Secure Compilation

an extensive introduction

Marco Patrignani

9th October 2017

CISPA
Center for IT-Security, Privacy and Accountability

2017-10-09 Secure Compilation

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so a language note i presume you all watch got do you watch it with subtitles? turn the m off, do yourselves a favour

this is to say, that if you don't understand stuff or if you have questiosn just ask – even in italian

2017-10-09 Secure Compilation

Collaborators

Collaborators

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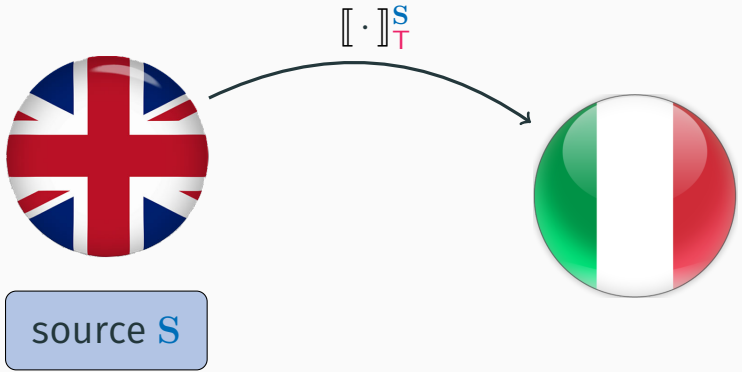

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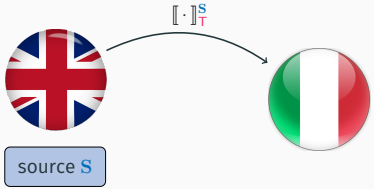

your brains are currently translating from english to italian

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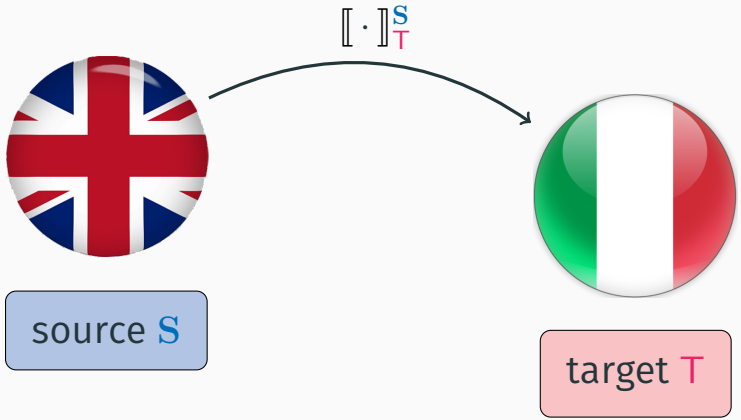

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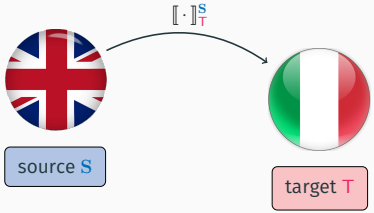

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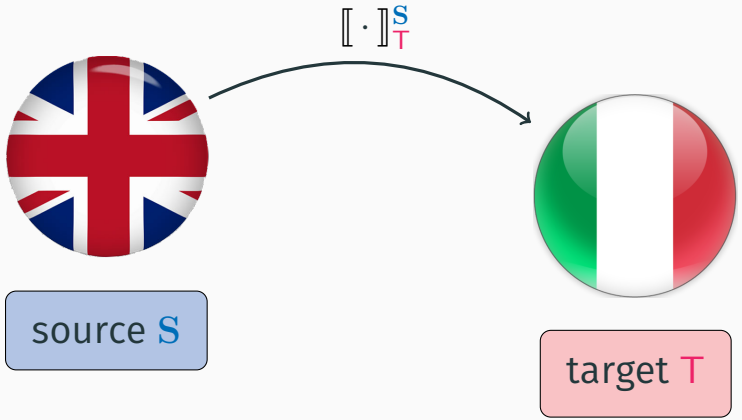

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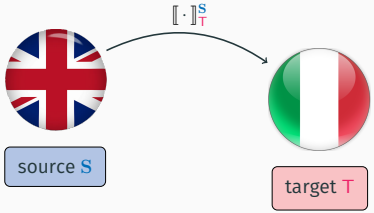

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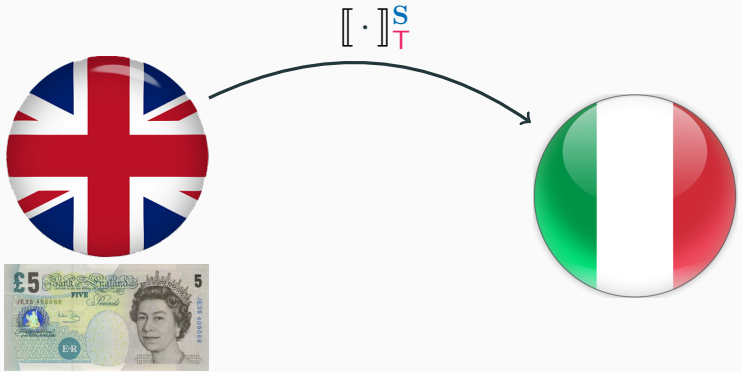

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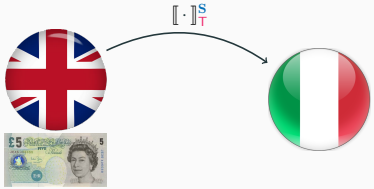

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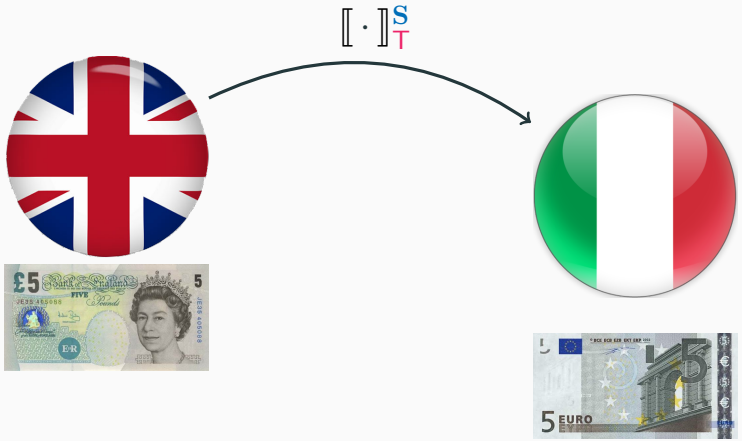

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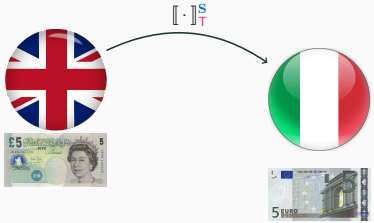

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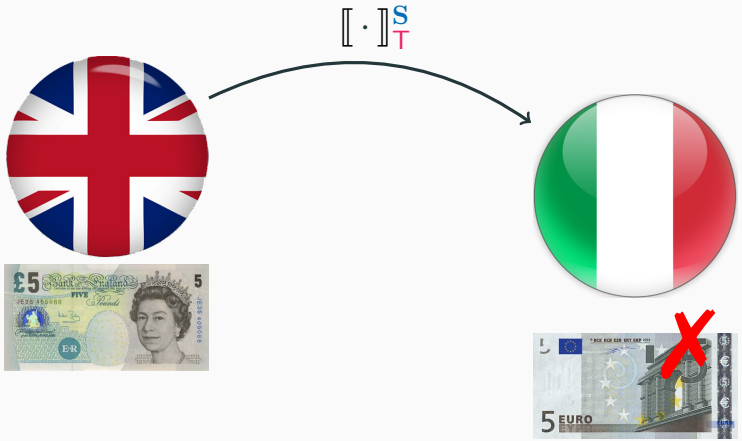

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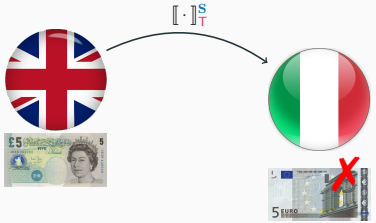

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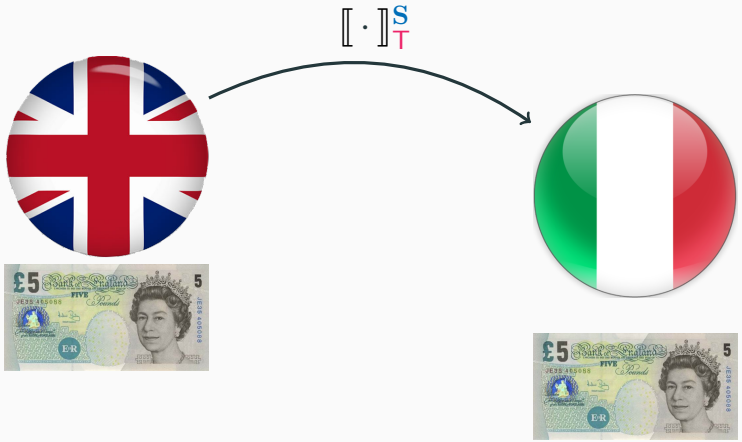

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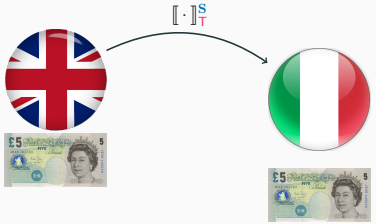

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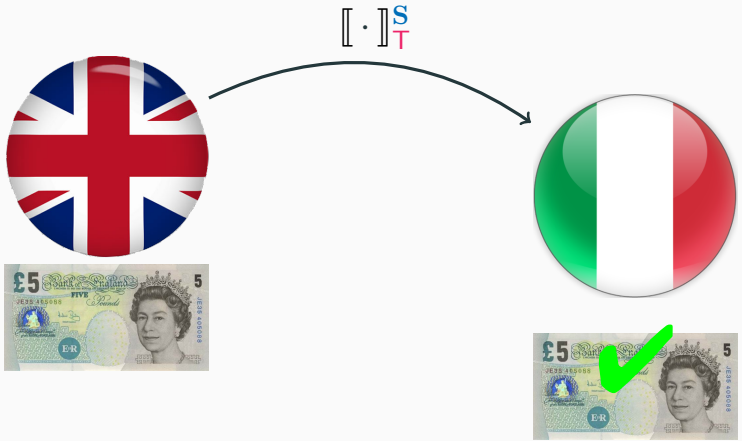

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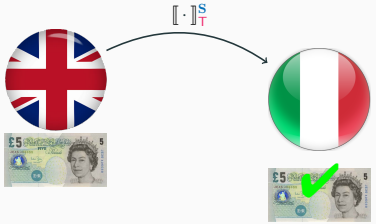

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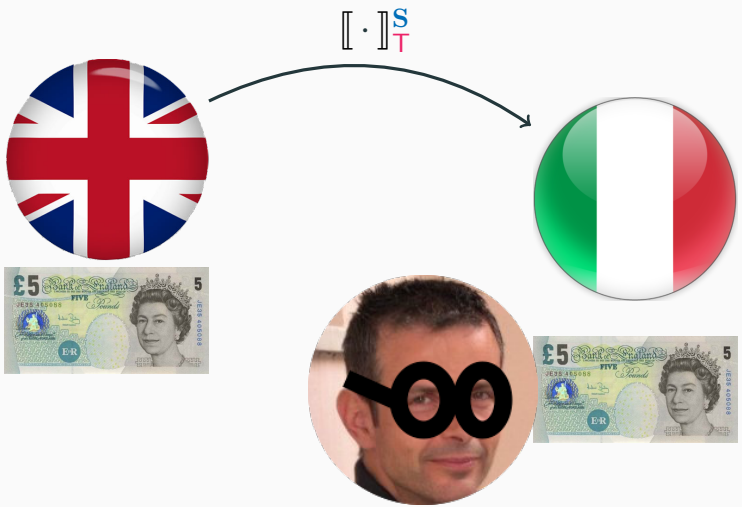

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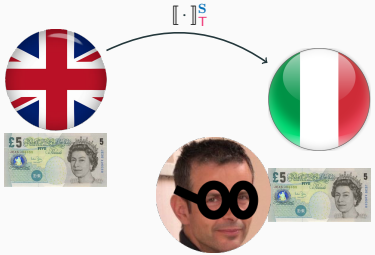

exploits: buffer overflow, privilege escalation

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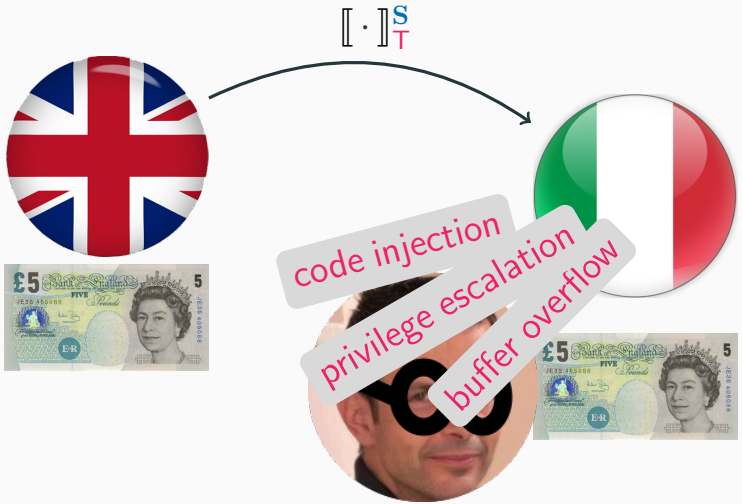

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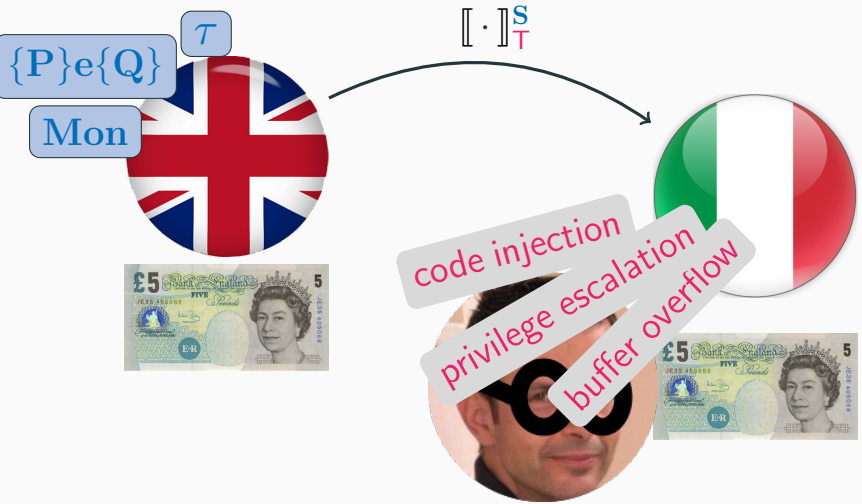

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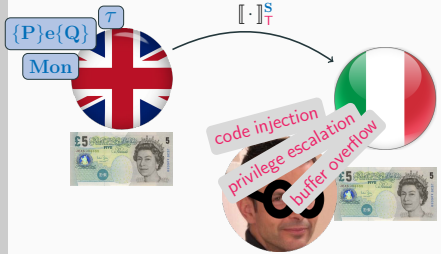

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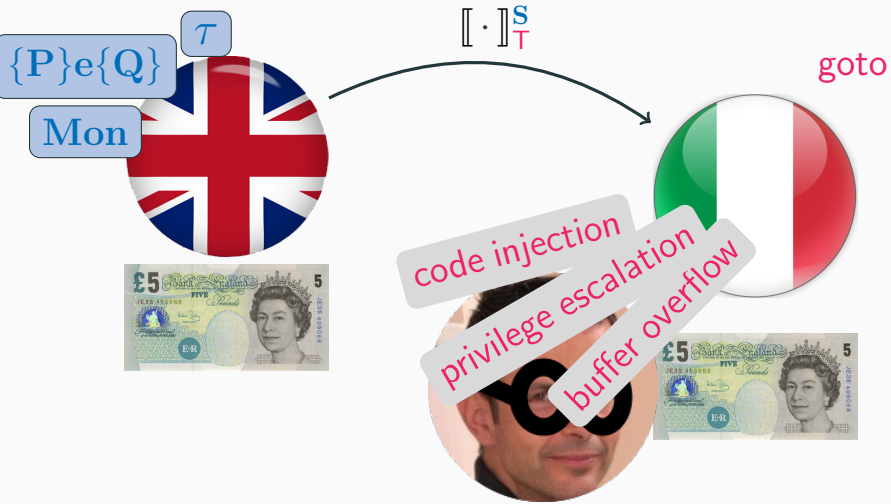

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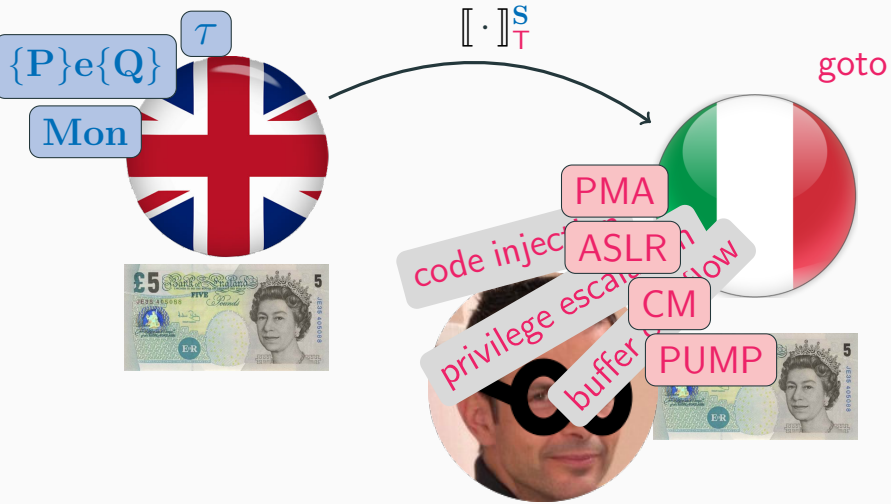

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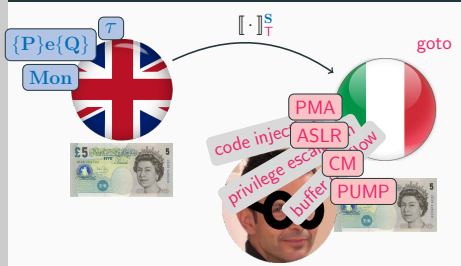
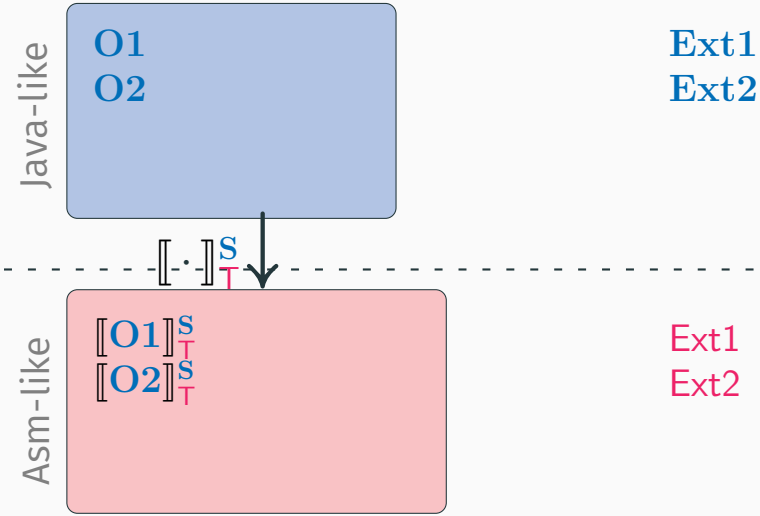


Memory Allocation Issues Patrignani *et al.*'15'16



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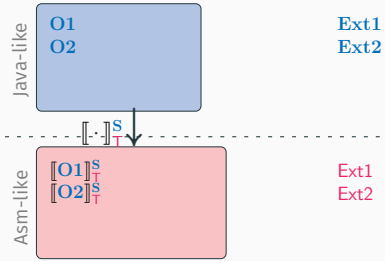

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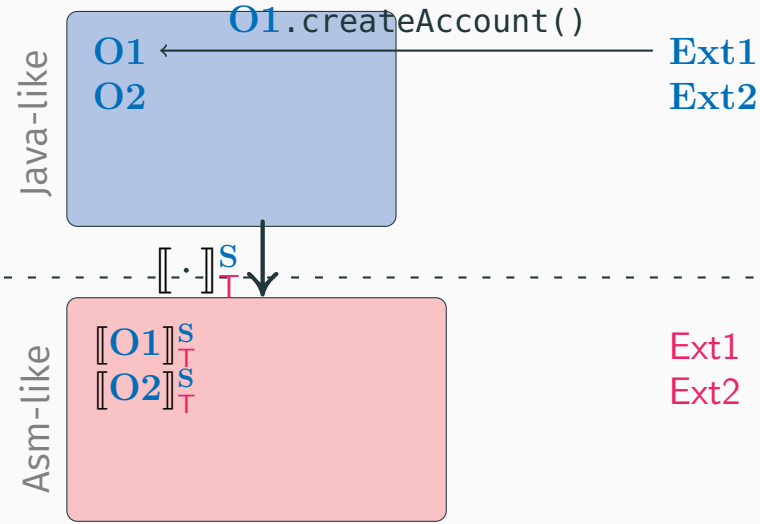

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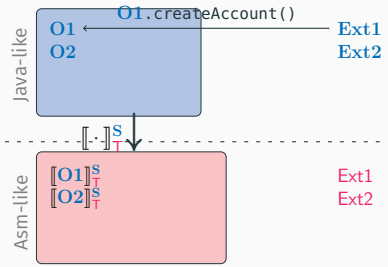

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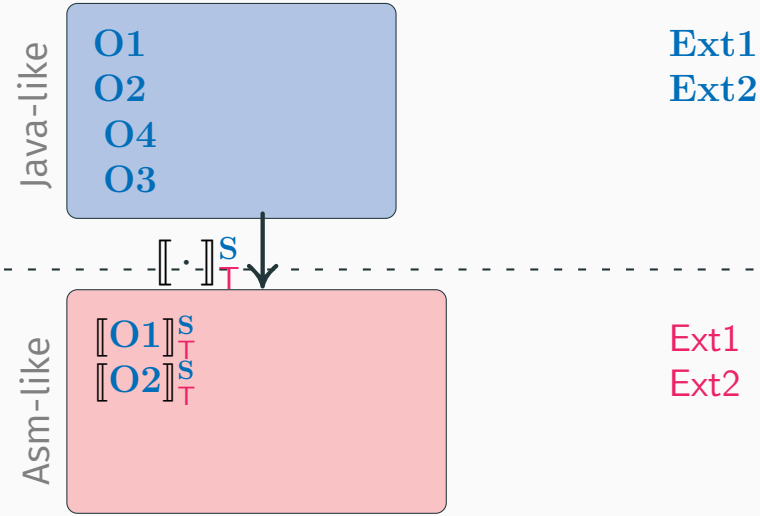

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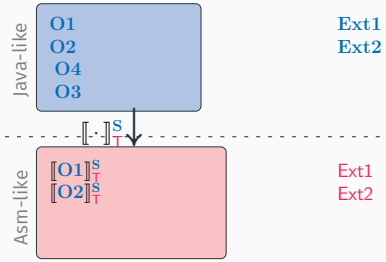

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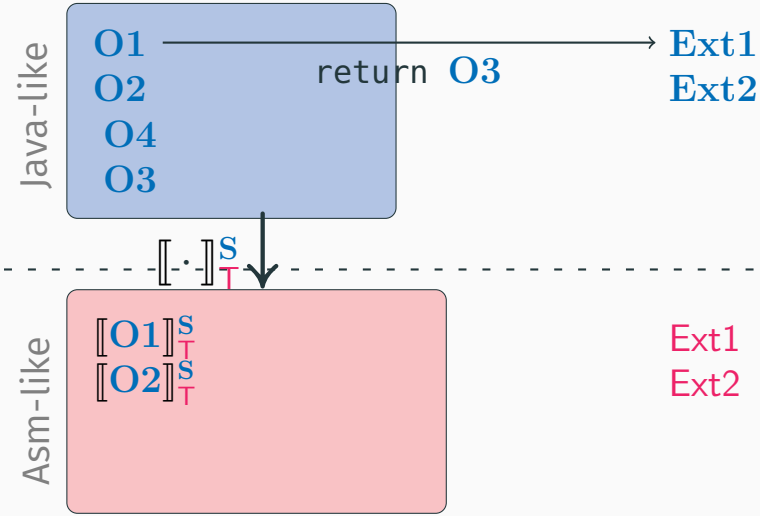

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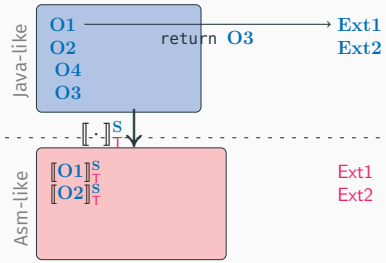

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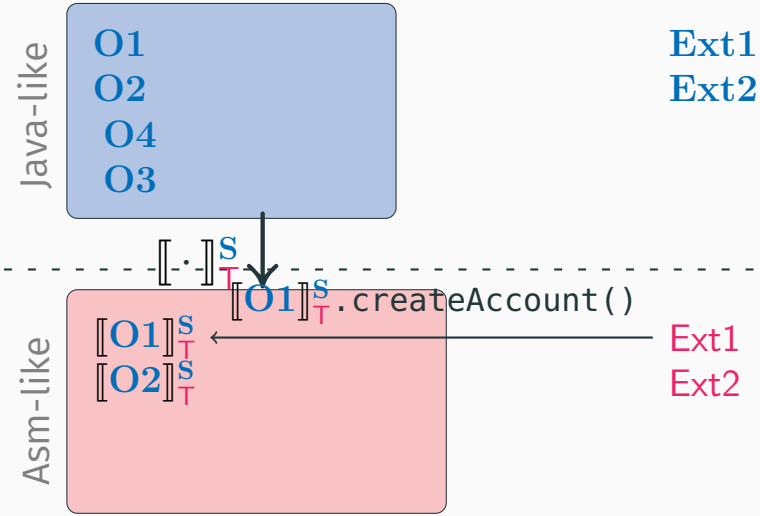

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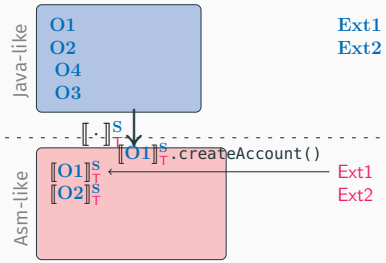

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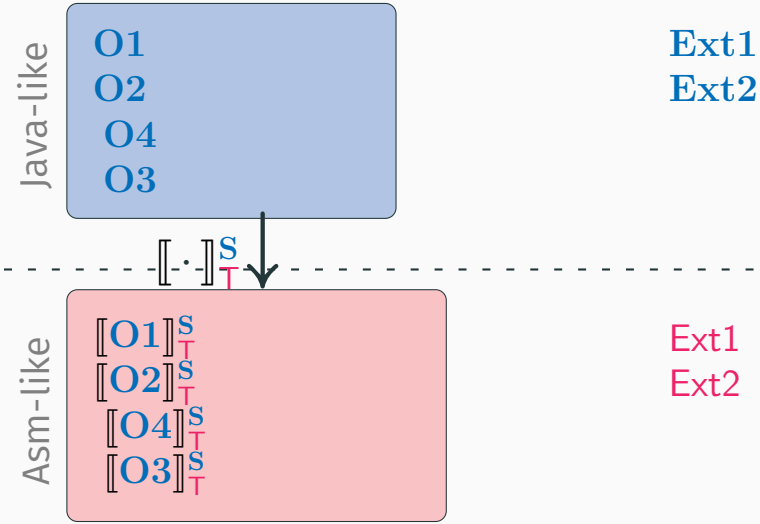

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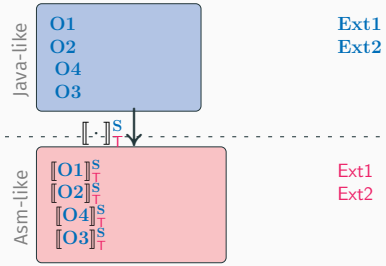

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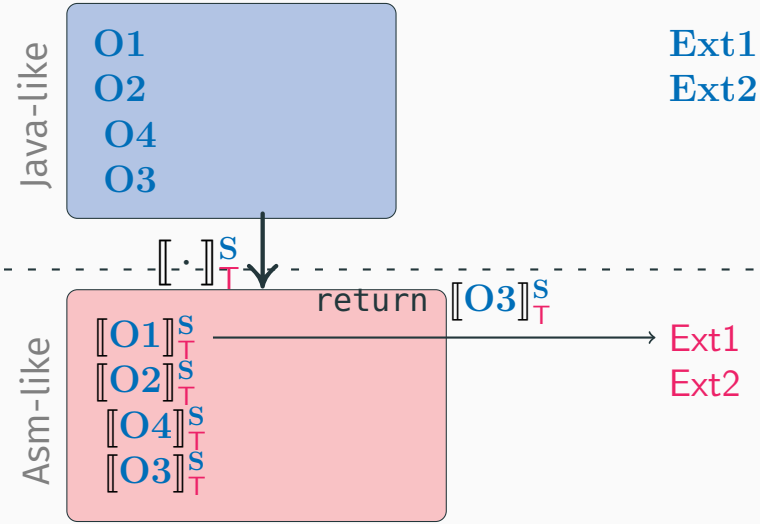

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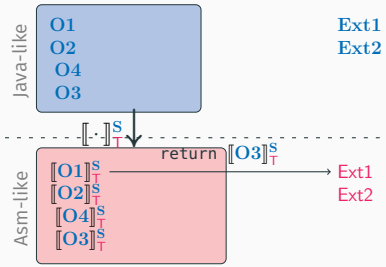

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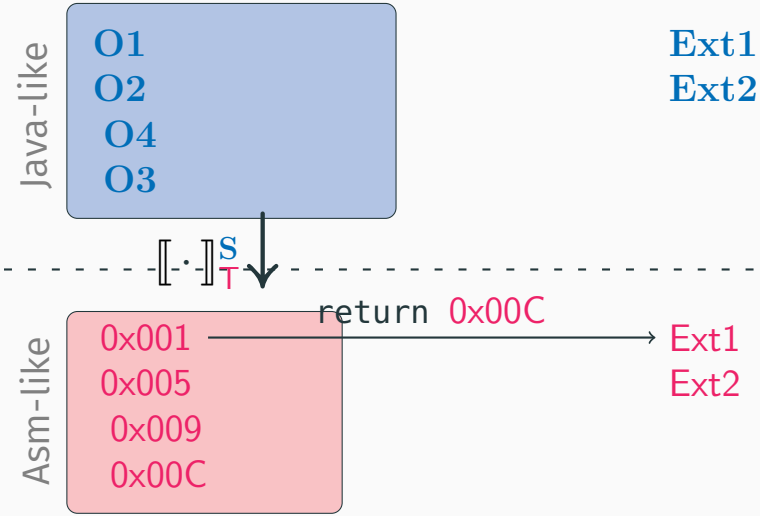

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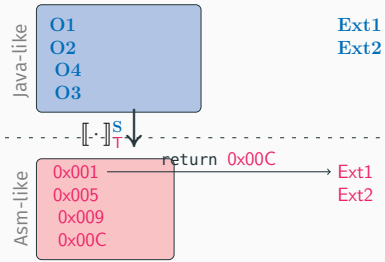

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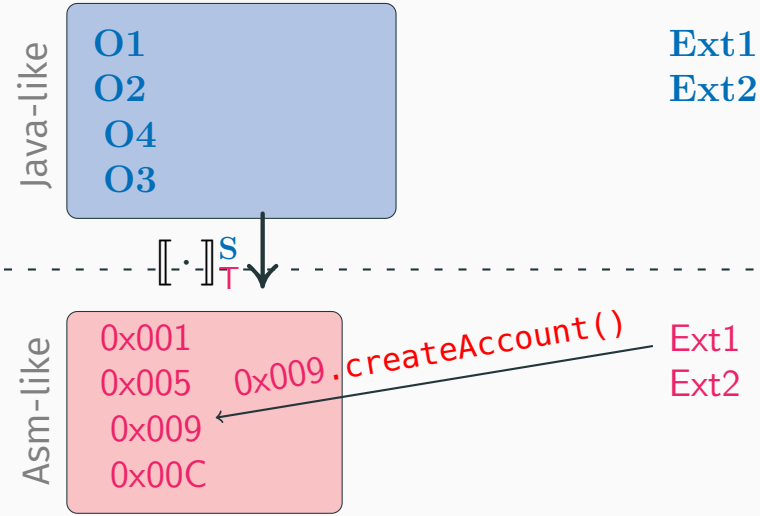

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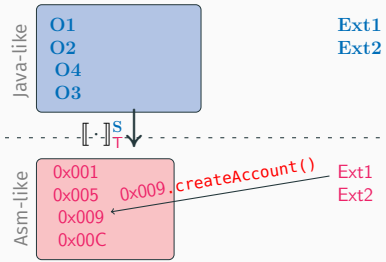

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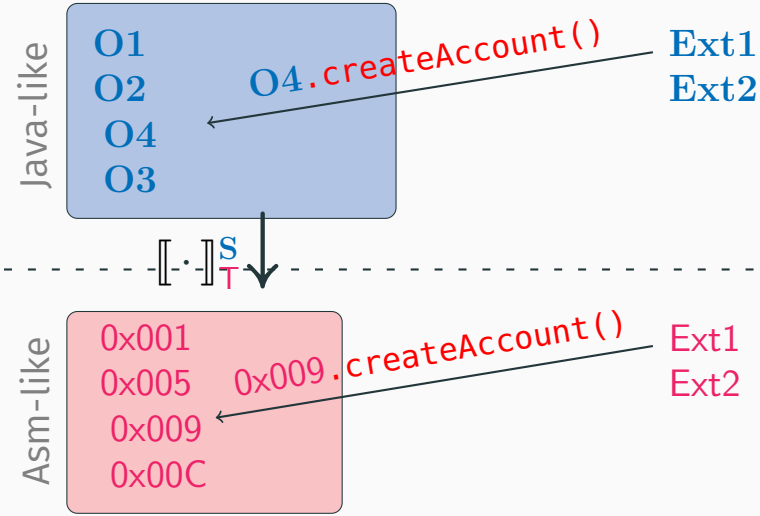

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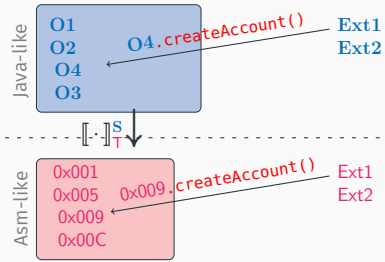

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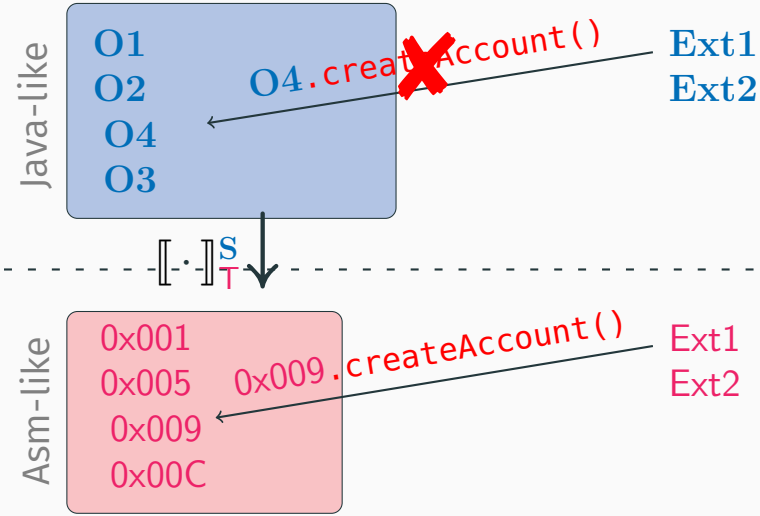

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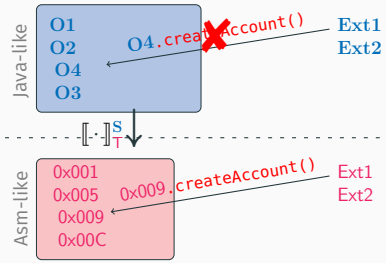

Memory Allocation Issues Patrignani *et al.*'15'16

Issue: Oid guessing
Solution: keep a map from Oid to random numbers

Ext1
Ext2

Ext1
Ext2

Asm-lik

0x005

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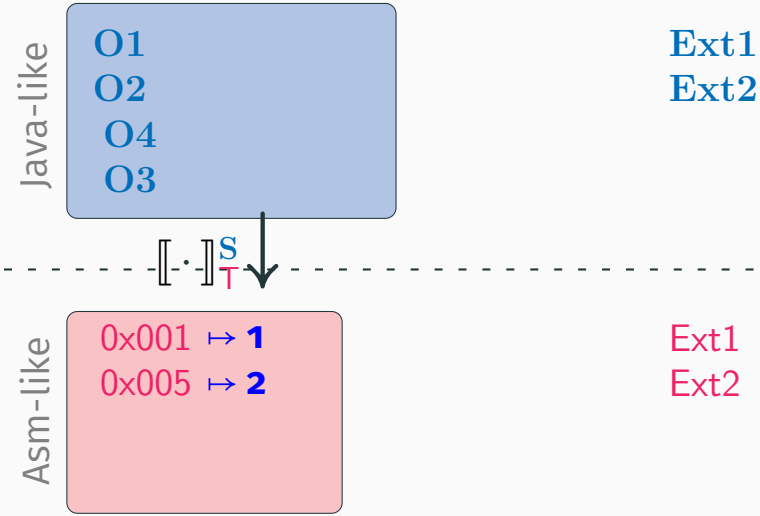

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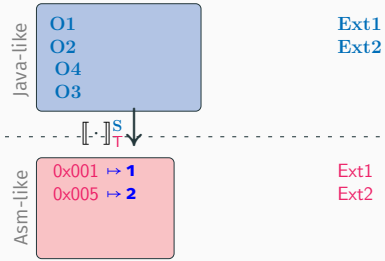

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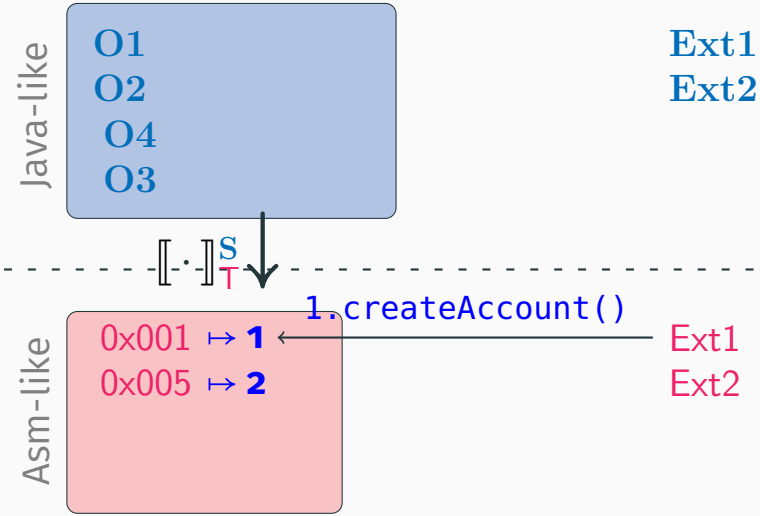

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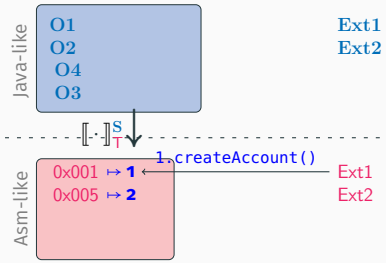

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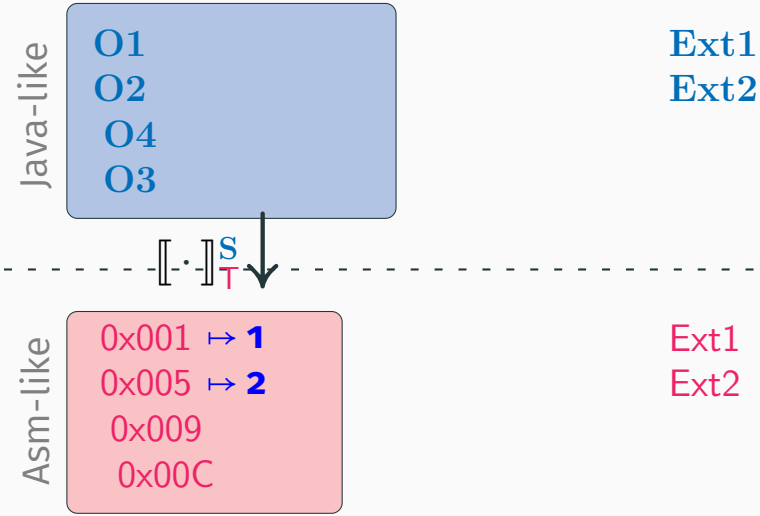

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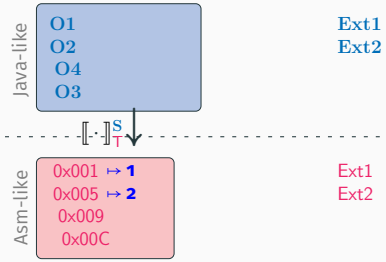

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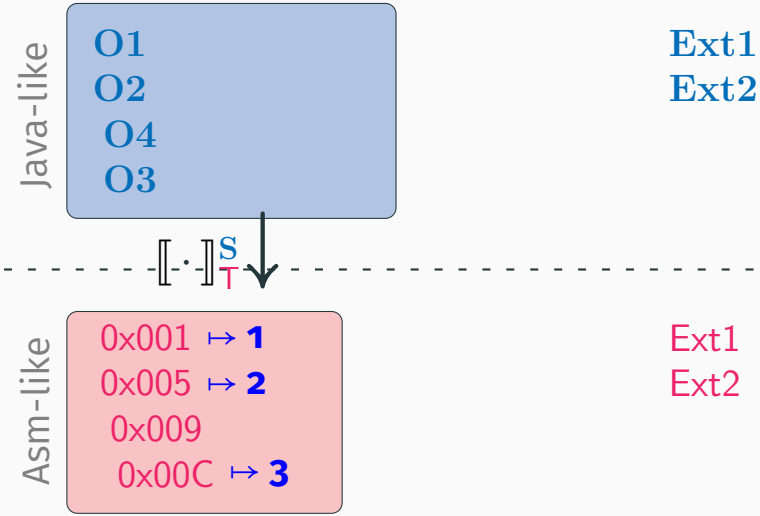

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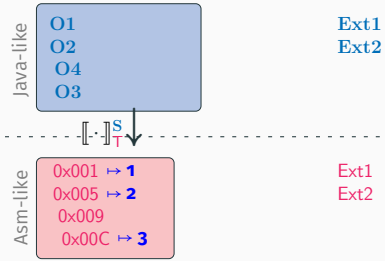

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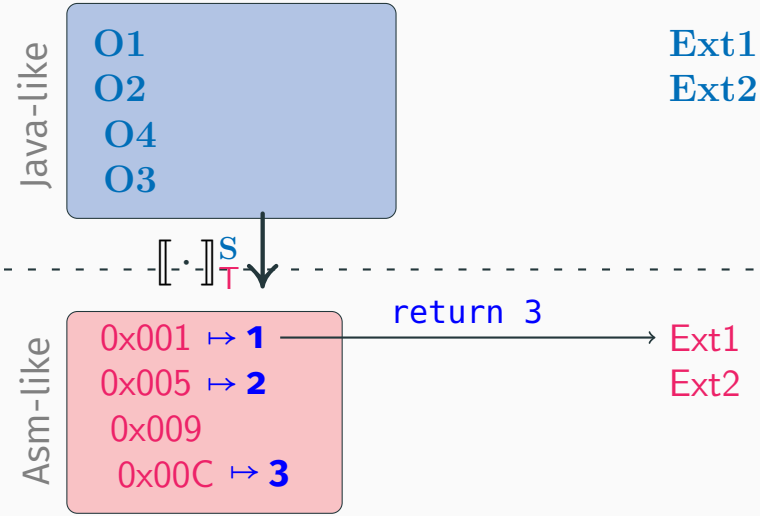
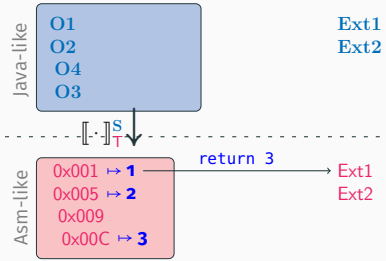


Memory Allocation Issues Patrignani *et al.*'15'16



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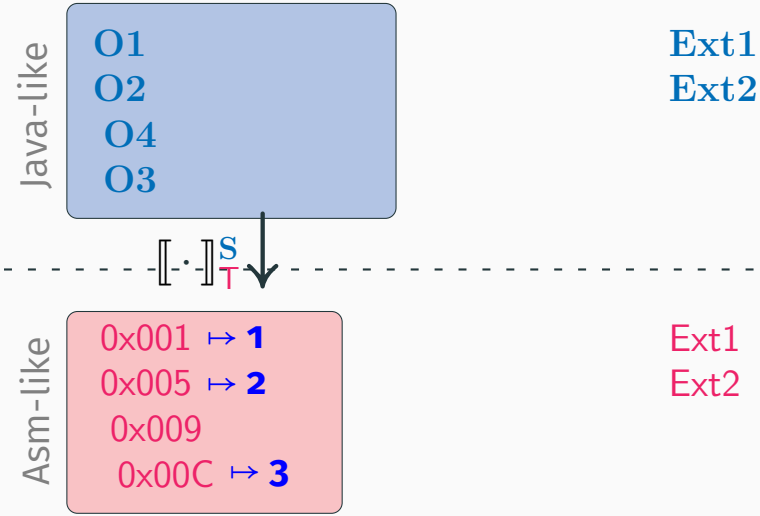

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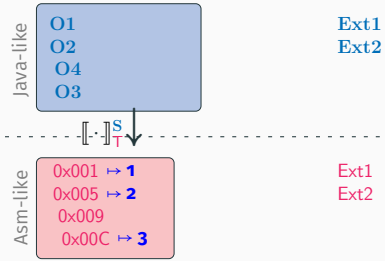

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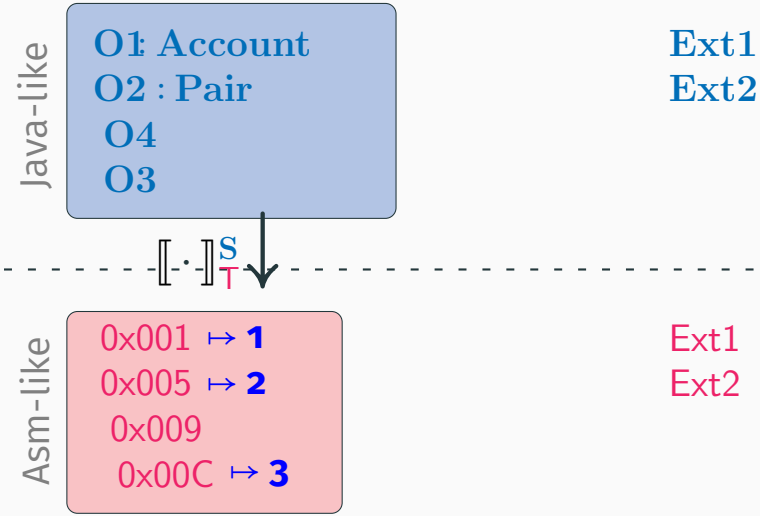

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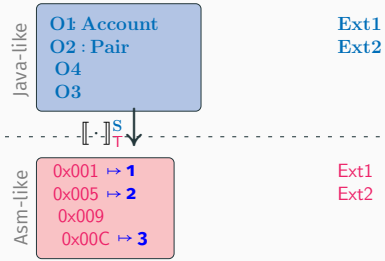

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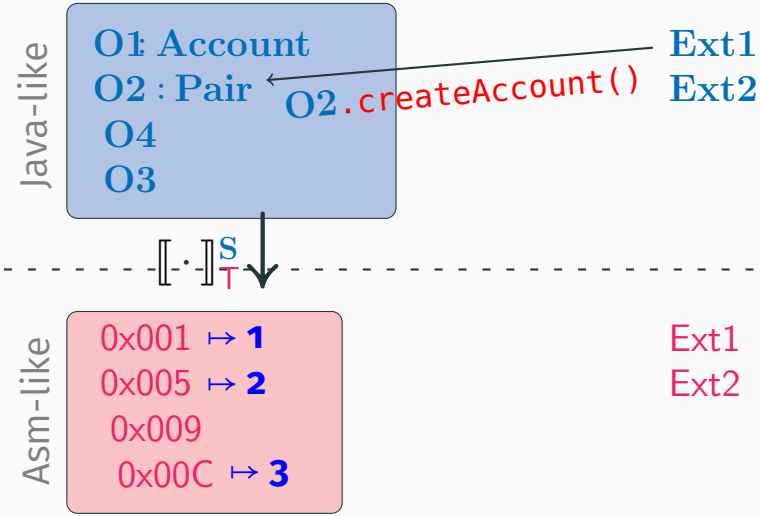

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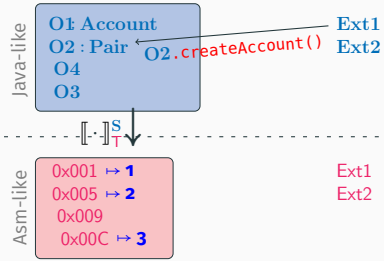

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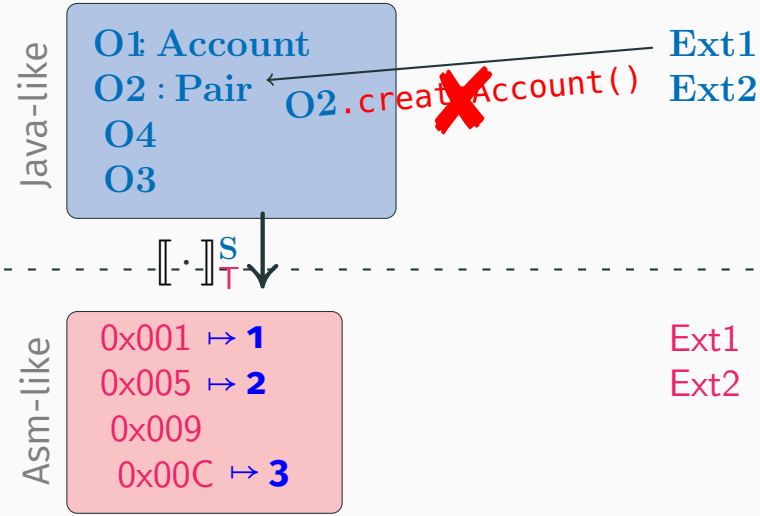

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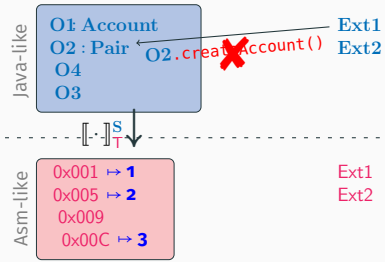

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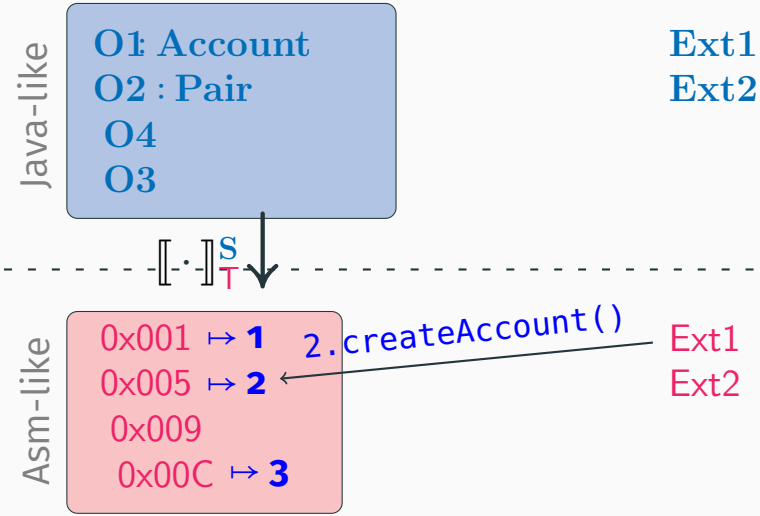

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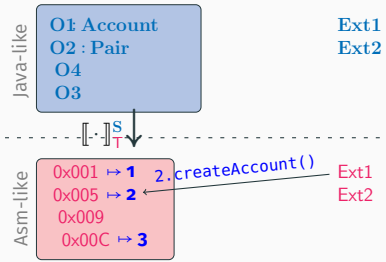

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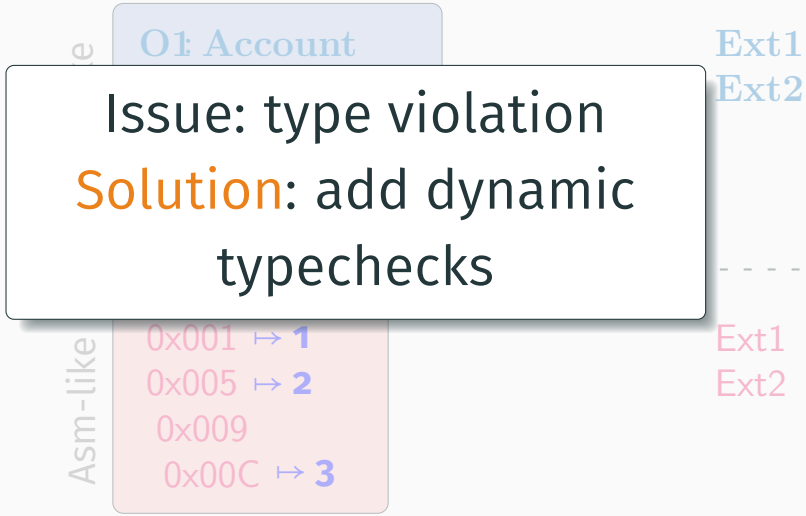

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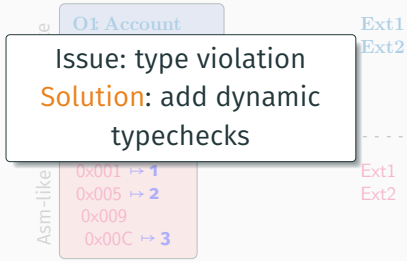
Solution: add dynamic typechecks

Memory Allocation Issues Patrignani *et al.*'15'16



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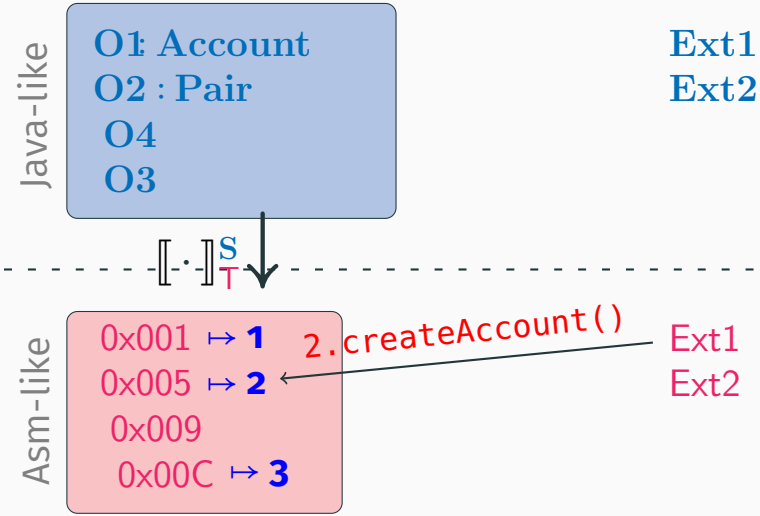

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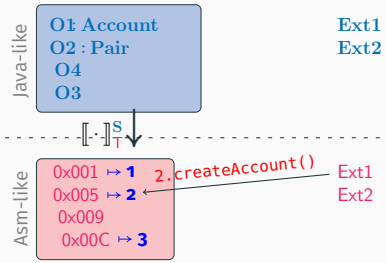

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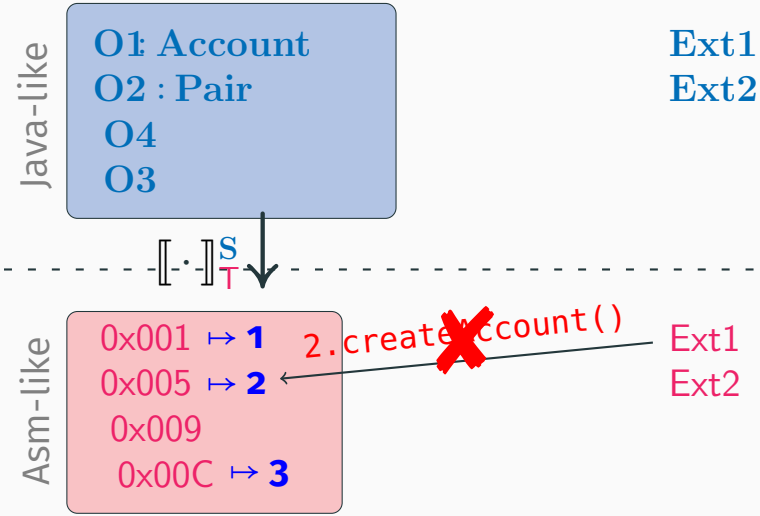

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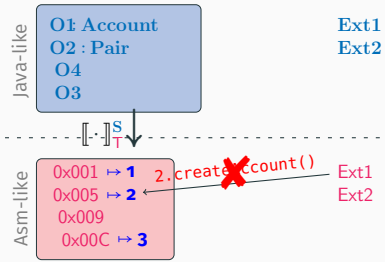

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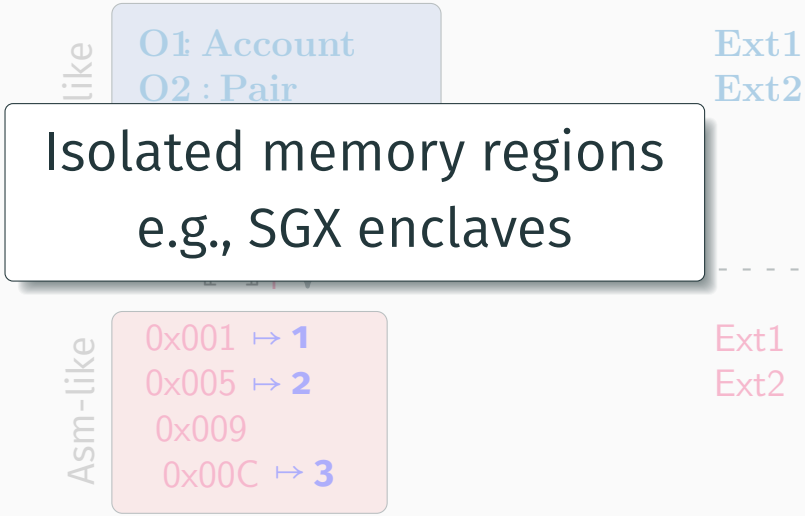

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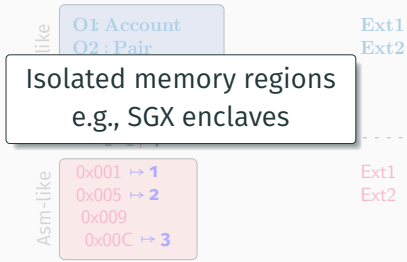

efficiency issues are the price to pay

Memory Allocation Issues Patrignani *et al.*'15'16

- design
- implement
- 

Ext1
Ext2

Ext1
Ext2

Asm-

0x009
0x00C ↦ 3

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Secure Compilation Criteria

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The Origins of the Secure Compiler

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,*

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

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secure compilation is a broad field that received contributions from many researchers, many of which are in this room today.

around the end of the 90's came a line of works that contributed greatly to the idea we have nowadays of Secure Compilation,

The Origins of the Secure Compiler

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

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many works using FA have been made

and FA has also been studied by Parrow that tells us when it's possible

Fully Abstract Compilation Influence

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Why
does Fully Abstract Compilation entail security?

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Compiler Full Abstraction

x = 1;	x = 0;
x ++;	x+= 2;
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1. let's look at FA, informaly

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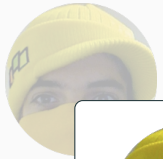

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1. note that the observers have different powers!
   the target one is not subject to what happens in the source, so if S has types, he's not subject to them if the language allows him to, he could also jump in mid code!
   but if FA holds, either those bad things cannot arise/are prevented or they are also doable in the source

Why is FAC Secure?

-  is an attacker linking or injecting target code

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1. the difference in observers power is at the root of the reasons why FA is a good def for SC
   2 reasons: what attacks are prevented
   what properties are secured

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4. memory allocation
5. well-bracketed control flow

Agten *et al.*'12, Abadi and Plotkin '10, Jagadeesan *et al.*'11

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1. Second reason: what is FA preserving

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2017-10-09

Secure Compilation

Not All That Glitters is Gold

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  [Patrignani *et al.*'16, Juglaret *et al.*'16]

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1. Is that it? Well, no, fa has a number of shortcomings, unfortunately, which we started unveiling only recently.

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1. first off, when studied in an untyped target setting, it enforces nothing about modularity

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1. secondly, it does not support languages with undefined behaviour

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1. some security properties are not upheld by it for example a simple declassification policy ... ... though someone may say that it's a matter of changing the kind of equivalence to be preserved

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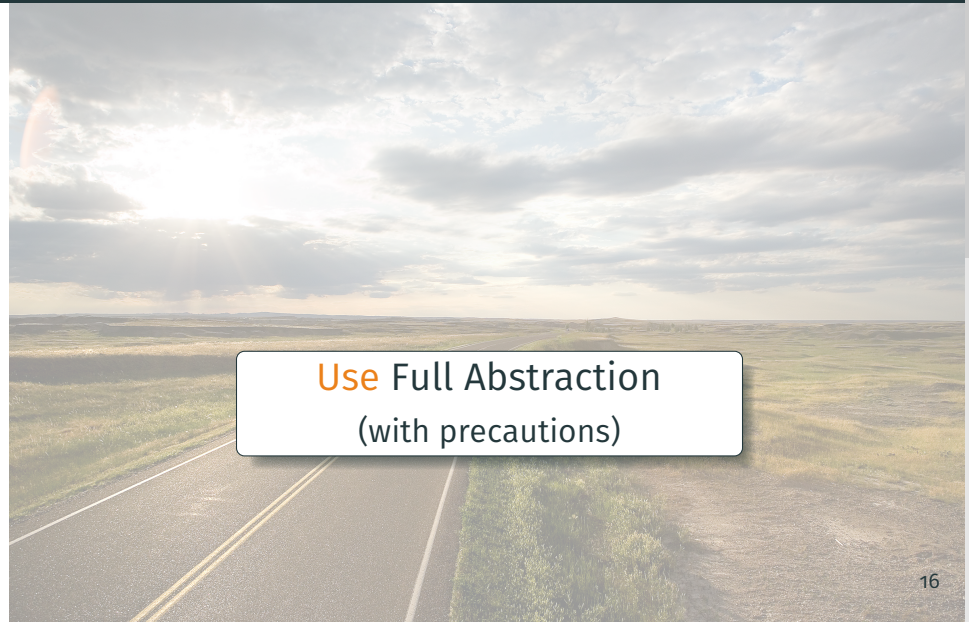
- Preserves hypersafety under certain conditions [Patrignani and Garg '17]

1. finally, the list of security properties it preserves is obtained by example,
   it is not clear if there should be more to that list, or what is definitively not there.
   for this, we have a paper under submission that defines what (a specific form of) fa preserves in terms of classes of hyperproperties, but i'll not go into details here

Perspective on Foundations

Perspective on Foundations

Perspective on Foundations



Perspective on Foundations

Use Full Abstraction
(with precautions)

1. So: what now?
   this has potential.
   we can keep using FA as we've done and in similar settings: it's fine!

Perspective on Foundations

Perspective on Foundations

Invent
new definitions

Use Full Abstraction
(with precautions)

1. So: what now?
   this has potential.
   we can keep using FA as we've done and in similar settings: it's fine!

Perspective on Foundations

Perspective on Foundations

Improve Full Abstraction

Invent
new definitions

Use Full Abstraction
(with precautions)

1. some of us are discussing more specific statements of SC just tailored to specific properties of interest

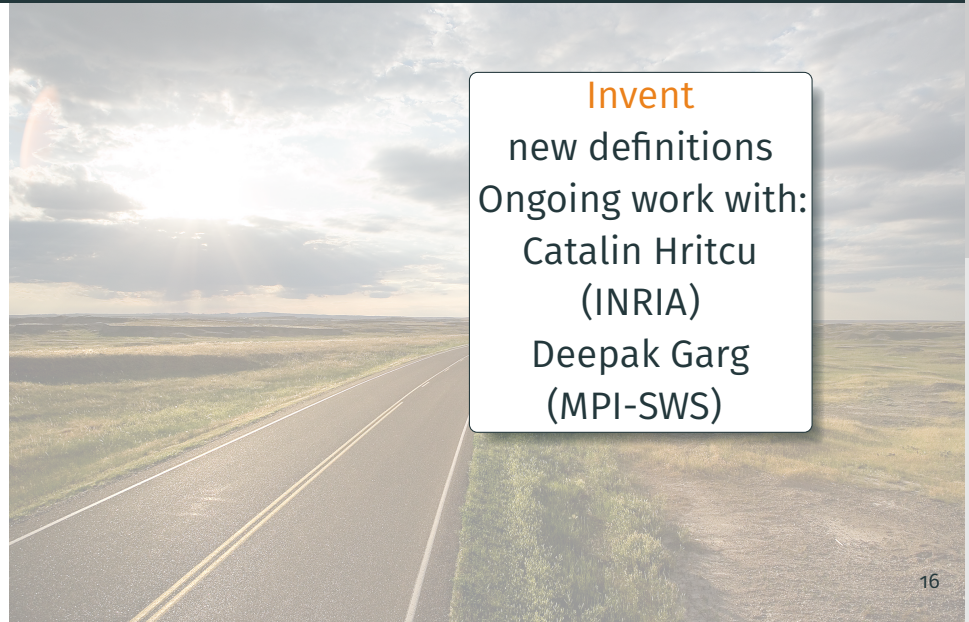
Perspective on Foundations

Perspective on Foundations

Invent
new definitions

1. some of us have already started looking into this: catalin's SCC, our TPC, though they all show a tight connection with fa

Perspective on Foundations



Invent
new definitions
Ongoing work with:
Catalin Hritcu
(INRIA)
Deepak Garg
(MPI-SWS)

Perspective on Foundations

Invent
new definitions
Ongoing work with:
Catalin Hritcu
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1. FA is not bad,
   but it can be improved:
   that's what we're after when we look at the foundations of this field

What More does Secure Compilation Offer?

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- study language techniques for proofs
- implement secure compilers to new security architectures

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Programming Languages Techniques for Secure Compilation

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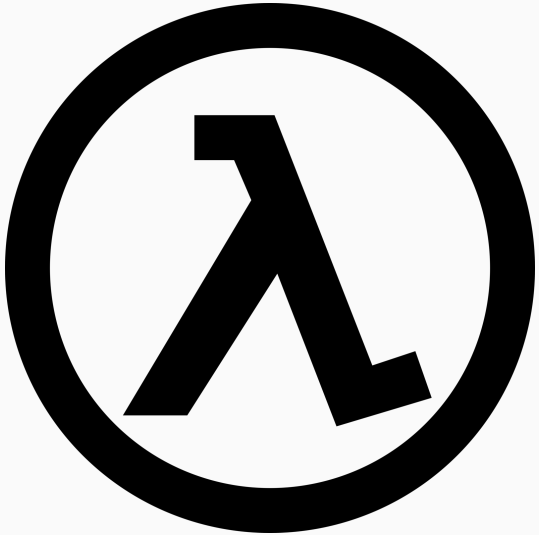
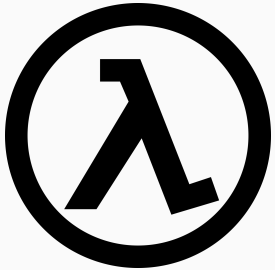
What PL Want



What PL Want



1. as we said, sc sits at the verge of PL and security. from the PL perspective, what is there to be challenged for SC?
   In this part of the talk, i'll focus on proof techniques for proving FA and the reason is that other definitions that we've seen also need to capture the additional power of target-level programs/contexts and reason about that. while the "how" it shows up

What PL Want

- better proof techniques

What PL Want

- better proof techniques

Proving FAC

$$\mathbf{P1} \simeq_{ctx} \mathbf{P2}$$

$$\Updownarrow$$

$$[\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}} \simeq_{ctx} [\![\mathbf{P2}]\!]^{\mathbf{S}}_{\mathsf{T}}$$

Proving FAC

$$\mathbf{P1} \simeq_{ctx} \mathbf{P2}$$

$$\Updownarrow$$

$$[\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}} \simeq_{ctx} [\![\mathbf{P2}]\!]^{\mathbf{S}}_{\mathsf{T}}$$

1. to prove fa, we need to prove the 2 parts of its coimplication
   if you don't see the observer don't worry, it's buried in here

Proving FAC

$$\mathbf{P1} \simeq_{ctx} \mathbf{P2}$$

$$\Uparrow$$

$$[\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}} \simeq_{ctx} [\![\mathbf{P2}]\!]^{\mathbf{S}}_{\mathsf{T}}$$

Proving FAC

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$$[\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}} \simeq_{ctx} [\![\mathbf{P2}]\!]^{\mathbf{S}}_{\mathsf{T}}$$

1. <= is easy, it follows from compiler correctness

Proving FAC

$$\mathbf{P1} \simeq_{ctx} \mathbf{P2}$$

$$\Downarrow$$

$$[\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}} \simeq_{ctx} [\![\mathbf{P2}]\!]^{\mathbf{S}}_{\mathsf{T}}$$

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$$\Downarrow$$

$$[\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}} \simeq_{ctx} [\![\mathbf{P2}]\!]^{\mathbf{S}}_{\mathsf{T}}$$

1. => is the hard one. let us now look a bit more in detail why is this difficult and how can we do this

Proving FAC

$$\mathbf{P1} \simeq_{ctx} \mathbf{P2}$$

$$\Downarrow$$

$$\forall \mathbb{C}.\mathbb{C}[[\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}}]\Downarrow \Longleftrightarrow \mathbb{C}[[\![\mathbf{P2}]\!]^{\mathbf{S}}_{\mathsf{T}}]\Downarrow$$

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1. well, here's the deal: we need to prove something over all target contexts, which is a notoriously complex feat to attain so we do what any sensible person would do, replace ceqT with something else

Proving FAC

$$\mathbf{P1} \simeq_{ctx} \mathbf{P2}$$

$$\Downarrow$$

$$[\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}} \doteq [\![\mathbf{P2}]\!]^{\mathbf{S}}_{\mathsf{T}}$$

Proving FAC
$\mathbf{P1} \simeq_{ctx} \mathbf{P2}$
$\Downarrow$
$[\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}} \doteq [\![\mathbf{P2}]\!]^{\mathbf{S}}_{\mathsf{T}}$

1. and now there are 2 schools of thought
   - trace equivalence
   - logical relations

Proving FAC

$$\mathbf{P1} \simeq_{ctx} \mathbf{P2}$$

Jagadeesan *et al.*'11,
Agten *et al.*'12,
Patrignani *et al.*'15'16,
Juglaret *et al.*'16

$$[\![\mathbf{P1}]\!]_{\mathsf{T}} \simeq [\![\mathbf{P2}]\!]_{\mathsf{T}}$$

Proving FAC

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Abadi *et al.*'00'01'02'
Bugliesi *et al.*'07
Adao *et al.*'06
Fournet *et al.*'13

$$[\![\mathbf{P1}]\!]_{\top} \sim [\![\mathbf{P2}]\!]_{\top}$$

Proving FAC
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Ahmed *et al.*'8'11'14'15'16'17,
Devriese *et al.*'16

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Proving FAC with Logical Relations

$$\mathbf{P1} \simeq_{ctx} \mathbf{P2}$$

approx. compiler security

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approx. compiler security

$$\mathbb{C}\Big[[\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}}\Big] \Downarrow_{\mathsf{n}} \overset{?}{\Rightarrow} \mathbb{C}\Big[[\![\mathbf{P2}]\!]^{\mathbf{S}}_{\mathsf{T}}\Big] \Downarrow_{\_}$$

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$$\langle\!\langle \mathbb{C} \rangle\!\rangle_{\mathbf{n}} \sim_n \mathbb{C}$$
$$\mathbf{P1} \sim_{\_} [\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}}$$

(1)

$$\mathbb{C}\left[[\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}}\right] \Downarrow_{\mathsf{n}} \overset{?}{\Rightarrow} \mathbb{C}\left[[\![\mathbf{P2}]\!]^{\mathbf{S}}_{\mathsf{T}}\right] \Downarrow_{\_}$$

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approx. compiler security

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approx. compiler security

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$$\mathbb{C}\left[[\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}}\right] \Downarrow_{\mathsf{n}} \overset{?}{\Rightarrow} \mathbb{C}\left[[\![\mathbf{P2}]\!]^{\mathbf{S}}_{\mathsf{T}}\right] \Downarrow_{\_}$$

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approx. compiler security

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approx. compiler security

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Proving FAC with Logical Relations

$$\mathbf{P1} \simeq_{ctx} \mathbf{P2}$$

$$\langle\!\langle \mathbb{C} \rangle\!\rangle_{\mathbf{n}}[\mathbf{P1}] \Downarrow_{\_} \underset{(2)}{\Rightarrow} \langle\!\langle \mathbb{C} \rangle\!\rangle_{\mathbf{n}}[\mathbf{P2}] \Downarrow_{\_}$$

$$\langle\!\langle \mathbb{C} \rangle\!\rangle_{\mathbf{n}} \sim_n \mathbb{C}$$
$$\mathbf{P1} \sim_{\_} [\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}}$$

(1)

$$\mathbb{C}\left[[\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}}\right] \Downarrow_{\mathsf{n}} \overset{?}{\Rightarrow} \mathbb{C}\left[[\![\mathbf{P2}]\!]^{\mathbf{S}}_{\mathsf{T}}\right] \Downarrow_{\_}$$

$$[\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}} \overset{?}{\simeq}_{ctx} [\![\mathbf{P2}]\!]^{\mathbf{S}}_{\mathsf{T}}$$

approx. compiler security

Proving FAC with Logical Relations

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approx. compiler security

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Proving FAC with Logical Relations

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$$[\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}} \overset{?}{\simeq}_{ctx} [\![\mathbf{P2}]\!]^{\mathbf{S}}_{\mathsf{T}}$$

approx. compiler security

Proving FAC with Logical Relations

$$\mathbf{P1} \simeq_{ctx} \mathbf{P2}$$

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approx. compiler security

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Proving FAC with Logical Relations

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$\mathbf{P1} \sim [\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathbf{T}}$ is obtained with standard techniques

Benton *et al.*'09'10

Hur *et al.*'11

Neis *et al.*'15

approx. compiler security

Proving FAC with Logical Relations

$\mathbf{P1} \simeq_{ctx} \mathbf{P2}$

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Benton *et al.*'09'10

Hur *et al.*'11

Neis *et al.*'15

approx. compiler security

1. so we need to define a relation for normal terms for relating programs

Proving FAC with Logical Relations

$\langle\!\langle \mathbb{C} \rangle\!\rangle_{\mathbf{n}} \sim \mathbb{C}$ requires

- back-translation of terms
- reasoning at the type of back-translated terms

$[\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}} \overset{?}{\simeq}_{ctx} [\![\mathbf{P2}]\!]^{\mathbf{S}}_{\mathsf{T}}$

approx. compiler security

Proving FAC with Logical Relations

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approx. compiler security

1. need to define a pseudo type and a relation at that pseudotype for back-translated terms

Proving FAC with Logical Relations

$\langle\!\langle \mathbb{C} \rangle\!\rangle_{\mathbf{n}} \sim \mathbb{C}$ requires

- back-translation of terms
- reasoning at the type of back-translated terms
- needed for all kinds of back-translation

$[\![\mathbf{P1}]\!]^{\mathbf{S}}_{\mathsf{T}} \overset{?}{\simeq}_{ctx} [\![\mathbf{P2}]\!]^{\mathbf{S}}_{\mathsf{T}}$

approx. compiler security

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approx. compiler security

1. for example, we proved a fa compiler from stlc+fix to ulc

Proving FAC with Logical Relations

$\langle\!\langle \mathbb{C} \rangle\!\rangle_{\mathbf{n}} \sim \mathbb{C}$ requires

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- reasoning at the type of back-translated terms
- needed for all kinds of back-translation
- needed for alternative criteria too

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approx. compiler security

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approx. compiler security

Security Architectures for Secure Compilation

Security Architectures for Secure Compilation

Security Architectures for SC

Security Architectures for SC

Security Architectures for SC

Security Architectures:

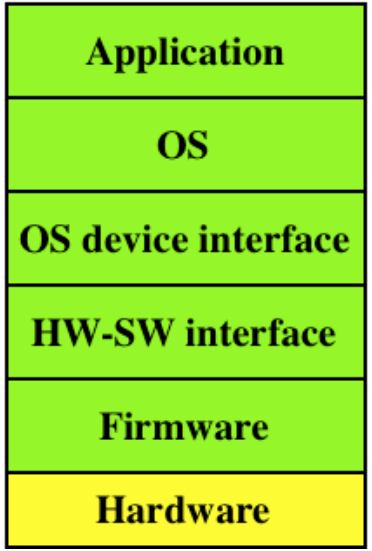
Security Architectures for SC

Security Architectures:

1. albeit formally, we devise compilers and we want them to be written and used.
   so let's change perspective and after looking at how to ensure that these compilers are secure,
   let' look at how to write them.

Security Architectures for SC

Security A



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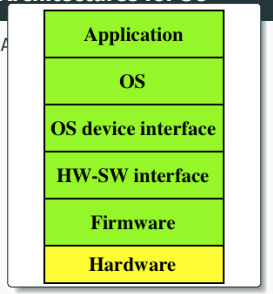

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   SGX Enclaves (aka PMA), ASLR, TAL, PUMP. Cheri are all examples of security architectures which support secure compilation and whose development allowed us to devise sc for them

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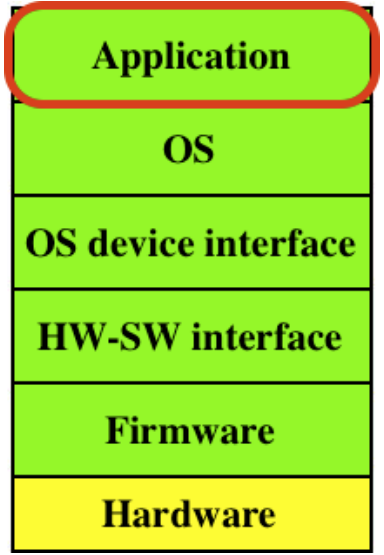

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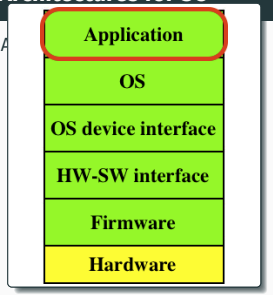

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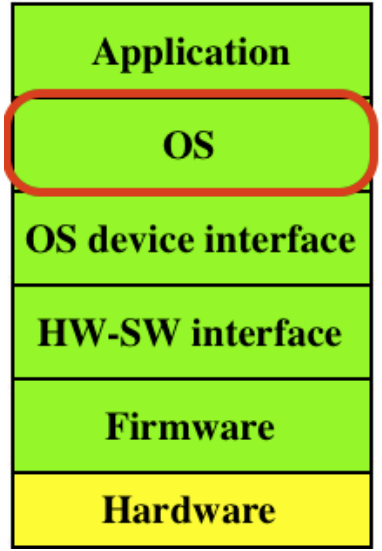

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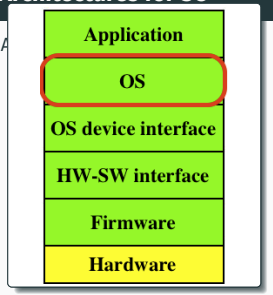

1. sec arch are needed because we simply can't SC to our pcs without having to trust huge codebases so we rely on special machines that give us additional security primitives for the compiler to rely on
   - isolation / randomisation / types / tags / capabilities
   these let us devise secure compilers that have a

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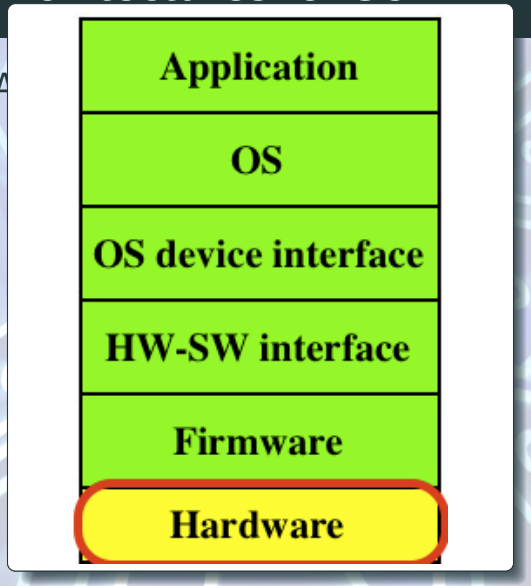

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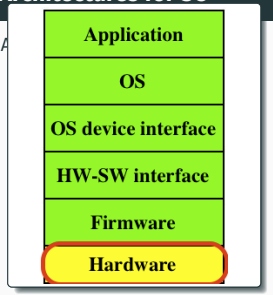

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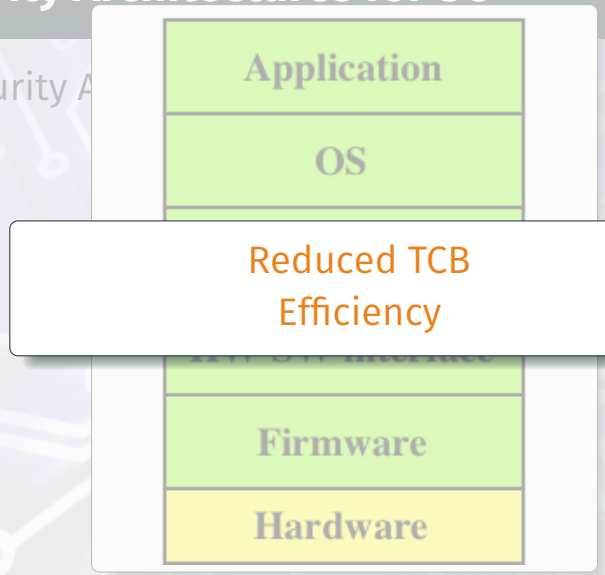

Reduced TCB
Efficiency

Security Architectures for SC

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Security Architectures:

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Capability Machines: Cheri

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- Hardware support for fine-grained Capabilities

Capability Machines: Cheri
Capability Machines
- Hardware support for fine-grained Capabilities

1. now i want to discuss some of the most recent and interesting of these sec arch: cap machs
cap machs bring the capability principle to hardware, so they are directly usable at the assembly level

Capability Machines: Cheri

Capability Machines

- Ha
  Ca

Capability Mantra:
subjects
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in this case subj = instructions, operations = r/w/x, objs are memory areas/addresses

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description of a cheri cap

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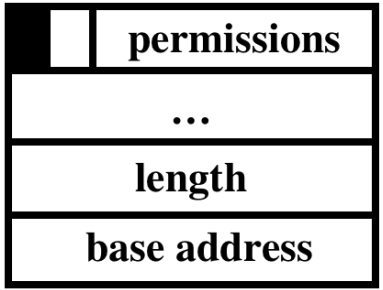

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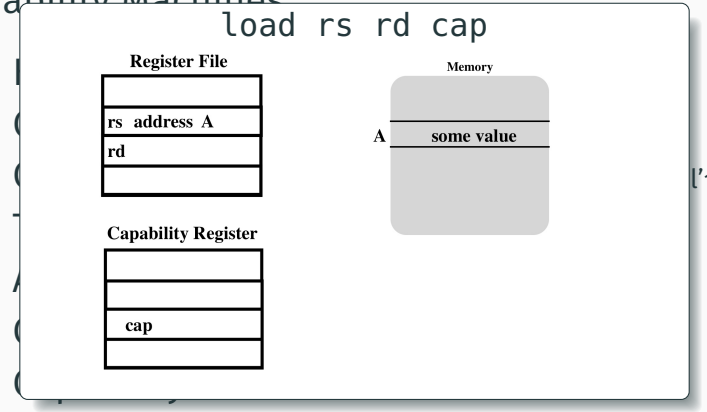

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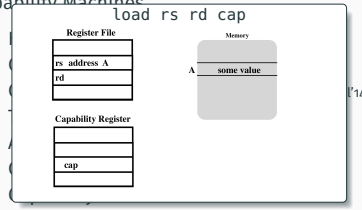

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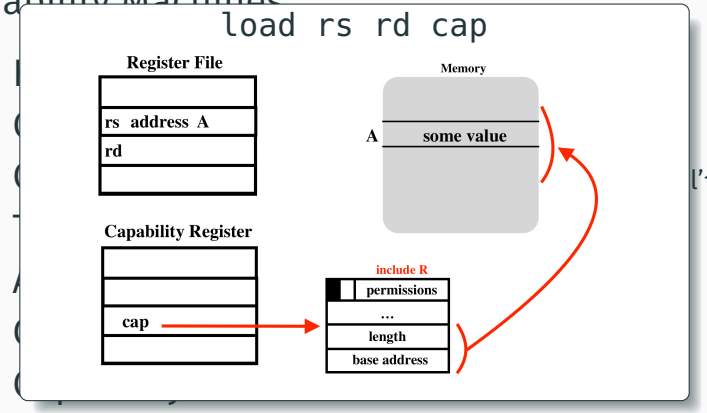

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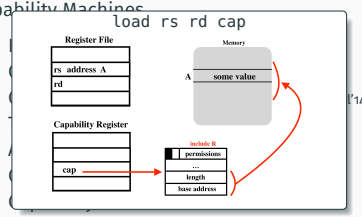

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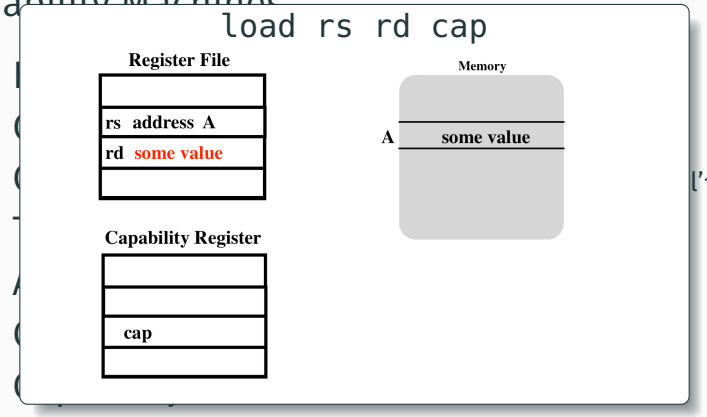

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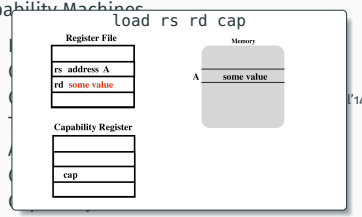

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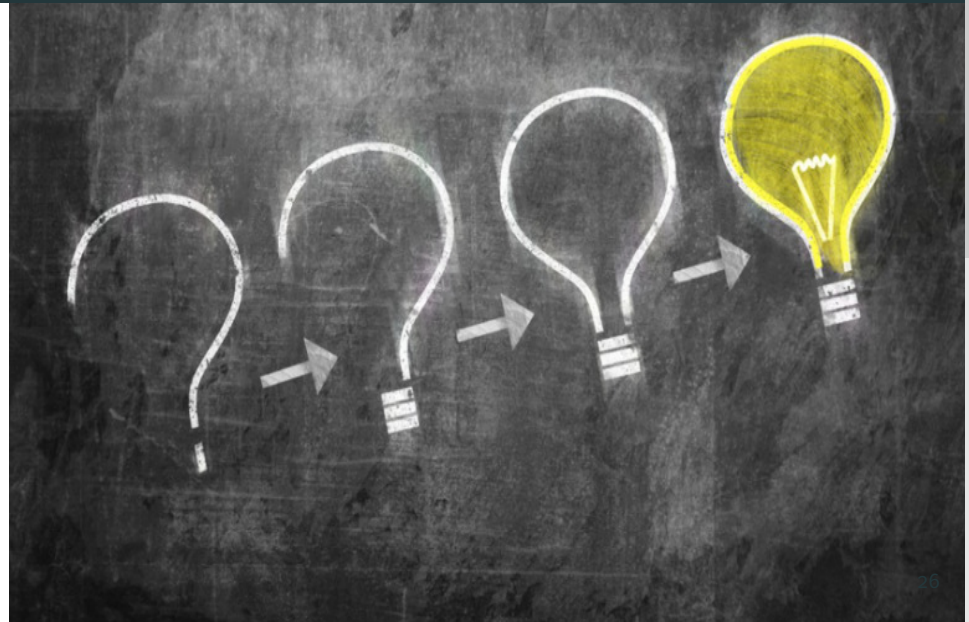

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