Secure Compilation: Formal Foundations and (Some) Applications

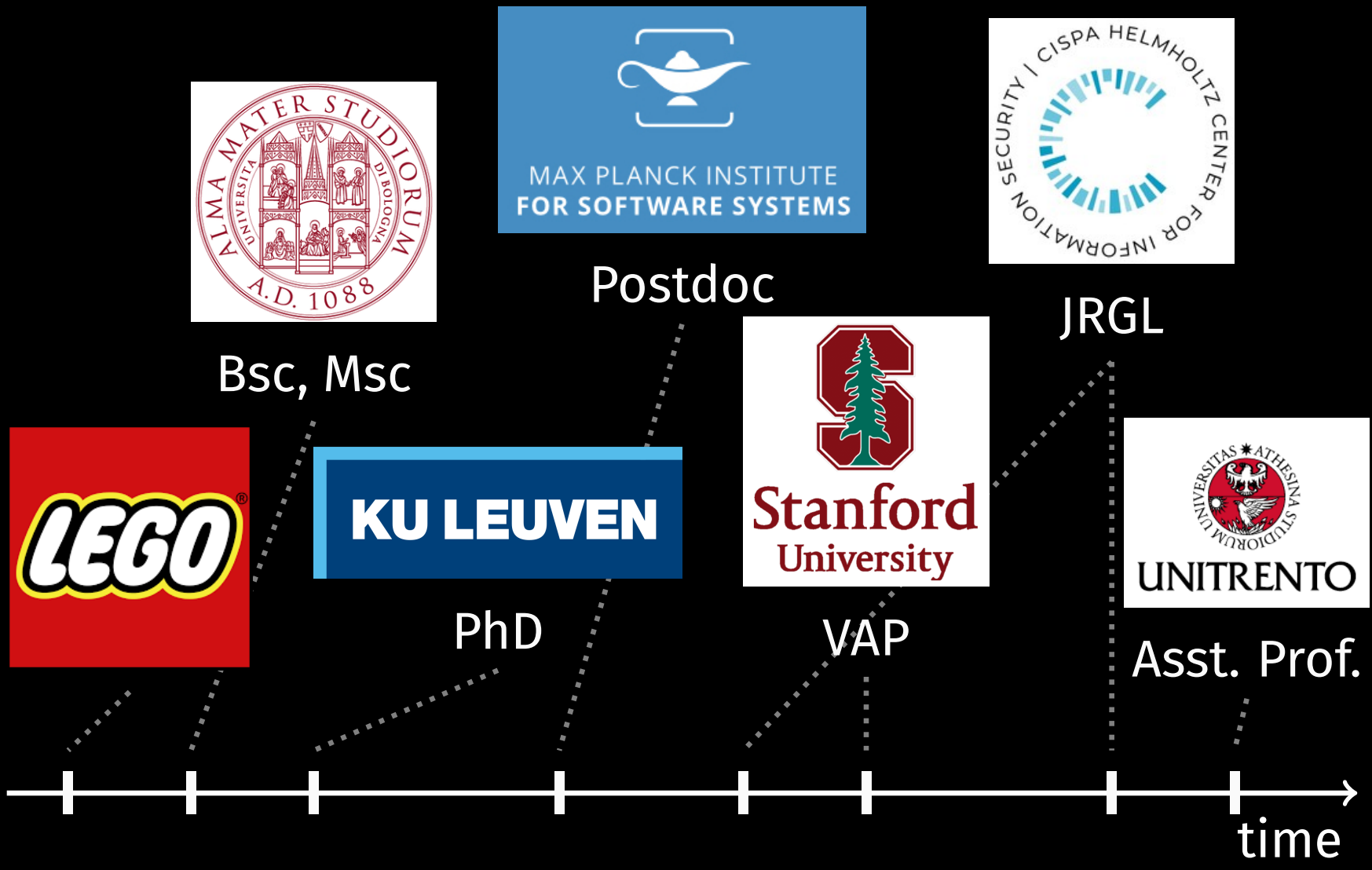
Marco Patrignani[1]

03 April 2024

1 UNIVERSITÀ DI TRENTO

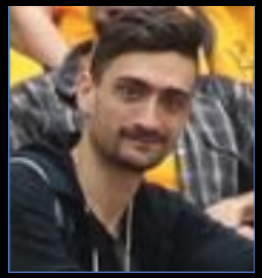
Who Am I ?

Marco Patrignani



Special Thanks to:

(wrt the contents of this talk)





















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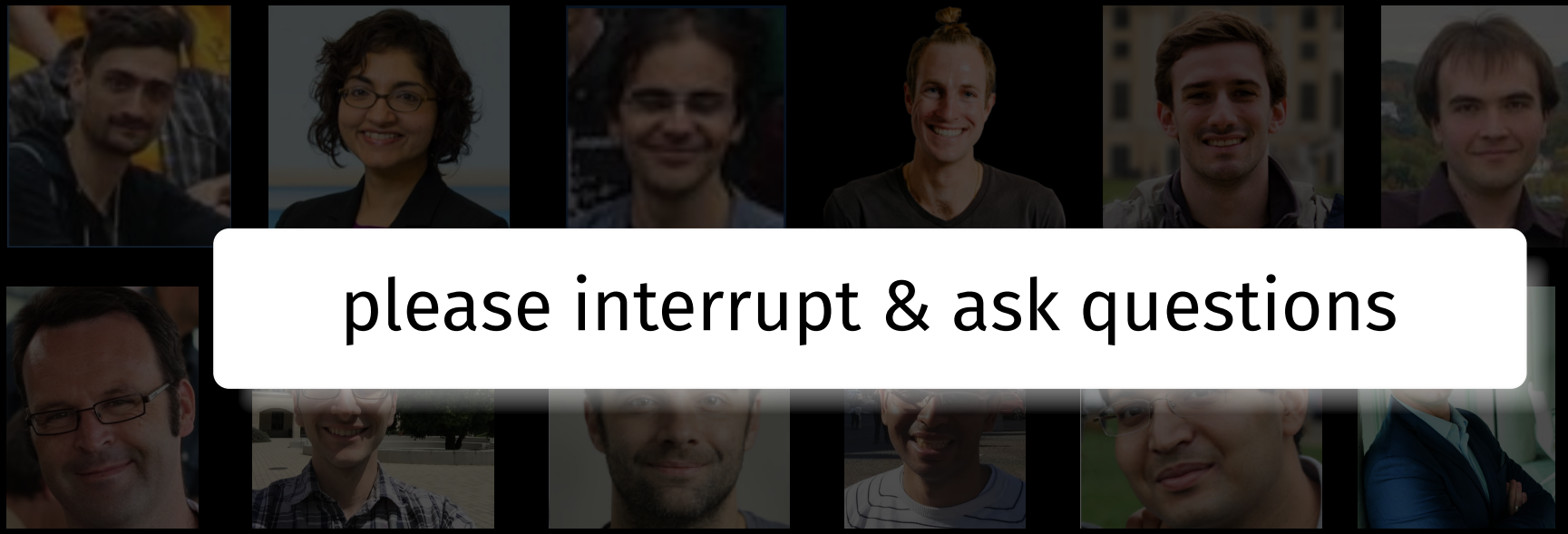

please interrupt & ask questions

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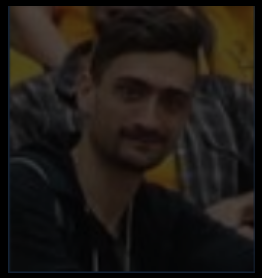
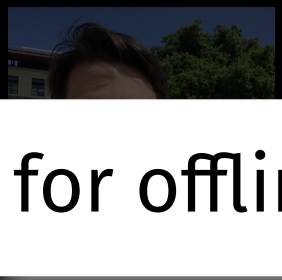
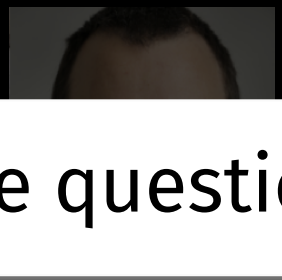
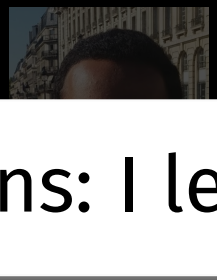
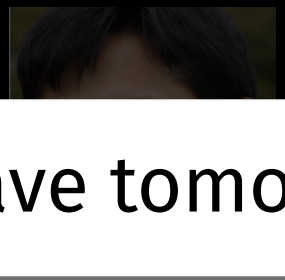
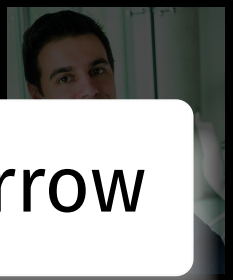


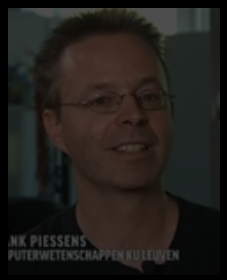




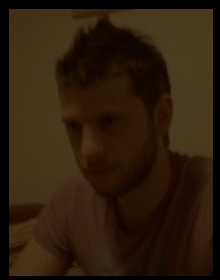
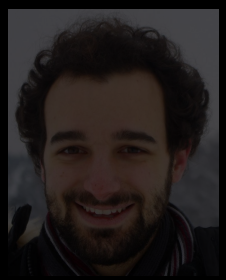







for offline questions: I leave tomorrow






Foundations of Secure Compilation

Programming Languages: Pros and Cons

Good PLs ( , 

,  ,  , ...) provide:

- helpful abstractions to write secure code

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Good PLs ( , 

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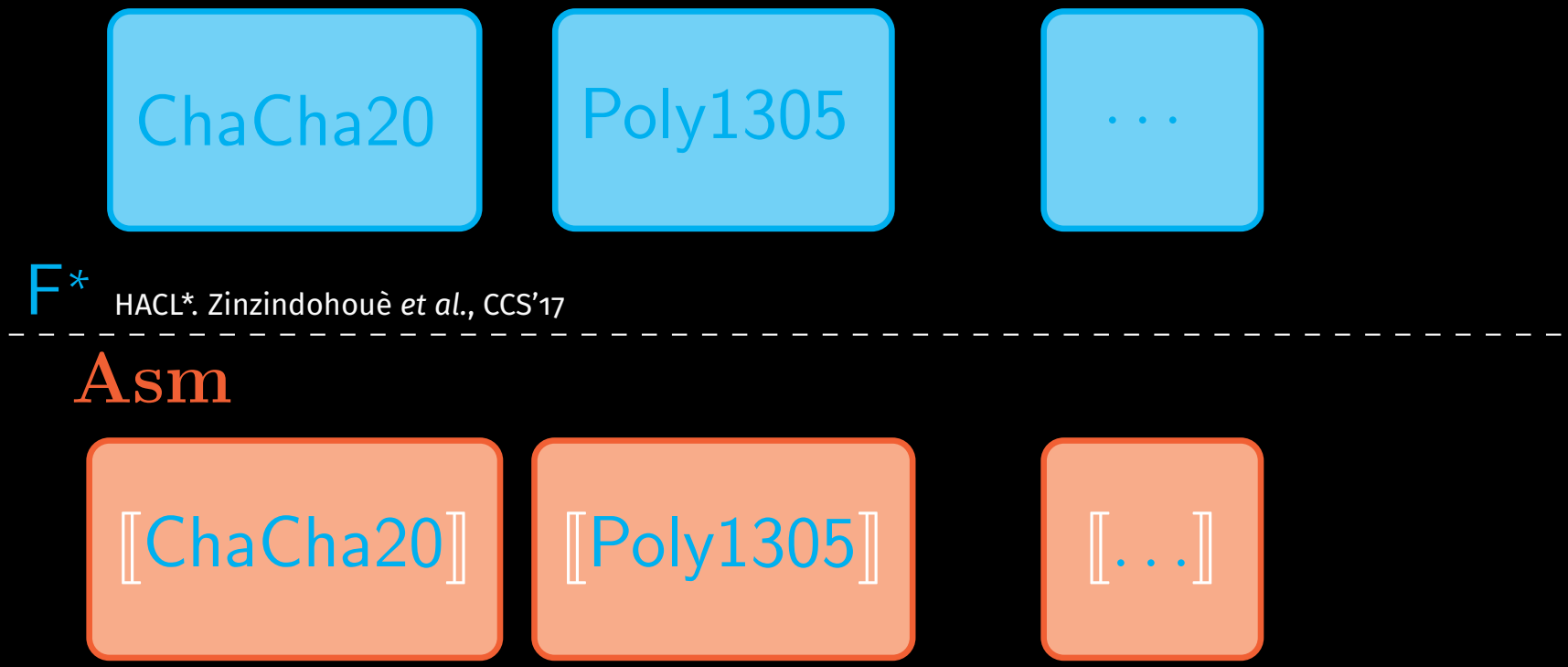
- when compiled ($[\![\cdot]\!]$) and linked with adversarial target code
- these abstractions are NOT enforced

Secure Compilation: Example



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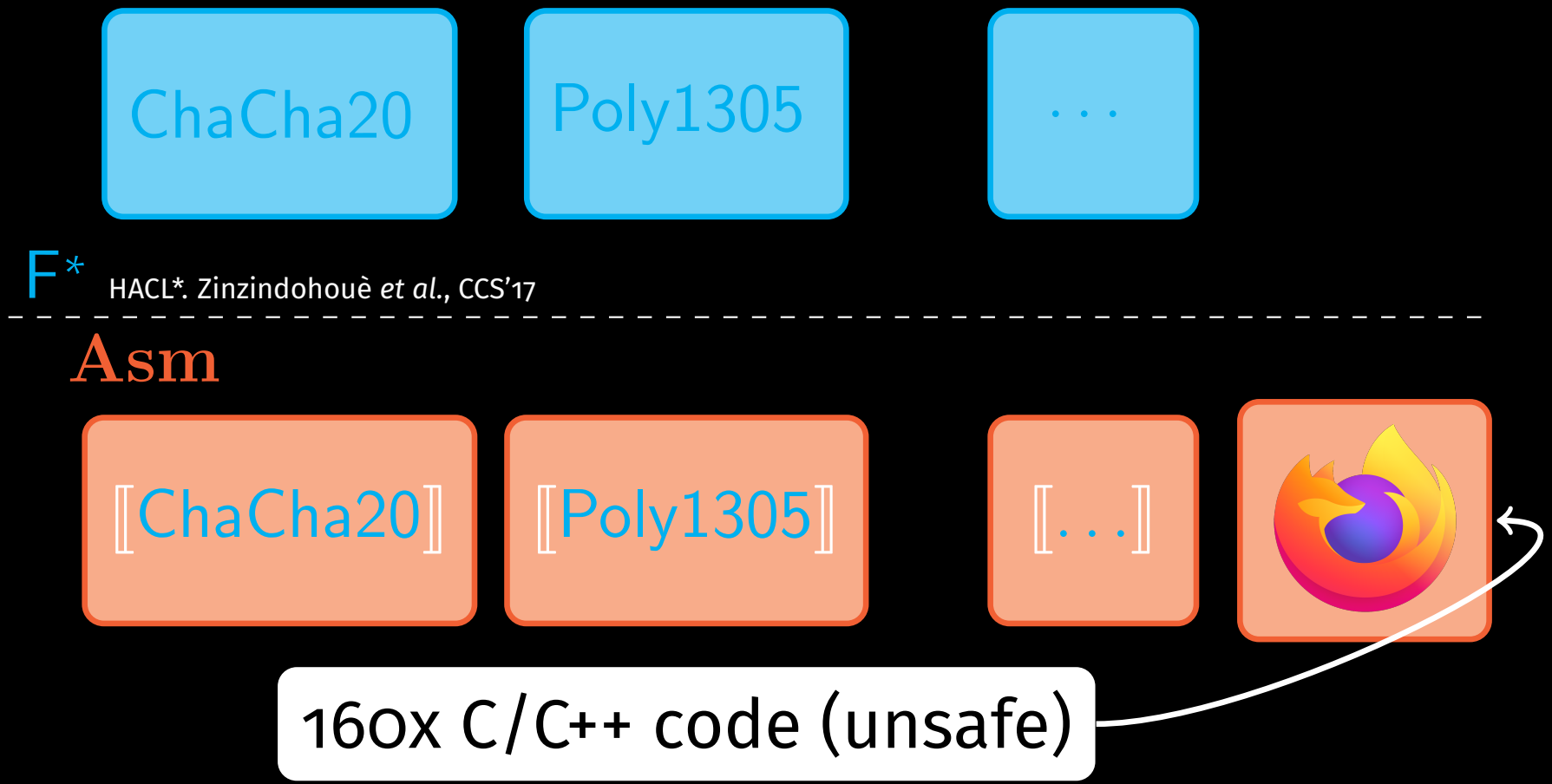

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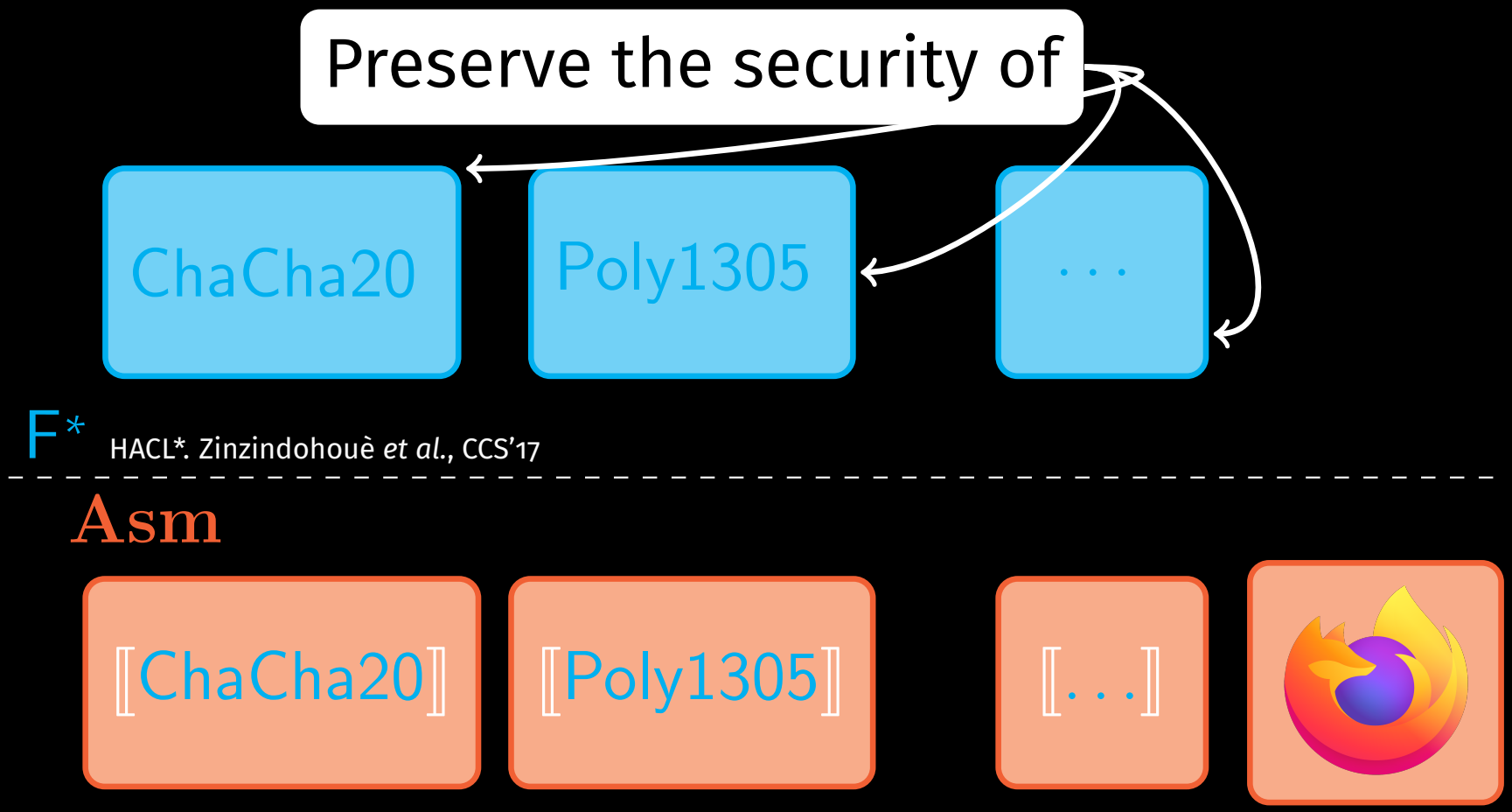

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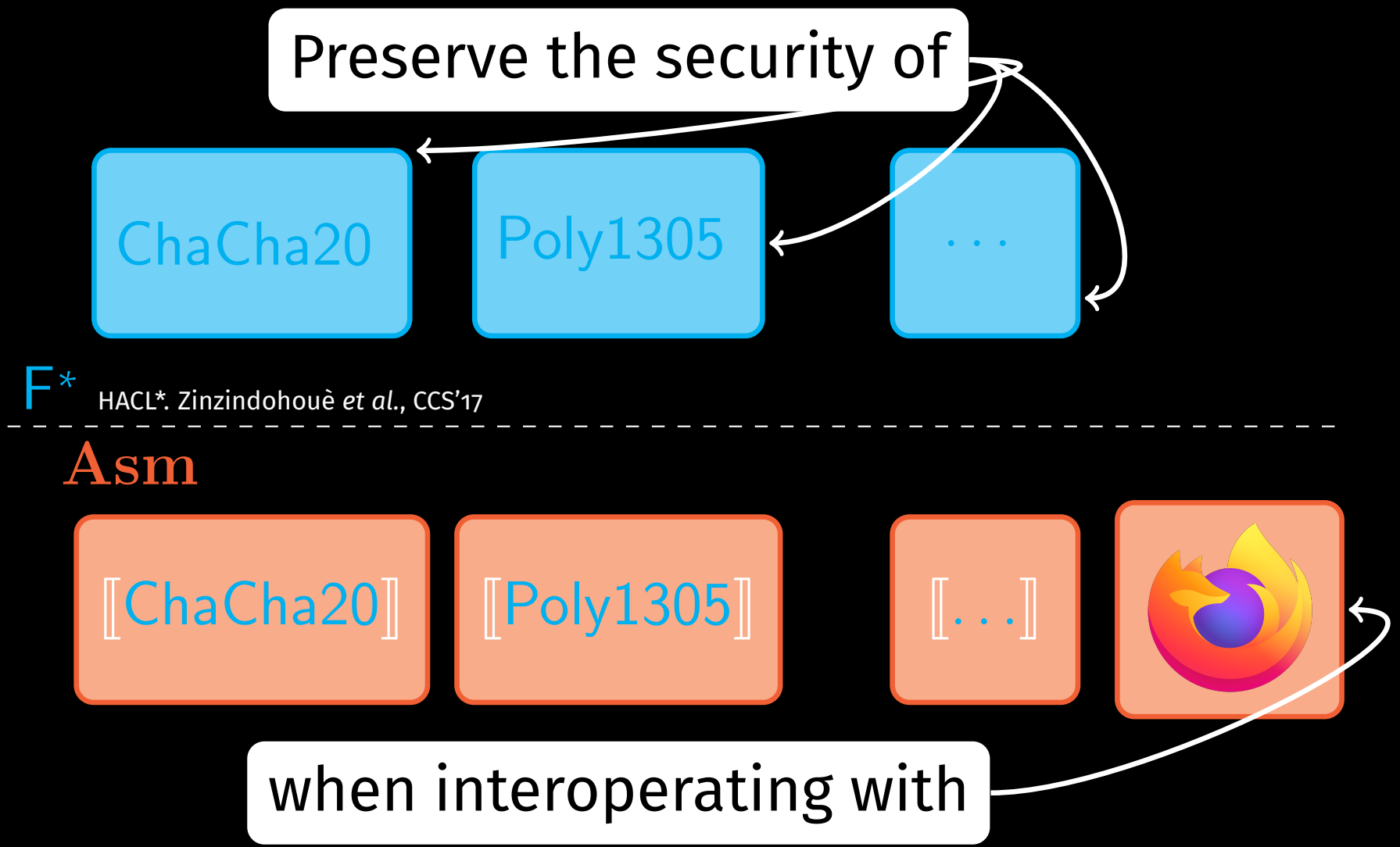

Secure Compilation: Example

Correct compilation

ChaCha20 | Poly1305 | . . .

F* HACL*. Zinzindohouè *et al.*, CCS'17

Asm

⟦ChaCha20⟧ | ⟦Poly1305⟧ | ⟦. . .⟧

Secure Compilation: Example

Secure compilation

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Secure Compilation: Example

Enable source-level security reasoning

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Quest for Foundations

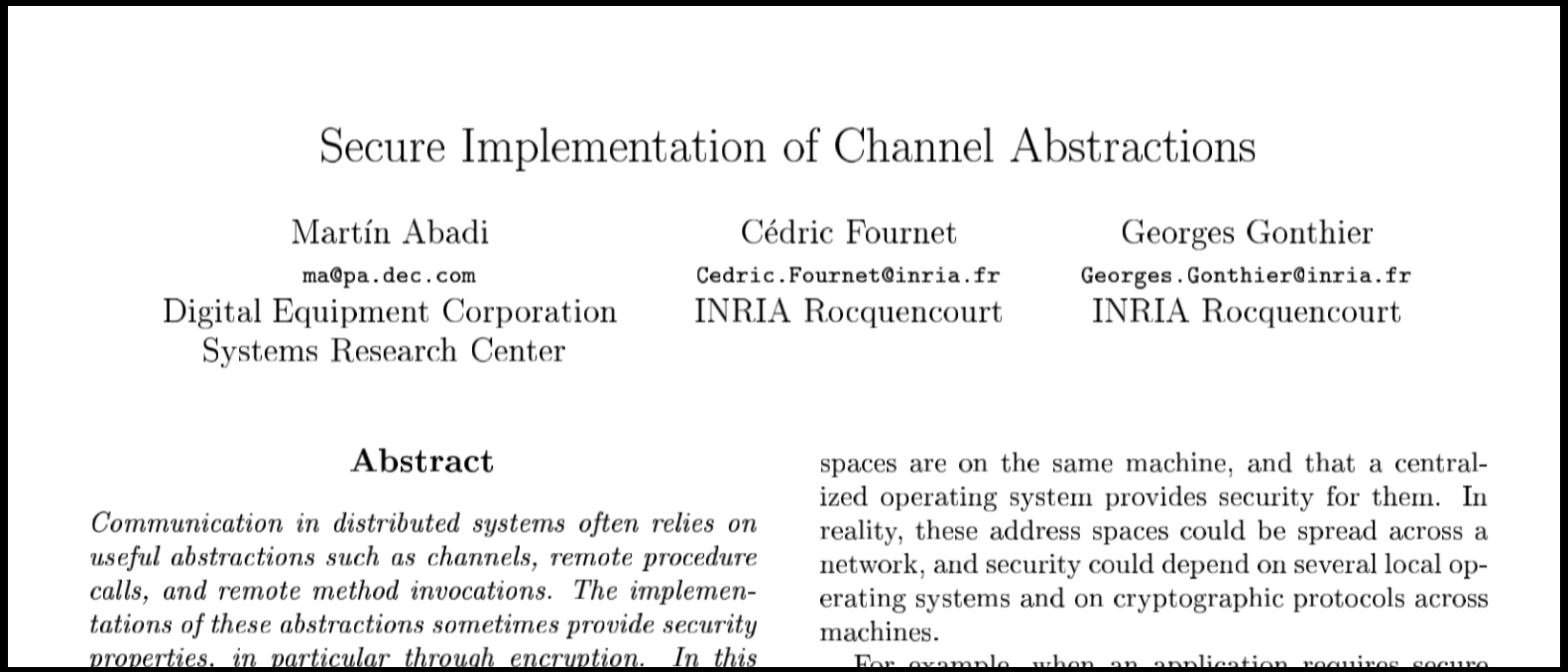
What does it mean for a compiler to be secure?

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

Martín Abadi
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Systems Research Center

Cédric Fournet
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INRIA Rocquencourt

Georges Gonthier
Georges.Gonthier@inria.fr
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

Fully Abstract Compilation to JavaScript

Secure Implementations for Typed Session Abstractions

Typed Closure Conversion Preserves Observational Equivalence

Amal Ahmed Matthias Blume
Toyota Technological Institute at Chicago
{amal,blume}@tti-c.org

Fully-Abstract Compilation by Approximate Back-Translation

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

Beyond Good and Evil

Formalizing the Security Guarantees of Compartmentalizing Compilation

Secure Compilation of Object-Oriented Components to Protected Module Architectures

Marco Patrignani, Dave Clarke, and Frank Piessens

iMinds-DistriNet, Dept. Computer Sci

A Secure Compiler for ML Module

Local Memory via Layout Randomization

James Riely

Corin Pitcher Julian Rathke
University of Southampton

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

Amal Ahmed

Matthias Blume
Google
blume@google.com

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

- FAC: useful for language expressiveness

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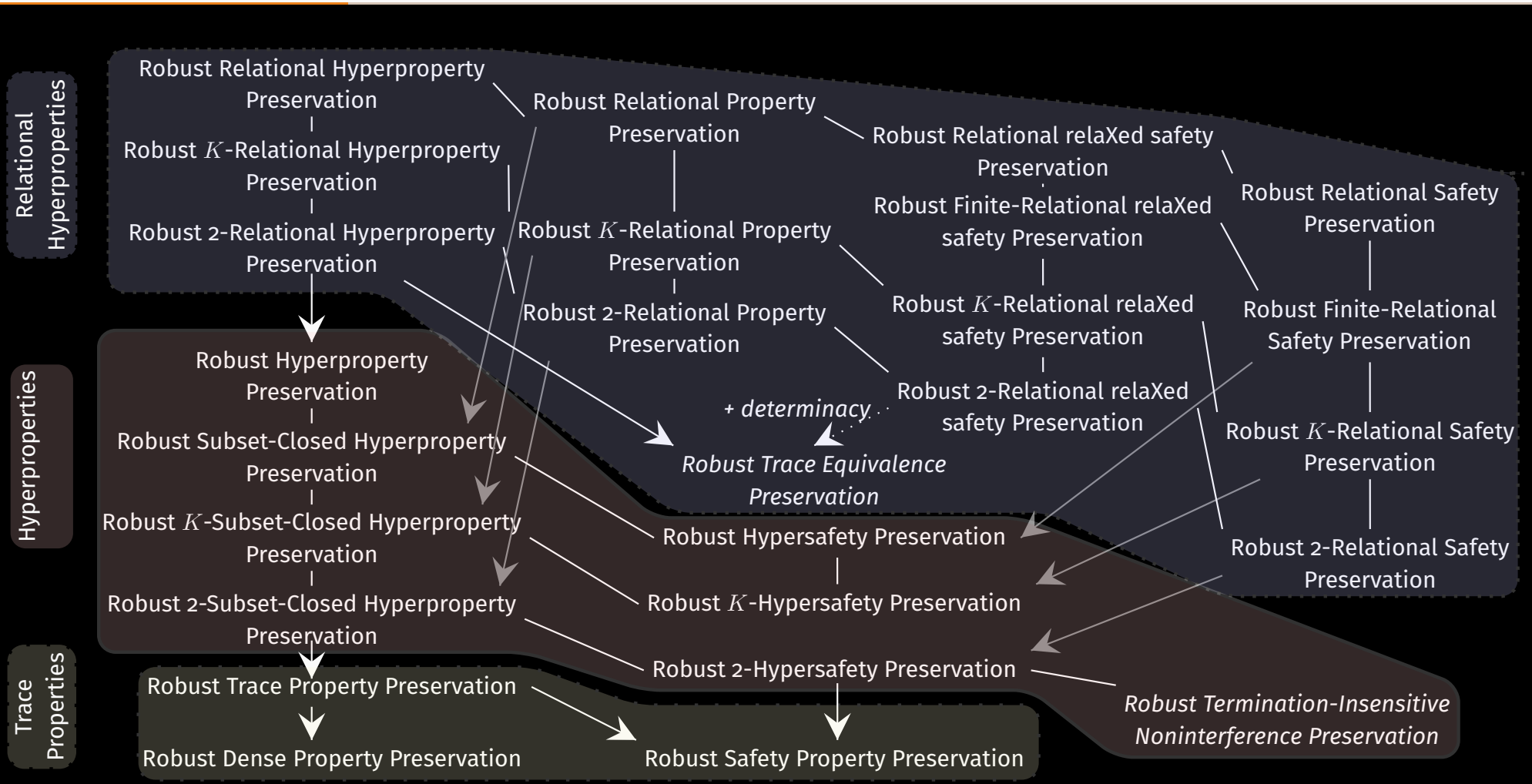
  preserve classes of (hyper)properties

Clarkson & Schneider JCS '10

Robust Compilation (RC) Criteria

CSF'19, ESOP'20, Toplas'21



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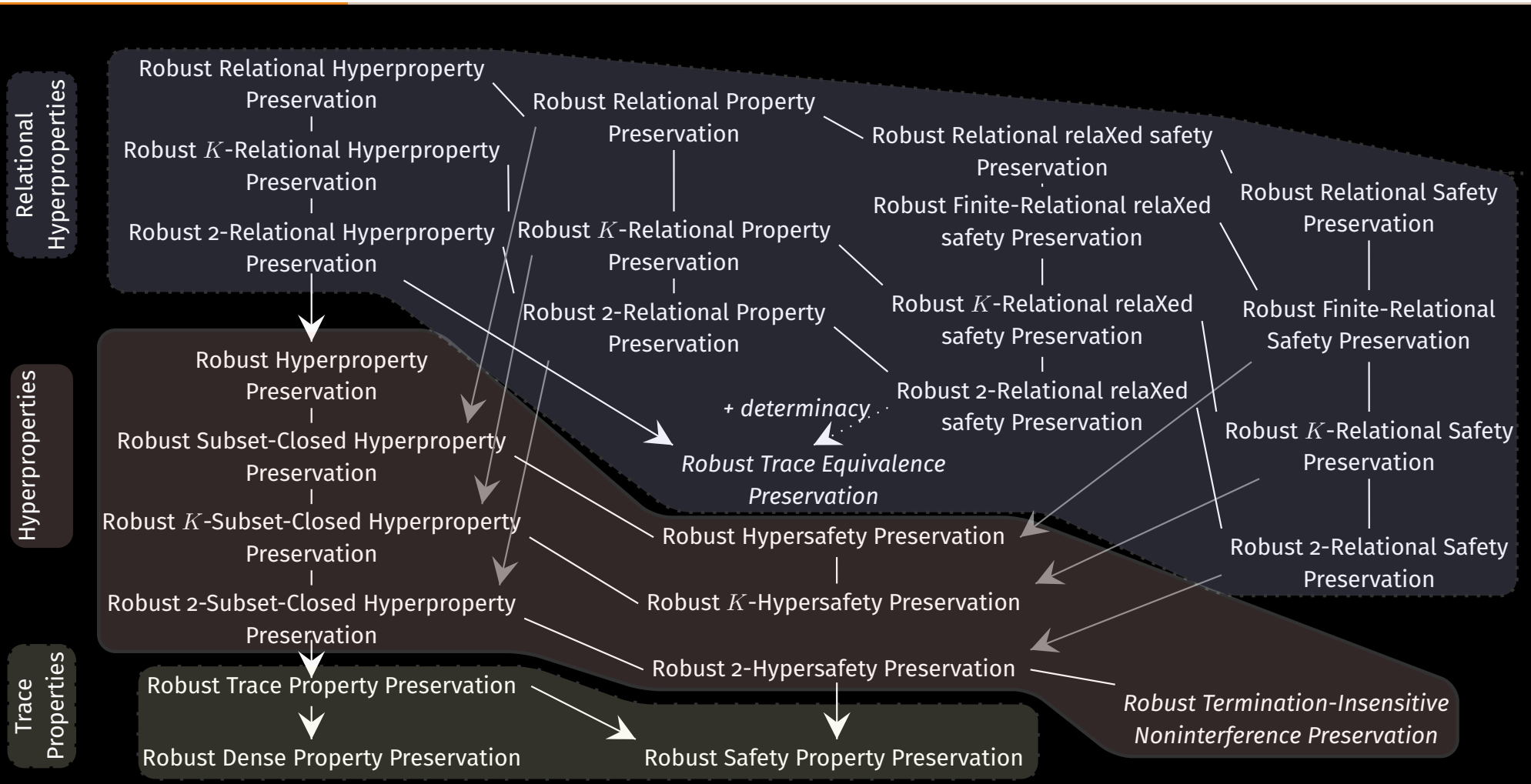

Tradeoffs for code efficiency, security guarantees, proof complexity

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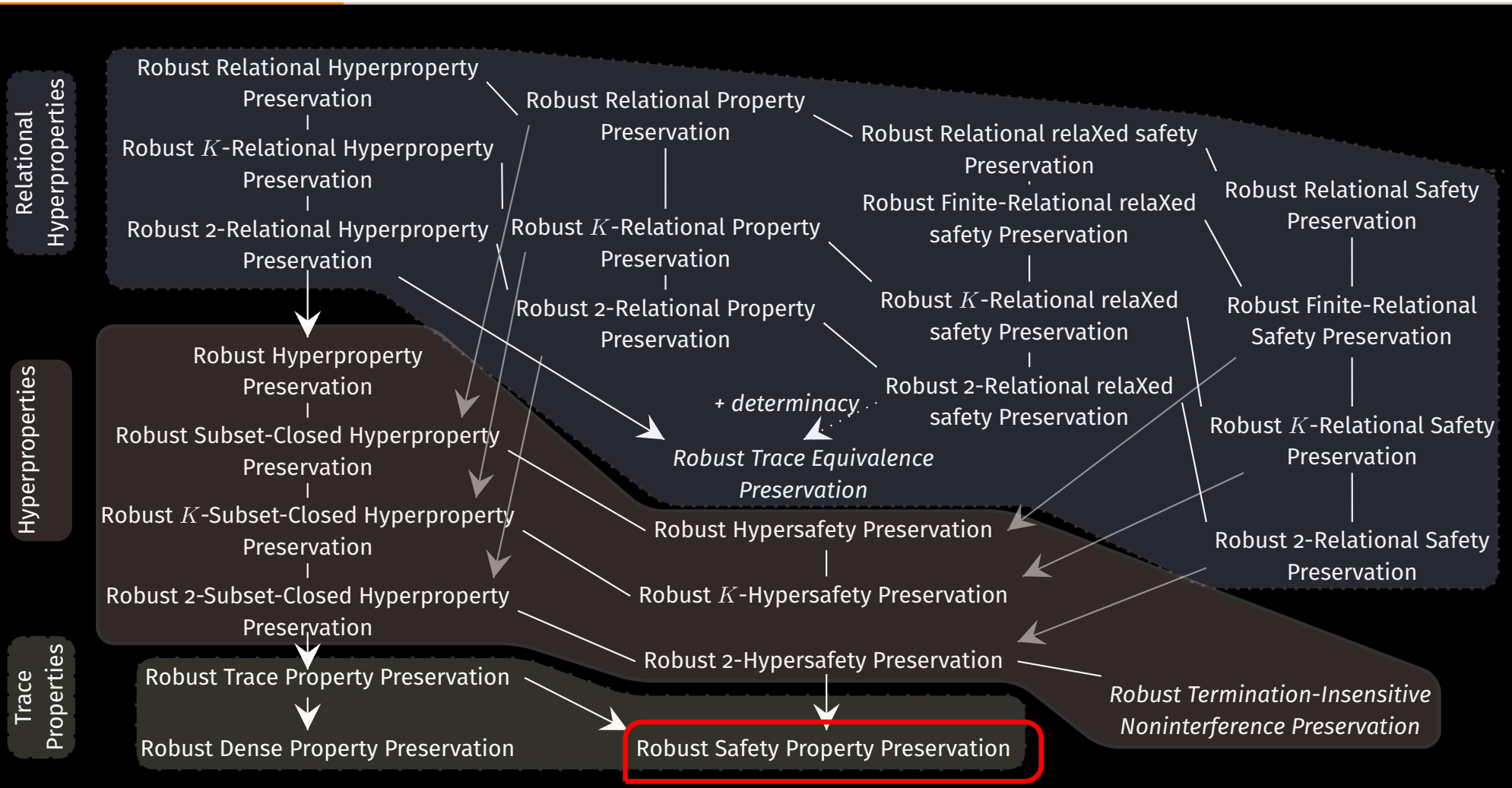

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Each point has two equivalent criteria:

- $\mathrm{Property} - \mathrm{ful}$:
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In Depth Example: RSC

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Secure Compilation Threat Model

- 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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What can we do with these foundations?

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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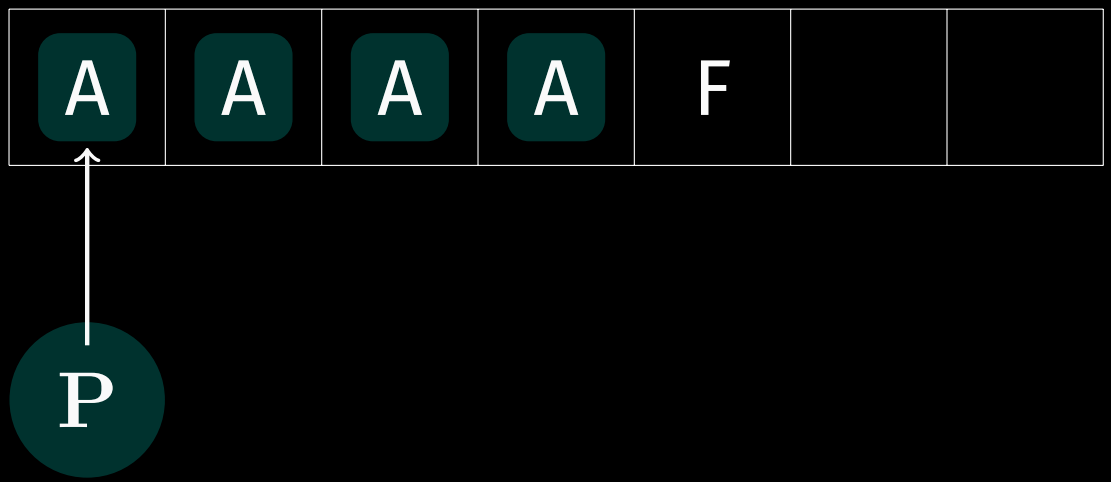

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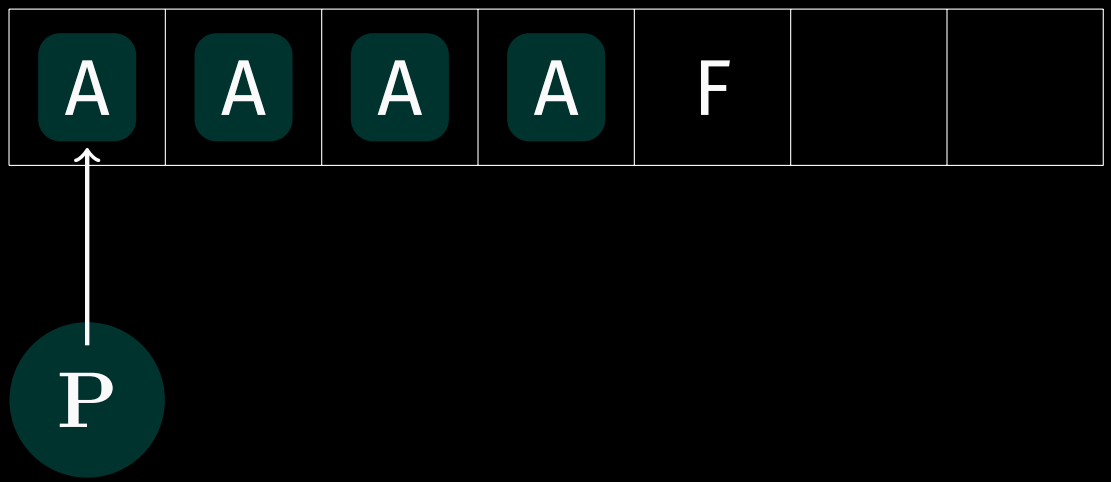

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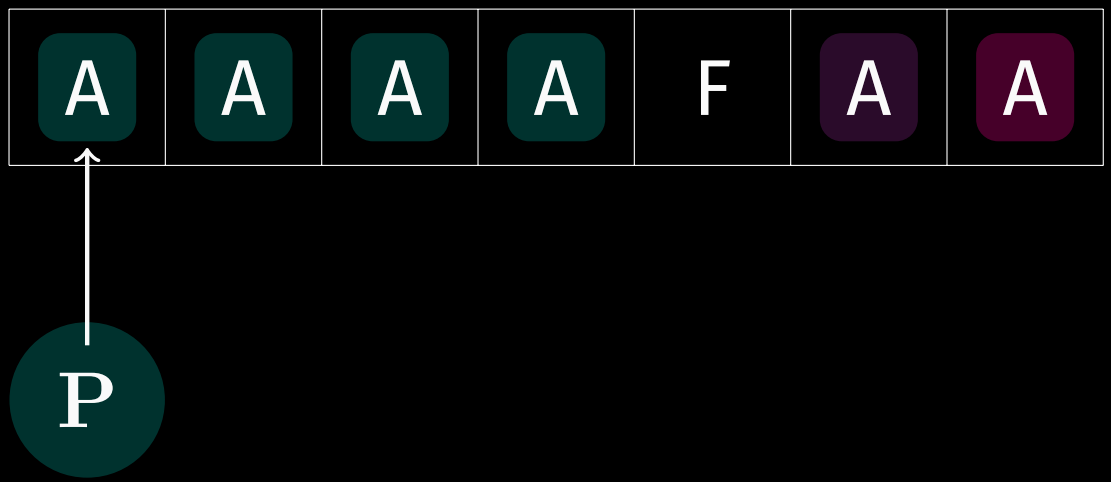

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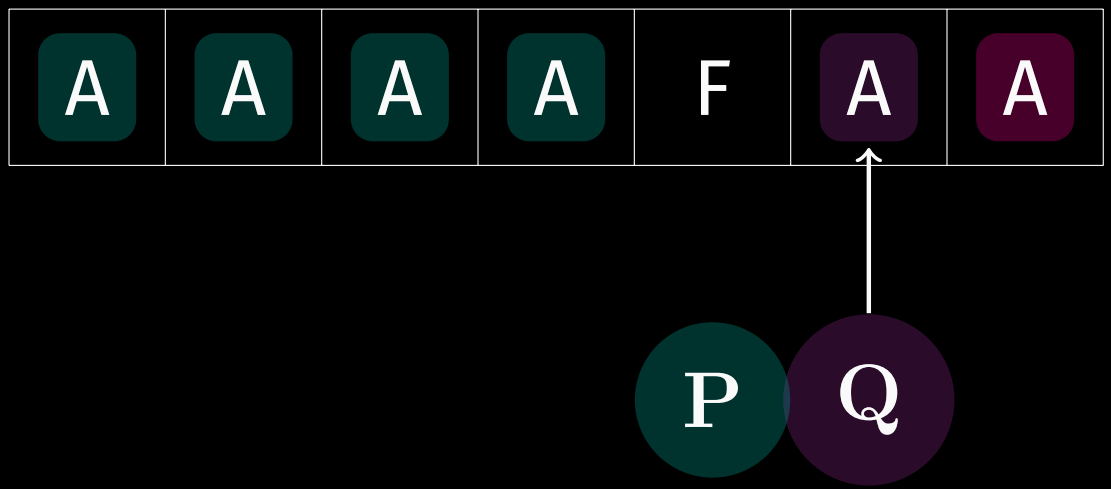

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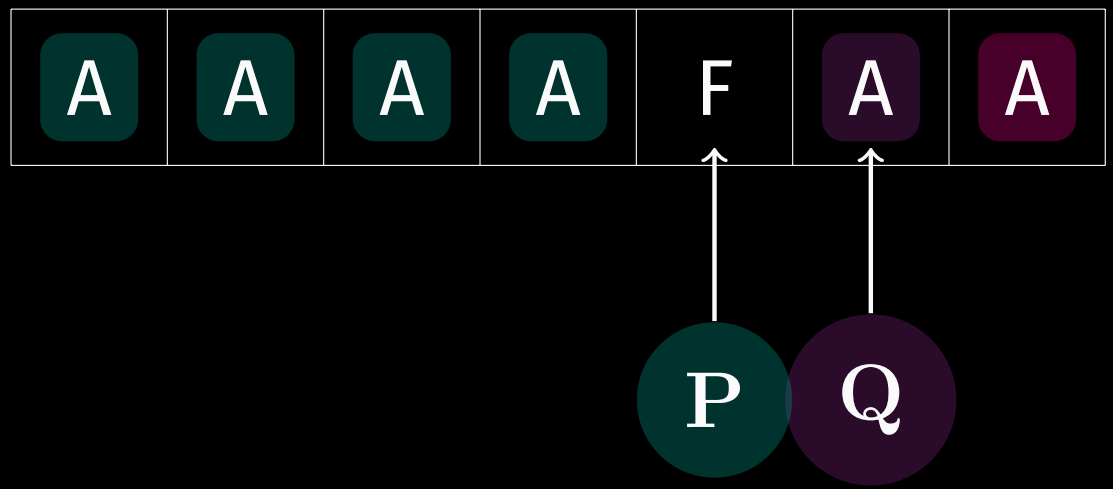

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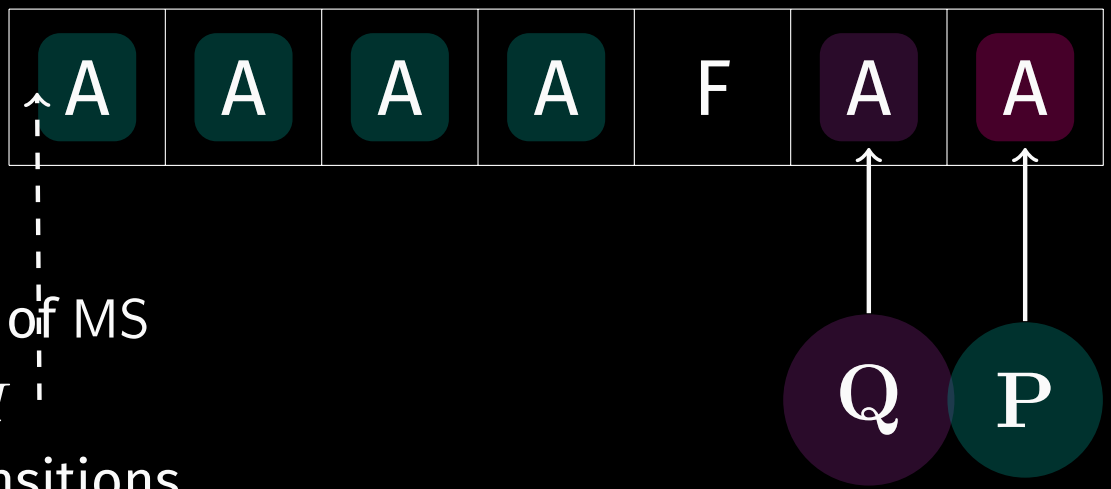

Monitor encoding of MS
with state M
and actions for transitions

Memory-Safe WebAssembly (`MSWAsm`)

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  - handle_add, handle_slice

Compiling from C to MSWAsm

- pointer becomes handle

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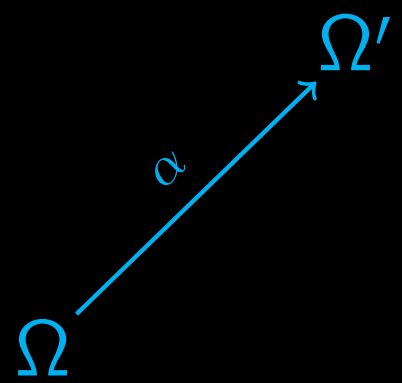

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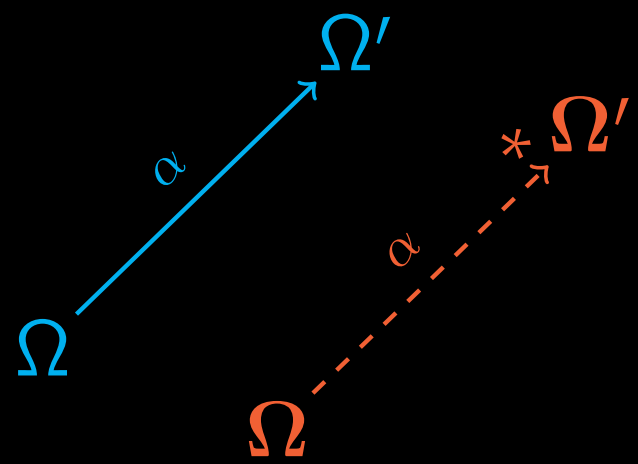

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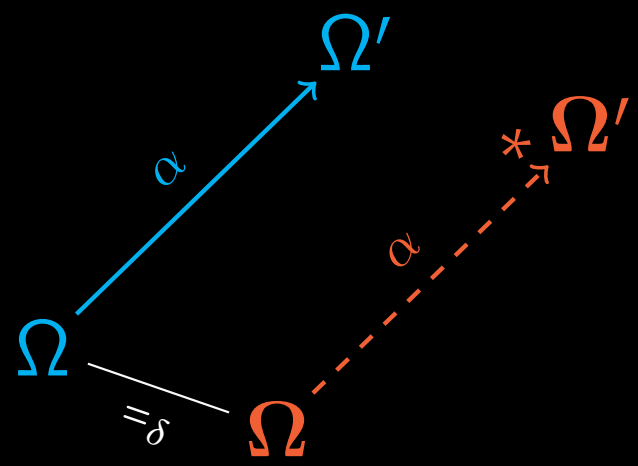

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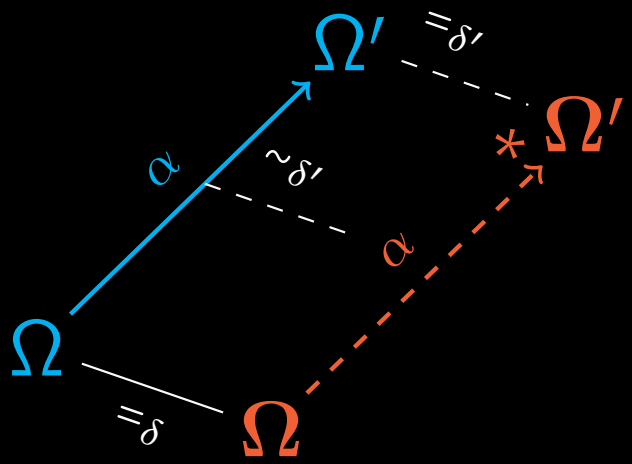

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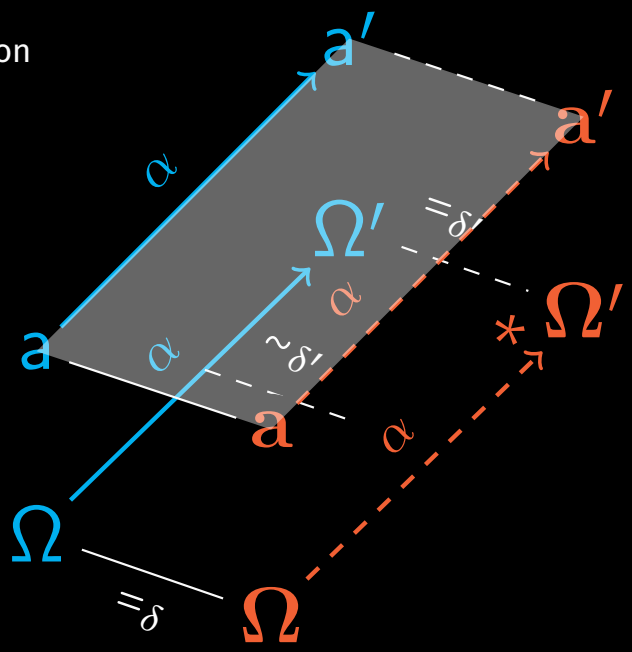

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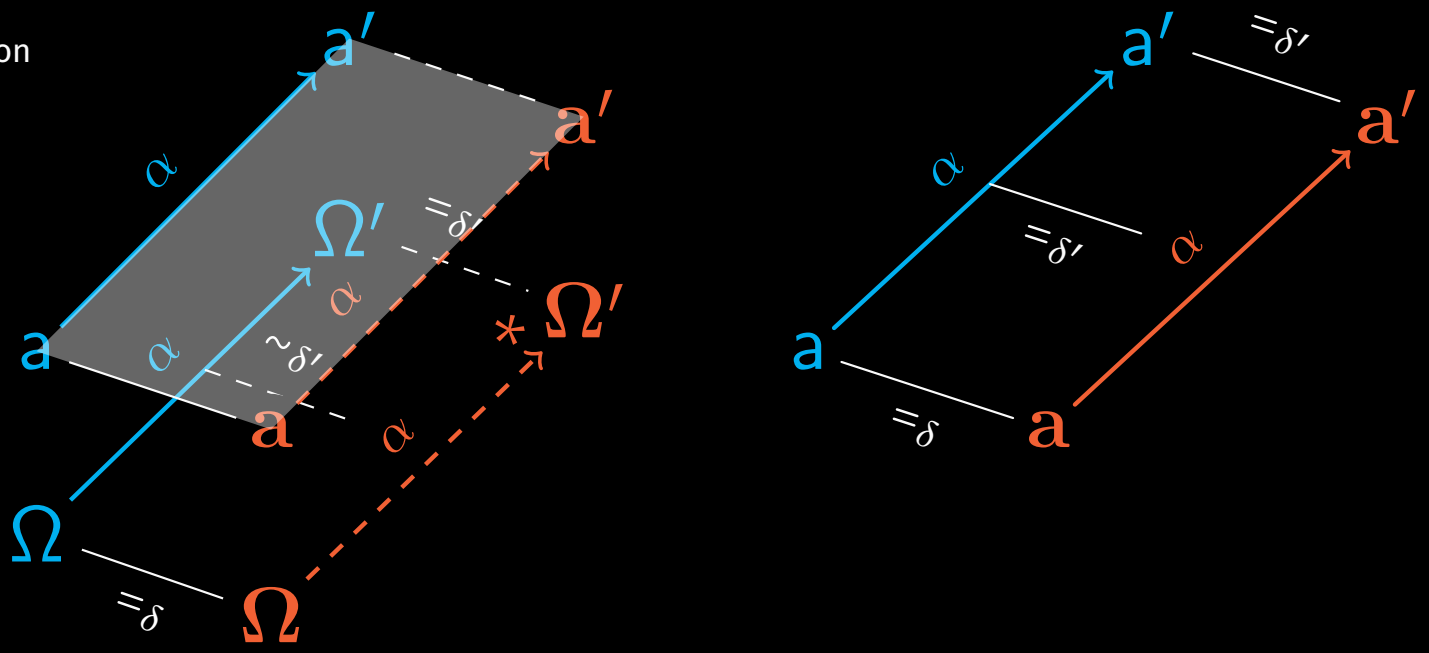

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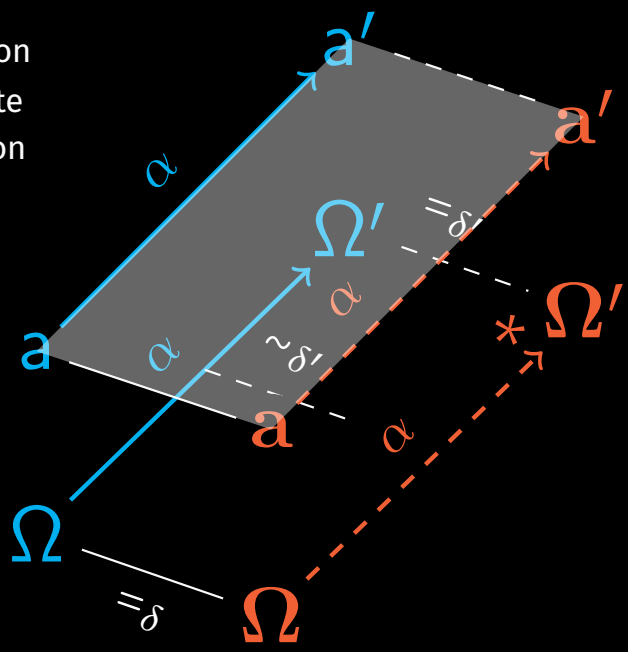

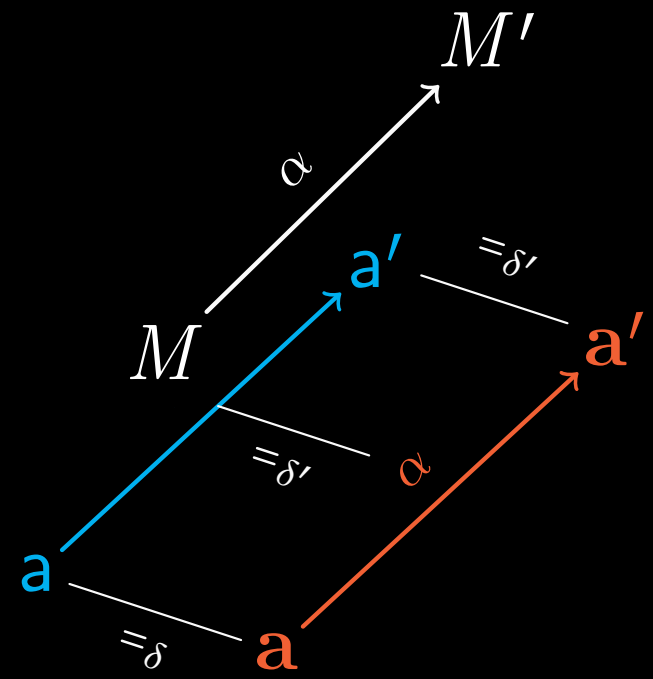

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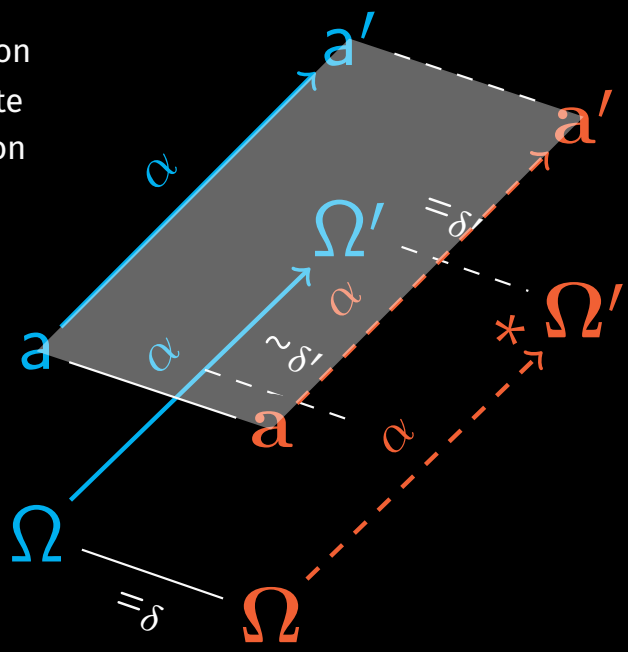

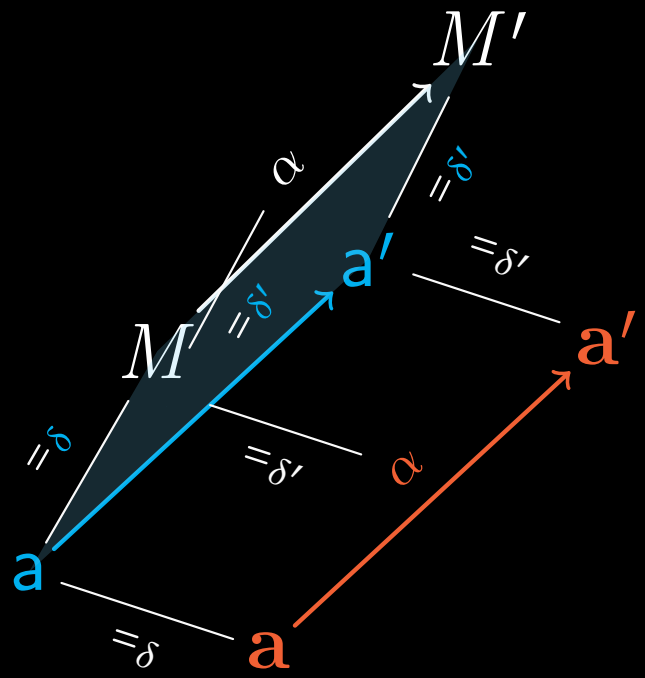

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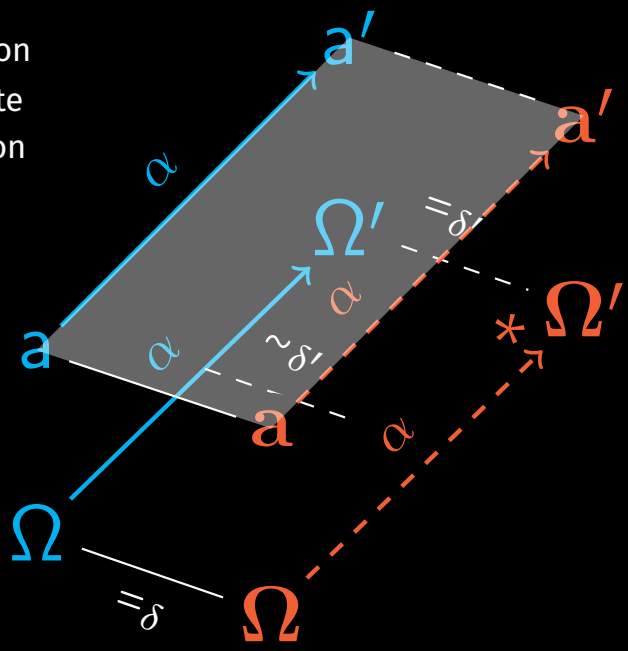

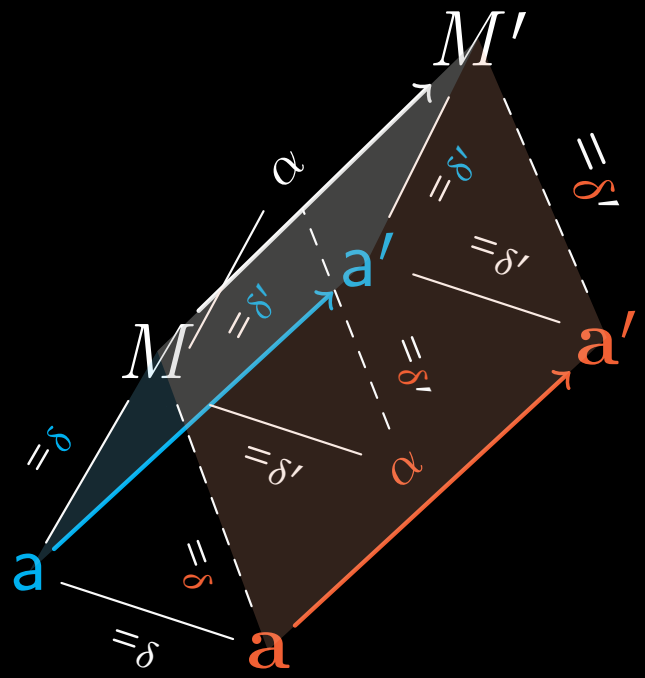

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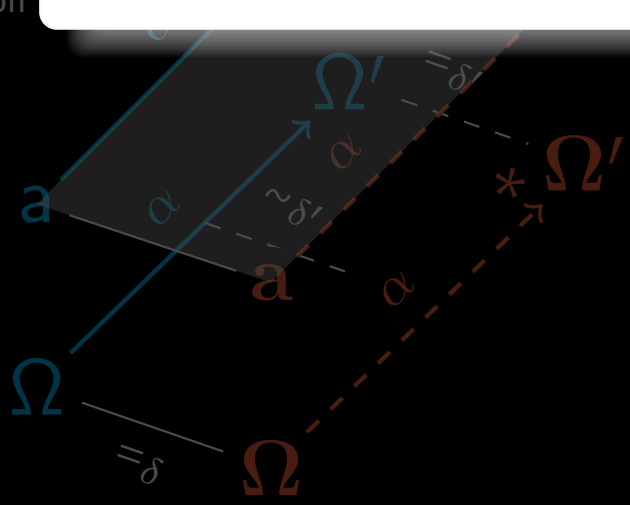

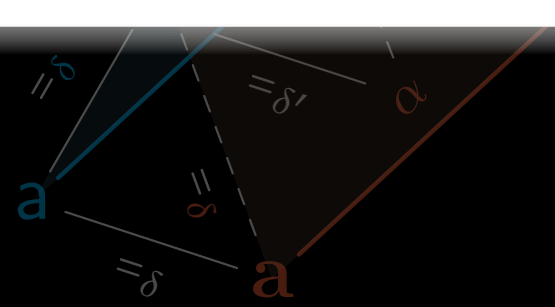

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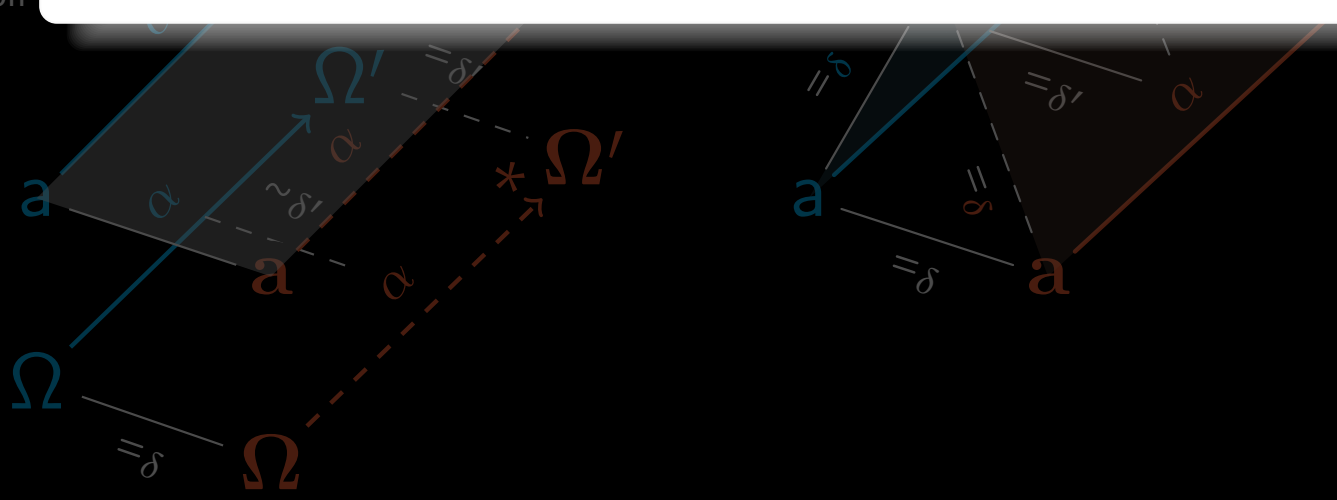

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Challenge: how to ensure $\mathbf{A}$ actions do not affect MS?

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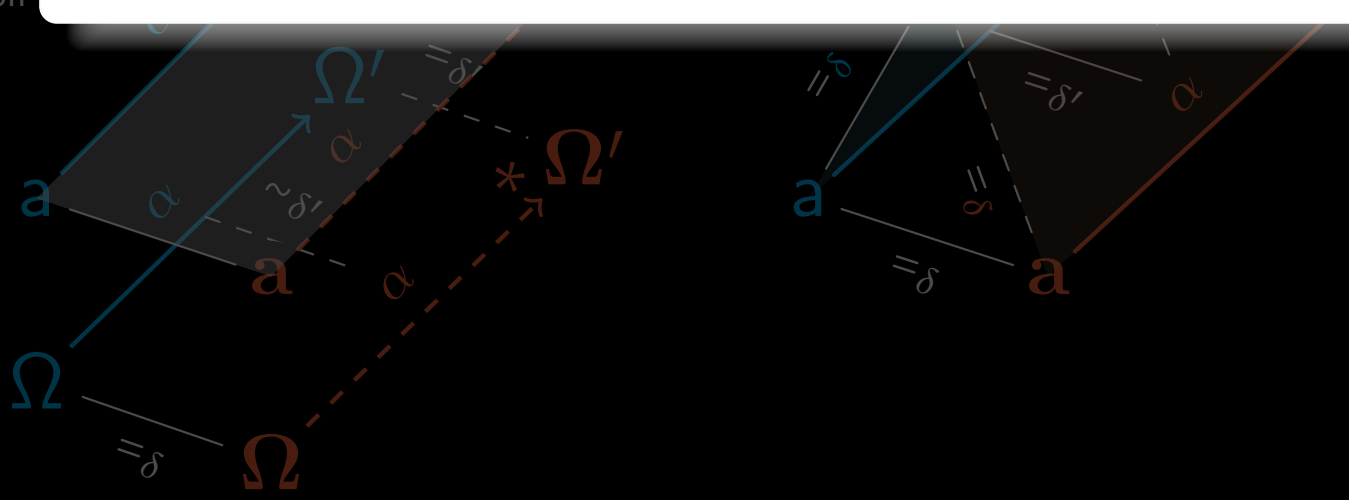

Robust Cryptographic Constant Time

(wip)

(Robust) Cryptographic Constant Time

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

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Micro-architectural Attacks (Spectre)

CCS'21

Speculative Semantics & SNI

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

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

call f 128

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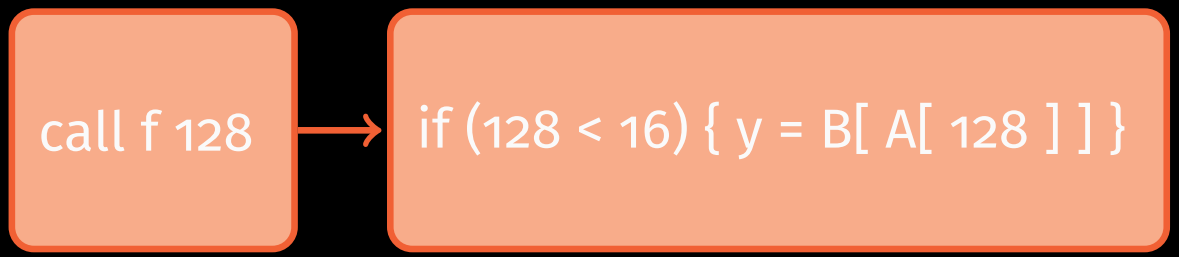

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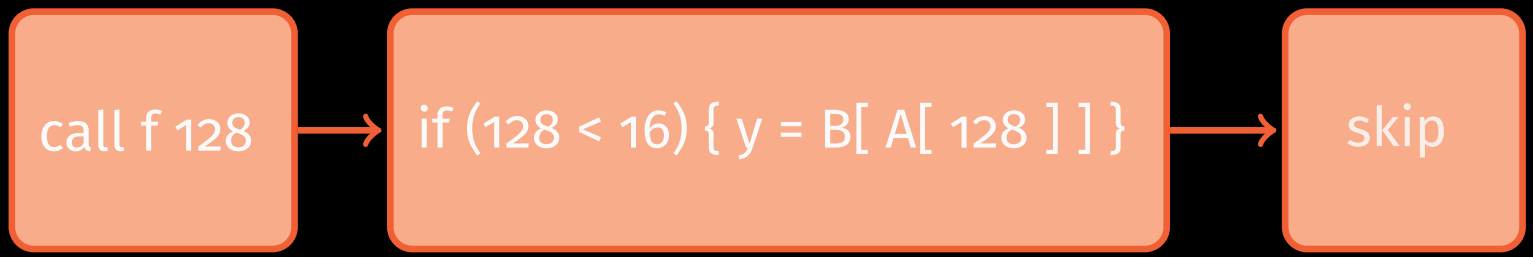

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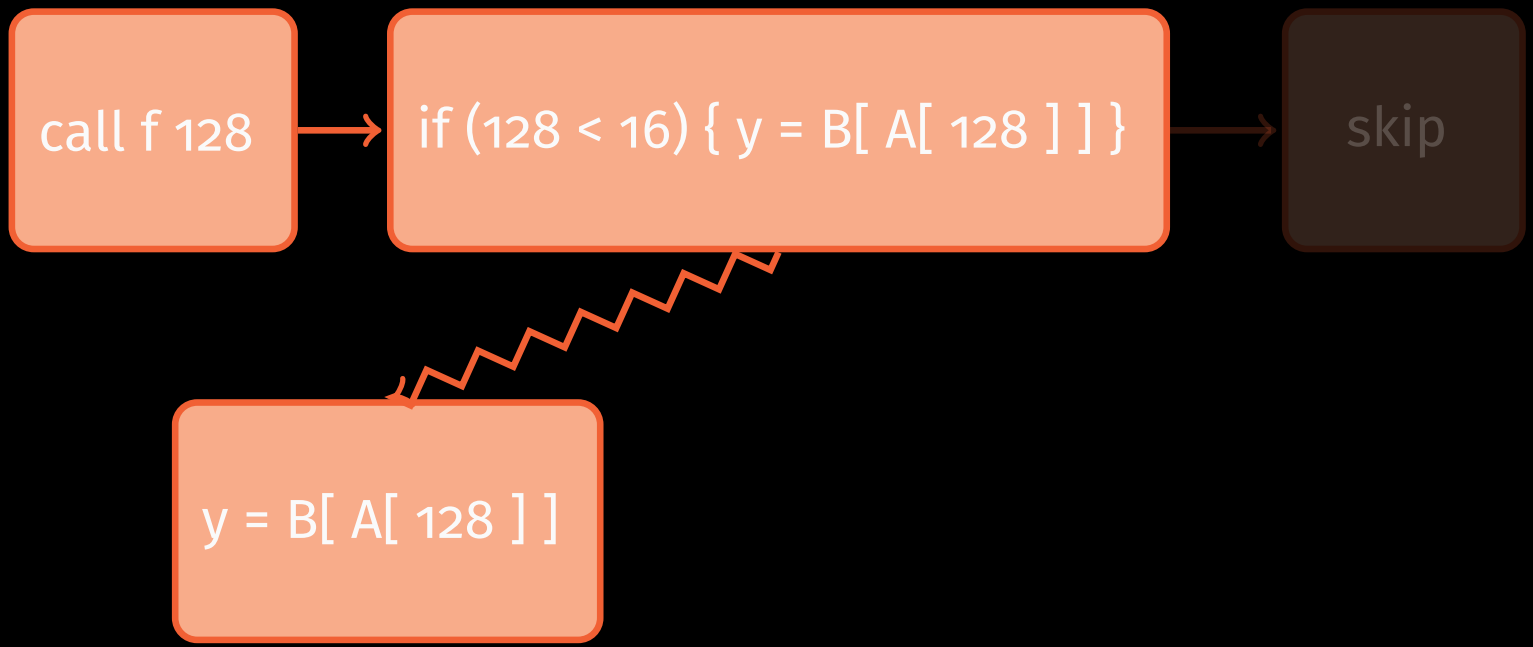

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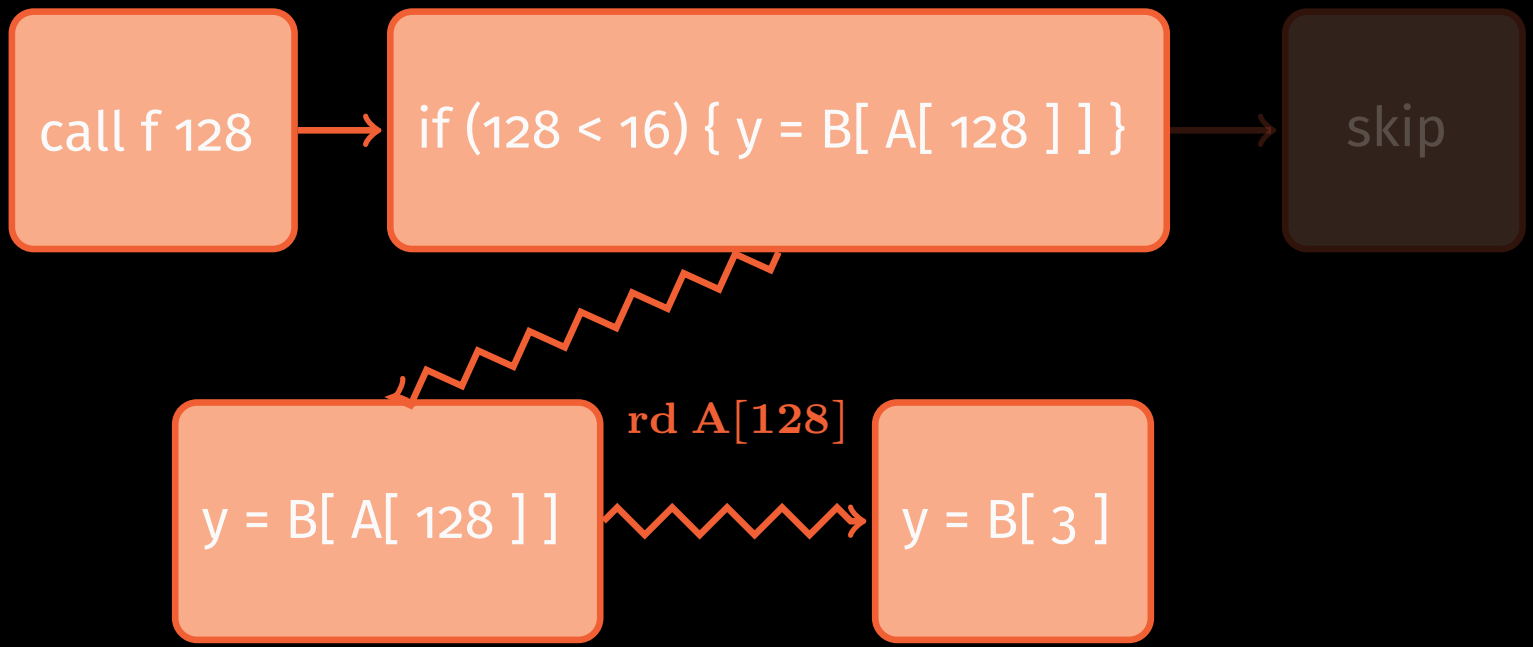

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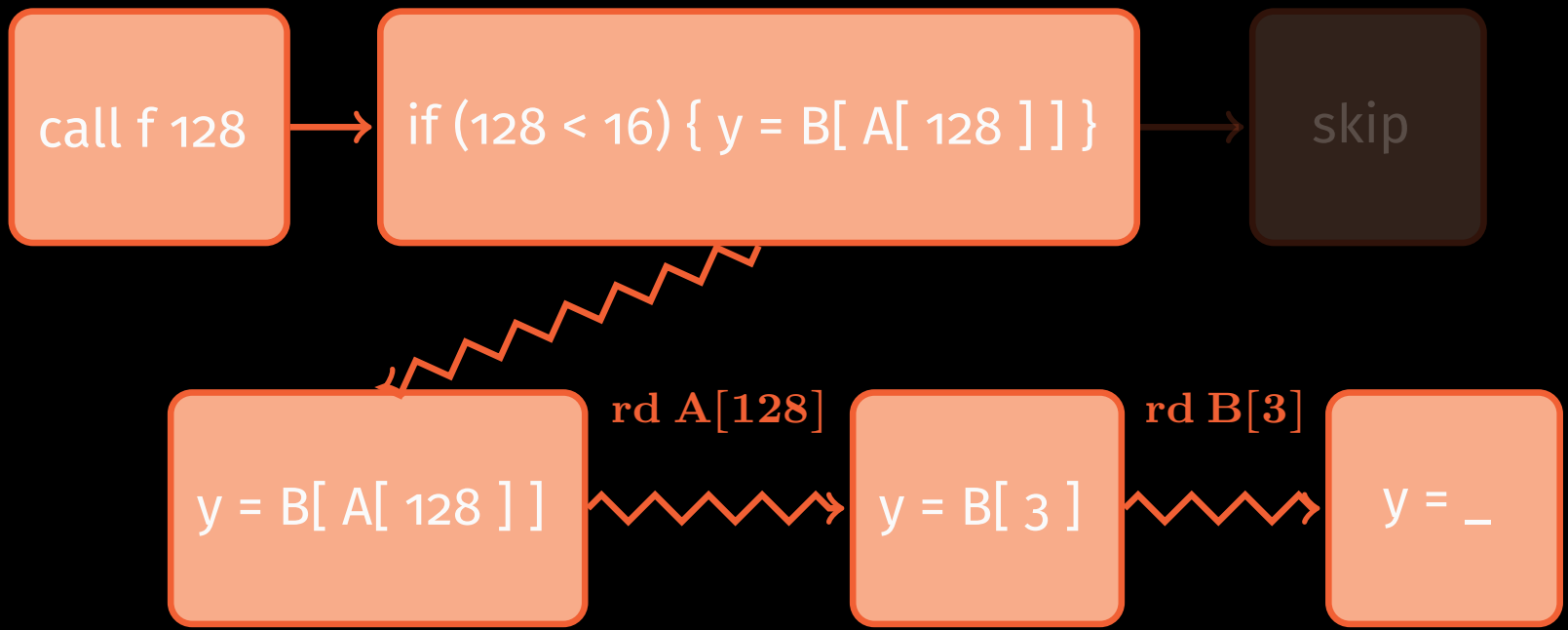

Speculative Semantics & SNI

Guarnieri *et al.* S&P'21

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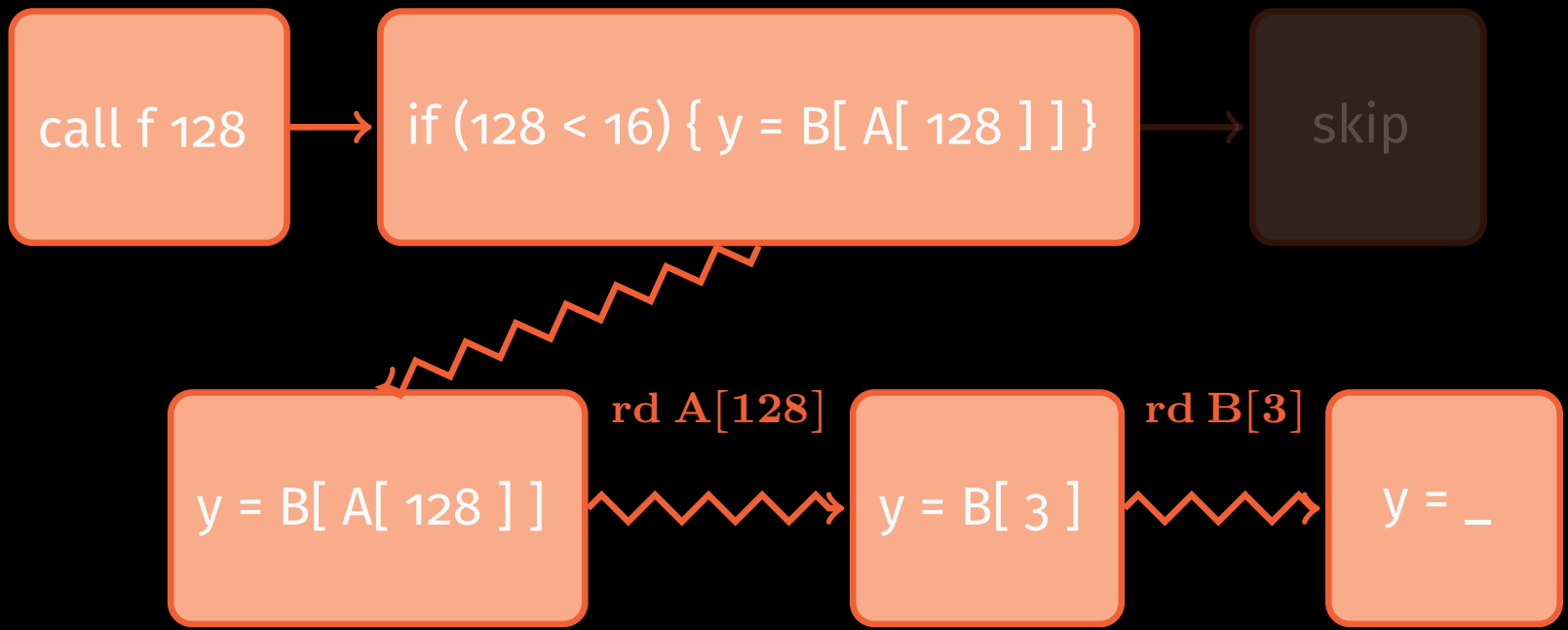

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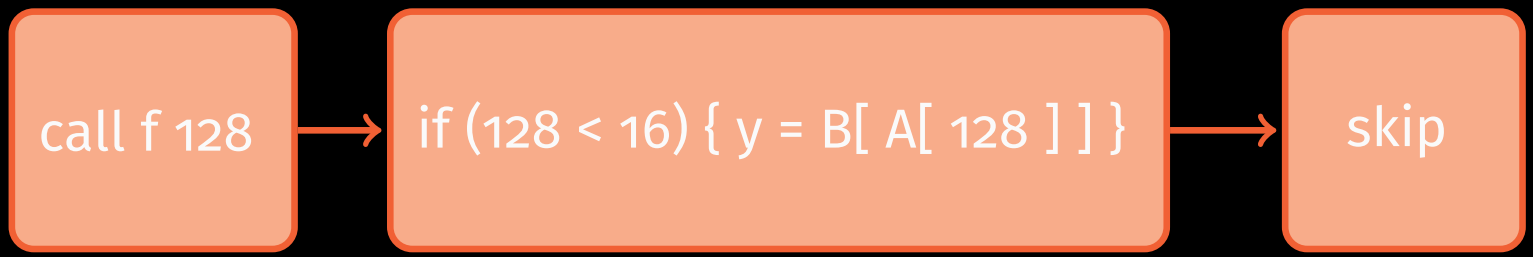

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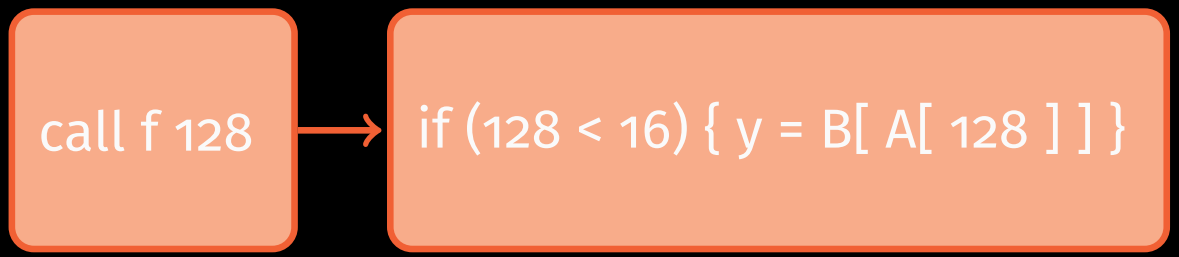

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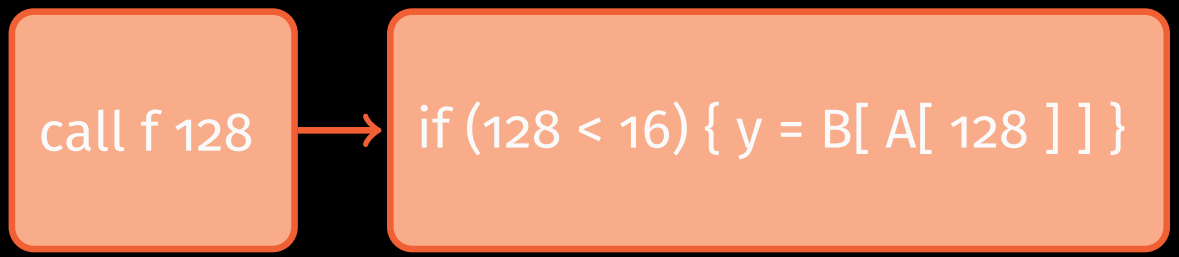

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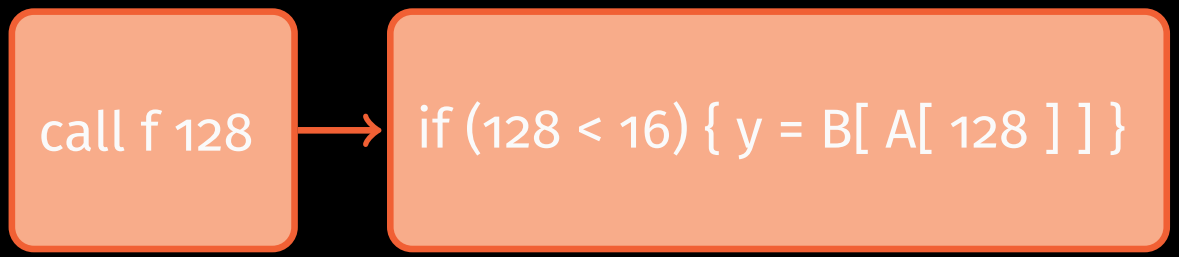

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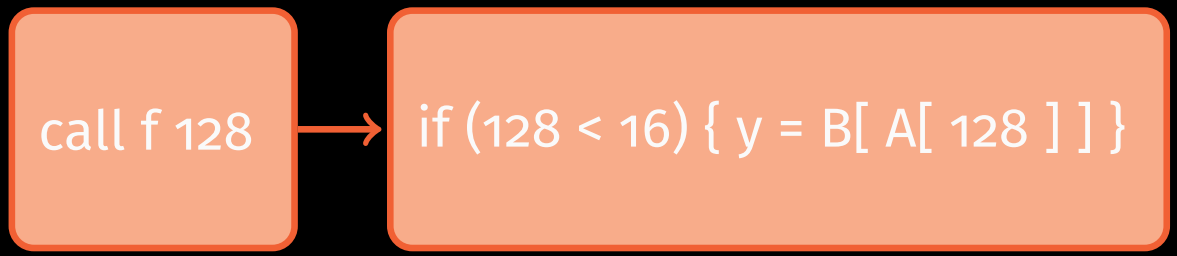

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Speculative Semantics & SNI

Guarnieri *et al.* S&P'21

A program is SNI ($\vdash \mathbf{P} : \mathbf{SNI}$) 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: $\mathbf{rd\ A[128]}$ $\mathbf{rd\ B[3]}$
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Speculative Semantics & SNI

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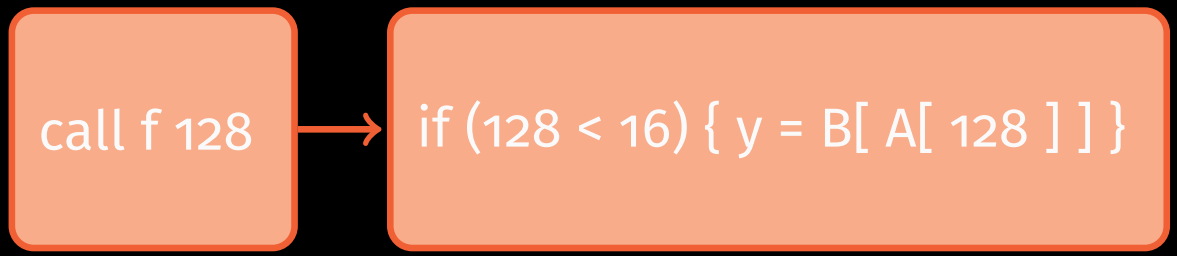

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Problems Problems Problems ...

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

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

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

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call f 128

pc : S

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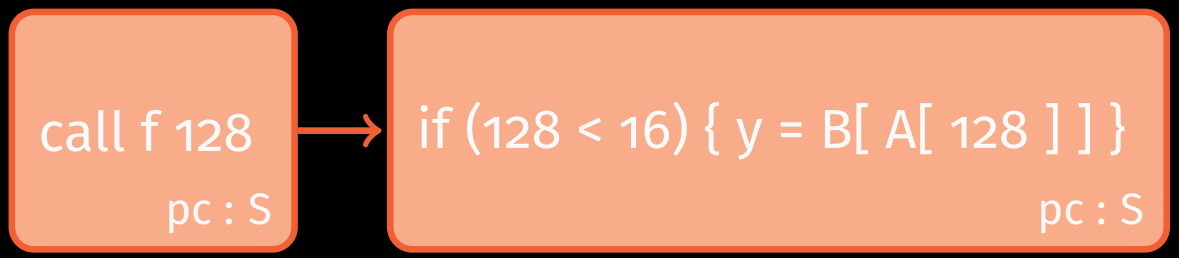

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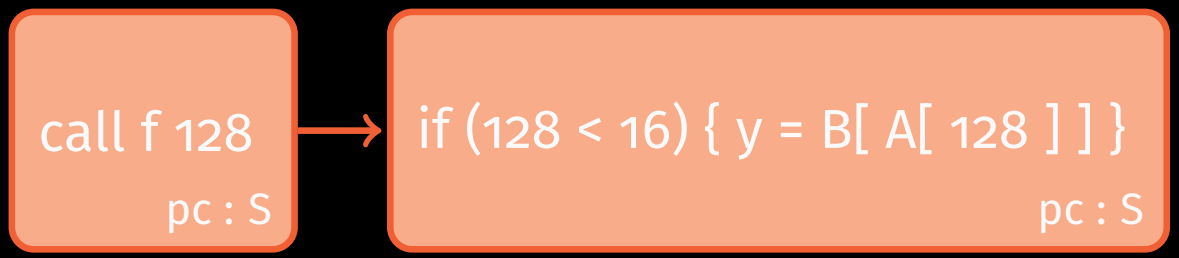

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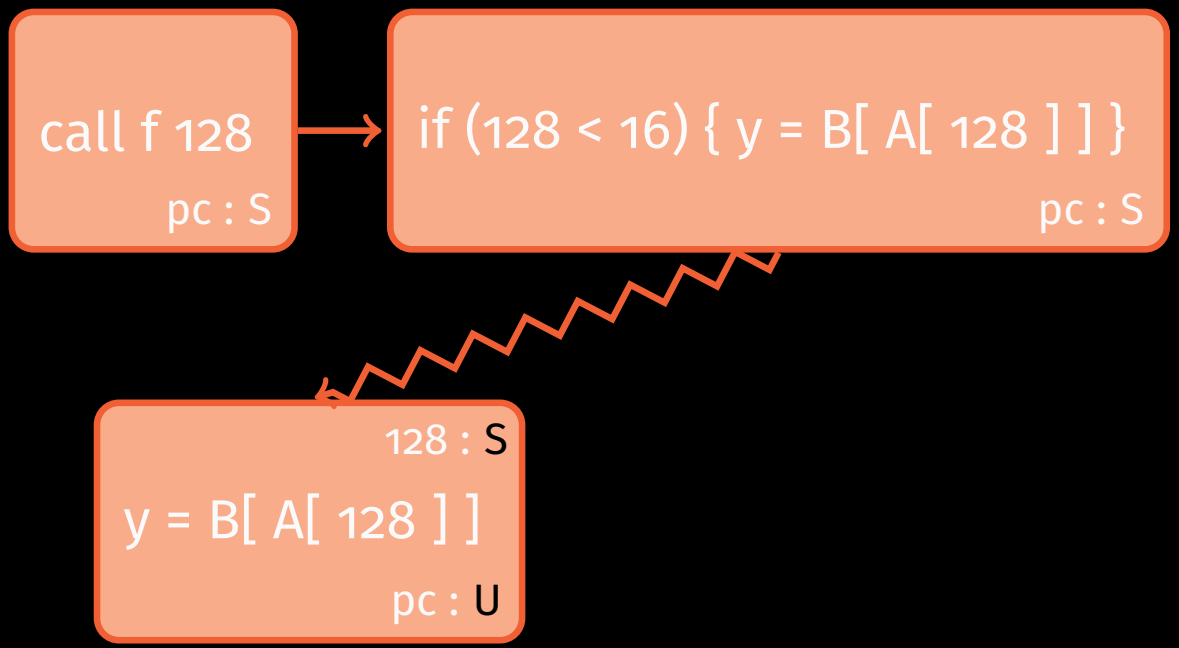

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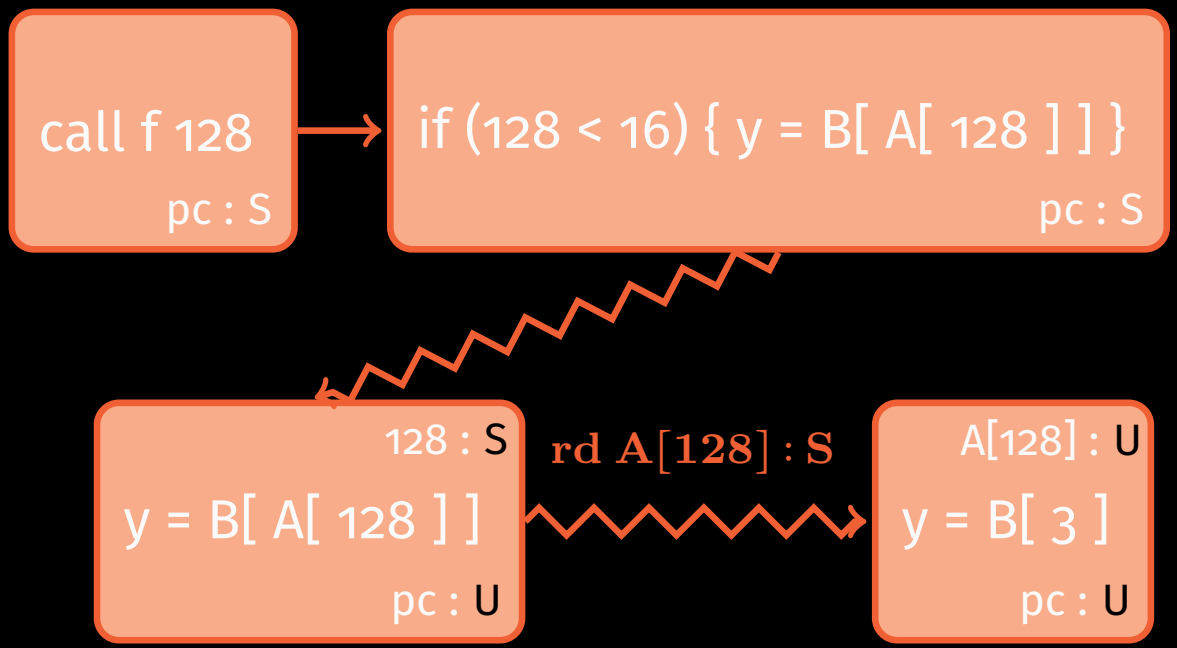

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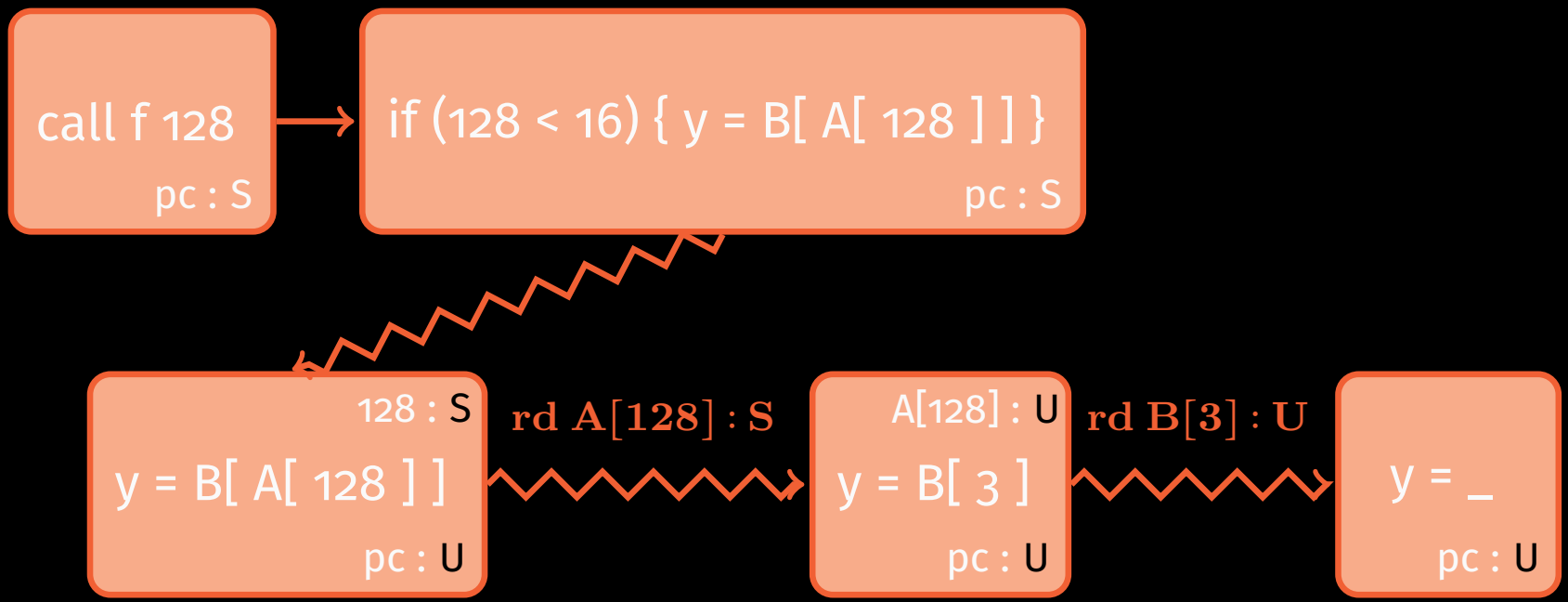

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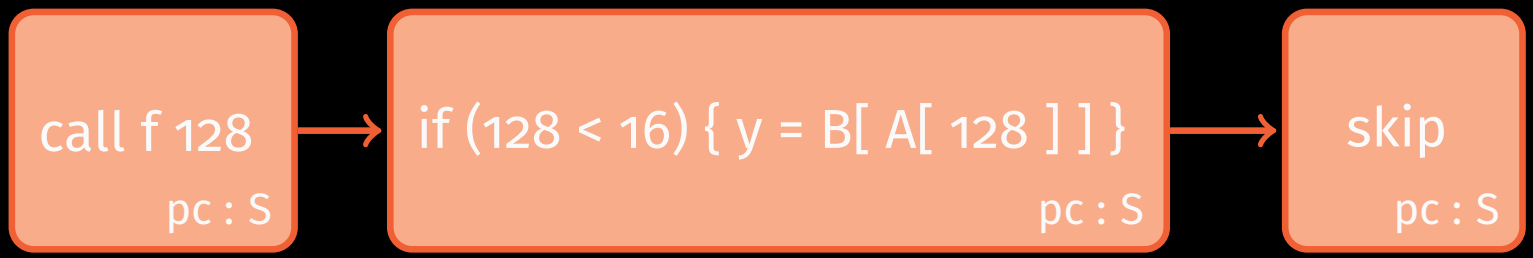

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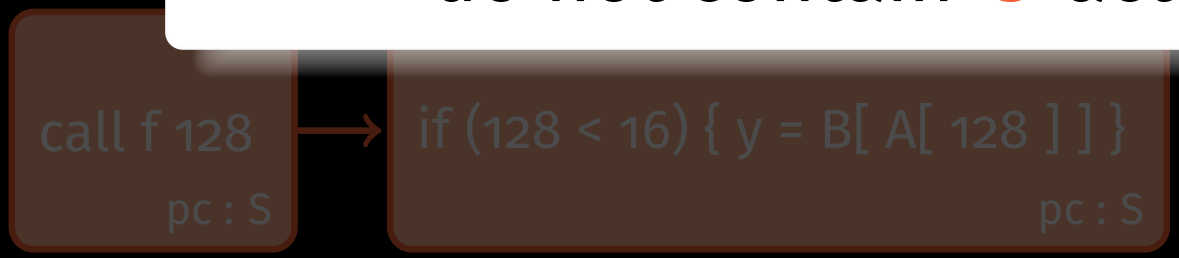

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Secure Compilation Framework for Spectre

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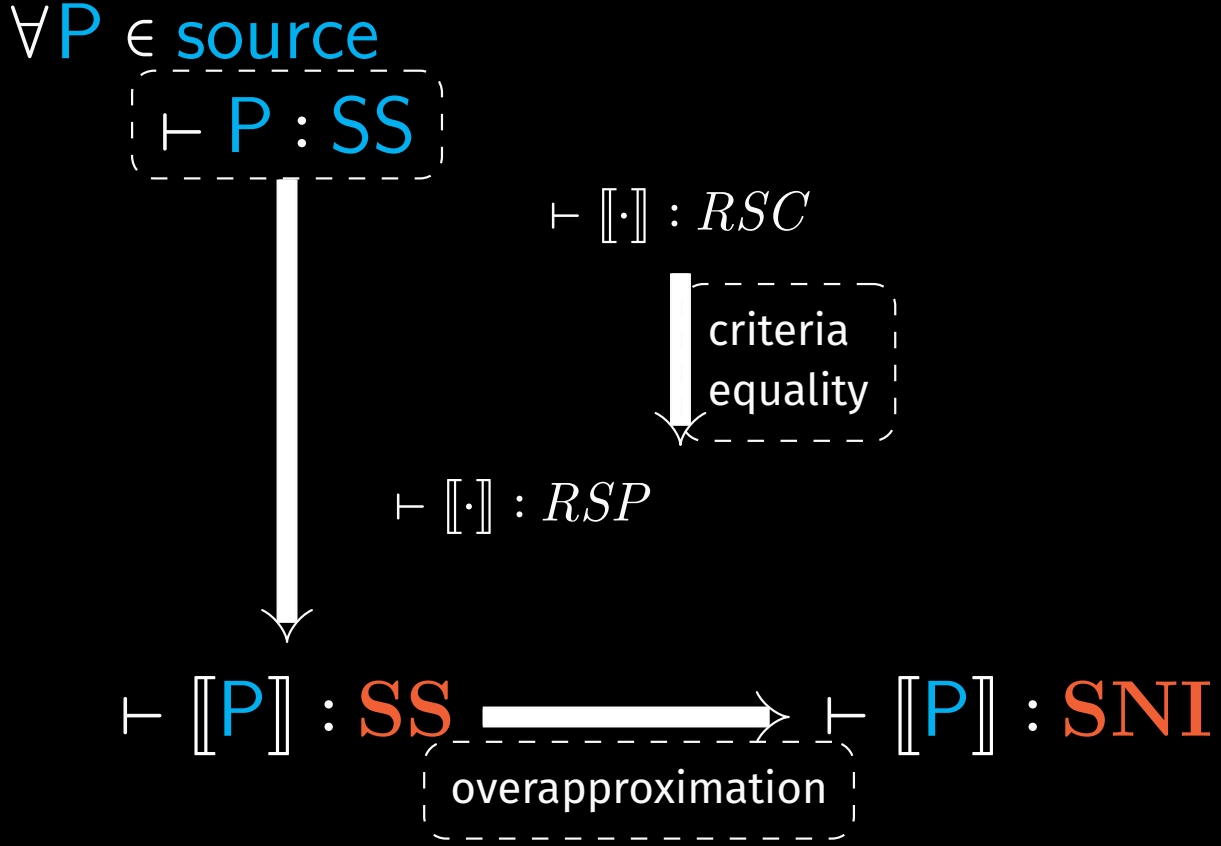

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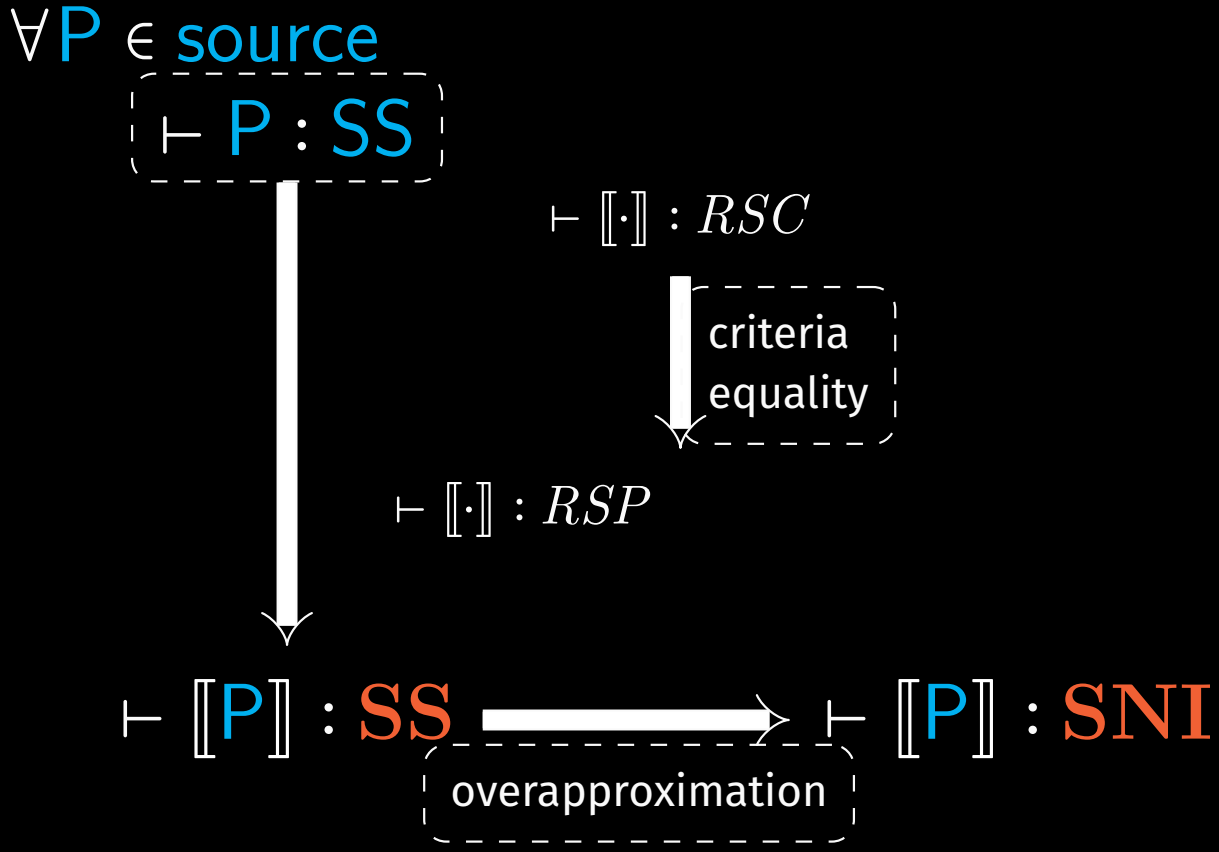

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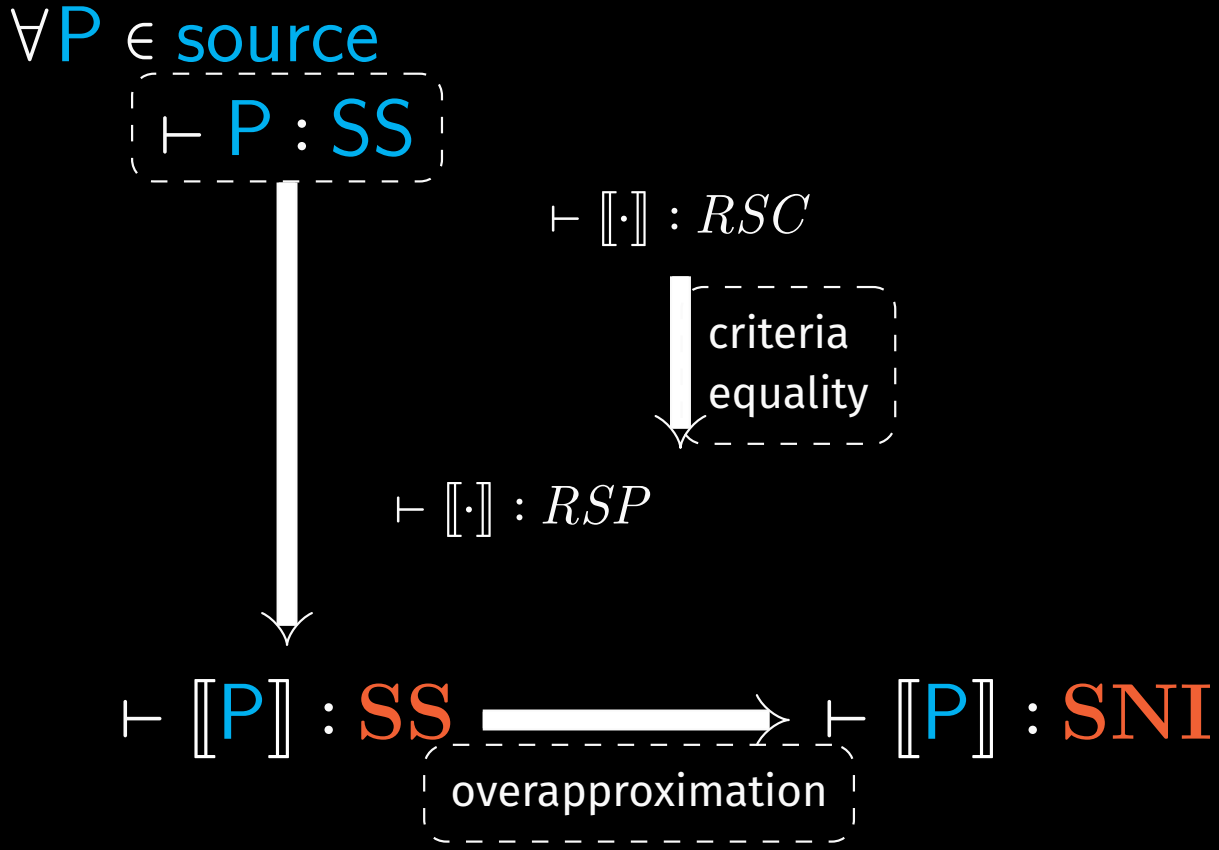

- dashed premises are already discharged
- to show security: simply prove RSC

RSSC **for** `lfence`

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call f 128

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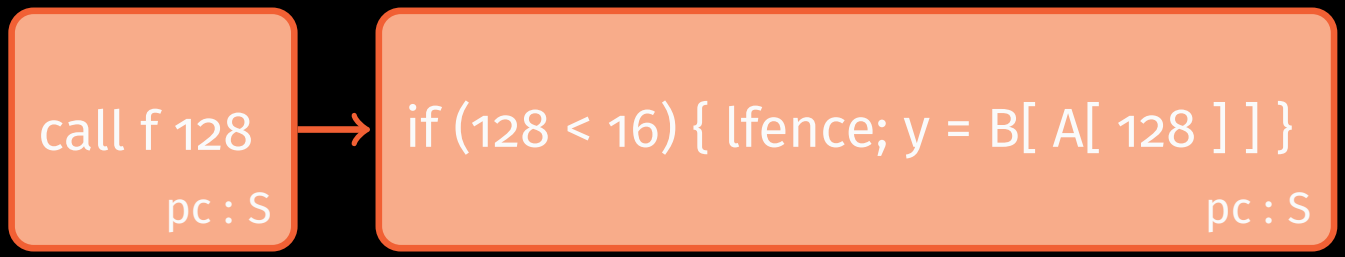

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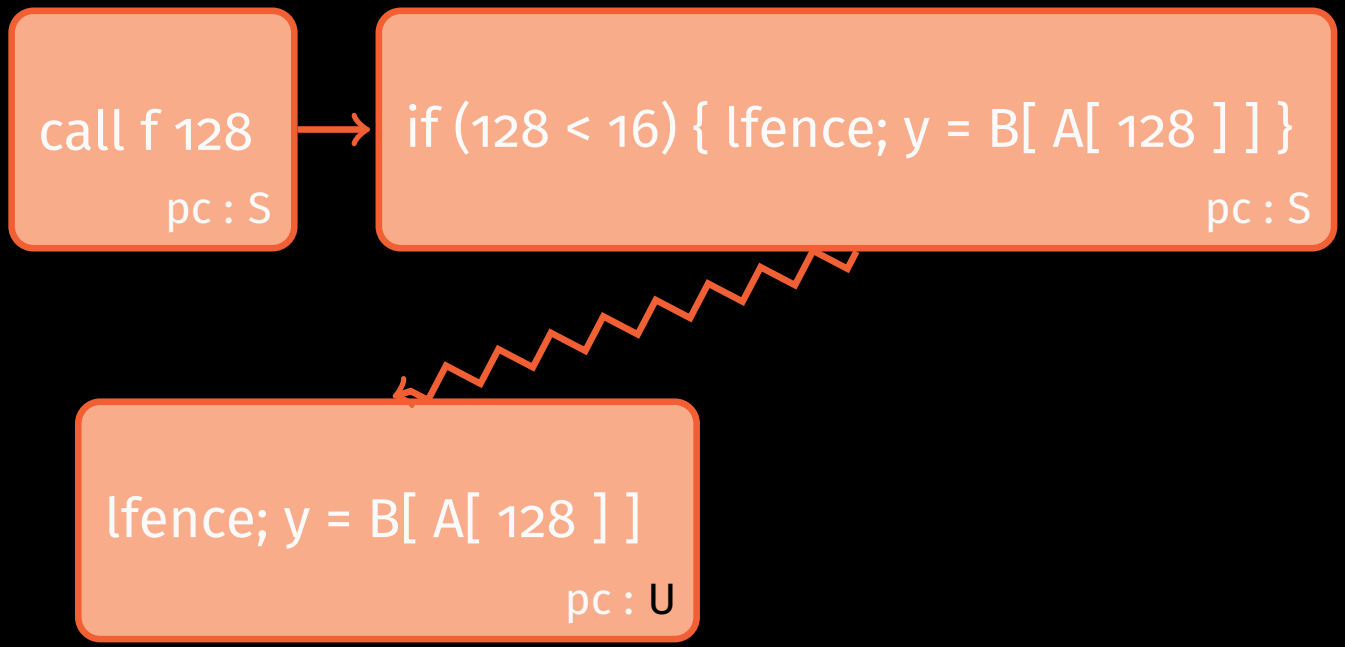

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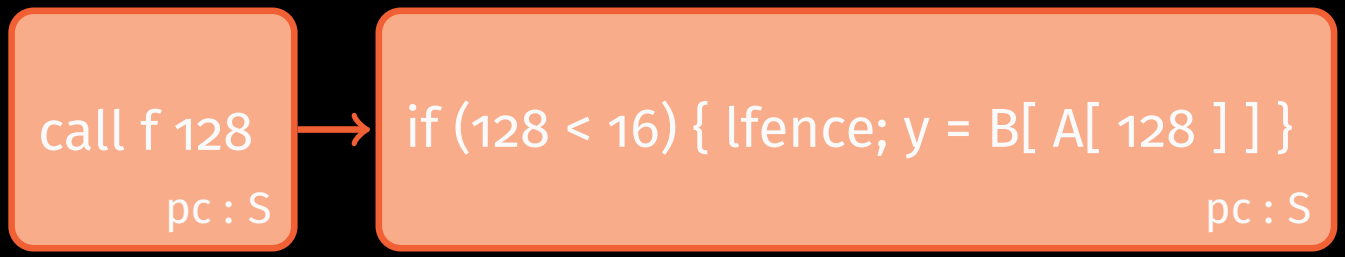

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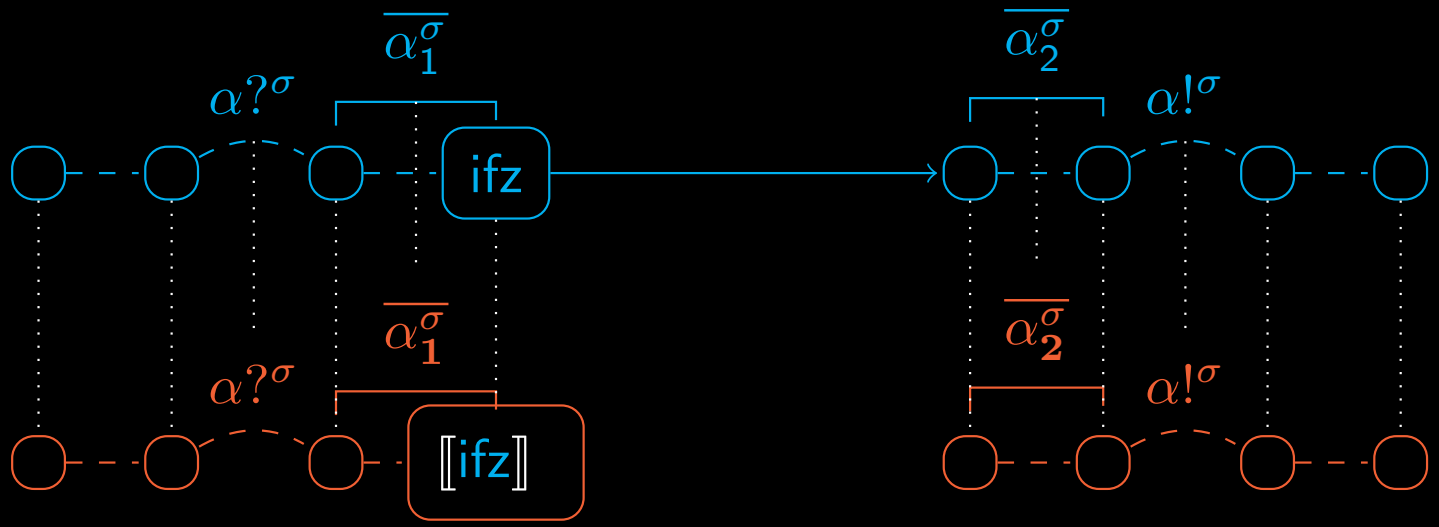

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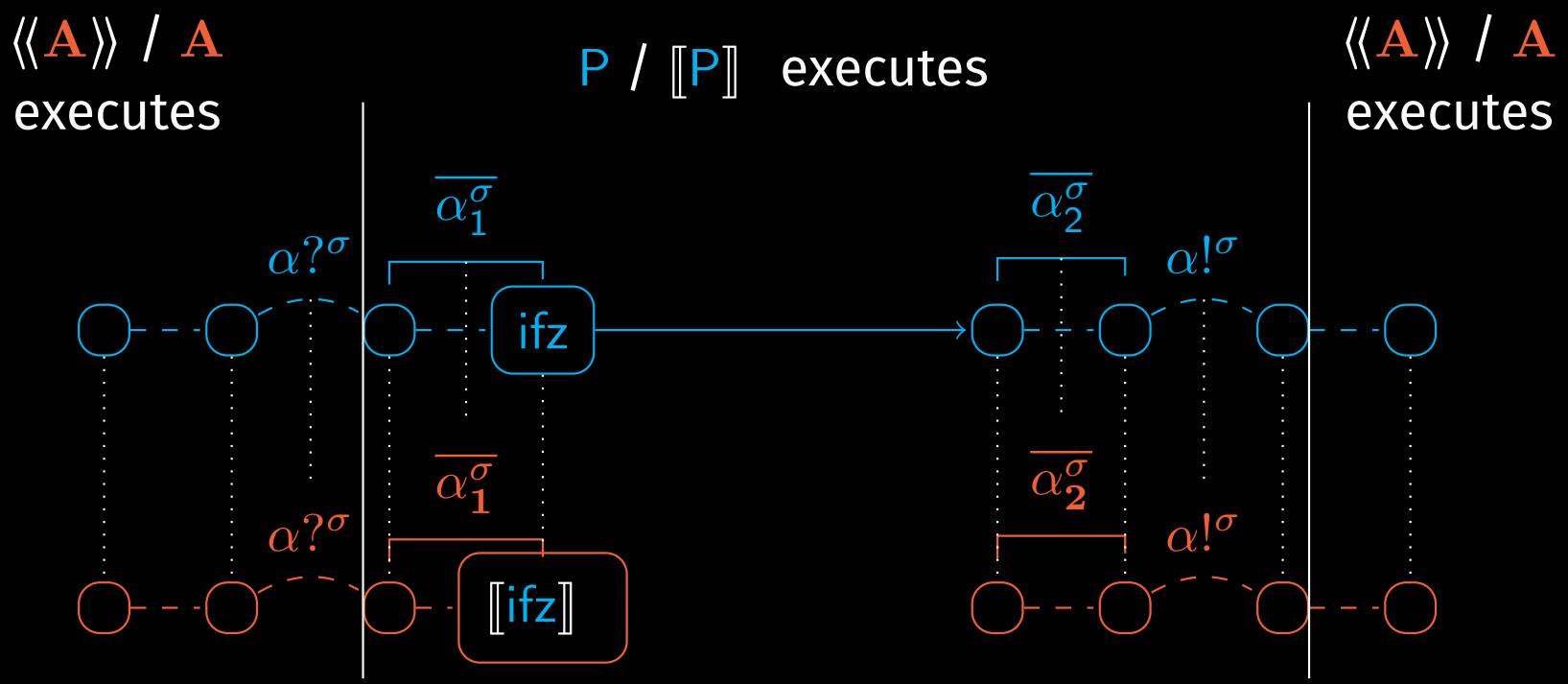

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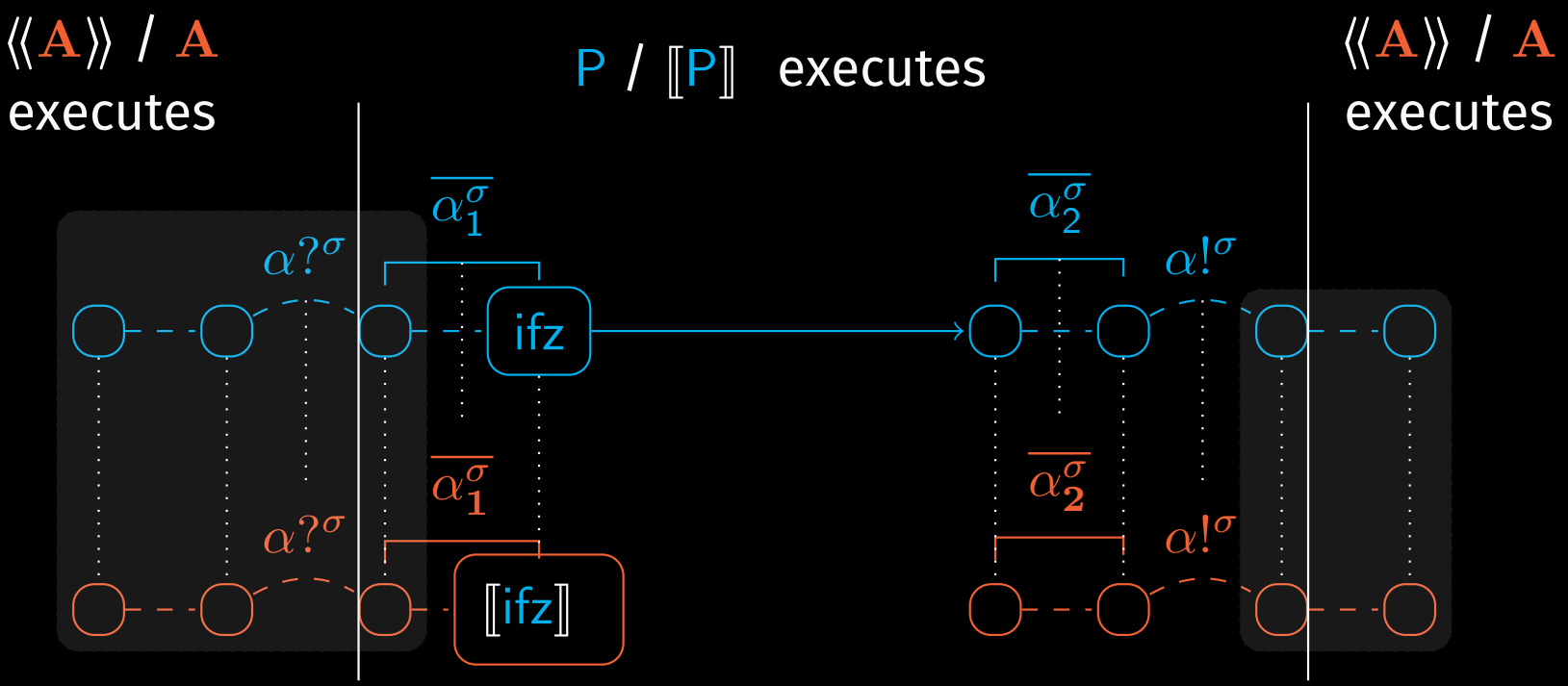

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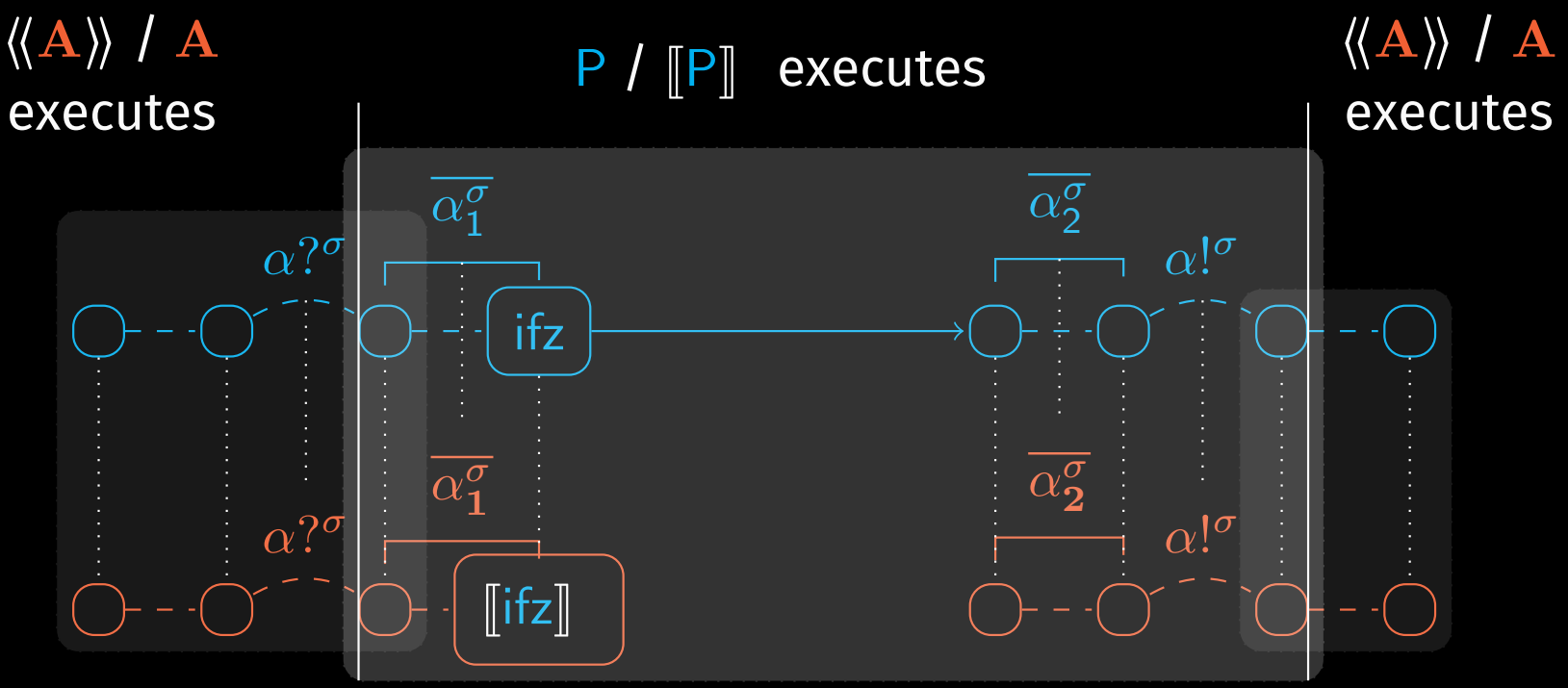

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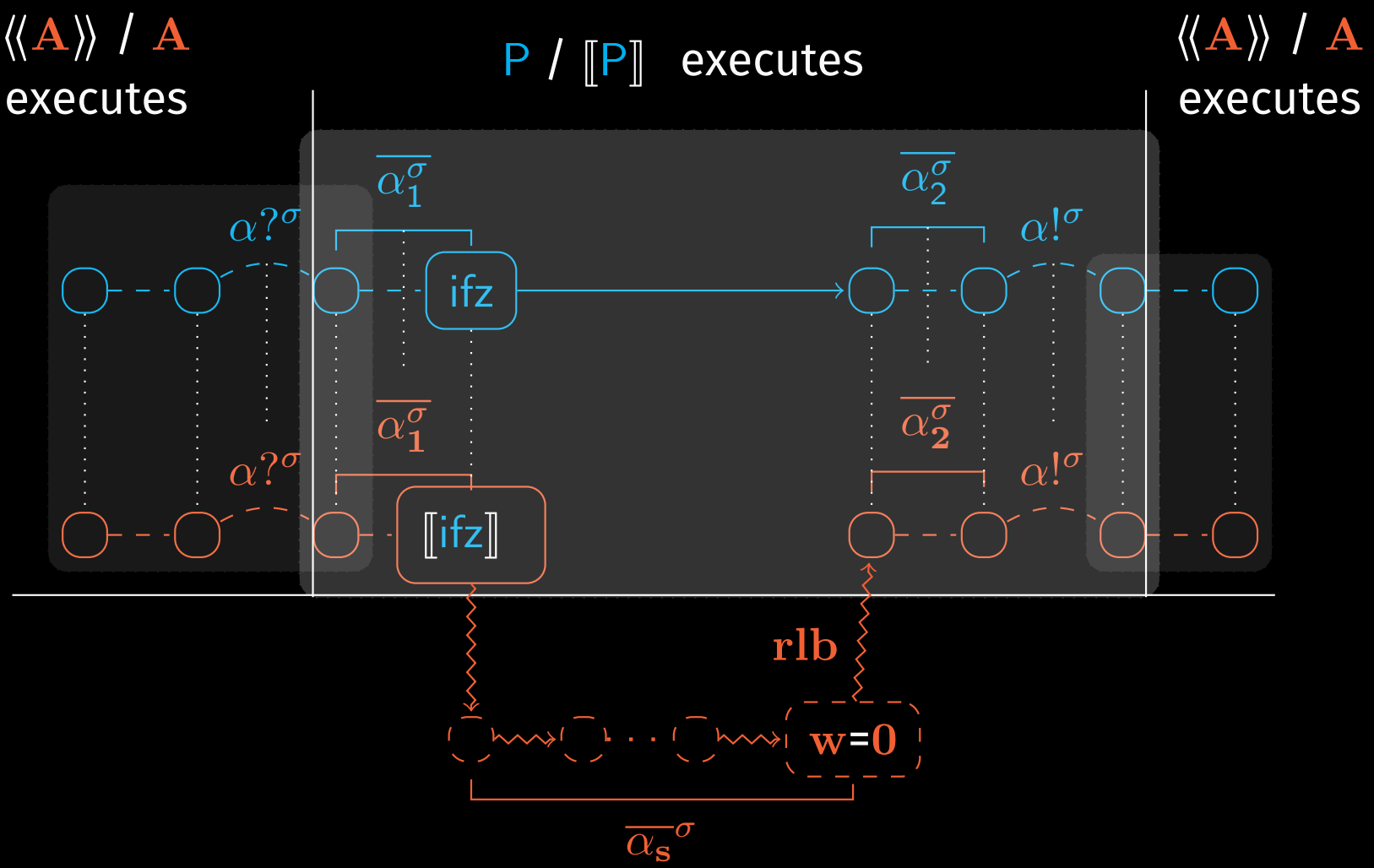

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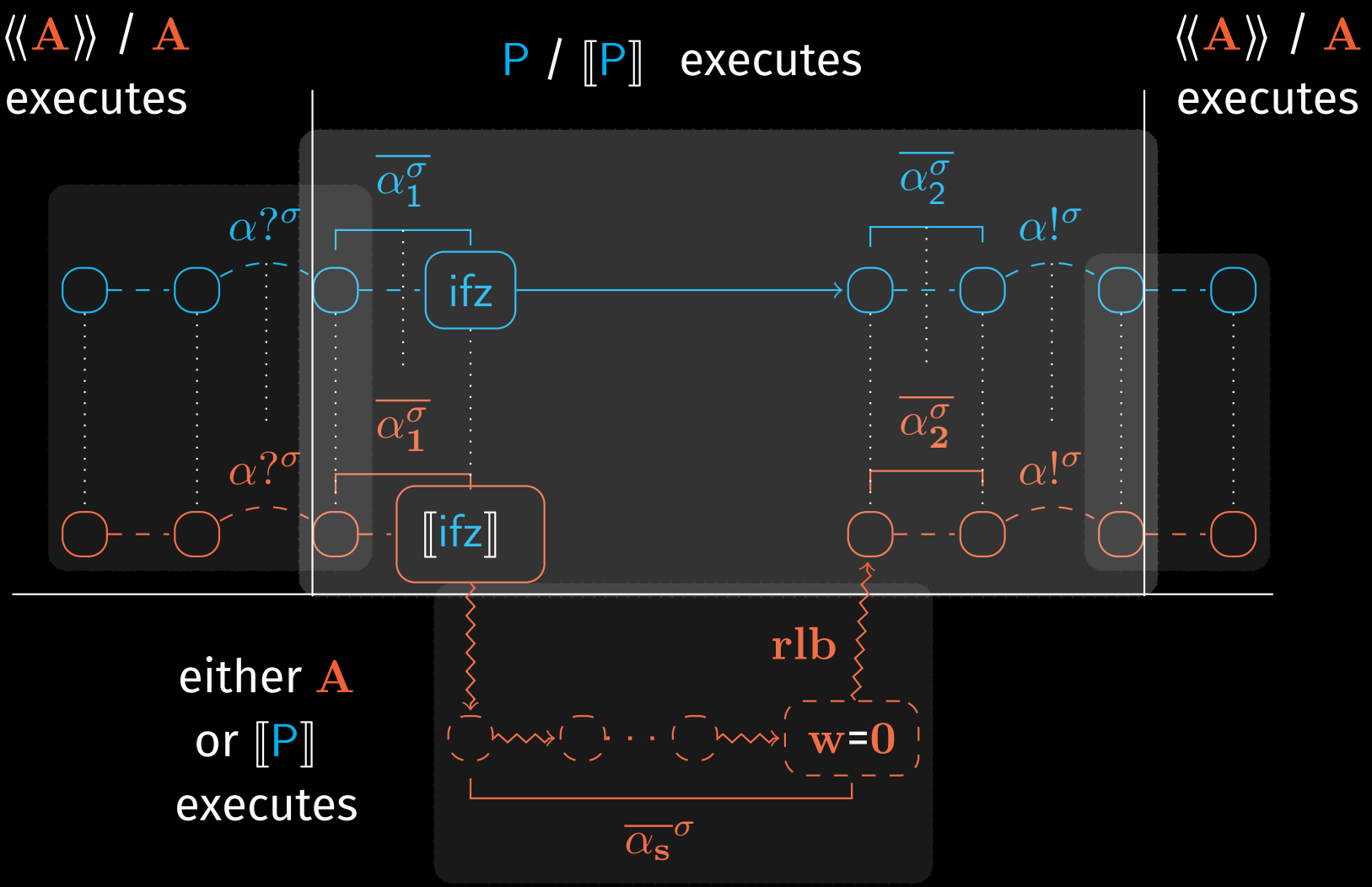

What Then?

- SNIv1, SNIv2, SNIv4, SNIv5

Kocher *et al.* S&P'19

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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

$$[\![\cdot]\!] \vdash \mathsf{RHP} \stackrel{\text{def}}{=} \forall \mathsf{P}, \mathbf{A}.\ \exists \mathsf{A}.\ \forall t.$$

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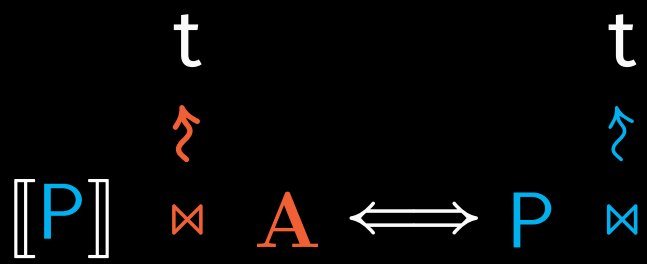

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This talk: generic flavour, geared towards the newer theories

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 $r \in \{0,1\}^n$
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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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- attackers A & S (corrupting parties etc.)

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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

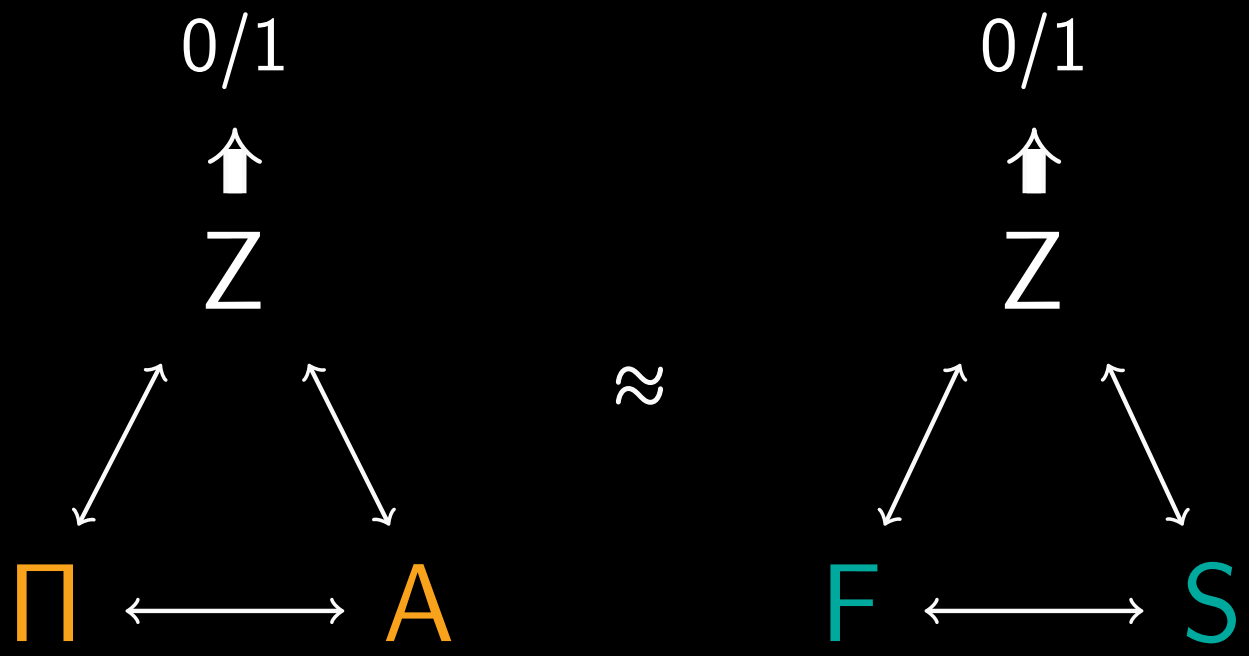
Upon receiving $(\texttt{Com}, sid, y)$ from P_i, P_j outputs $(\texttt{Receipt}, sid, cid, P_i, P_j)$

- 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.

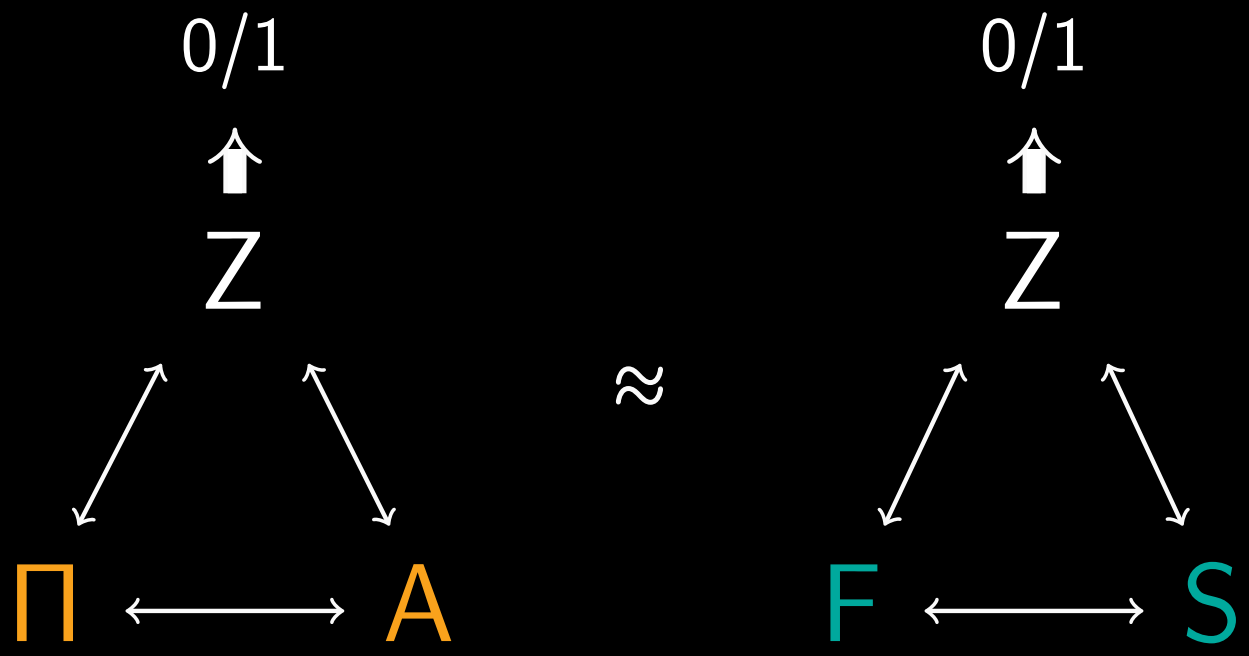
- attackers A & S (corrupting parties etc.)
- environments Z (objective witness)

UC (Semi-formally)



↔ represent communication channels

UC (Semi-formally)

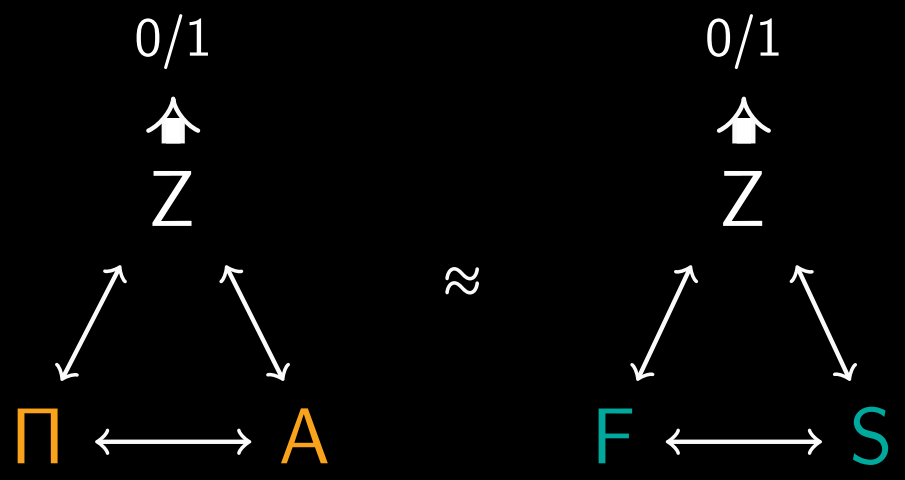


$\leftrightarrow$ represent communication channels

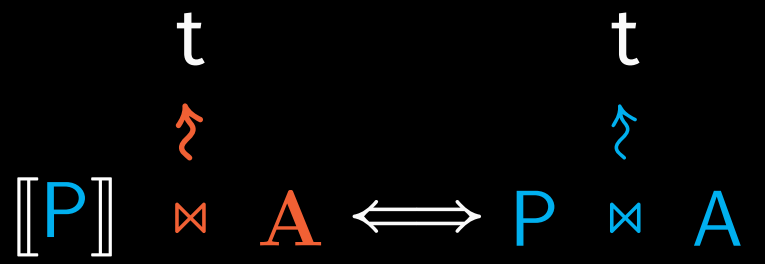
$$\Pi \vdash_{UC} \mathsf{F} \stackrel{\text{def}}{=} \forall \text{poly } \mathsf{A}, \exists \mathsf{S}, \forall \mathsf{Z}.$$
$$\text{Exec}[\mathsf{Z}, \mathsf{A}, \Pi] \approx \text{Exec}[\mathsf{Z}, \mathsf{S}, \mathsf{F}]$$

A Closer Look

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



$\forall P, \mathbf{A}. \exists A. \forall t.$



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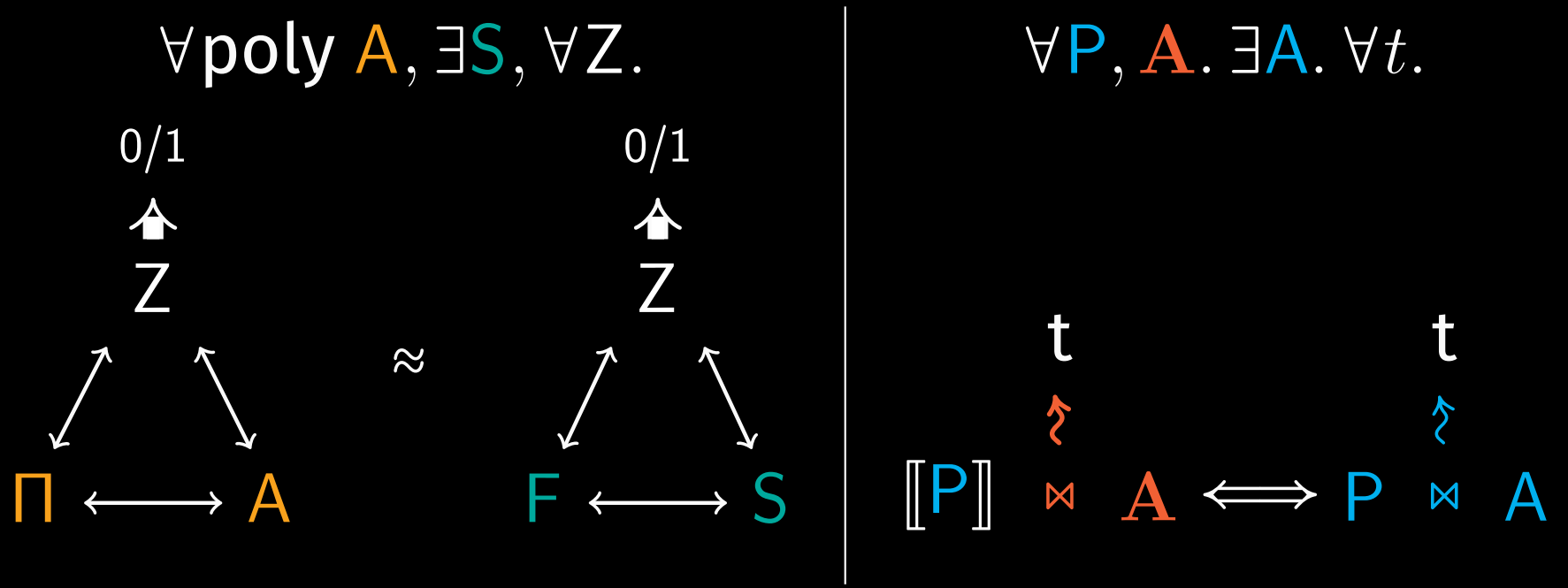

Isabelle'd both perfect and computational UC

Analogy

UC			SC
protocol	Π	$[\![\mathsf{P}]\!]$	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 $\Pi \to \mathrm{F}$		$[\![\cdot]\!]\colon \mathrm{P} \to \mathbf{P}$ compiler	
general composition result		…	

Analogy Results

- transfer UC results from ITMs to any $\mathtt{S}$/$\mathtt{T}$

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- Mechanised UC for 1/2 Wireguard in `Cryptoverif` CSF'24

Conclusion

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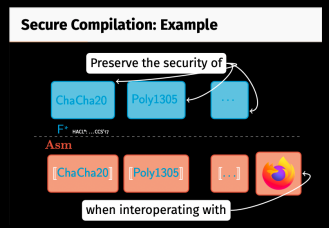
- secure compilation threat model



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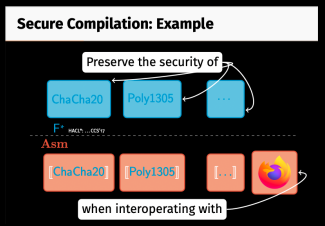
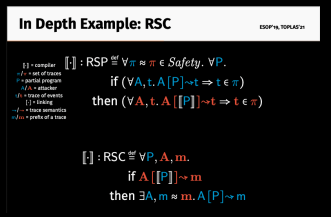


- formal foundations: RSC, RHP



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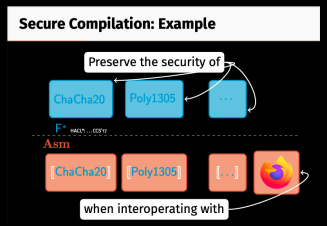

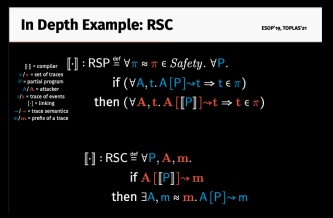

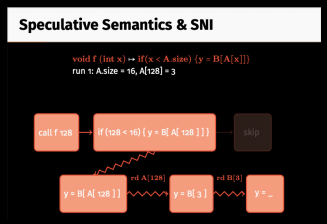

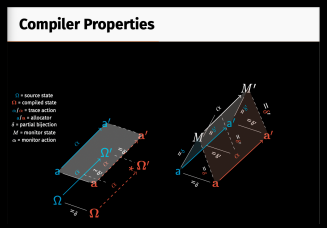

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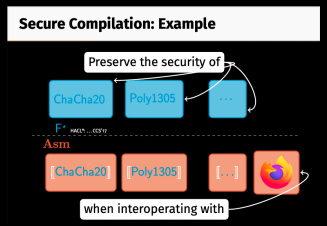
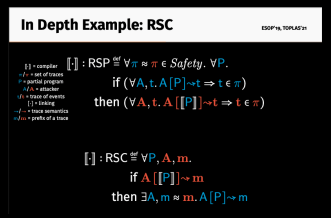
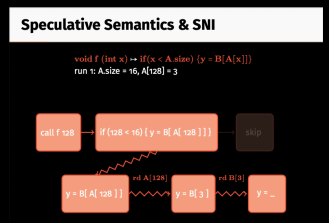
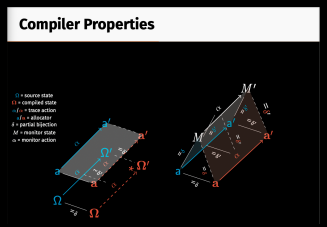
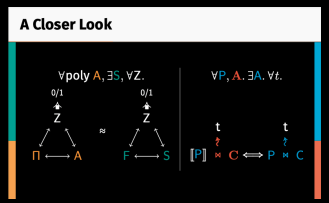
- connection with UC











Future

- More foundations questions?

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- SC for emerging security archs?

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

Questions?