Secure Compilation: Formal Foundations and (Some) Applications

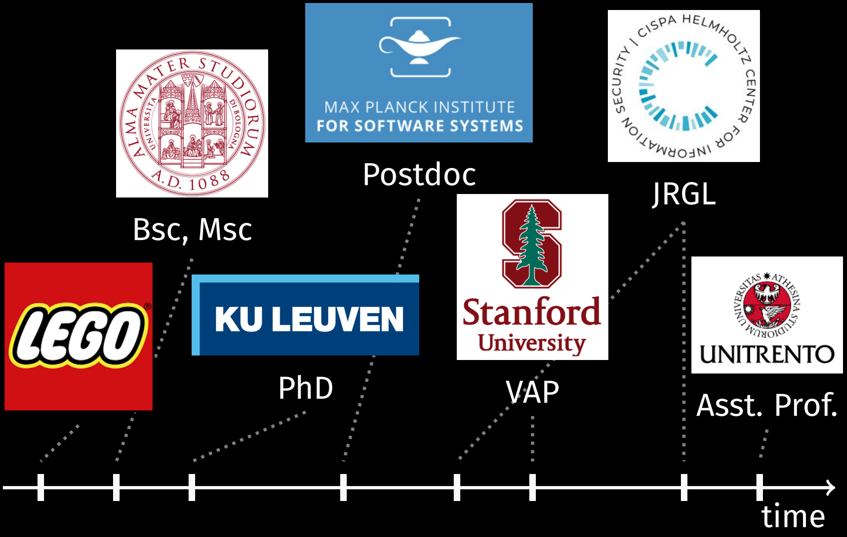
Marco Patrignani

UNIVERSITÀ DI TRENTO

03 April 2024

Who Am I ?

Marco Patrignani


LEGO
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA A.D. 1088
KU LEUVEN
MAX PLANCK INSTITUTE FOR SOFTWARE SYSTEMS
Stanford University
CISPA HELMHOLTZ CENTER FOR INFORMATION SECURITY
UNITRENTO

Bsc, Msc

PhD

Postdoc

VAP

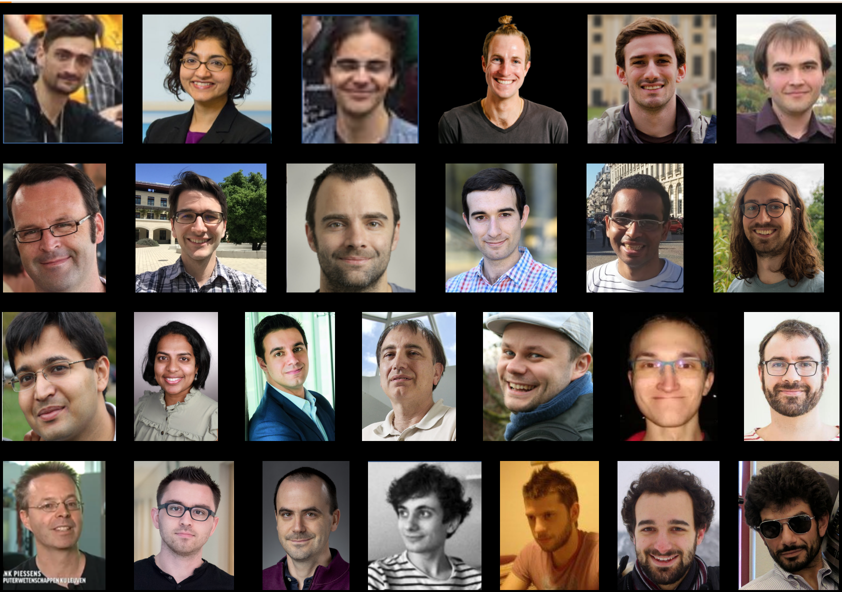
JRGL

Asst. Prof.

time

Special Thanks to:

(wrt the contents of this talk)



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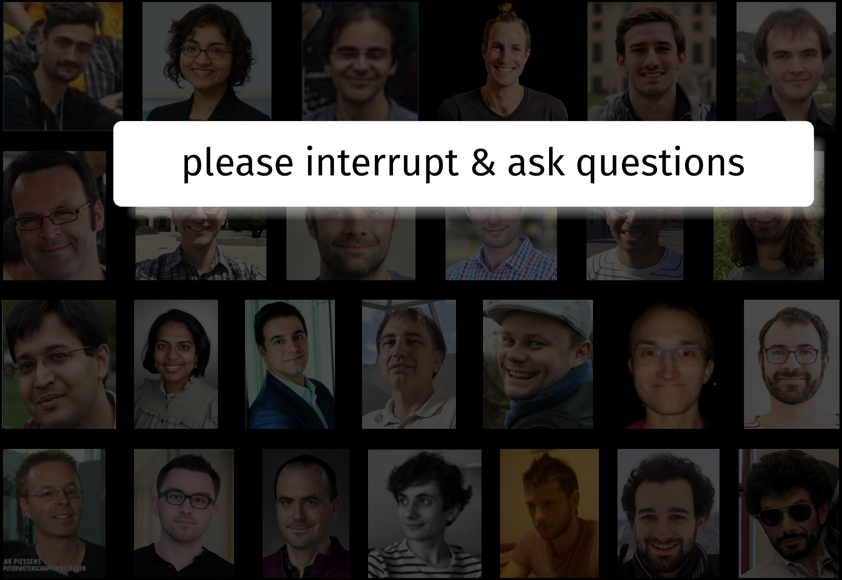

please interrupt & ask questions

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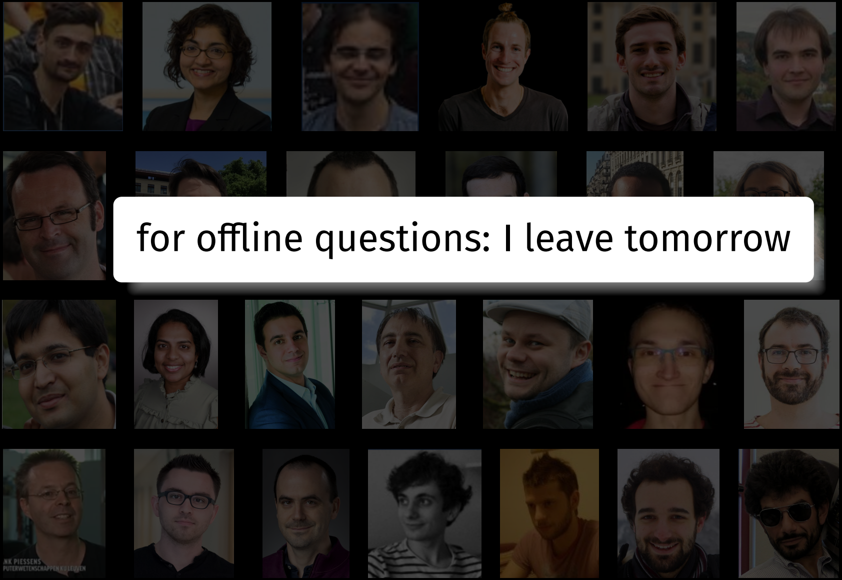

for offline questions: I leave tomorrow

Foundations of Secure Compilation

Programming Languages: Pros and Cons

Good PLs (R, TypeScript, >λ=, F*, …) provide:

- helpful abstractions to write secure code

Programming Languages: Pros and Cons

Good PLs (R, TypeScript, λ, F, …) provide:

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but

- when compiled ($\llbracket \cdot \rrbracket$) and linked with adversarial target code

Programming Languages: Pros and Cons

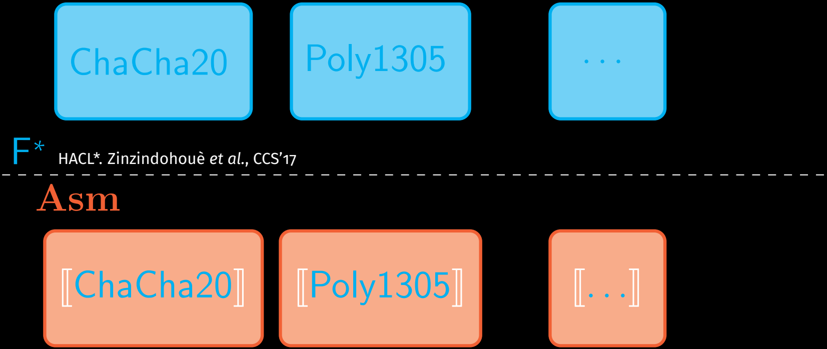
Good PLs (R, TypeScript, >λ=, ★, …) provide:

- helpful abstractions to write secure code

but

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

Secure Compilation: Example



ChaCha20

Poly1305

$\cdots$

F^*

HACL*. Zinzindohouè *et al.*, CCS'17

Asm

$[\![\text{ChaCha20}]\!]$

$[\![\text{Poly1305}]\!]$

$[\![\ldots]\!]$

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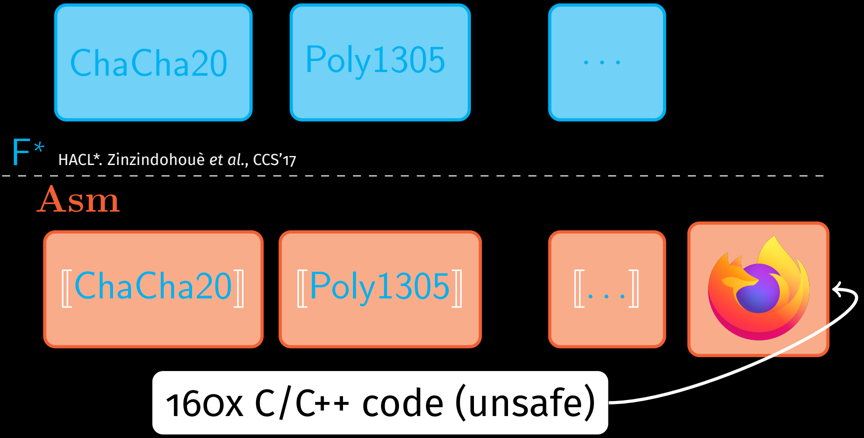


ChaCha20

Poly1305

. . .

F*

HACL*. Zinzindohouè *et al.*, CCS'17

Asm

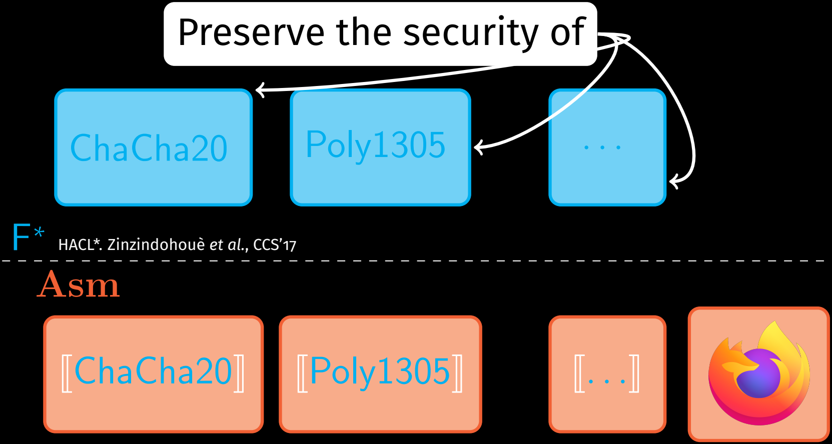
⟦ChaCha20⟧

⟦Poly1305⟧

⟦. . .⟧

160x C/C++ code (unsafe)

Secure Compilation: Example



Preserve the security of

ChaCha20

Poly1305

$\cdots$

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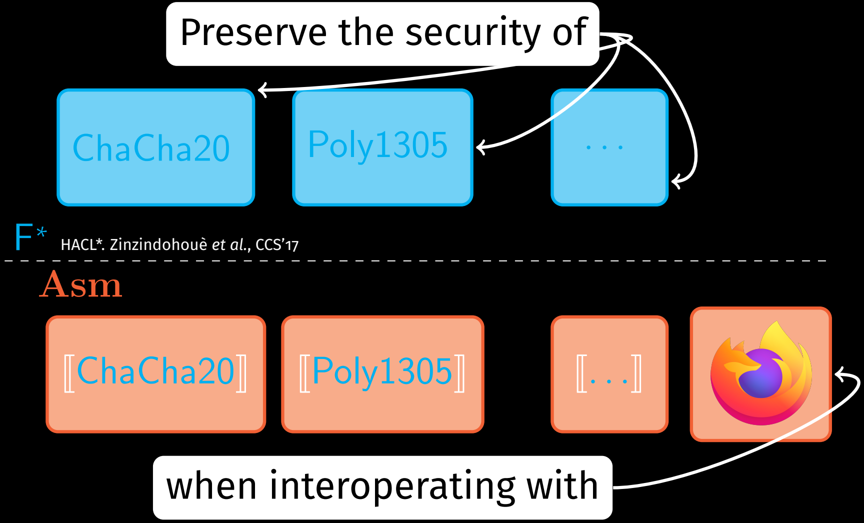

Preserve the security of

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Asm

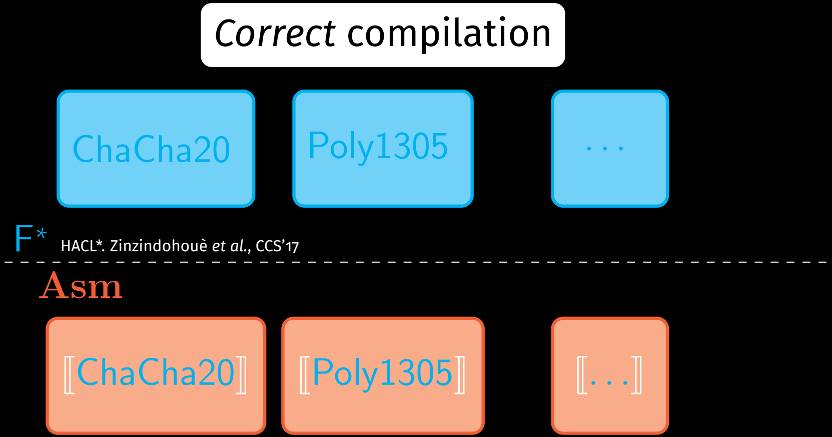
$[\![\text{ChaCha20}]\!]$

$[\![\text{Poly1305}]\!]$

$[\![\dots]\!]$

when interoperating with

Secure Compilation: Example



Correct compilation

ChaCha20

Poly1305

...

F^*

HACL*. Zinzindohouè *et al.*, CCS’17

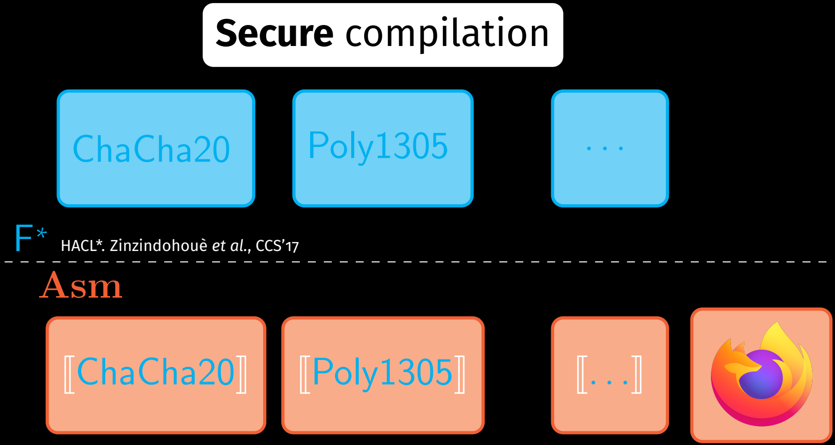
Asm

⟦ChaCha20⟧

⟦Poly1305⟧

⟦...⟧

Secure Compilation: Example



Secure compilation

ChaCha20

Poly1305

. . .

F*

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Asm

$[\![\text{ChaCha20}]\!]$

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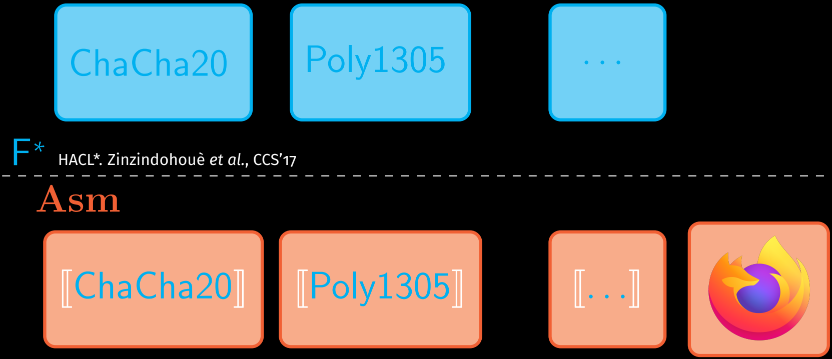
$[\![\ldots]\!]$

Secure Compilation: Example

Enable source-level security reasoning



ChaCha20

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⟦. . .⟧

Quest for Foundations

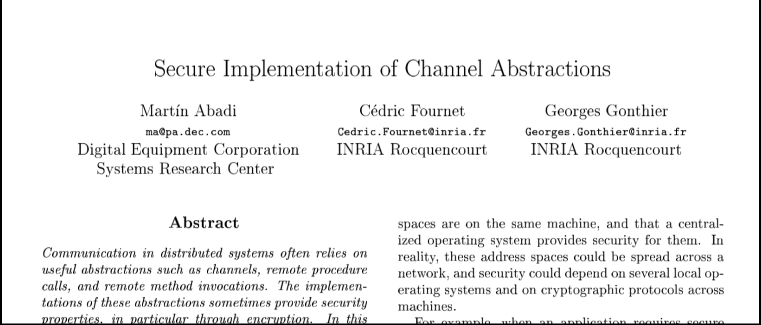
What does it mean for a compiler to be secure?

Quest for Foundations

What does it mean for a compiler to be secure?

Analogous questions are answered for type systems, correct compilation, ...

Once Upon a Time in Process Algebra



Secure Implementation of Channel Abstractions

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INRIA Rocquencourt

Abstract

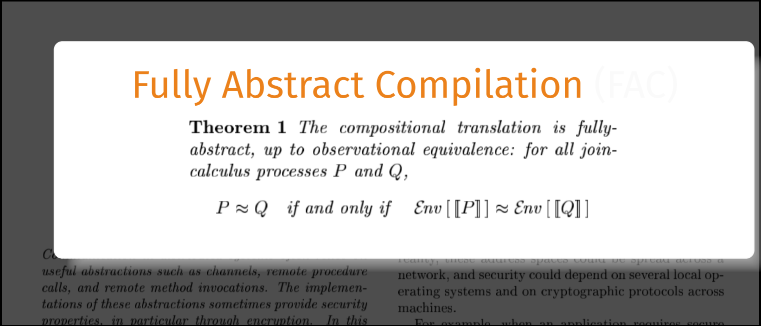
Communication in distributed systems often relies on useful abstractions such as channels, remote procedure calls, and remote method invocations. The implementations of these abstractions sometimes provide security properties, in particular through encryption. In this

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

Challenge: define that their implementation of secure channels via cryptography was secure

Once Upon a Time in Process Algebra



Fully Abstract Compilation (FAC)

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

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

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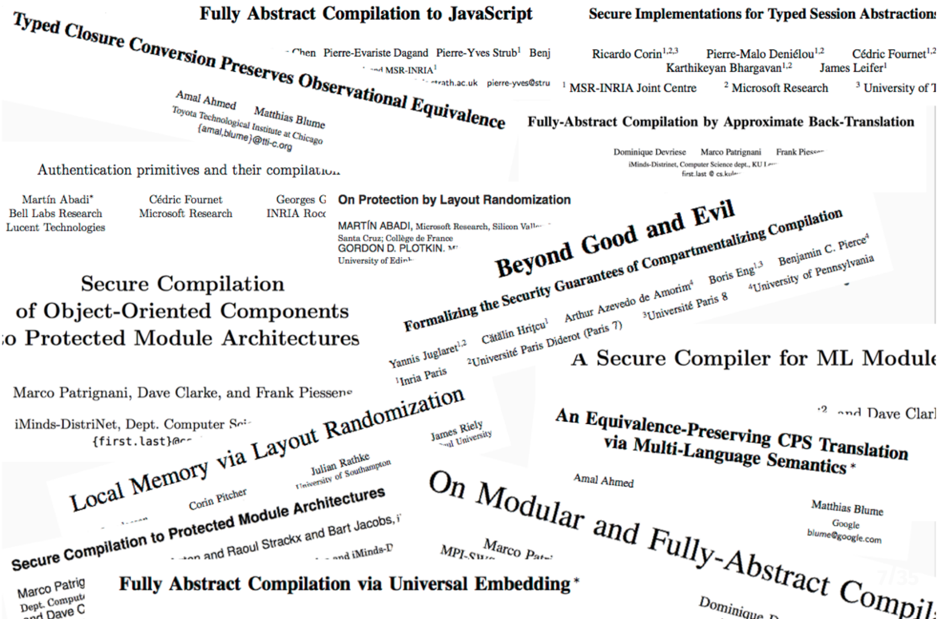
Fully Abstract Compilation Influence

ACM CSUR'19



Typed Closure Conversion Preserves Observational Equivalence

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Fully Abstract Compilation to JavaScript

-Chen Pierre-Evariste Dagand Pierre-Yves Strub[1] Benj
-nd MSR-INRIA[1]
-trath.ac.uk pierre-yves@stru

Secure Implementations for Typed Session Abstractions

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

Dominique Devriese Marco Patrignani Frank Piess-
iMinds-Distrinet, Computer Science dept., KU L-
first.last @ cs.kule-

Authentication primitives and their compilation

Martín Abadi* Cédric Fournet Georges G
Bell Labs Research Microsoft Research INRIA Rocq
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 Hriţcu[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 Sci-
{first.last}@c-

A Secure Compiler for ML Module

-2 and Dave Clar

Local Memory via Layout Randomization

Corin Pitcher Julian Rathke James Riely
University of Southampton -ul University

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

Amal Ahmed Matthias Blume
Google
blume@google.com

Secure Compilation to Protected Module Architectures

-on and Raoul Strackx and Bart Jacobs, i
-nd iMinds-D

On Modular and Fully-Abstract Compil

Marco Patr-
MPI-SWS

Dominique D

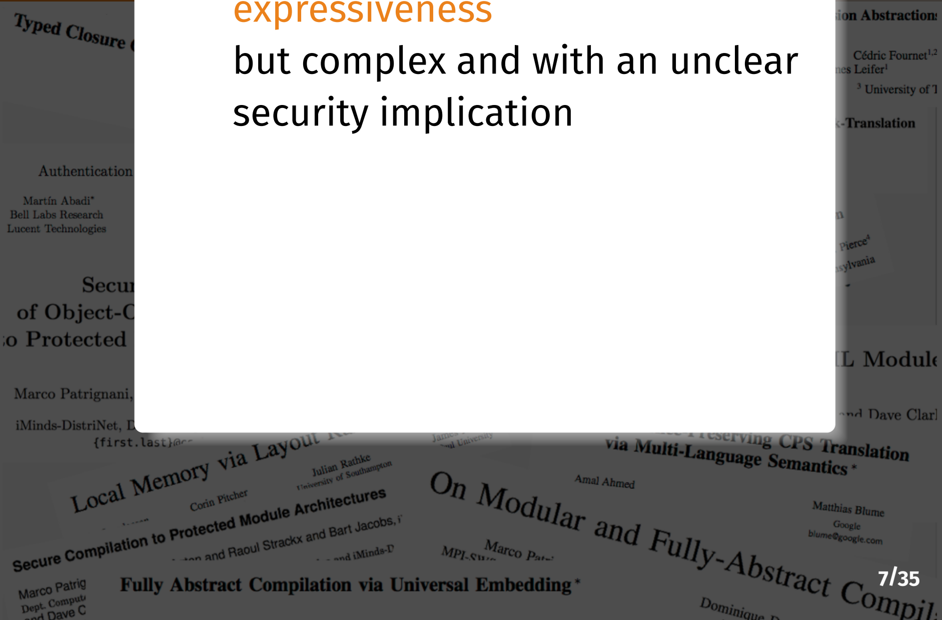
Marco Patrig
Dept. Comput
and Dave C

Fully Abstract Compilation via Universal Embedding *

Fully A

CSUR'19

- FAC: useful for language expressiveness
  but complex and with an unclear security implication



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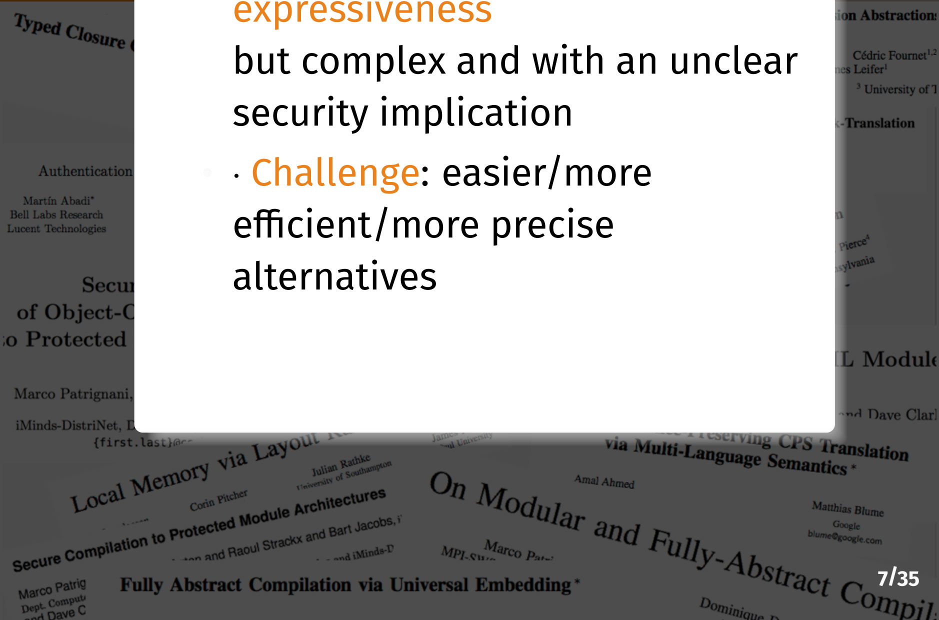
- Challenge: easier/more efficient/more precise alternatives



Typed Closure

Authentication

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Bell Labs Research
Lucent Technologies

Secu
of Object-C
o Protected

Marco Patrignani,

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ion Abstraction

Cédric Fournet1,2
nes Leifer1
3 University of T

-Translation

Pierce4
sylvania

L Module

nd Dave Clarl

Local Memory via Layout

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Secure Compilation to Protected Module Architectures

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Dept. Comput
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Fully Abstract Compilation via Universal Embedding*

On Modular and Fully-Abstract Compil

Marco Pat
MPI-SWS

Preserving CPS Translation
via Multi-Language Semantics*

Amal Ahmed

Matthias Blume
Google
blume@google.com

Dominique

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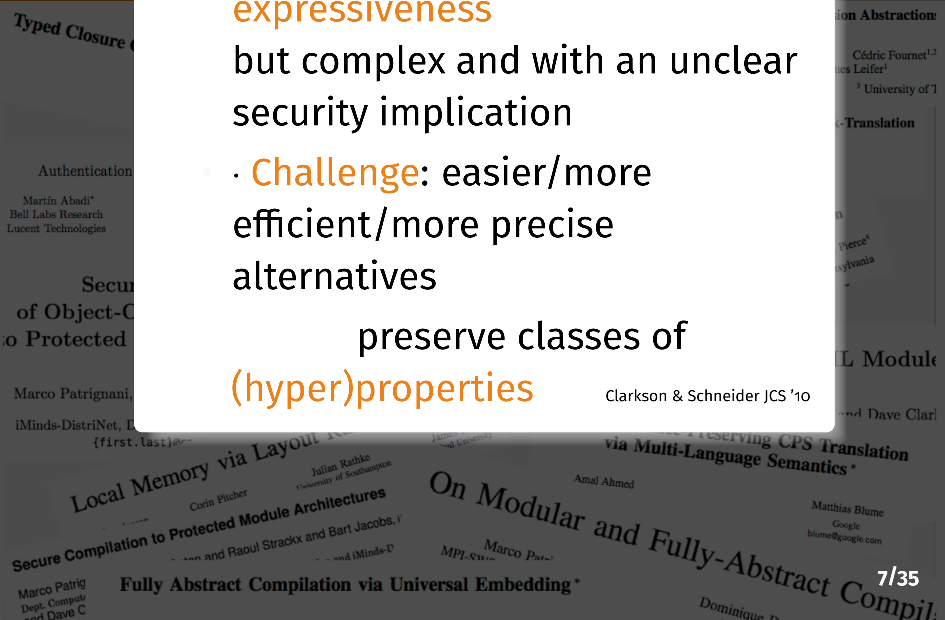
preserve classes of (hyper)properties

Clarkson & Schneider JCS '10



Typed Closure C

Authentication

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On Modular and Fully-Abstract Compil

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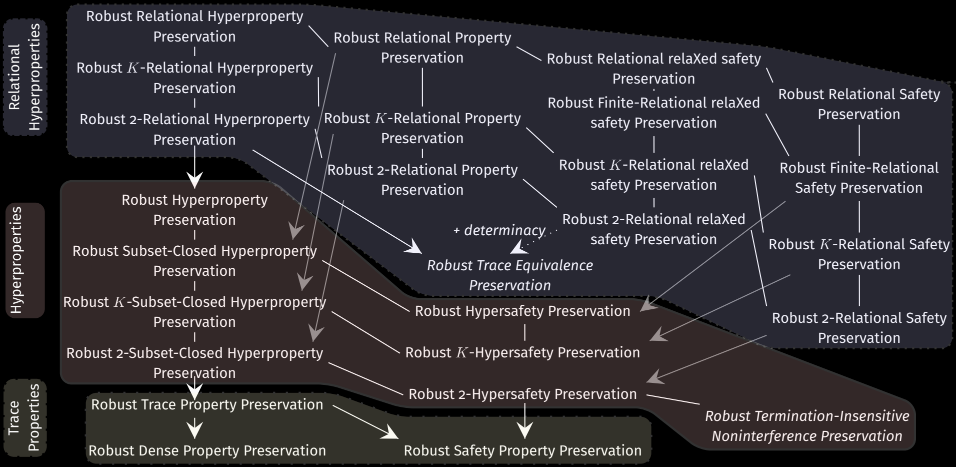
Fully Abstract Compilation via Universal Embedding *

Dominique D

Robust Compilation (RC) Criteria

CSF'19, ESOP'20, Toplas'21



Relational Hyperproperties

Hyperproperties

Trace Properties

Robust Relational Hyperproperty Preservation

Robust K-Relational Hyperproperty Preservation

Robust 2-Relational Hyperproperty Preservation

Robust Relational Property Preservation

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Robust 2-Relational Property Preservation

Robust Relational relaXed safety Preservation

Robust Finite-Relational relaXed safety Preservation

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Robust Relational Safety Preservation

Robust Finite-Relational Safety Preservation

Robust K-Relational Safety Preservation

Robust 2-Relational Safety Preservation

+ determinacy

Robust Trace Equivalence Preservation

Robust Hyperproperty Preservation

Robust Subset-Closed Hyperproperty Preservation

Robust K-Subset-Closed Hyperproperty Preservation

Robust 2-Subset-Closed Hyperproperty Preservation

Robust Hypersafety Preservation

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Robust 2-Hypersafety Preservation

Robust Termination-Insensitive Noninterference Preservation

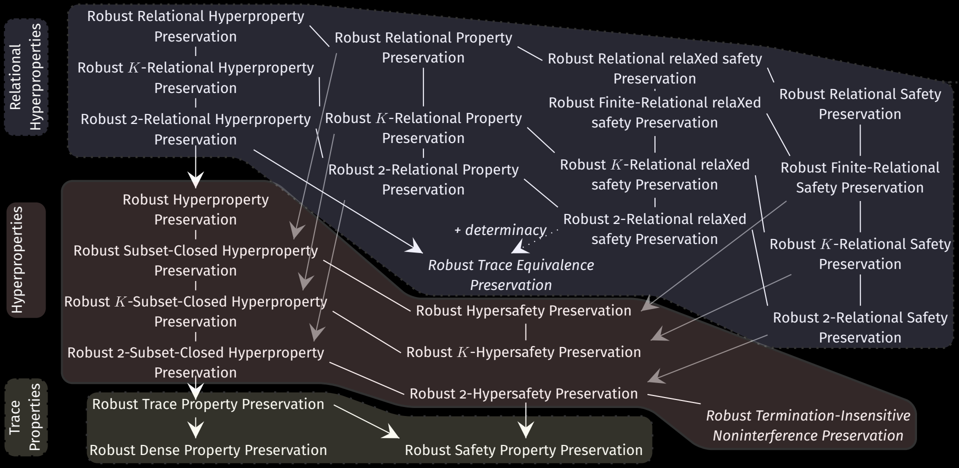
Robust Trace Property Preservation

Robust Dense Property Preservation

Robust Safety Property Preservation

Robust Compilation (RC) Criteria

CSF'19, ESOP'20, Toplas'21



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+ *determinacy*

Robust Trace Equivalence Preservation

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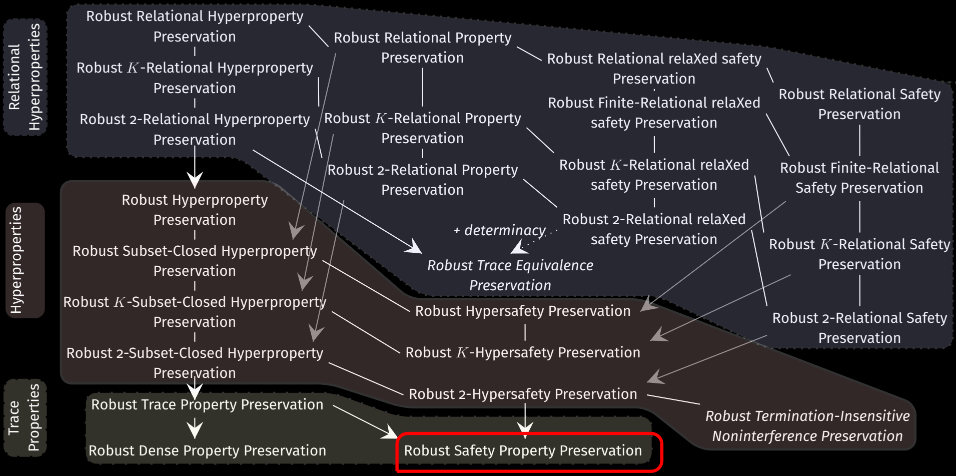
Tradeoffs for code efficiency, security guarantees, proof complexity

Robust Compilation (RC) Criteria

CSF'19, ESOP'20, Toplas'21



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Tradeoffs for code efficiency, security guarantees, proof complexity

Robust Criteria: Intuition

Each point has two equivalent criteria:

- $\mathrm{Property-ful}:$
  - clearly tells what class it preserves

Robust Criteria: Intuition

Each point has two equivalent criteria:

- $\mathbf{Property-ful}:$
    - + clearly tells what class it preserves
    - - harder to prove

Robust Criteria: Intuition

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- Property – free :
  - + easier to prove

Robust Criteria: Intuition

Each point has two equivalent criteria:

- $\text{Property} - \text{ful}:$
  - + clearly tells what class it preserves
  - - harder to prove
- $\text{Property} - \text{free}:$
  - + easier to prove
  - - unclear what security classes are preserved

In Depth Example: RSC

ESOP'19, TOPLAS'21

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

In Depth Example: RSC

ESOP'19, TOPLAS'21

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

π / π = set of traces

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

In Depth Example: RSC

ESOP'19, TOPLAS'21

$\llbracket\cdot\rrbracket$ = compiler

π / π = set of traces

P = partial program

$$\llbracket\cdot\rrbracket : \mathsf{RSP} \overset{\mathsf{def}}{=} \forall \pi \approx \pi \in \mathit{Safety}.\ \forall \mathsf{P}.$$

In Depth Example: RSC

ESOP'19, TOPLAS'21

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

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P = partial program

A/**A** = attacker

t/**t** = trace of events

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

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$\rightsquigarrow$ / $\rightsquigarrow$ = trace semantics

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

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$$\text{if } (\forall \mathrm{A}, \mathrm{t}.\ \mathrm{A}\,[\mathrm{P}] \rightsquigarrow \mathrm{t} \Rightarrow \mathrm{t} \in \pi)$$

In Depth Example: RSC

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$$\text{if } (\forall \mathsf{A}, \mathsf{t}.\ \mathsf{A}\left[\mathsf{P}\right] \rightsquigarrow \mathsf{t} \Rightarrow \mathsf{t} \in \pi)$$

$$\text{then } (\forall \mathbf{A}, \mathbf{t}.\ \mathbf{A}\left[[\![\mathsf{P}]\!]\right] \rightsquigarrow \mathbf{t} \Rightarrow$$

In Depth Example: RSC

ESOP'19, TOPLAS'21

$[\![\cdot]\!]$ = compiler
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P = partial program
$A / \mathbf{A}$ = attacker
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$$[\![\cdot]\!] : \mathrm{RSP} \overset{\text{def}}{=} \forall \pi \approx \pi \in \mathit{Safety}.\ \forall P.$$

$$\text{if } (\forall A, t.\ A[P] \rightsquigarrow t \Rightarrow t \in \pi)$$

$$\text{then } (\forall \mathbf{A}, \mathbf{t}.\ \mathbf{A}[[\![P]\!]] \rightsquigarrow \mathbf{t} \Rightarrow \mathbf{t} \in \pi)$$

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A / $\mathbf{A}$ = attacker
t / $\mathbf{t}$ = trace of events
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$\rightsquigarrow$ / $\rightsquigarrow$ = trace semantics

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

$$\text{if } (\forall \mathsf{A}, \mathsf{t}.\ \mathsf{A}[\mathsf{P}] \rightsquigarrow \mathsf{t} \Rightarrow \mathsf{t} \in \pi)$$

$$\text{then } (\forall \mathbf{A}, \mathbf{t}.\ \mathbf{A}[[\![\mathsf{P}]\!]] \rightsquigarrow \mathbf{t} \Rightarrow \mathbf{t} \in \pi)$$

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

In Depth Example: RSC

ESOP’19, TOPLAS’21

$\llbracket\cdot\rrbracket$ = compiler
$\pi / \boldsymbol{\pi}$ = set of traces
P = partial program
$\mathsf{A} / \mathbf{A}$ = attacker
$\mathsf{t} / \mathbf{t}$ = trace of events
$[\cdot]$ = linking
$\rightsquigarrow / \rightsquigarrow$ = trace semantics
$\mathsf{m} / \mathbf{m}$ = prefix of a trace

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ESOP'19, TOPLAS'21

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- robust, active attacker ($\forall \mathbf{A}$)

robust safety works, e.g., Swasey *et al.* OOPSLA’17, Sammler *et al.* POPL’20

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'20

- i

What can we do with these foundations?

- trace-based security behaviour ($\mathsf{m}/\mathbf{m}$)

Talk Outline

Robust Memory Safety POPL'23

Robust Cryptographic Constant Time (wip)

Micro-architectural Attacks (Spectre) CCS'21

Security Architectures
(e.g., Cheri/ARM Morello, Sancus/Intel SGX, ...) Toplas'15, CSF'21, ...

Mechanise Cryptographic Proofs CSF'24 + wip

Conclusion

Robust Memory Safety

POPL’23

Memory Safety (Untyped, Intra-Object)

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Memarian *et al.* POPL'19, Azevedo de Amorim *et al.* POST'18

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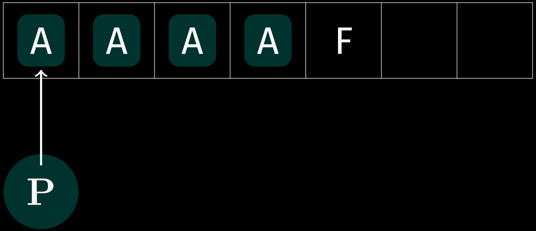

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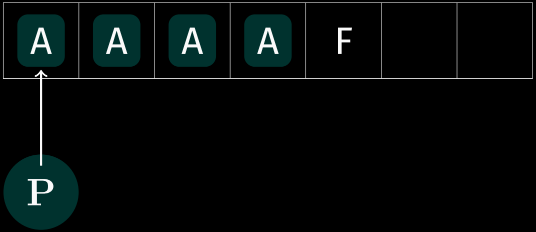

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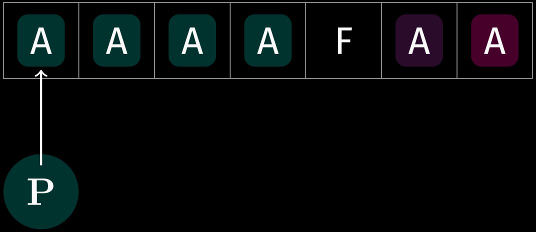

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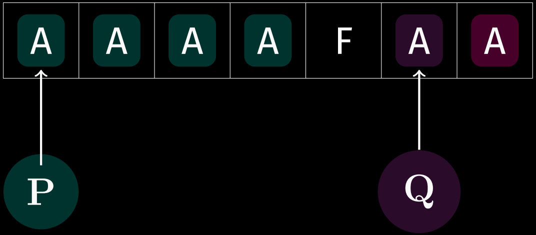

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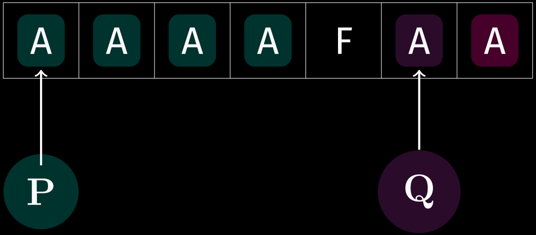

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ok

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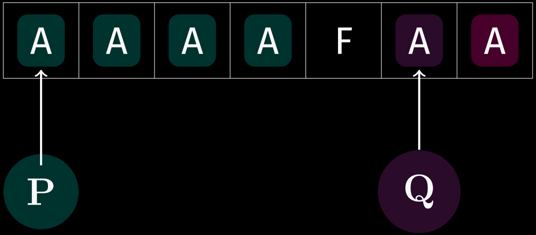

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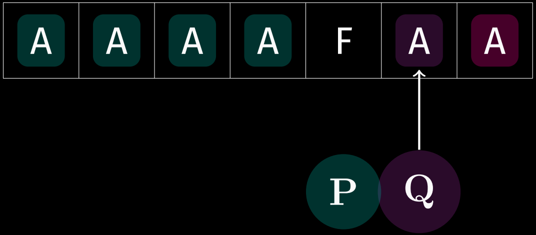

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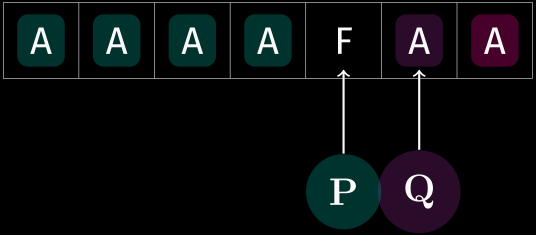

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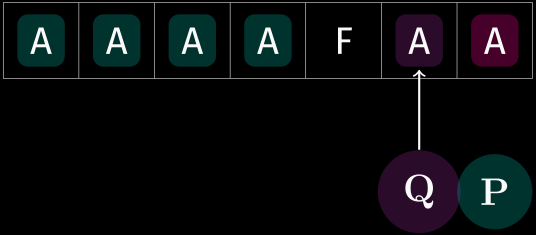

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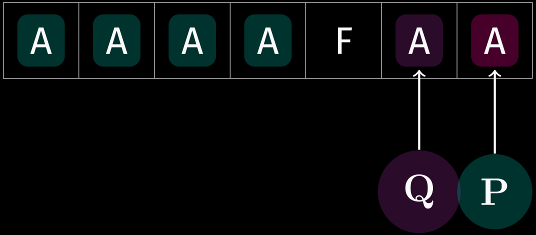

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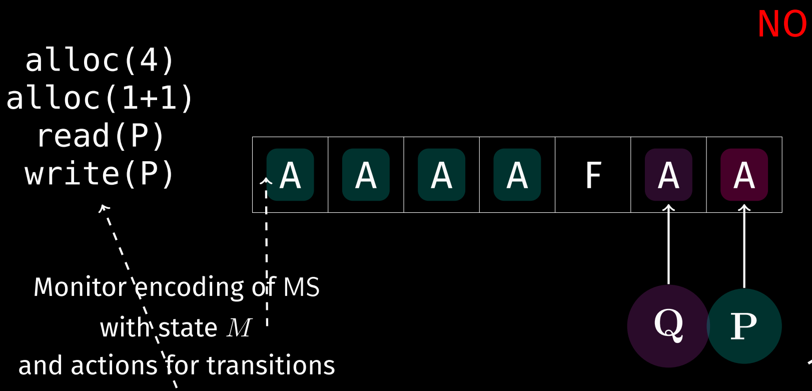

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Compiling from `C` to `MSWAsm`

- pointer becomes **handle**

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Compiler Properties

Ω = source state

α/α = trace action

$$\begin{tikzcd}
 & \Omega' \\
\Omega \arrow[ur, "\alpha"] &
\end{tikzcd}$$

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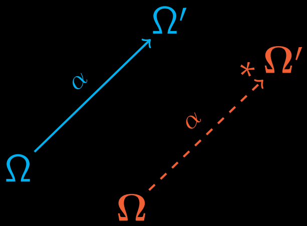

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\Omega \arrow[r, "\alpha"] \arrow[d, dash, "=_{\delta}"'] & \Omega' \\
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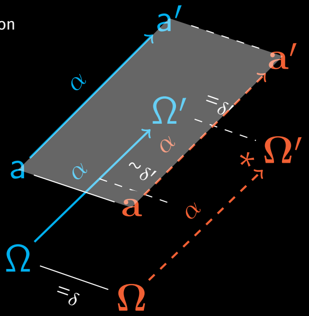

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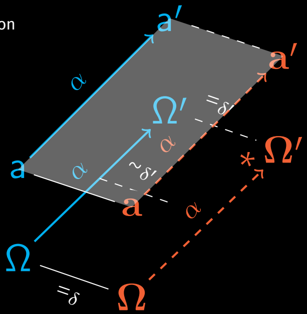

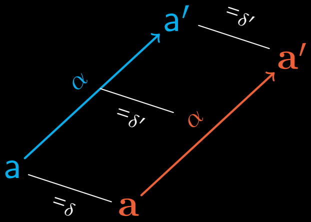

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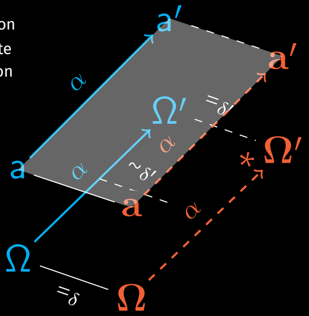

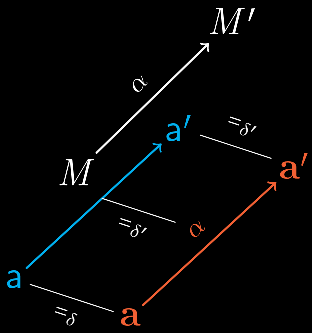

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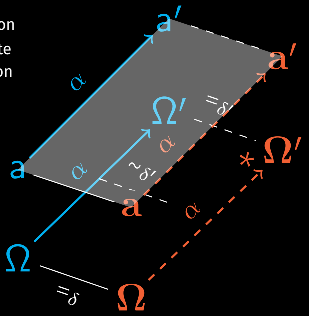

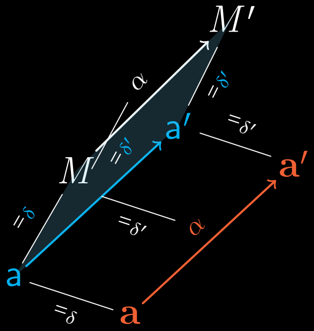

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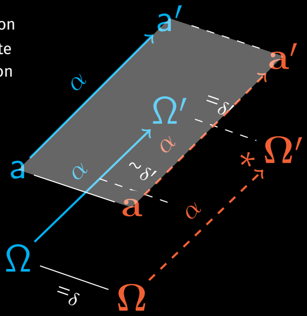

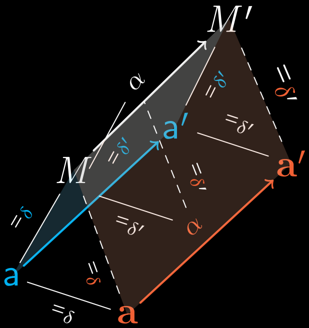

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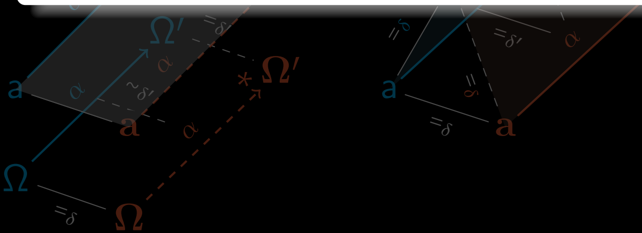

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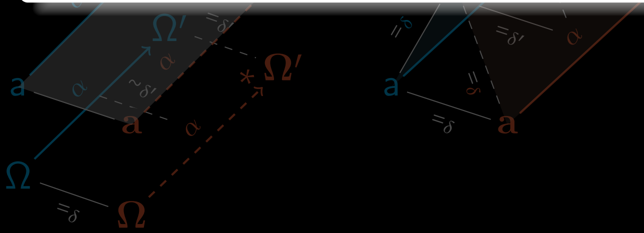

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Challenge: how to ensure $\mathbf{A}$ actions do not affect MS?

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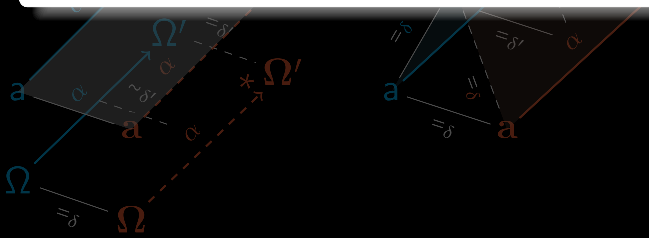

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Bernstein ’15, Barbosa *et al.* S&P’21

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- Challenge: crypto devs do not know where their code is used

Compiler Preserving RCT

- Goal: protect a crypto library from any application using it
- crypto developers already zero out memory before calling apps (e.g., Libsodium)
- Challenge: crypto devs must make their code CT
- Solution: devise CT code e.g., Bacelar Almeida *et al.* CCS'17
- Challenge: crypto devs do not know where their code is used
- Solution: use a compiler that preserves RCT

Micro-architectural Attacks (Spectre)

CCS'21

Speculative Semantics & SNI

Guarnieri *et al.* S&P'21

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

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

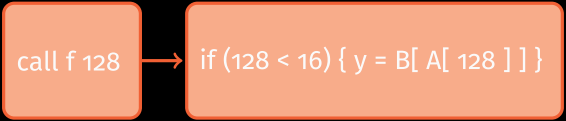
call f 128

Speculative Semantics & SNI

Guarnieri *et al.* S&P'21

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

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



Speculative Semantics & SNI

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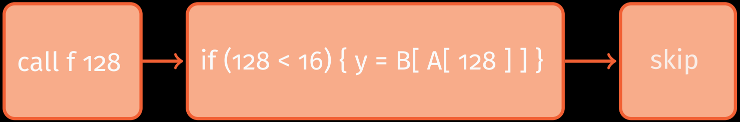
run 1: A.size = 16, A[128] = 3



call f 128

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

skip

Speculative Semantics & SNI

Guarnieri *et al.* S&P'21

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

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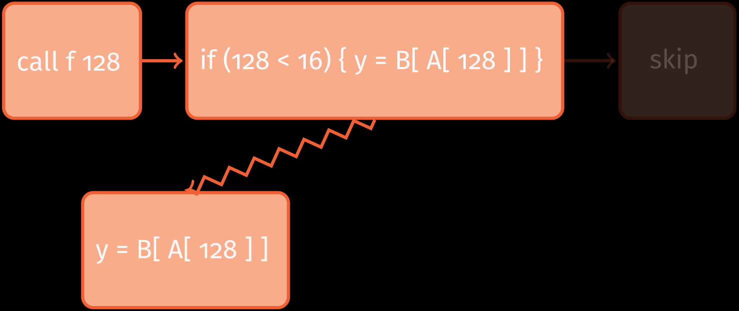

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Guarnieri *et al.* S&P'21

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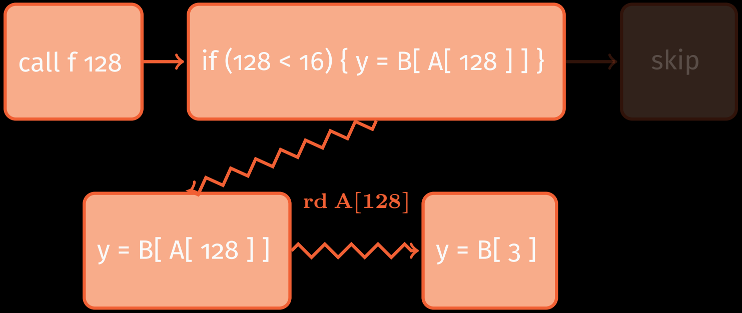

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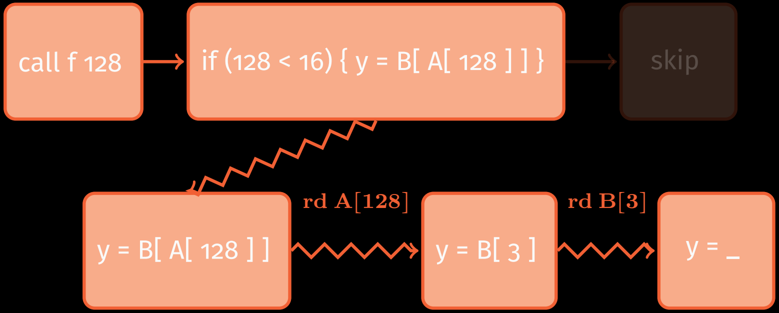

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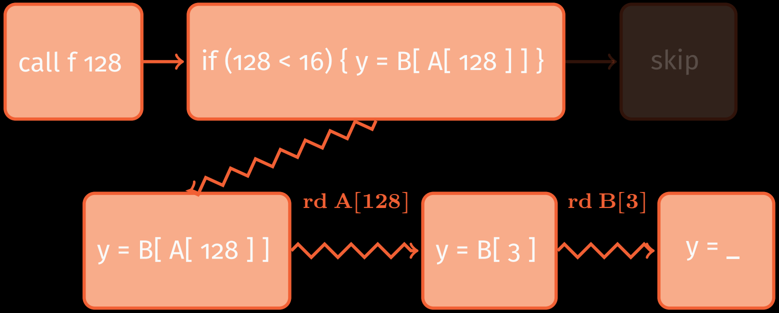

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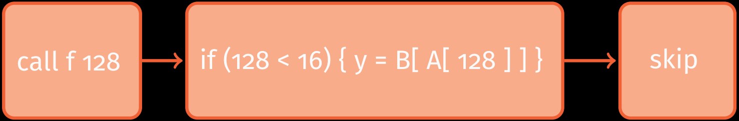


trace 1: $\mathbf{rd\ A[128]}$ $\mathbf{rd\ B[3]}$

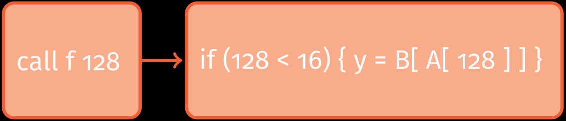
Speculative Semantics & SNI

Guarnieri *et al.* S&P'21

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

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

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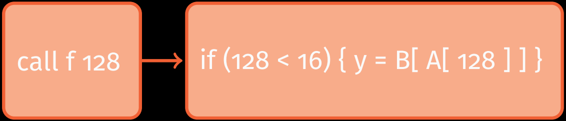

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$\mathbf{rd\ A[128]}$

Speculative Semantics & SNI

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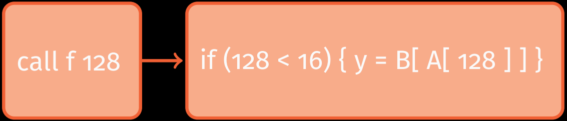

call f 128

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

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

$\mathbf{rd\ A[128]}$ $\mathbf{rd\ B[7]}$

Speculative Semantics & SNI

Guarnieri *et al.* S&P'21

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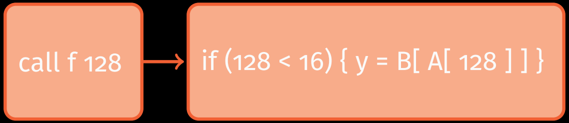

call f 128 → if (128 < 16) { y = B[A[128]] }

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

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

Speculative Semantics & SNI

Guarnieri *et al.* S&P'21

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

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

call f

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

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

Speculative Semantics & SNI

Guarnieri *et al.* S&P'21

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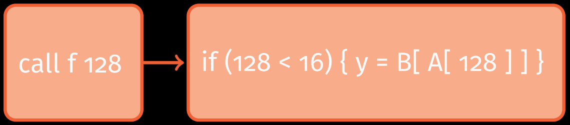
run 1: A.size = 16, A[128] = 3

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



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

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

Problems Problems Problems ...

Problem: Proving compiler preserves SNI is hard

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Solution: overapproximate SNI with a novel property: speculative safety (SS)

Speculative Safety (SS): 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

call f 128

pc : S

Speculative Safety (SS): Taint Tracking

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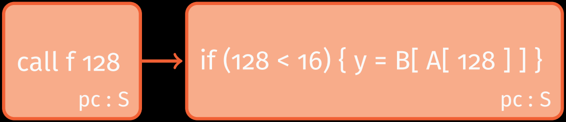

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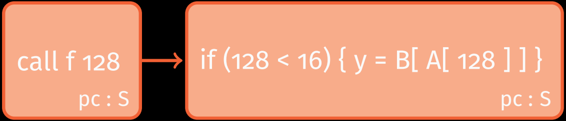

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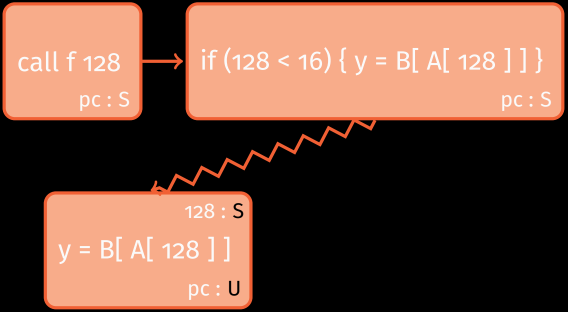

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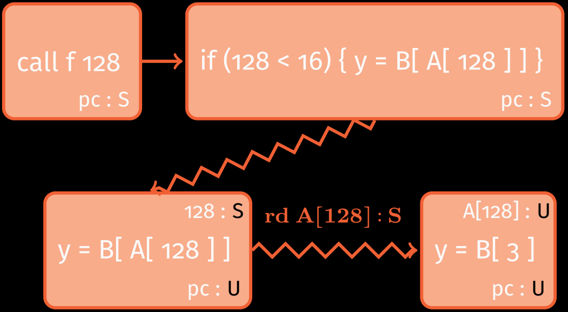

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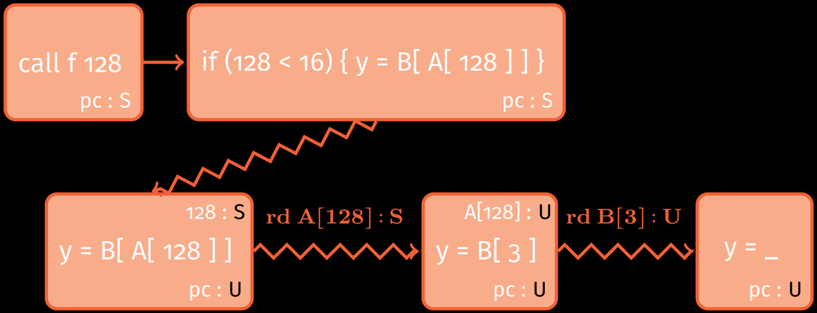
only 1 run needed: A.size=16, A[128]=3

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



call f 128

pc : S

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

pc : S

128 : S

y = B[A[128]]

pc : U

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

A[128] : U

y = B[3]

pc : U

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

y = _

pc : U

Speculative Safety (SS): Taint Tracking

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

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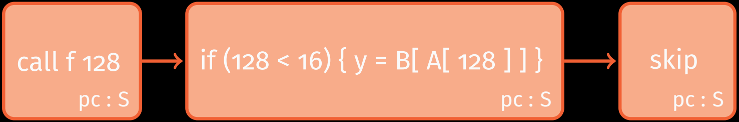


rd A[128] : S

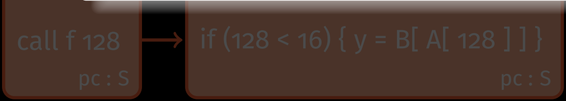
rd B[3] : U

Speculative Safety (SS): 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

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



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pc : S

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

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

Secure Compilation Framework for Spectre

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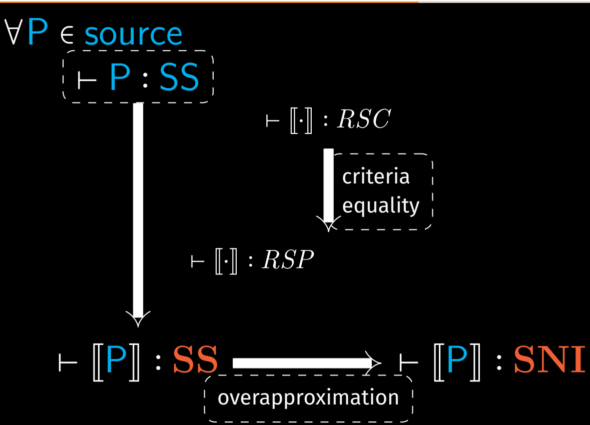


$\forall P \in$ source

$\vdash P : SS$

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

criteria
equality

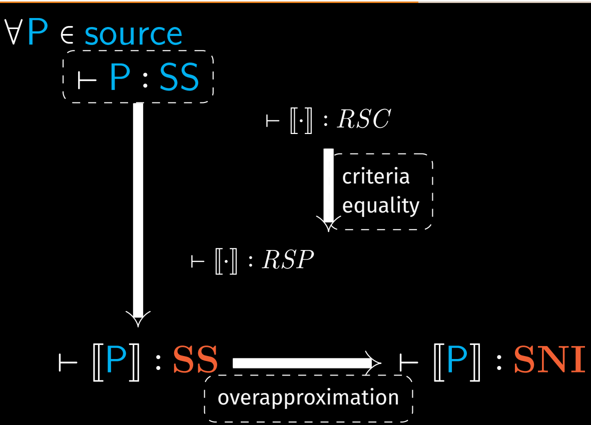
$\vdash [\![\cdot]\!] : RSP$

$\vdash [\![P]\!] : SS$

$\vdash [\![P]\!] : SNI$

overapproximation

Secure Compilation Framework for Spectre



$\forall$P $\in$ source

$\vdash$ P : SS

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

criteria equality

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

$\vdash [\![\mathrm{P}]\!] : \mathbf{SS}$

overapproximation

$\vdash [\![\mathrm{P}]\!] : \mathbf{SNI}$

- dashed premises are already discharged

Secure Compilation Framework for Spectre

$\forall P \in \text{source}$

$$\begin{tikzcd}
\vdash P : \mathrm{SS} \arrow[dd] & & \vdash \llbracket\cdot\rrbracket : RSC \arrow[d, "\text{criteria equality}"] \\
& \vdash \llbracket\cdot\rrbracket : RSP & \\
\vdash \llbracket P \rrbracket : \mathrm{SS} \arrow[rr, "\text{overapproximation}"'] & & \vdash \llbracket P \rrbracket : \mathbf{SNI}
\end{tikzcd}$$

- dashed premises are already discharged
- to show security: simply prove RSC

RSC **for** `lfence`

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

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

call f 128

pc : S

RSC for `lfence`

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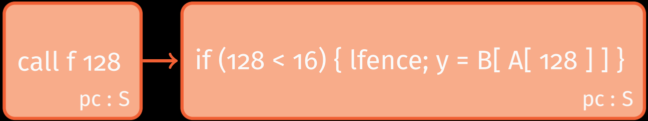

call f 128

pc : S

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

pc : S

RSC **for** `lfence`

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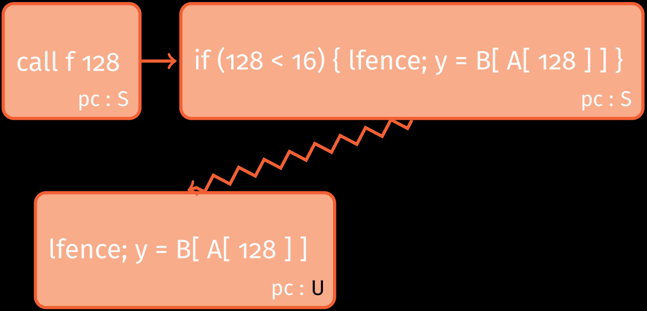

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if (128 < 16) { lfence; y = B[A[128]] }
pc : S
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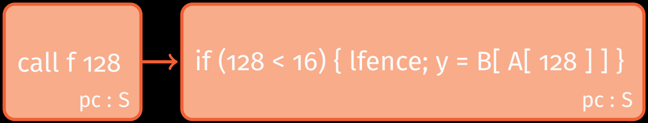

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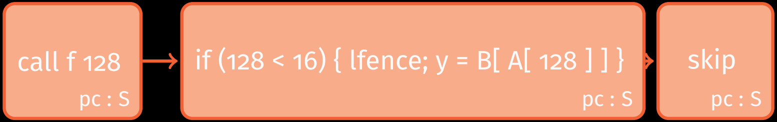
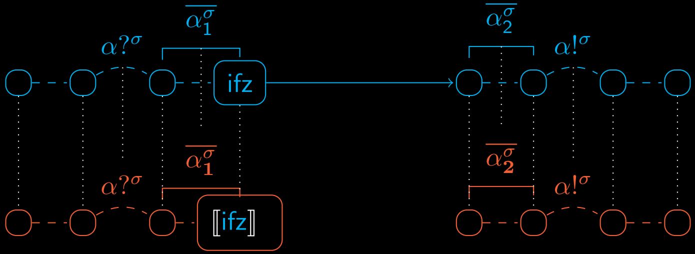
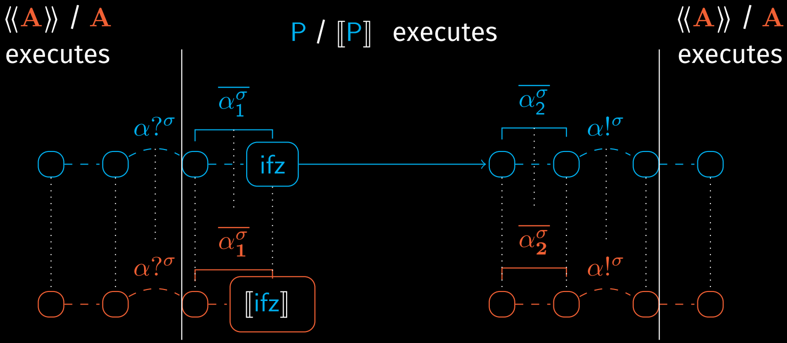


Proofs Insight

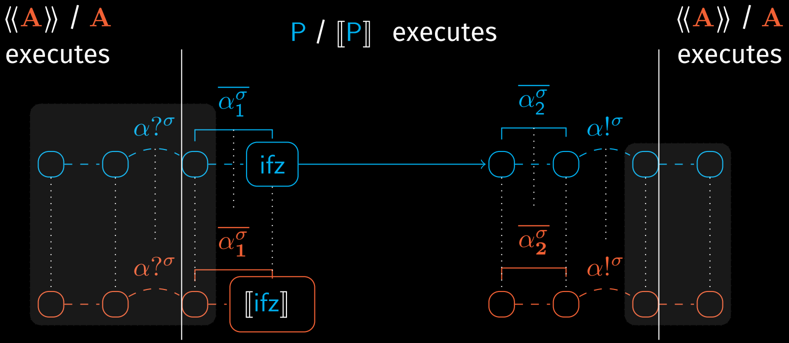

$\overline{\alpha_1^\sigma}$
$\alpha?^\sigma$
ifz
$\overline{\alpha_2^\sigma}$
$\alpha!^\sigma$
$\overline{\alpha_{\mathbf{1}}^\sigma}$
$\alpha?^\sigma$
$[\![\text{ifz}]\!]$
$\overline{\alpha_{\mathbf{2}}^\sigma}$
$\alpha!^\sigma$

Proofs Insight



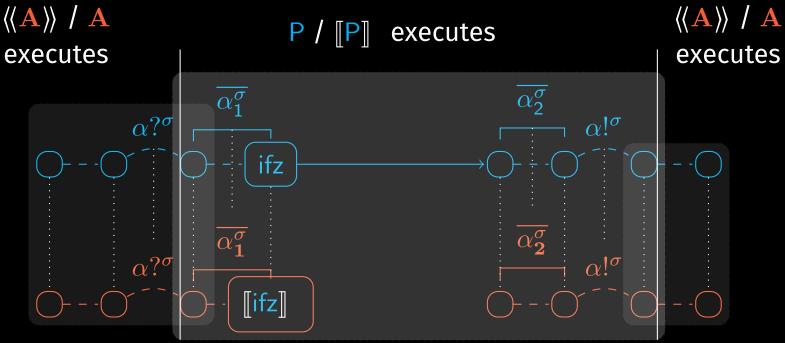
$\langle\!\langle \mathbf{A} \rangle\!\rangle$ / $\mathbf{A}$ executes
P / ⟦P⟧ executes
$\langle\!\langle \mathbf{A} \rangle\!\rangle$ / $\mathbf{A}$ executes
$\overline{\alpha_1^\sigma}$
$\overline{\alpha_2^\sigma}$
$\alpha?^\sigma$
$\alpha!^\sigma$
ifz
$\overline{\alpha_{\mathbf{1}}^\sigma}$
$\overline{\alpha_{\mathbf{2}}^\sigma}$
$\alpha?^\sigma$
$\alpha!^\sigma$
⟦ifz⟧

Proofs Insight



$\langle\!\langle \mathbf{A} \rangle\!\rangle$ / $\mathbf{A}$ executes
P / ⟦P⟧ executes
$\langle\!\langle \mathbf{A} \rangle\!\rangle$ / $\mathbf{A}$ executes
$\overline{\alpha_1^\sigma}$
$\overline{\alpha_2^\sigma}$
$\alpha?^\sigma$
$\alpha!^\sigma$
ifz
$\overline{\alpha_1^\sigma}$
$\overline{\alpha_2^\sigma}$
$\alpha?^\sigma$
$\alpha!^\sigma$
⟦ifz⟧

Proofs Insight



$\langle\!\langle \mathbf{A} \rangle\!\rangle$ / $\mathbf{A}$
executes
P / ⟦P⟧ executes
$\langle\!\langle \mathbf{A} \rangle\!\rangle$ / $\mathbf{A}$
executes
$\overline{\alpha_1^\sigma}$
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ifz
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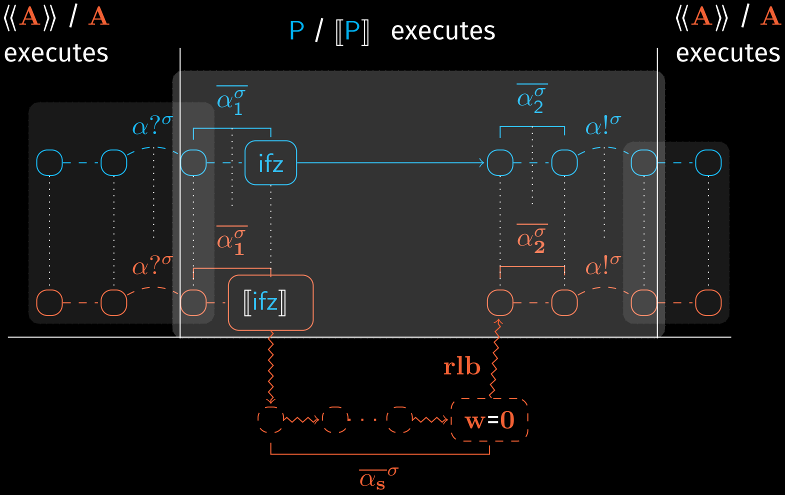
$\overline{\alpha_{\mathbf{1}}^\sigma}$
$\overline{\alpha_{\mathbf{2}}^\sigma}$
$\alpha?^\sigma$
⟦ifz⟧
$\alpha!^\sigma$

Proofs Insight



$\langle\!\langle \mathbf{A} \rangle\!\rangle$ / $\mathbf{A}$ executes

P / $[\![\mathrm{P}]\!]$ executes

$\langle\!\langle \mathbf{A} \rangle\!\rangle$ / $\mathbf{A}$ executes

$\overline{\alpha_1^\sigma}$

$\overline{\alpha_2^\sigma}$

$\alpha?^\sigma$

$\alpha!^\sigma$

ifz

$\overline{\alpha_{\mathbf{1}}^\sigma}$

$\overline{\alpha_{\mathbf{2}}^\sigma}$

$\alpha?^\sigma$

$\alpha!^\sigma$

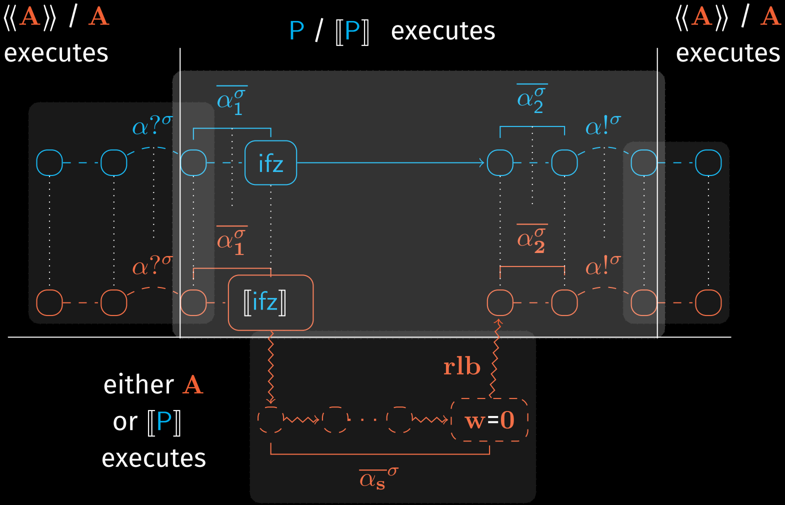
$[\![\mathrm{ifz}]\!]$

rlb

w=0

$\overline{\alpha_{\mathbf{s}}}^\sigma$

Proofs Insight



$\langle\!\langle \mathbf{A} \rangle\!\rangle$ / $\mathbf{A}$ executes
P / ⟦P⟧ executes
$\langle\!\langle \mathbf{A} \rangle\!\rangle$ / $\mathbf{A}$ executes
$\overline{\alpha_1^\sigma}$
$\overline{\alpha_2^\sigma}$
$\alpha?^\sigma$
$\alpha!^\sigma$
ifz
$\overline{\alpha_1^\sigma}$
$\overline{\alpha_2^\sigma}$
$\alpha?^\sigma$
$\alpha!^\sigma$
⟦ifz⟧
either $\mathbf{A}$ or ⟦P⟧ executes
rlb
$\mathbf{w}=\mathbf{0}$
$\overline{\alpha_\mathbf{s}}^\sigma$

What Then?

- SNIv1, SNIv2, SNIv4, SNIv5

Kocher *et al.* S&P'19

What Then?

- SNIv1, SNIv2, SNIv4, SNIv5

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- Challenge: can we compose lfence(SNIv1) and retpoline(SNIv5)?

Security Architectures

(e.g., Cheri/ARM Morello, Sancus/Intel SGX, …) Toplas'15, CSF'21, …

Mechanise Cryptographic Proofs

CSF’24 + wip

Robust Hyperproperty Preservation

$$\llbracket\cdot\rrbracket \vdash \mathsf{RHP} \overset{\mathsf{def}}{=} \forall \mathsf{P}, \mathbf{A}.\ \exists \mathsf{A}.\ \forall t.$$

$$\mathbf{A}\left[\llbracket \mathsf{P} \rrbracket\right] \rightsquigarrow t \iff \mathsf{A}\left[\mathsf{P}\right] \rightsquigarrow t$$

Robust Hyperproperty Preservation

$$\begin{tikzcd}
& t & & & & t & \\
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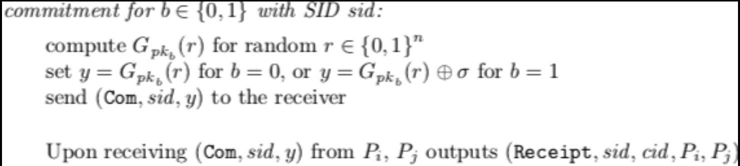
This talk: generic flavour, geared towards the newer theories

UC Base Notions: ITMs

Canetti and Fischlin Crypto'01

- protocols Π (using concrete crypto)



commitment for $b \in \{0,1\}$ *with SID sid:*

```
    compute $G_{pk_b}(r)$ for random $r \in \{0,1\}^n$
    set $y = G_{pk_b}(r)$ for $b = 0$, or $y = G_{pk_b}(r) \oplus \sigma$ for $b = 1$
    send $(\texttt{Com}, sid, y)$ to the receiver

    Upon receiving $(\texttt{Com}, sid, y)$ from $P_i$, $P_j$ outputs $(\texttt{Receipt}, sid, cid, P_i, P_j)$
```

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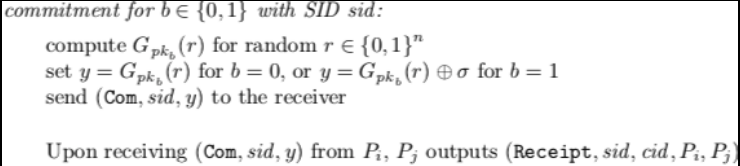

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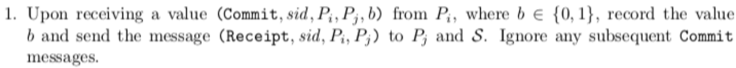
- functionalities F (using abstract notions)



1. Upon receiving a value $(\texttt{Commit}, sid, P_i, P_j, b)$ from P_i, where $b \in \{0,1\}$, record the value b and send the message $(\texttt{Receipt}, sid, P_i, P_j)$ to P_j and $\mathcal{S}$. Ignore any subsequent Commit messages.

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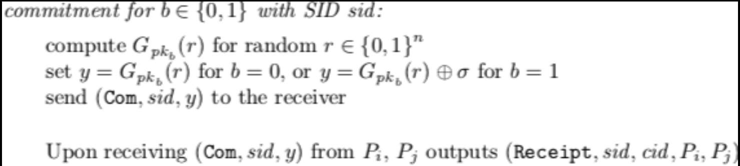

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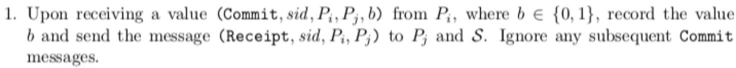

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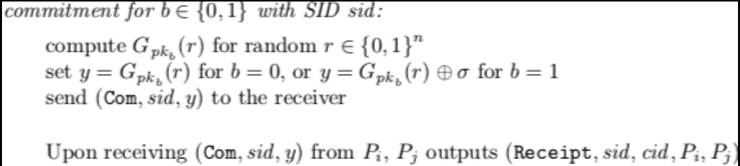

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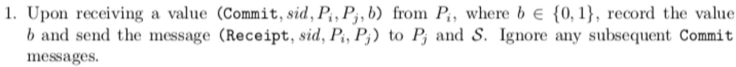

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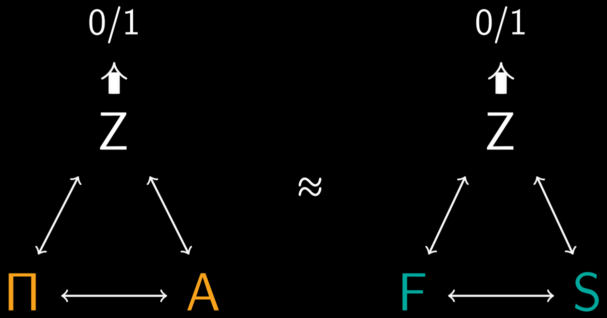
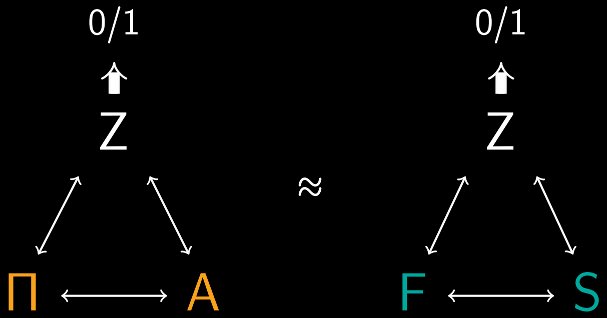
- environments Z (objective witness)

UC (Semi-formally)



↔ represent communication channels

UC (Semi-formally)



↔ represent communication channels

$$\Pi \vdash_{UC} F \overset{\text{def}}{=} \forall \text{poly } A, \exists S, \forall Z.$$
$$\text{Exec}[Z, A, \Pi] \approx \text{Exec}[Z, S, F]$$

A Closer Look

$$\forall \text{poly } A, \exists S, \forall Z.$$

$$\begin{tikzcd}
 & 0/1 & & & & 0/1 & \\
 & Z \arrow[u, Rightarrow] \arrow[dl, leftrightarrow] \arrow[dr, leftrightarrow] & & & & Z \arrow[u, Rightarrow] \arrow[dl, leftrightarrow] \arrow[dr, leftrightarrow] & \\
\Pi \arrow[rr, leftrightarrow] & & A & \approx & F \arrow[rr, leftrightarrow] & & S
\end{tikzcd}$$

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\end{tikzcd}$$

Isabelle’d both perfect and computational UC

Analogy

UC		*SC*	
protocol	Π	$\llbracket P \rrbracket$	compiled program
concrete attacker	A	$\mathbf{A}$	target context
ideal functionality	F	P	source program
simulator	S	A	source context
environment, output	Z, $0/1$	t, $\rightsquigarrow$	trace, semantics
communication	$\leftrightarrow$	$[\,]$	linking
probabilistic equiv.	$\approx$	$\Longleftrightarrow$	trace equality

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human translation $\Pi \to F$		$[\![\cdot]\!]$: $P \to \mathbf{P}$ compiler	
general composition result		$\ldots$	

Analogy Results

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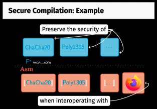
- Mechanised UC for 1-Bit Commitment in `Deepsec` submission
- Mechanised UC for 1/2 Wireguard in `Cryptoverif` CSF'24

Conclusion

Conclusion

- secure compilation threat model



Secure Compilation: Example

Preserve the security of

ChaCha20

Poly1305

· · ·

F*

HACL*: ... CCS'17

Asm

[ChaCha20]

[Poly1305]

[. . .]

when interoperating with

Conclusion

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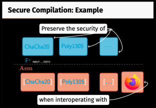

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Preserve the security of

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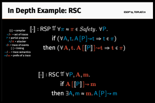

In Depth Example: RSC

ESOP'19, TOPLAS'21

⟦·⟧ = compiler
π / π = set of traces
P = partial program
A / A = attacker
t / t = trace of events
[·] = linking
⇝ / ⇝ = trace semantics
m / m = prefix of a trace

$$\llbracket\cdot\rrbracket : \mathrm{RSP} \overset{\mathrm{def}}{=} \forall \pi \approx \pi \in \mathit{Safety}.\ \forall \mathrm{P}.\ \text{if } (\forall \mathrm{A}, \mathrm{t}.\ \mathrm{A}[\mathrm{P}] \rightsquigarrow \mathrm{t} \Rightarrow \mathrm{t} \in \pi)\ \text{then } (\forall \mathrm{A}, \mathrm{t}.\ \mathrm{A}[\llbracket \mathrm{P} \rrbracket] \rightsquigarrow \mathrm{t} \Rightarrow \mathrm{t} \in \pi)$$

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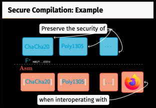

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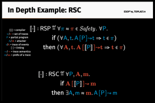

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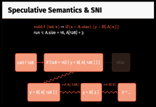
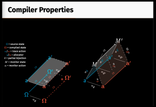
- robust compilation use-cases (MS, CT, SNI)



Speculative Semantics & SNI

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

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



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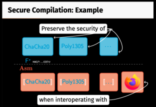

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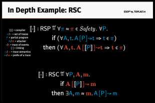

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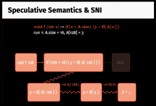

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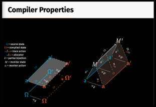

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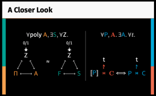
- connection with UC



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Future

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Come to PRISC’25, co-located with POPL’25.

Questions?