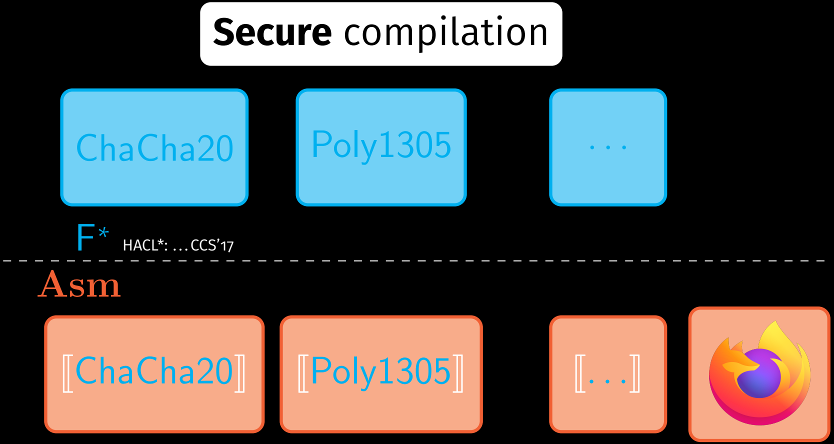
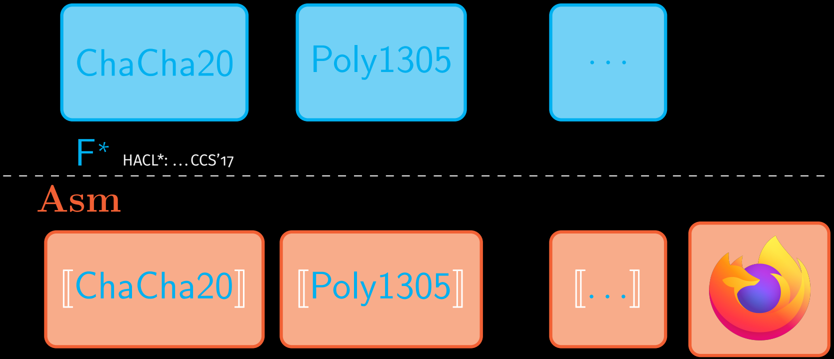


Secure Compilation: Example

Enable source-level security reasoning



Quest for Foundations

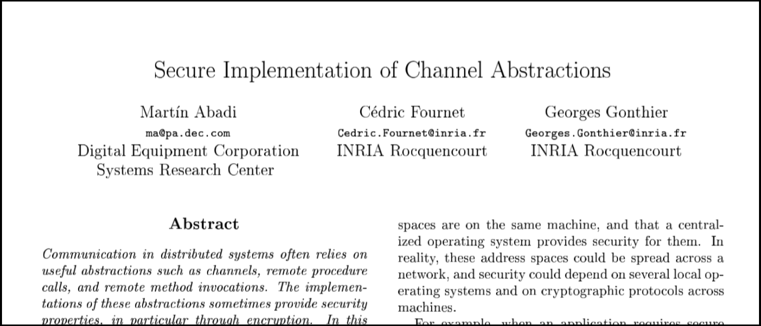
What does it mean for a compiler to be secure?

Quest for Foundations

What does it mean for a compiler to be secure?

Known for type systems, CC but not for SC

Once Upon a Time in Process Algebra



Secure Implementation of Channel Abstractions

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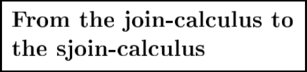
Abstract

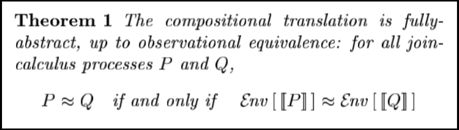
Communication in distributed systems often relies on useful abstractions such as channels, remote procedure calls, and remote method invocations. The implementations of these abstractions sometimes provide security properties, in particular through encryption. In this

spaces are on the same machine, and that a centralized operating system provides security for them. In reality, these address spaces could be spread across a network, and security could depend on several local operating systems and on cryptographic protocols across machines.

For example, when an application requires secure



From the join-calculus to the sjoin-calculus



Theorem 1 *The compositional translation is fully-abstract, up to observational equivalence: for all join-calculus processes P and Q,*

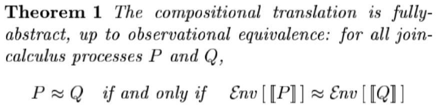
$$P \approx Q \quad \textit{if and only if} \quad \mathcal{E}nv\,[\,[\![P]\!]\,] \approx \mathcal{E}nv\,[\,[\![Q]\!]\,]$$

Once Upon a Time in Process Algebra

they needed a definition that their implementation of secure channels via cryptography was secure

Once Upon a Time in Process Algebra

Fully Abstract Compilation (FAC)



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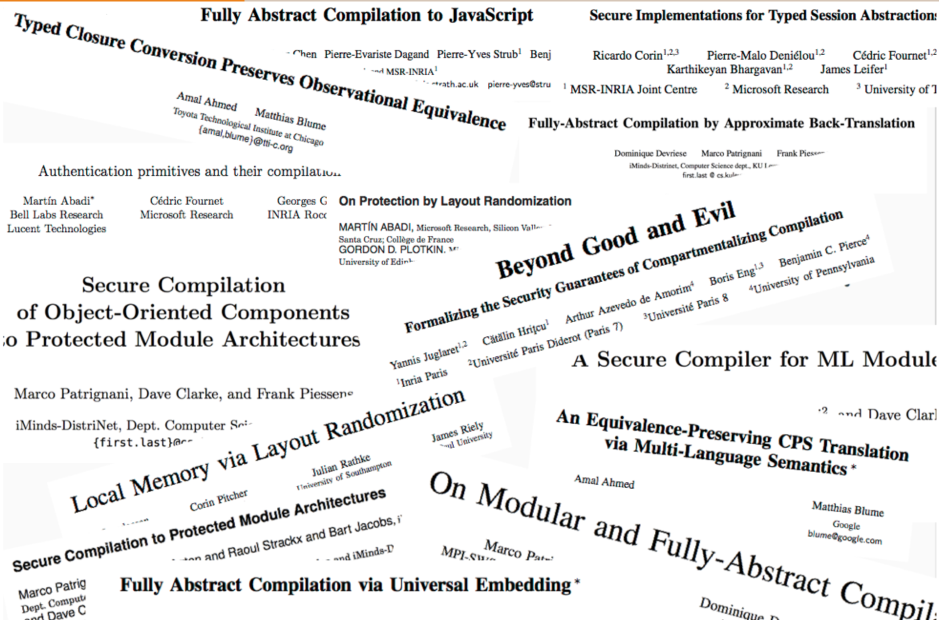
Fully Abstract Compilation Influence



Typed Closure Conversion Preserves Observational Equivalence

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Fully Abstract Compilation to JavaScript

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and MSR-INRIA[1]
strath.ac.uk pierre-yves@stru

Secure Implementations for Typed Session Abstraction

Ricardo Corin[1,2,3] Pierre-Malo Deniélou[1,2] Cédric Fournet[1,2]
Karthikeyan Bhargavan[1,2] James Leifer[1]
[1] MSR-INRIA Joint Centre [2] Microsoft Research [3] University of T

Fully-Abstract Compilation by Approximate Back-Translation

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iMinds-Distrinet, Computer Science dept., KU L
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Authentication primitives and their compilation

Martín Abadi* Cédric Fournet Georges G
Bell Labs Research Microsoft Research INRIA Roc
Lucent Technologies

On Protection by Layout Randomization

MARTÍN ABADI, Microsoft Research, Silicon Vall
Santa Cruz; Collège de France
GORDON D. PLOTKIN, M
University of Edin

Beyond Good and Evil

Formalizing the Security Guarantees of Compartmentalizing Compilation

Yannis Juglaret[1,2] Cătălin Hrițcu[1] Arthur Azevedo de Amorim[4] Boris Eng[1,3] Benjamin C. Pierce[4]
[1]Inria Paris [2]Université Paris Diderot (Paris 7) [3]Université Paris 8 [4]University of Pennsylvania

Secure Compilation of Object-Oriented Components to Protected Module Architectures

Marco Patrignani, Dave Clarke, and Frank Piessens

iMinds-DistriNet, Dept. Computer Sc
{first.last}@c

A Secure Compiler for ML Module

and Dave Clar

An Equivalence-Preserving CPS Translation via Multi-Language Semantics *

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Google
blume@google.com

Local Memory via Layout Randomization

Corin Pitcher Julian Rathke James Riely
University of Southampton University

Secure Compilation to Protected Module Architectures

Marco Patrig
Dept. Comput
and Dave C

and Raoul Strackx and Bart Jacobs,
and iMinds-D

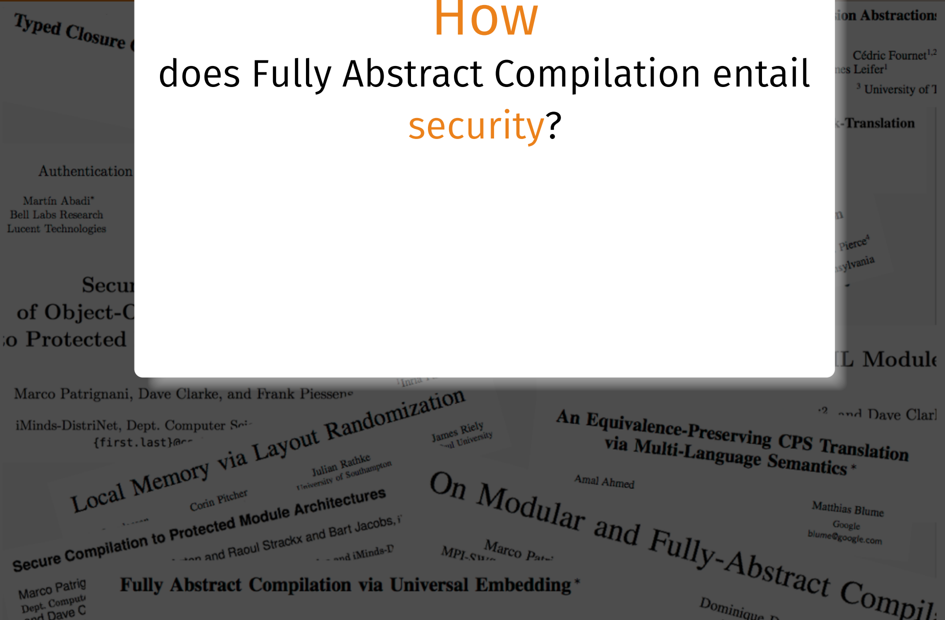
On Modular and Fully-Abstract Compil

Marco Patr
MPI-SWS

Dominique D

Fully Abstract Compilation via Universal Embedding *

Fully Abstract Compilation Influence



Typed Closure

Authentication

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Secur
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On Modular and Fully-Abstract Compil

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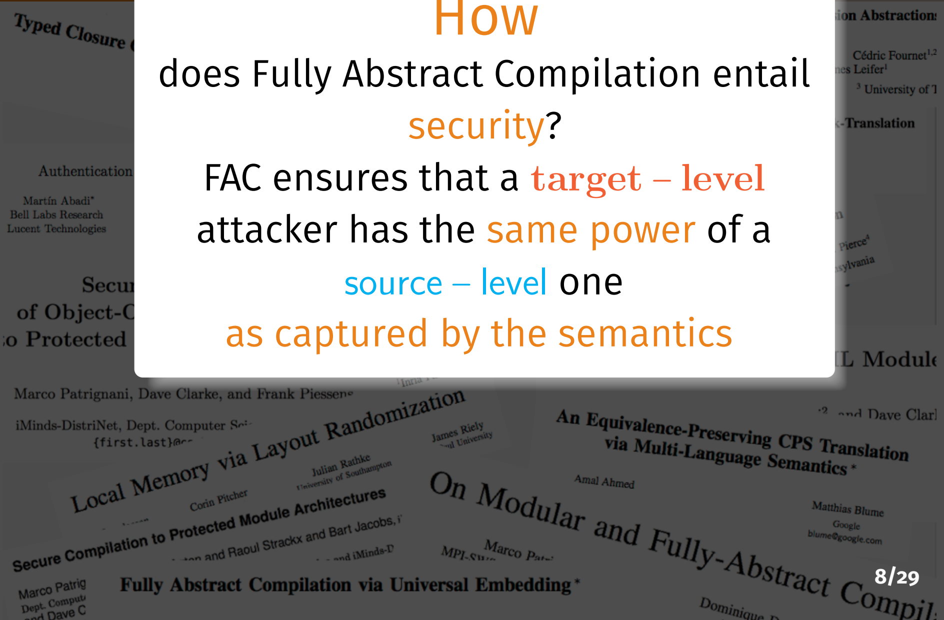
How

does Fully Abstract Compilation entail security?

Fully Abstract Compilation Influence



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Fully Abstract Compilation via Universal Embedding*

ion Abstractions

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-Translation

Pierce[4]
sylvania

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Marco Pat
MPI-SWS

Dominique D

How

does Fully Abstract Compilation entail

security?

FAC ensures that a $\mathbf{target-level}$

attacker has the same power of a

source – level one

as captured by the semantics

Fully Abstract Compilation: Definition

$$\mathsf{P}_1 \quad \simeq_{ctx} \quad \mathsf{P}_2$$

$$\Updownarrow$$

$$[\![\mathsf{P}_1]\!] \ \simeq_{ctx} \ [\![\mathsf{P}_2]\!]$$

Fully Abstract Compilation: Definition

$$\mathsf{P}_1 \quad \simeq_{ctx} \quad \mathsf{P}_2$$

$$\Uparrow$$

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Fully Abstract Compilation: Definition

$$\mathsf{P}_1 \quad \simeq_{ctx} \quad \mathsf{P}_2$$

$$\Downarrow$$

$$\forall \mathbf{A}.\, \mathbf{A}\left[\llbracket \mathsf{P}_1 \rrbracket\right]\Downarrow \iff \mathbf{A}\left[\llbracket \mathsf{P}_2 \rrbracket\right]\Downarrow$$

Are there Alternatives to FAC?

- FAC is not precise about security

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- this affects efficiency and proof complexity

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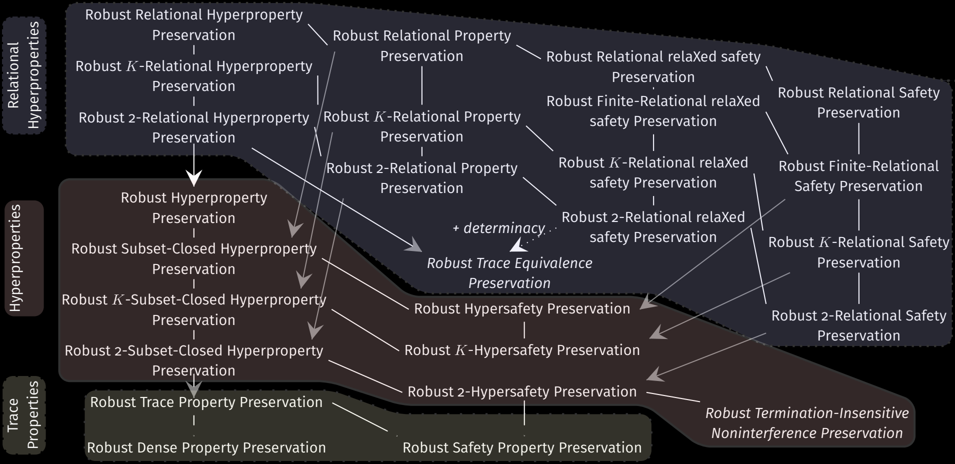
preserve classes of security (hyper)properties

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


Relational Hyperproperties
Hyperproperties
Trace Properties
Robust Relational Hyperproperty Preservation
Robust K-Relational Hyperproperty Preservation
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Robust Relational Property Preservation
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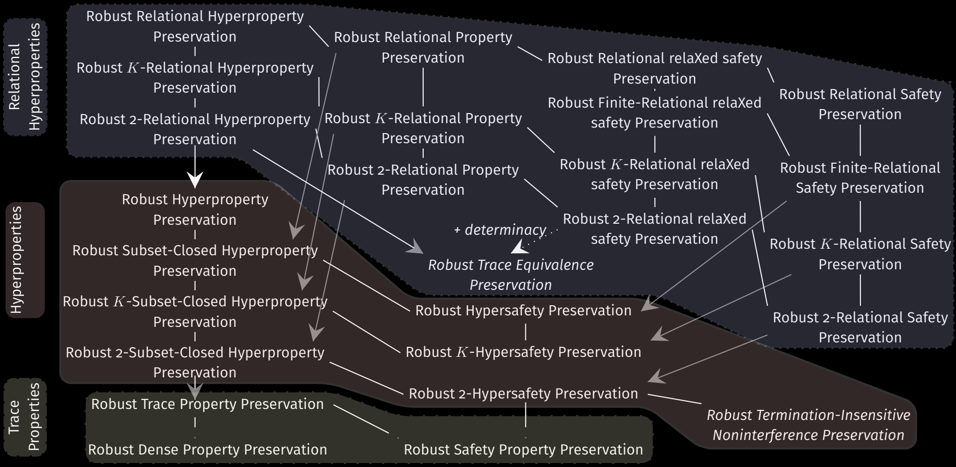
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Tradeoffs for code efficiency, security guarantees, proof complexity

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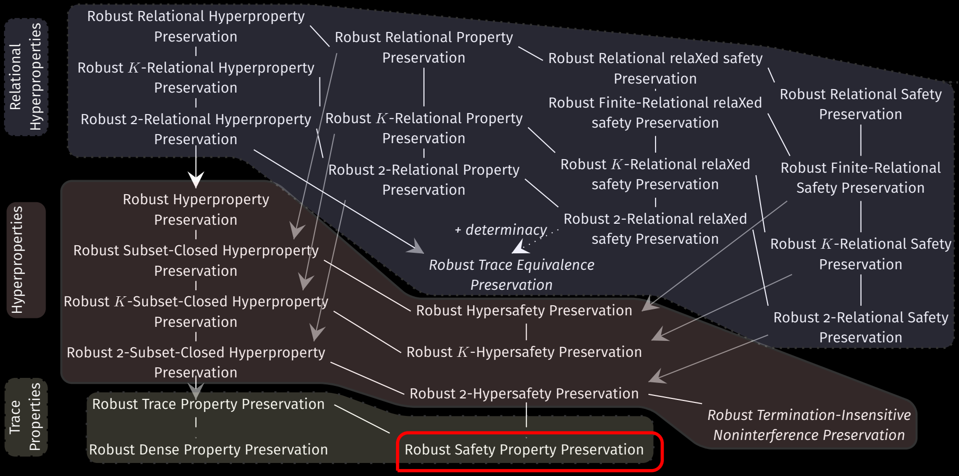
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Tradeoffs for code efficiency, security guarantees, proof complexity

Robust Criteria: Intuition

Each point has two equivalent criteria:

- $\textbf{Property – ful}:$
  - + clearly tells what class it preserves

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  - - unclear what security classes are preserved
  - = akin to some crypto statements (UC)

In Depth Example: RSC "Robustly-Safe Compilation ..." ESOP'19

$[\![\cdot]\!]$ = compiler $[\![\cdot]\!] : \mathsf{RSP} \overset{\text{def}}{=}$

In Depth Example: RSC “Robustly-Safe Compilation …” ESOP’19

$[\![\cdot]\!]$ = compiler
π / π = set of traces

$$[\![\cdot]\!] : \mathsf{RSP} \overset{\text{def}}{=} \forall \pi \approx \pi \in \mathit{Safety}.$$

In Depth Example: RSC “Robustly-Safe Compilation …” ESOP’19

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$[\cdot]$ = linking
$\rightsquigarrow$/$\boldsymbol{\rightsquigarrow}$ = trace semantics

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$$[\![\cdot]\!] : \mathsf{RSC} \overset{\text{def}}{=}$$

In Depth Example: RSC “Robustly-Safe Compilation …” ESOP’19

$[\![\cdot]\!]$ = compiler
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$\rightsquigarrow$ / $\rightsquigarrow$ = trace semantics
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$$\text{then } \exists \mathsf{A}, \mathsf{m}.\ \mathsf{A}\,[\mathsf{P}] \rightsquigarrow \mathsf{m} \text{ and } \mathsf{m} \approx \mathbf{m}$$

Understanding RSC

RSP/RSC:

- adaptable to reason about complex features: concurrency, undefined behaviour

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- provable if source is robustly-safe

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RSP:

- provable if source is robustly-safe

RSC:

- easiest backtranslation proof

RSC - FAC

Both:

RSC - FAC

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- robust ($\forall \mathbf{A}$)

RSC - FAC

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FAC:

- yields a language result

RSC - FAC

Both:

- robust ($\forall \mathbf{A}$)
- rely on program semantics ($\rightsquigarrow$ builds on $\Downarrow$)

FAC:

- yields a language result

RSC/RSP:

- extends the semantics ($\rightsquigarrow$) to focus on security

Is There More?

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Some still unknown foundations include:

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Exorcising Spectres with Secure Compilers

WIP

Speculative execution + branch prediction

Size of array **A**

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

Branch predictor

Speculative execution + branch prediction

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

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Branch predictor

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

✓ Architectural (ISA) state

✗ Microarchitectural state

Spectre V1

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void f(int x)
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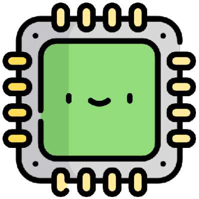

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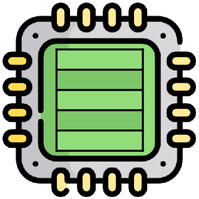

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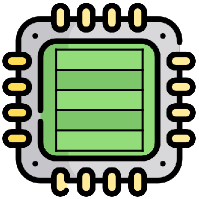

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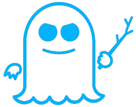

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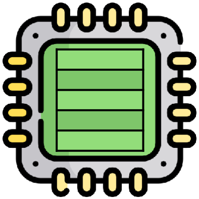

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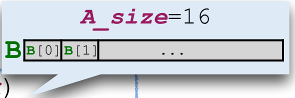

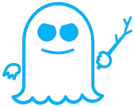

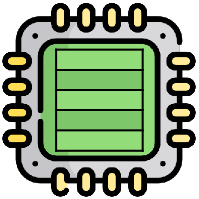

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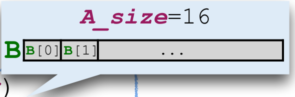

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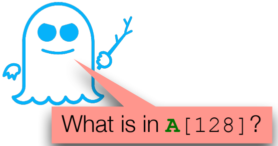

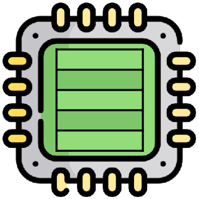

Spectre V1

A_size=16

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

```
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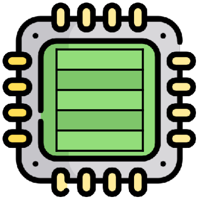

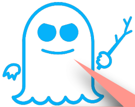

What is in A[128]?

1) Training

Spectre V1

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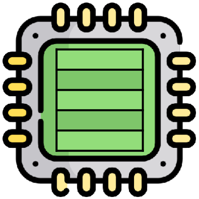

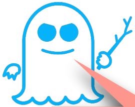

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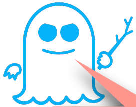

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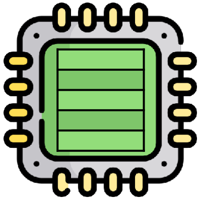

Spectre V1

```
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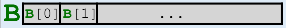

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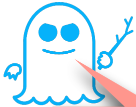

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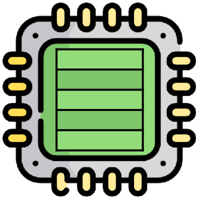

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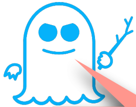

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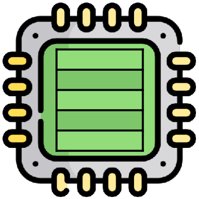

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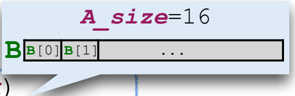
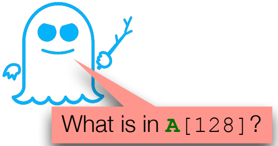
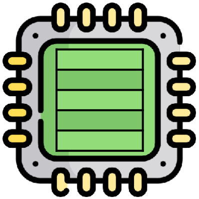
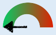






1) Training  `f(0);f(1);f(2); …`

2) Prepare cache

Spectre V1

```
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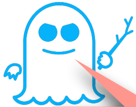
`B` | `B[0]` | `B[1]` | `...`



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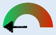
1) Training  `f(0);f(1);f(2); …`

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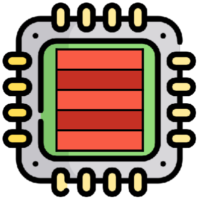

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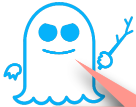

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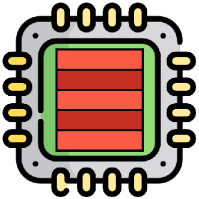

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3) Run with x = 128

Spectre V1

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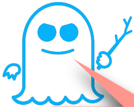

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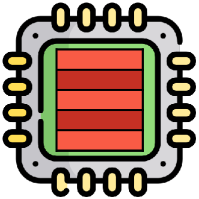

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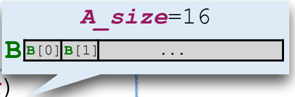

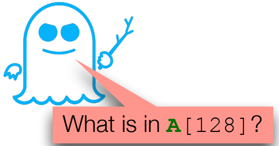

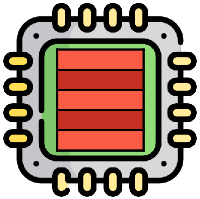

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Spectre V1

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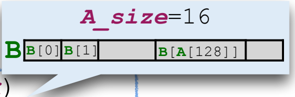

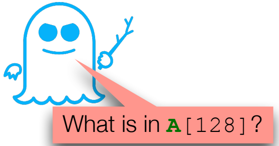

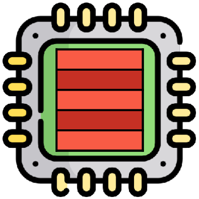

1) Training `f(0);f(1);f(2); …`

2) Prepare cache

3) Run with `x = 128`

Spectre V1

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

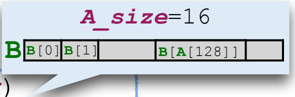

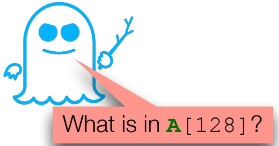

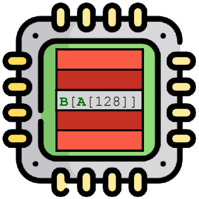

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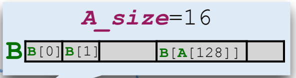

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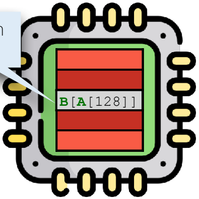
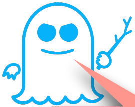
Depends on A[128]





What is in A[128]?

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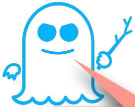
Spectre V1

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

A_size=16

B B[0] B[1] B[A[128]]



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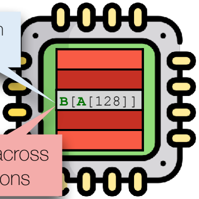

Persistent across speculations

Spectre V1

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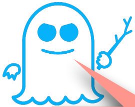

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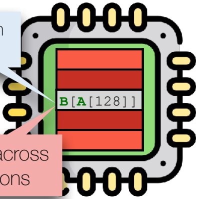

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2) Prepare cache

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

Goal

1. formalise `lfence` & `SLH` compilers

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5. prove the compilers attain RSSC

Goal Up Next

2. $\mathbf{T}$ must capture speculative execution ($\rightsquigarrow$)
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Speculative Semantics 101 “Spectector …” S&P’20

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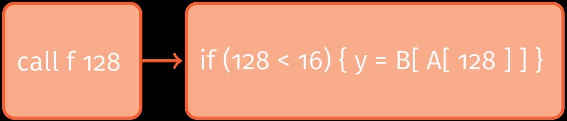

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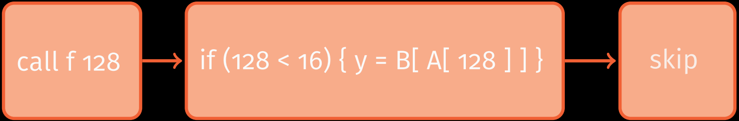

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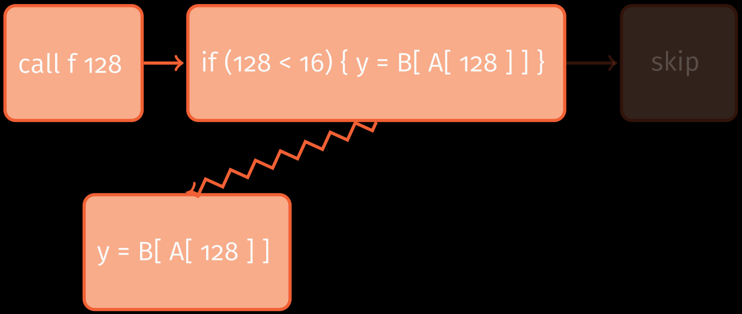

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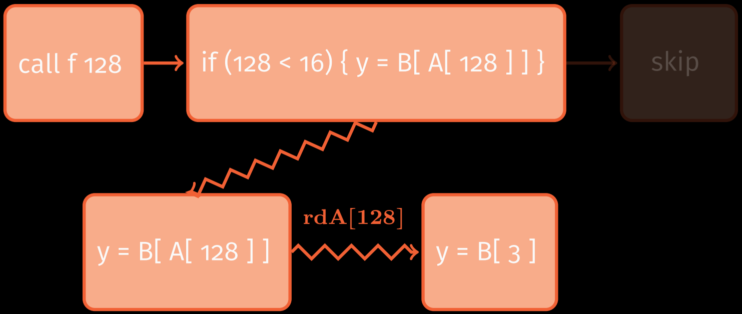

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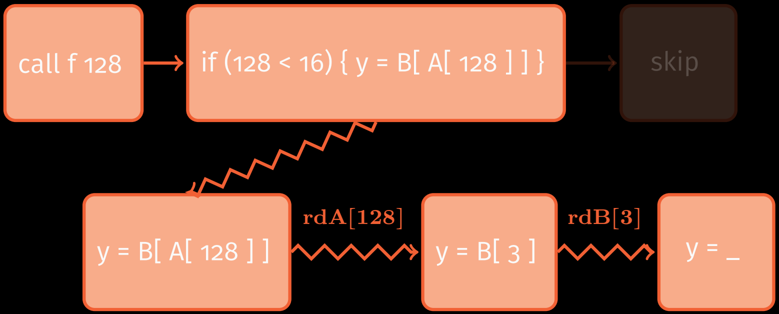

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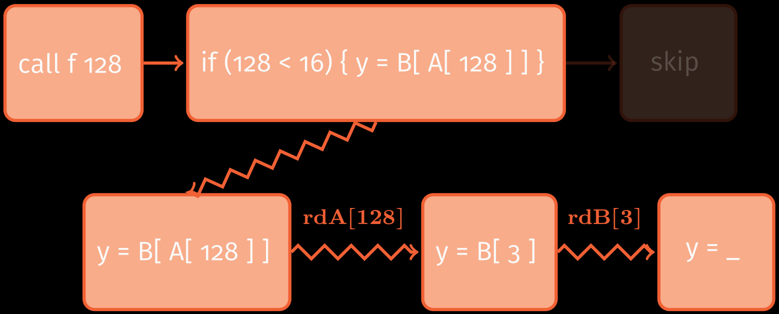

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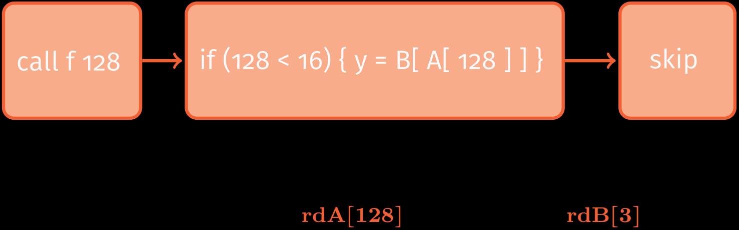
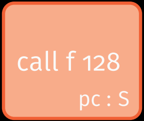


Speculative Safety (SS): Taint Tracking

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



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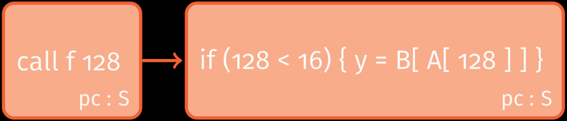

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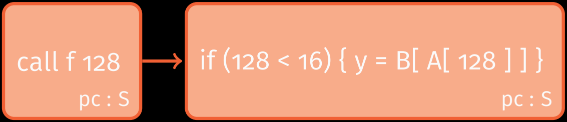

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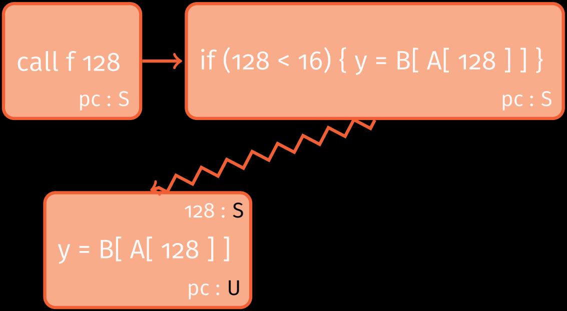

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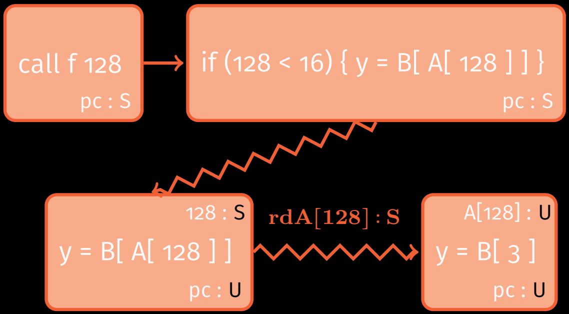

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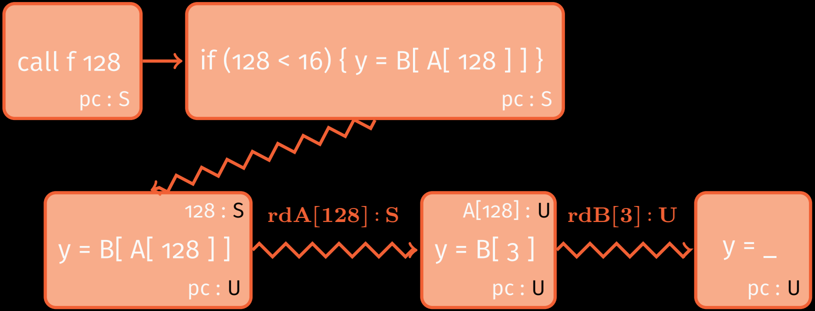

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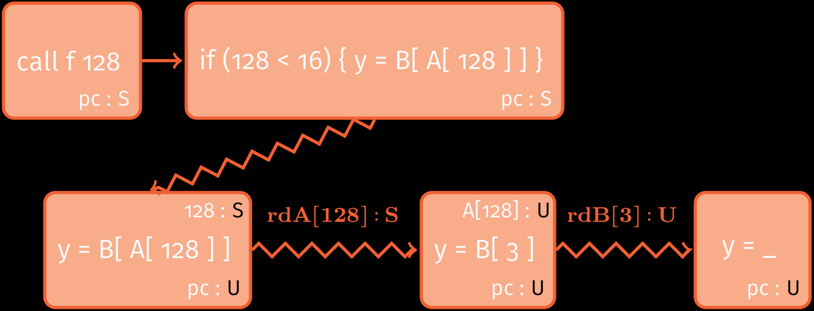

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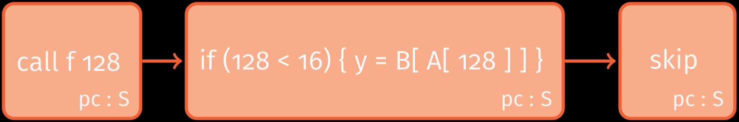

$\mathbf{rdA[128] : S}$ $\mathbf{rdB[3] : U}$

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

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

RSSC **for** `lfence`

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

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call f 128

pc : S

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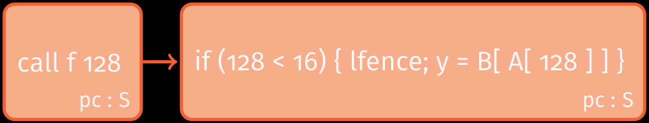

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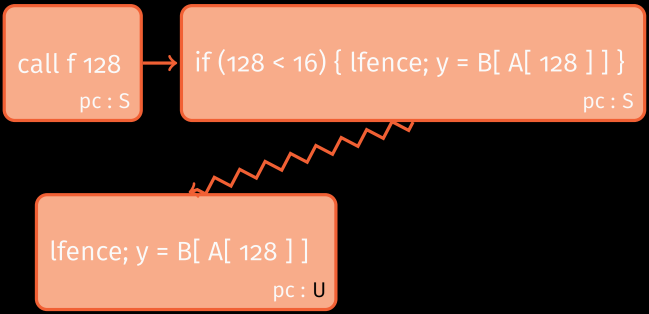

call f 128
pc : S
if (128 < 16) { lfence; y = B[A[128]] }
pc : S
lfence; y = B[A[128]]
pc : U

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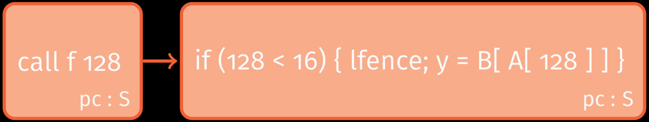

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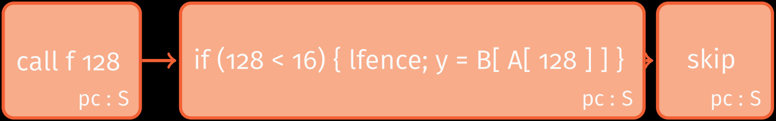

RSSC for SLH

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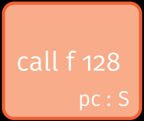

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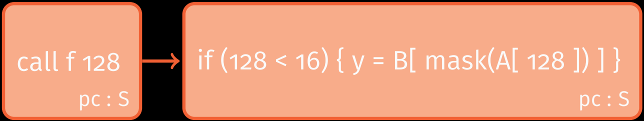

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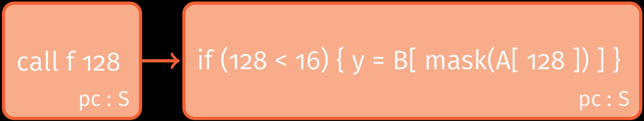

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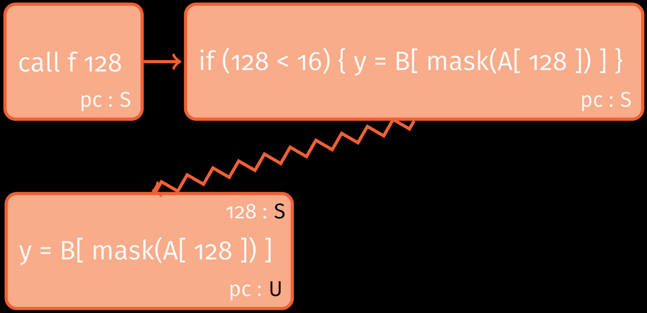
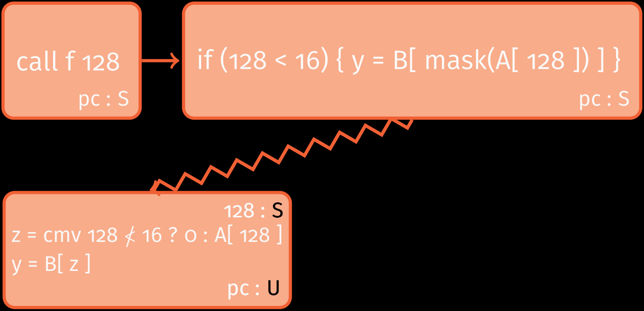


RSSC **for** SLH

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

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

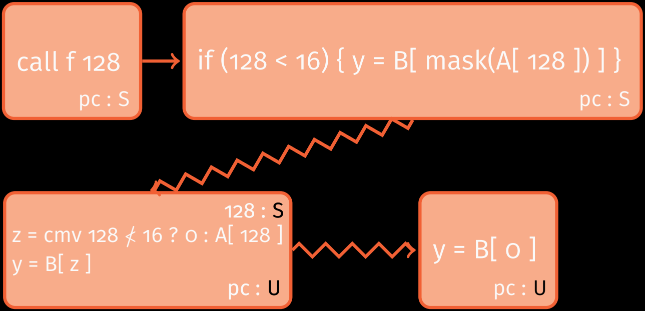


call f 128
pc : S
if (128 < 16) { y = B[mask(A[128])] }
pc : S
128 : S
z = cmv 128 ≮ 16 ? 0 : A[128]
y = B[z]
pc : U

RSSC **for** SLH

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

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



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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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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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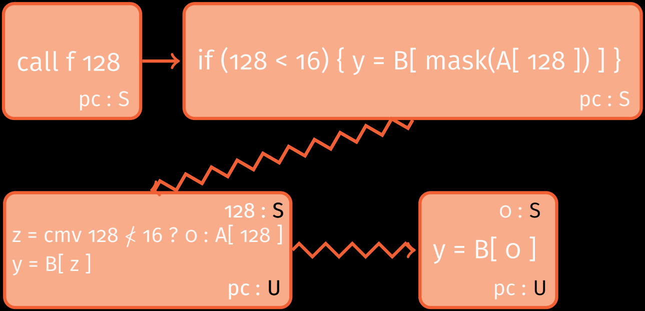
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RSSC **for** SLH

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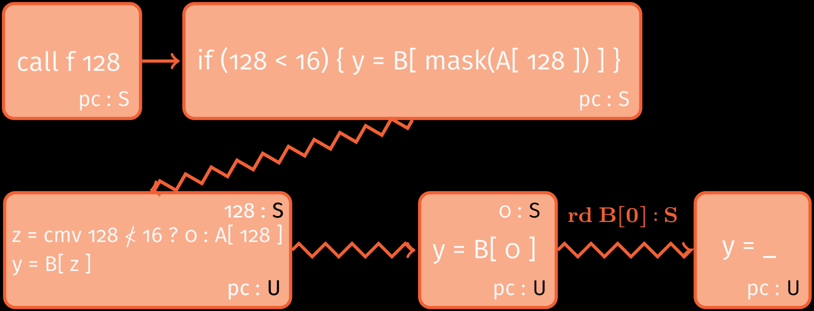
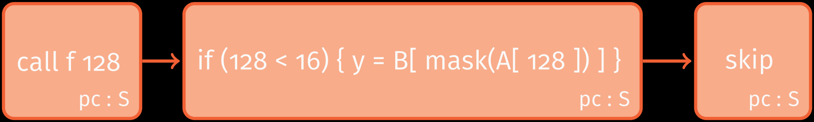


RSSC for SLH

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

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



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

Future Outlook

What More?

What More?

- secure compilation to webassembly
- secure compilation is universal composability
- secure compilation and optimisations
- secure compilation for linear languages
- …

Questions?