Formalizing Stack Safety as a Security Property

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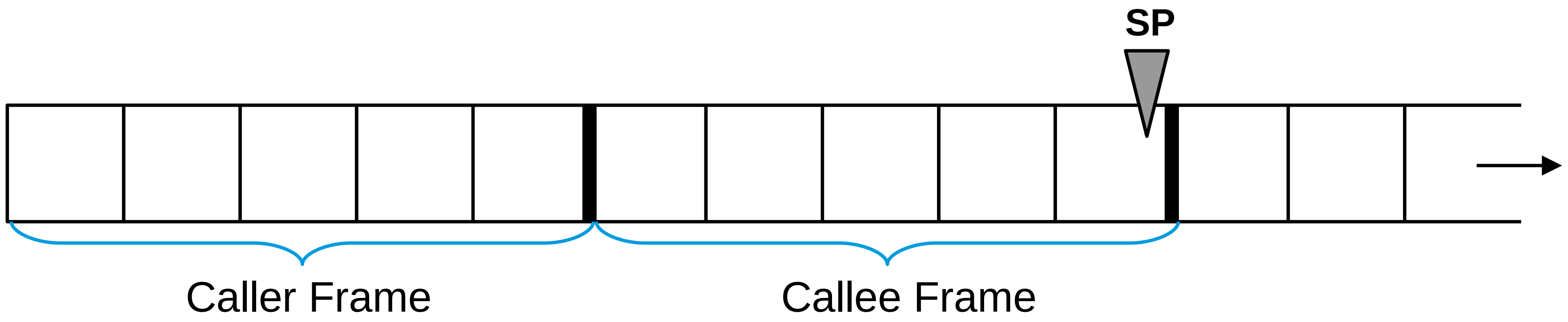
Benjamin C. Pierce	University of Pennsylvania
Andrew Tolmach	Portland State University

What Needs Protection on the Stack?



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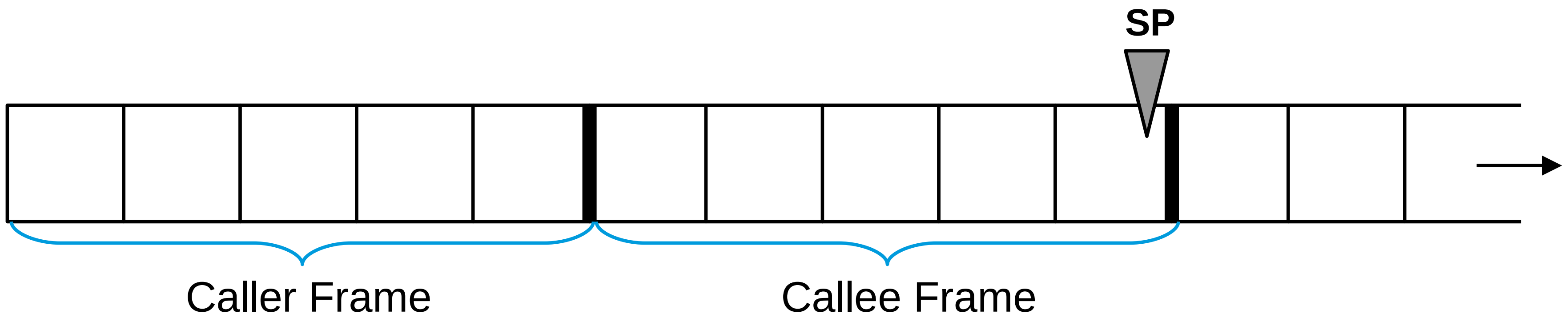

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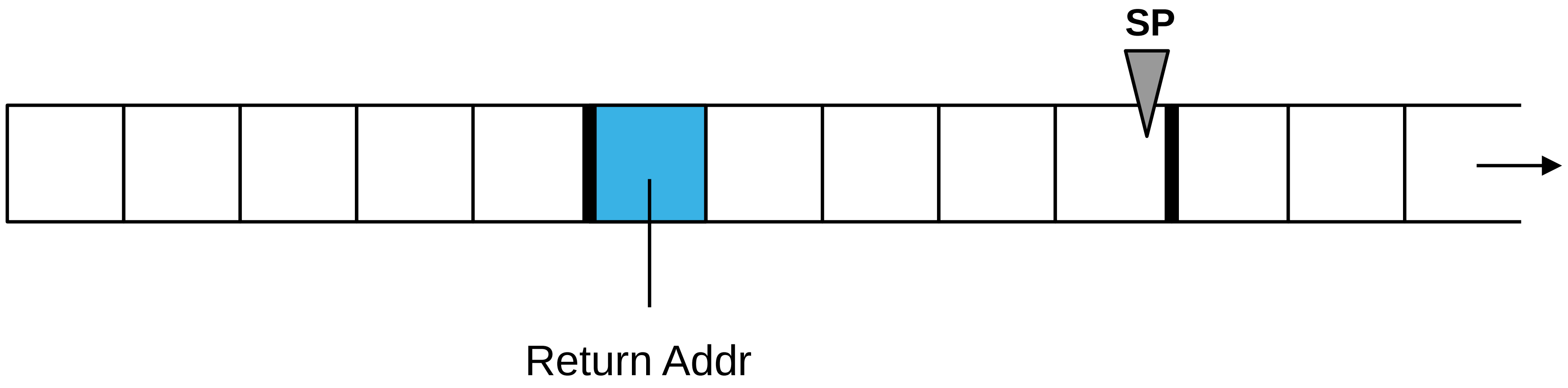

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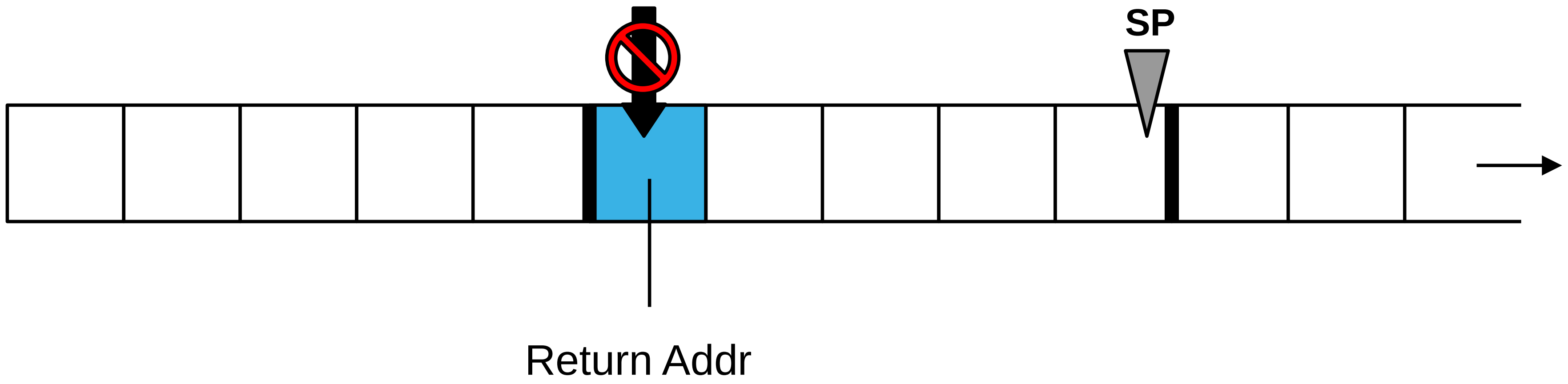

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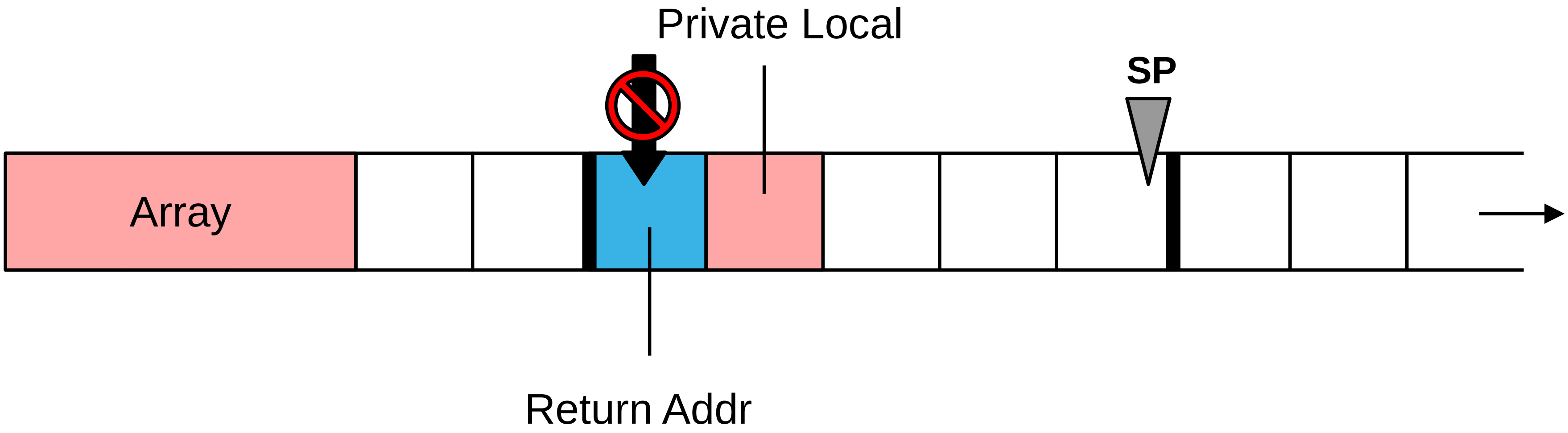

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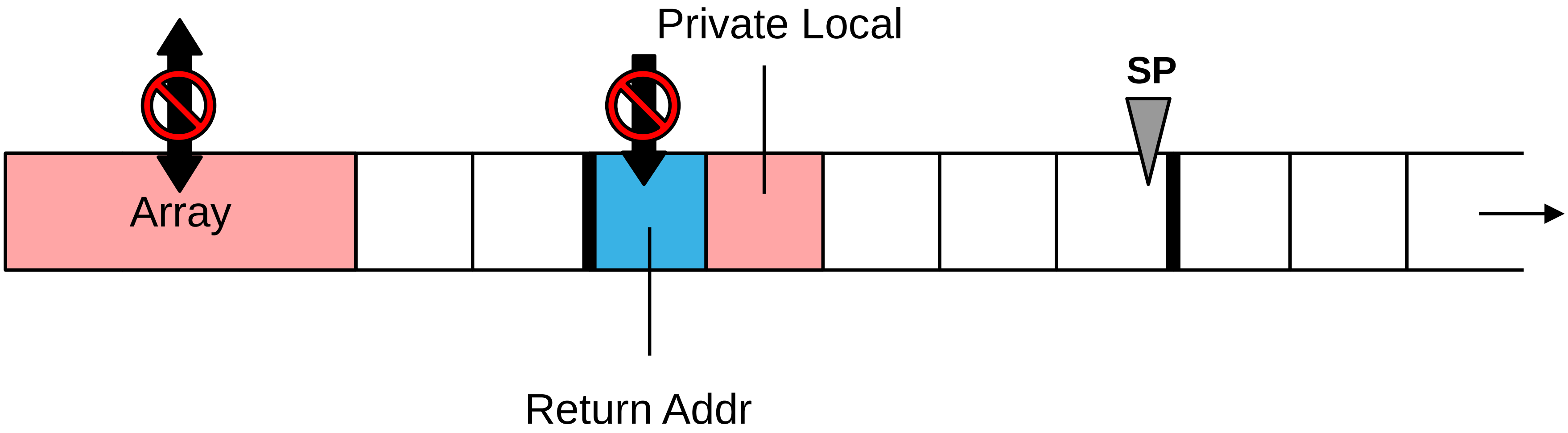

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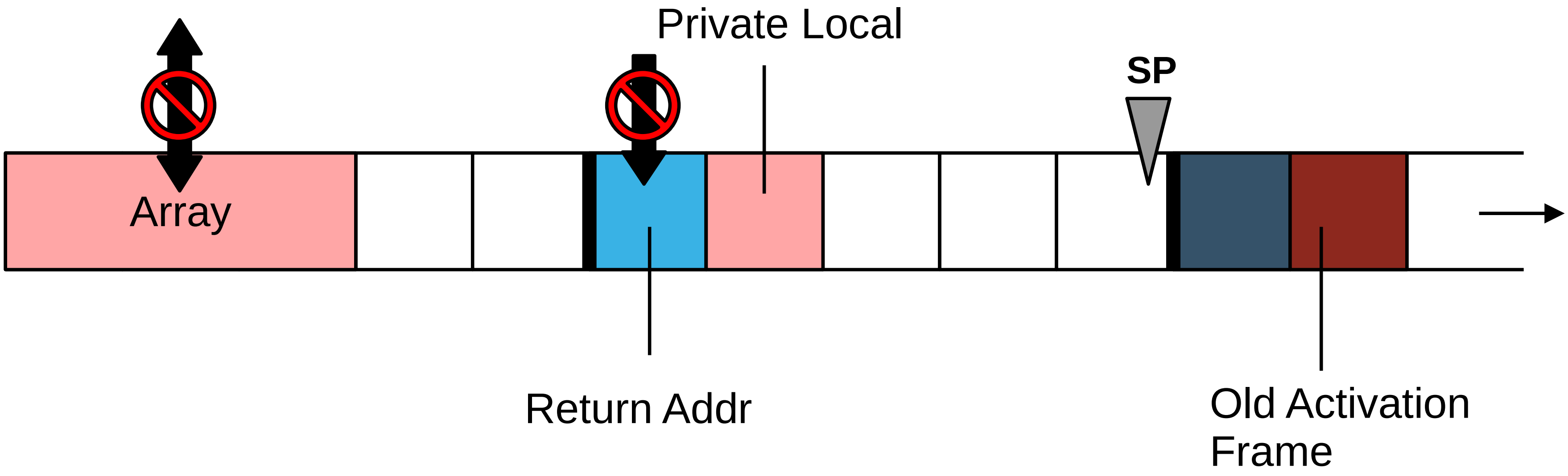

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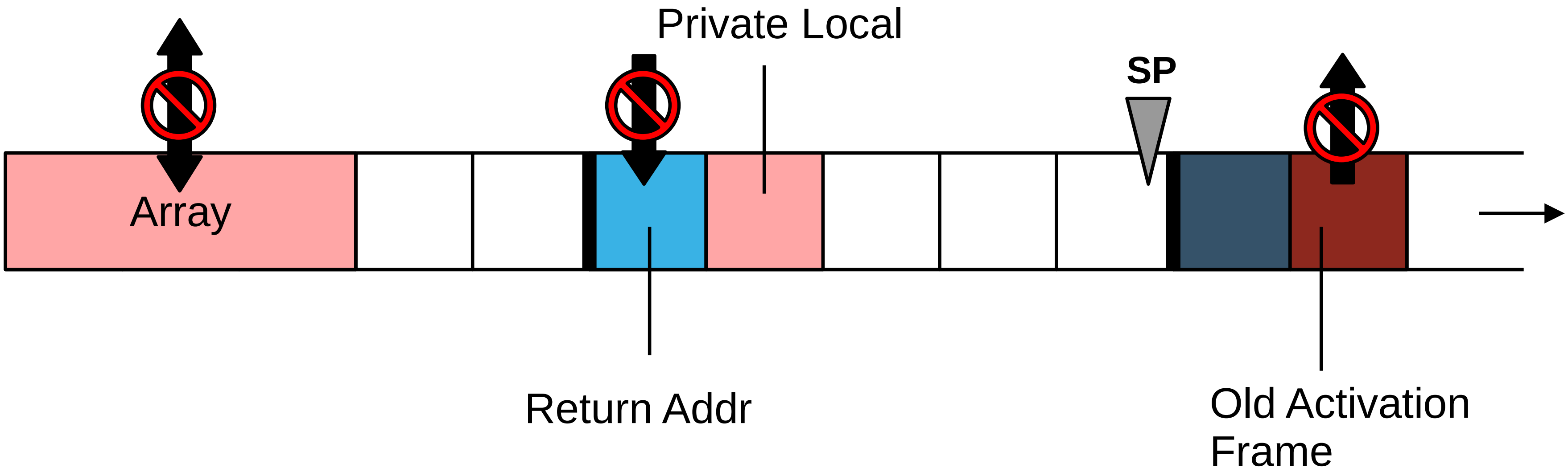

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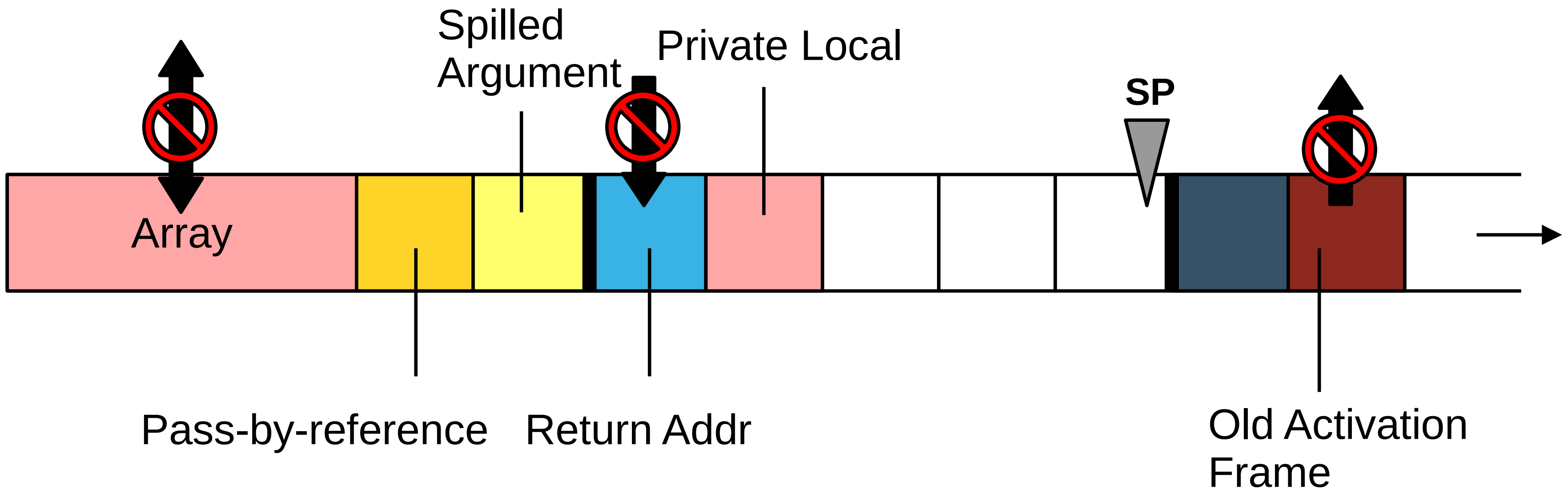

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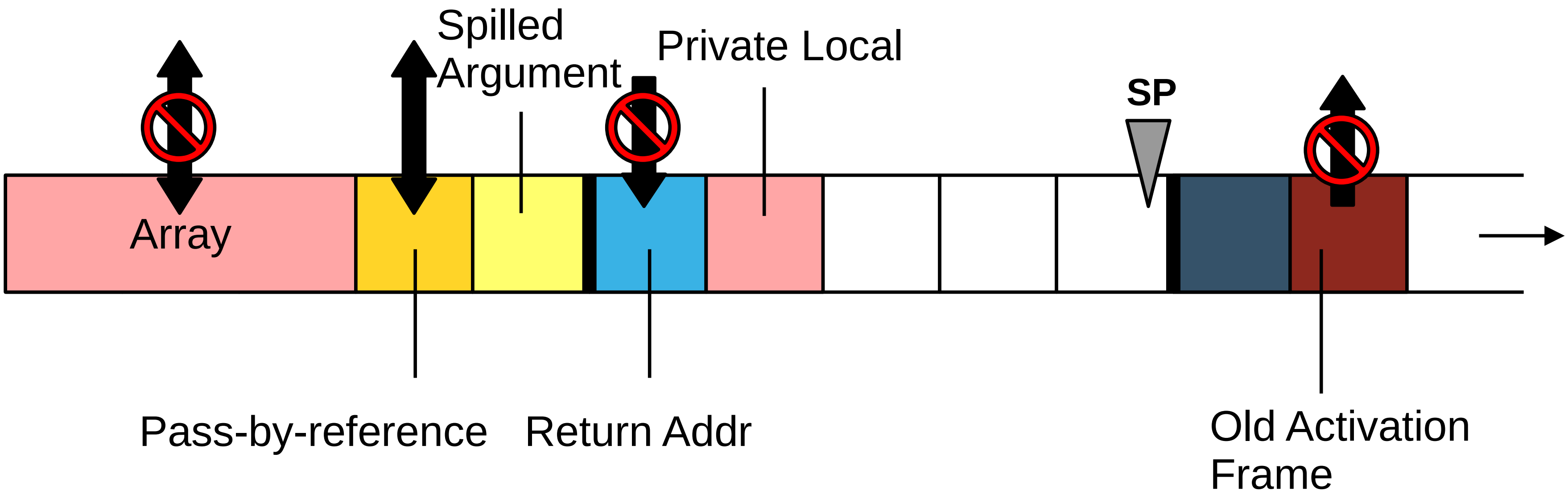

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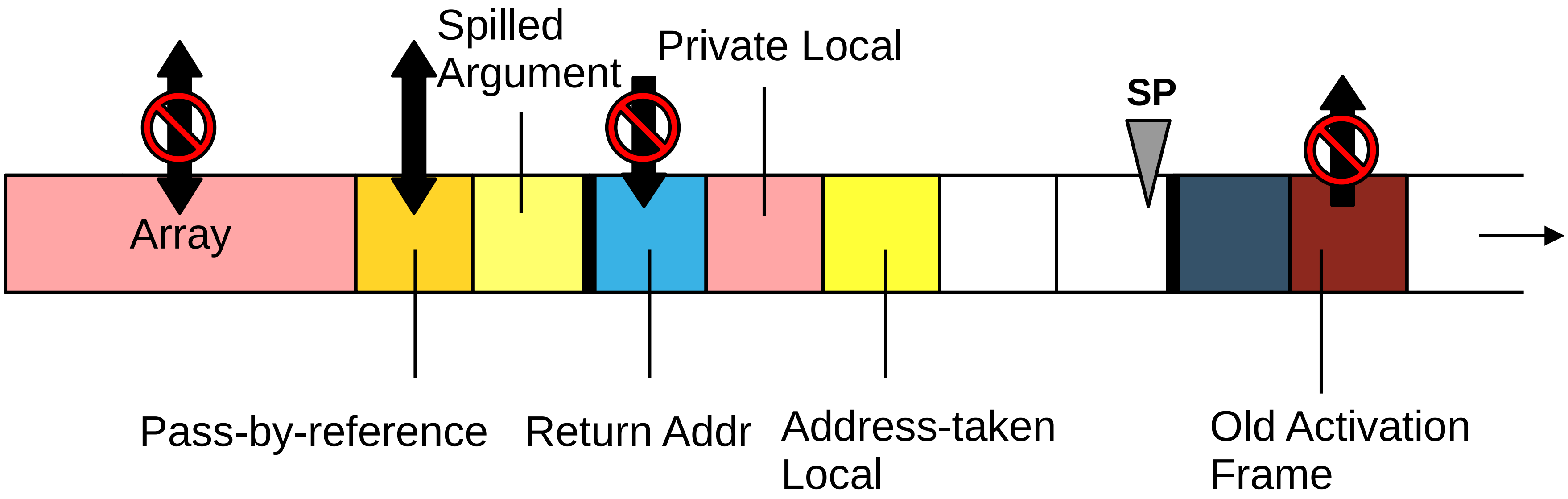
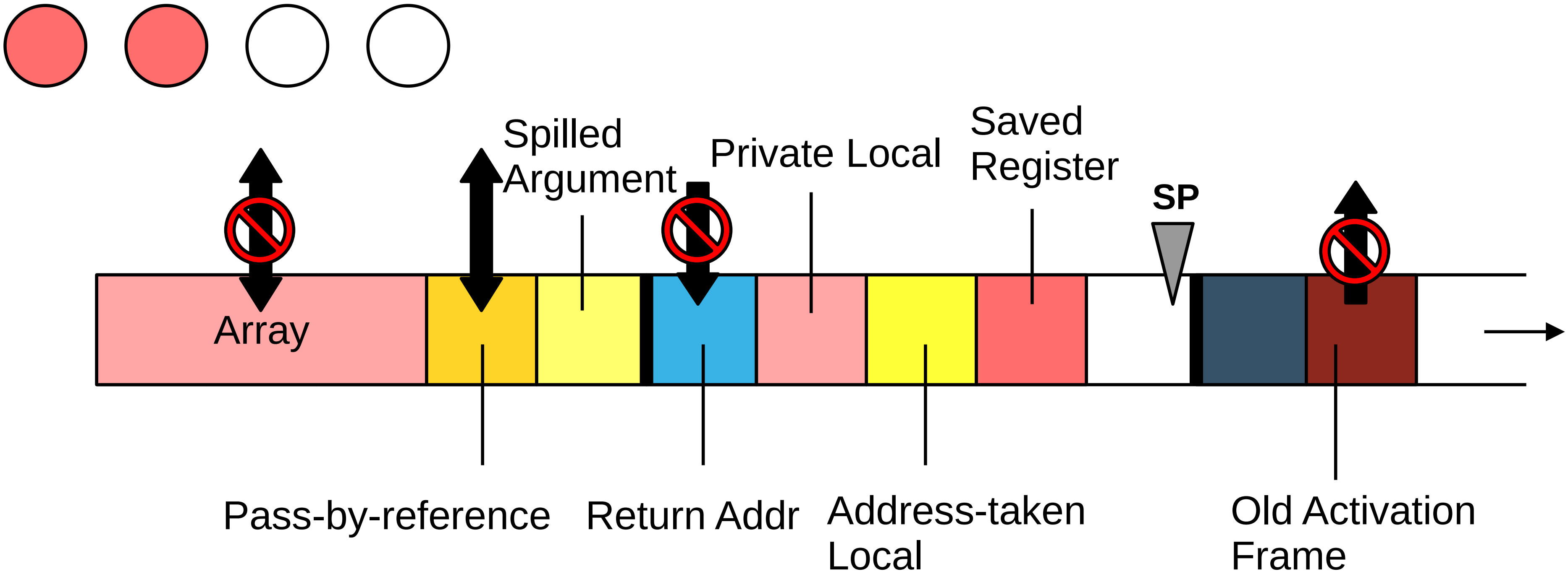


What Needs Protection on the Stack?

… And registers!



Protection Mechanisms

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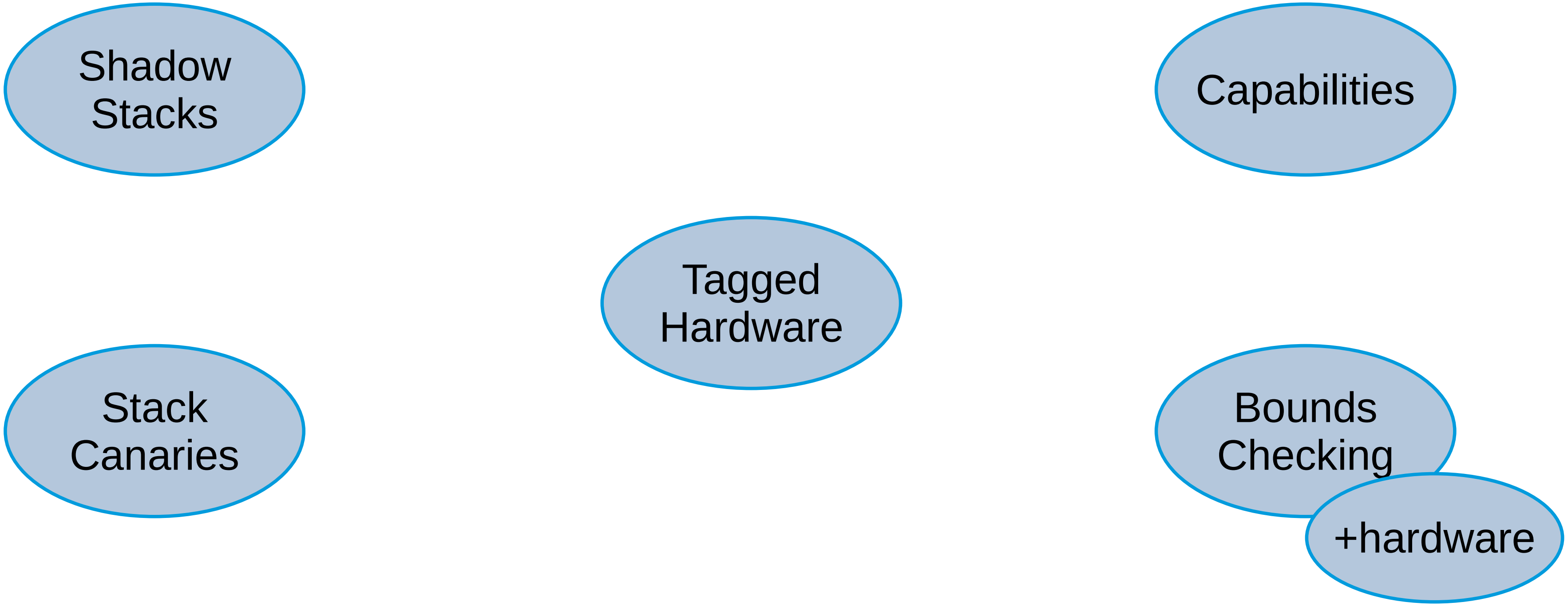

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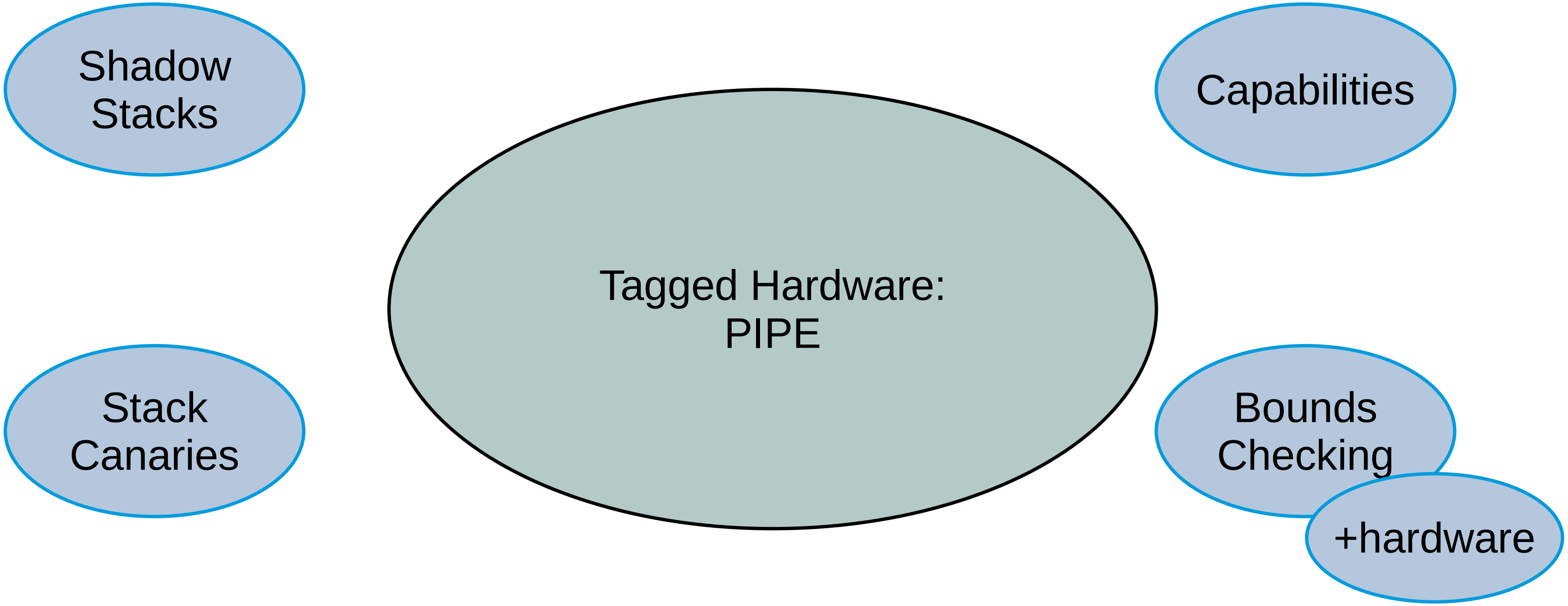

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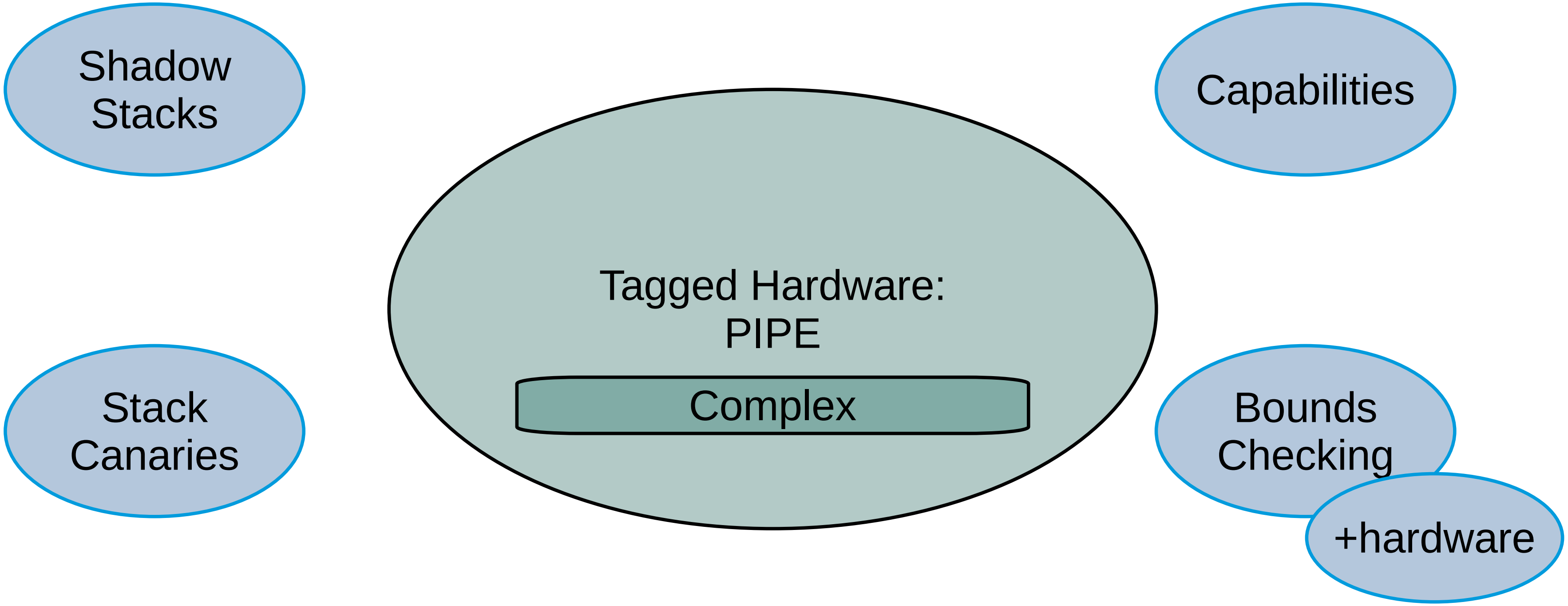

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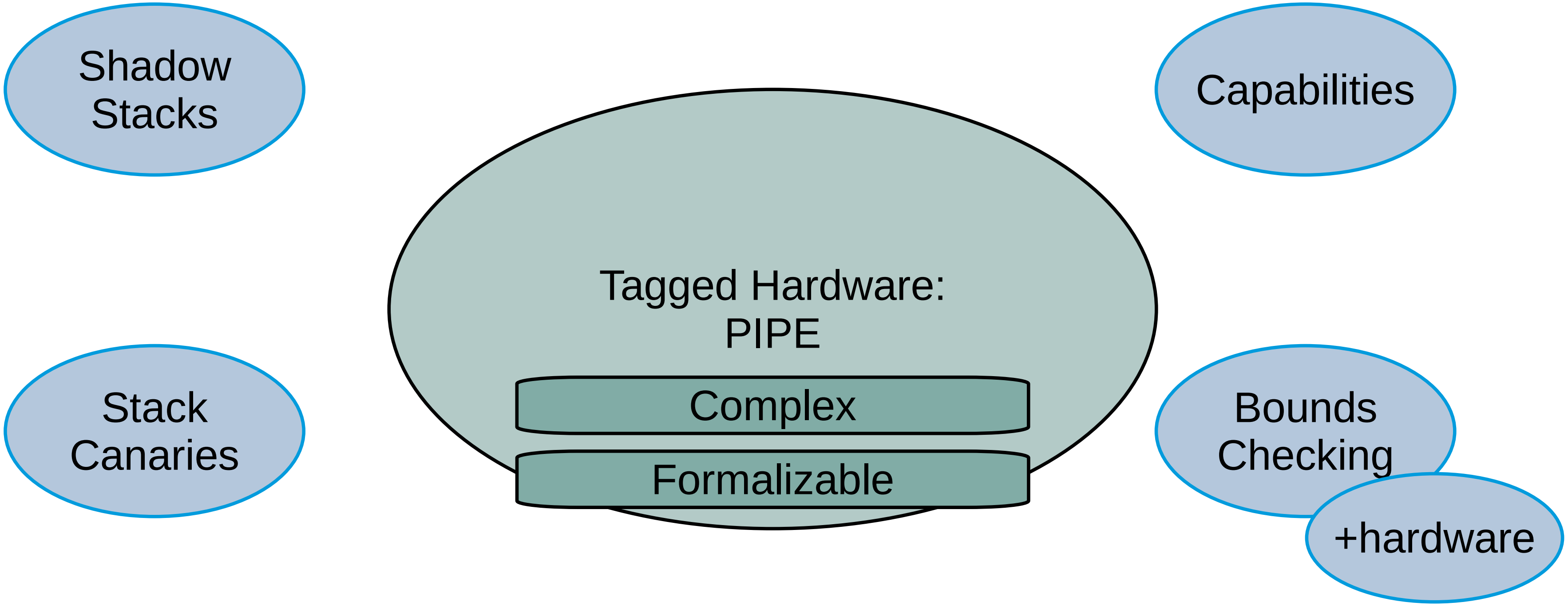

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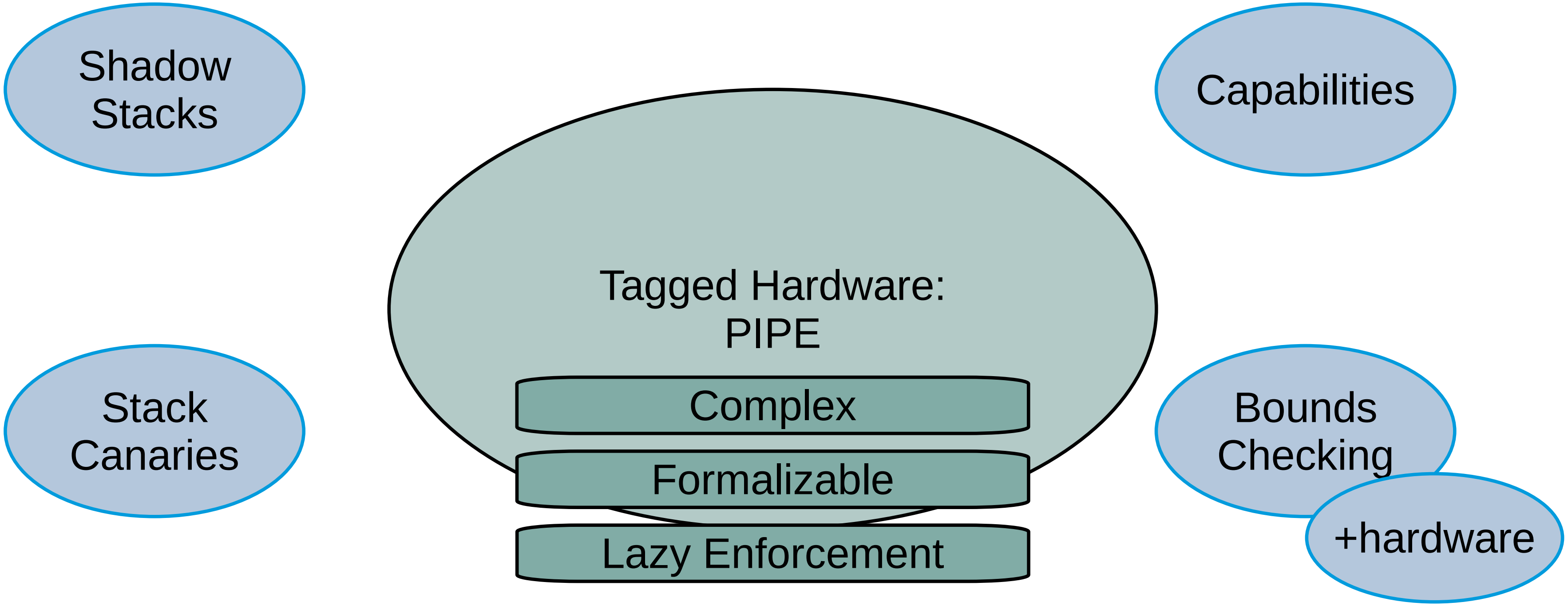

Seeking Specifications

Formal Properties Specifying Stack Safety,
Using Concepts from Theoretical Security

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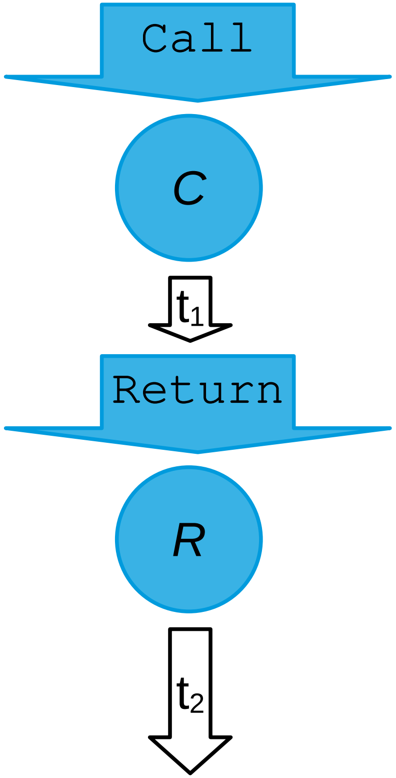
P (C,R,t_1,t_2) where



Seeking Specifications

Formal Properties Specifying Stack Safety,
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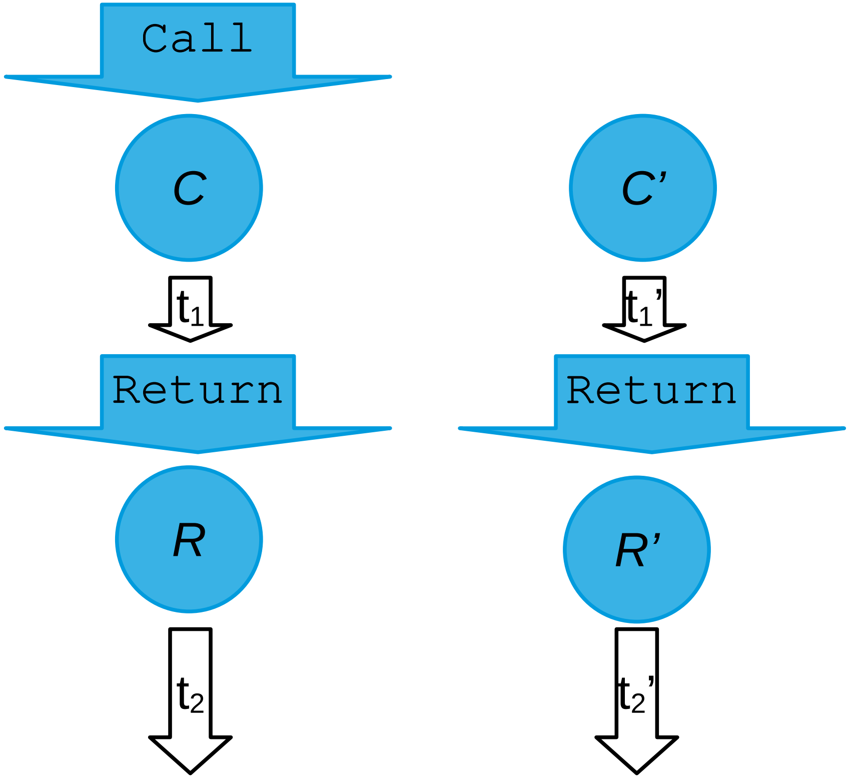
P (C,R,t_1,t_2) where

Or:
(C,R,t_1,t_2) R (C',R',t_1',t_2')



Contributions

Separate High-Level Security Notions

Observation-based Definitions for
Lazy Enforcement

Flexible Model of Language Features

Randomized Property-based Testing

Contributions

Separate High-Level Security Notions

- Well-bracketed Control Flow
- Caller Integrity
- Callee Confidentiality
- Caller Confidentiality
- Callee Integrity

Observation-based Definitions for Lazy Enforcement

Flexible Model of Language Features

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Contributions

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Pass-by-reference

Callee-save Registers

Tailcalls

… etc.

Contributions

Separate High-Level Security Notions

Observation-based Definitions for
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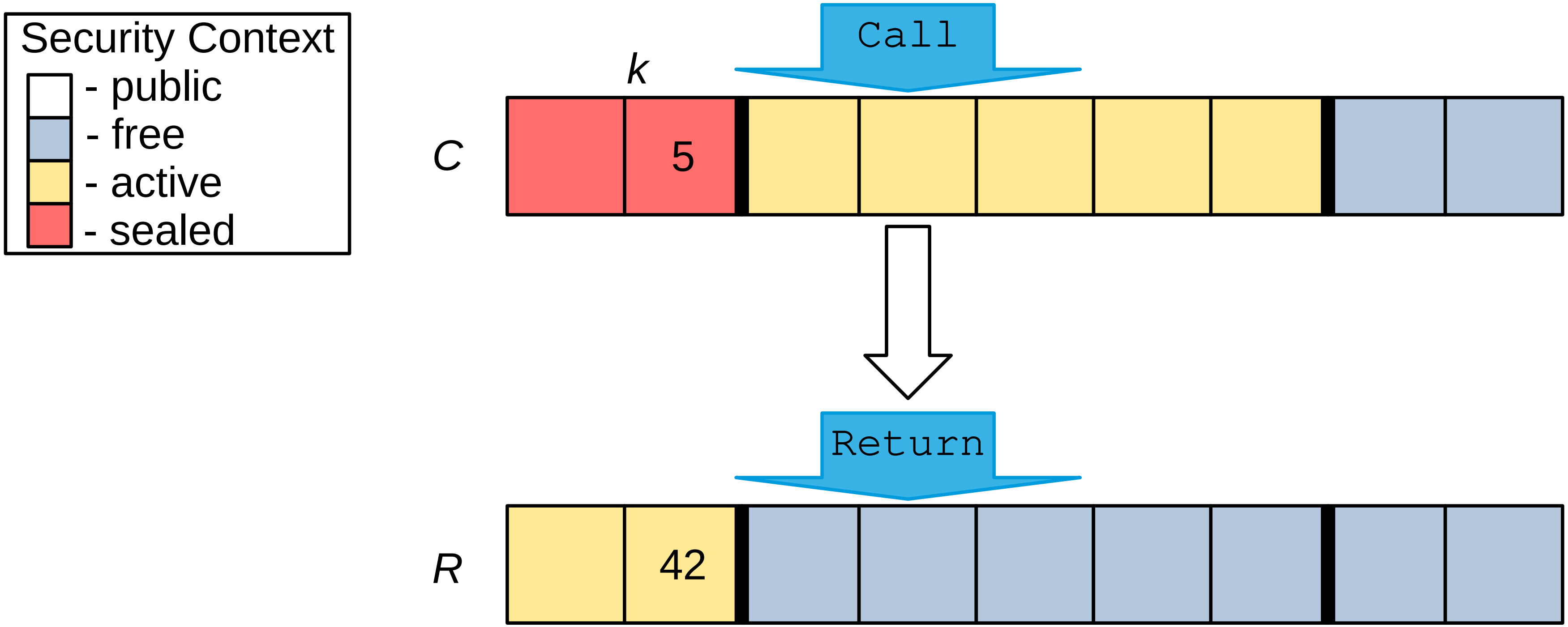
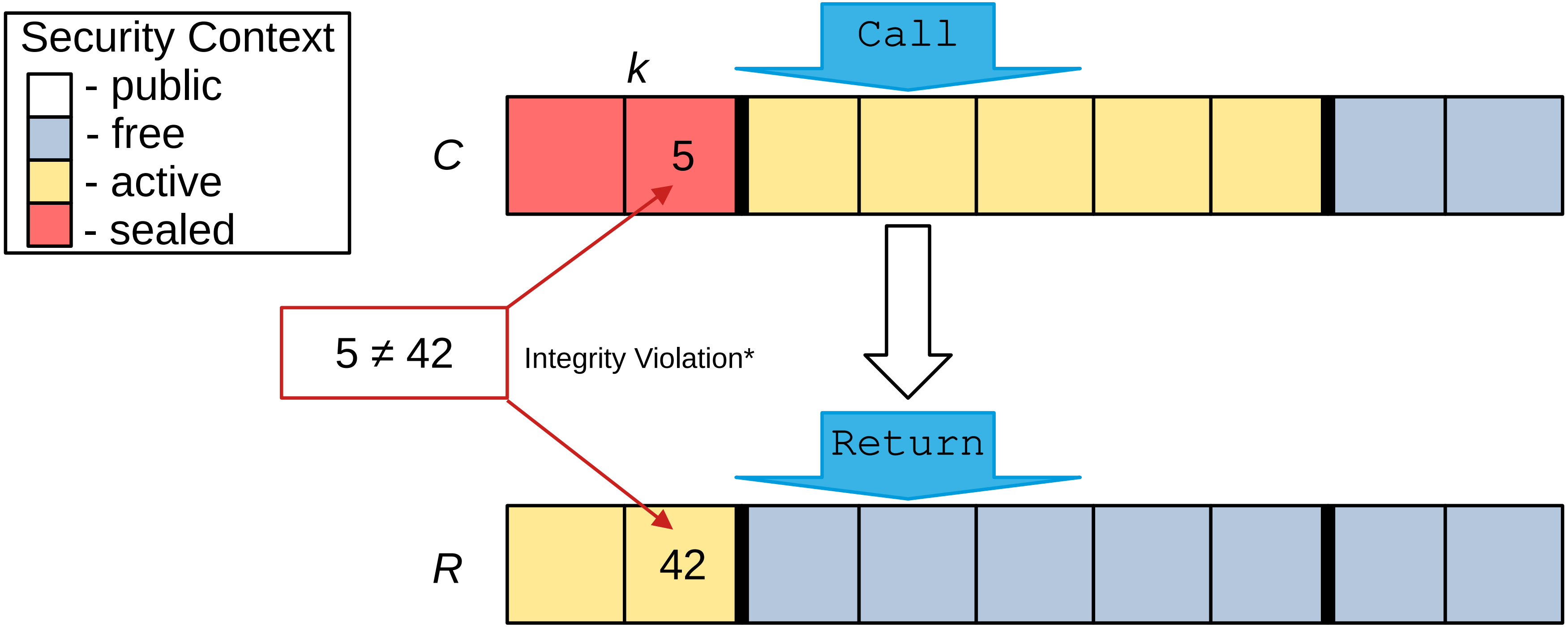
Caller Integrity



$$\forall\, C\; R\; k\,.\; k \in \mathit{sealed}(C) \rightarrow C[k] = R[k]$$

Caller Integrity



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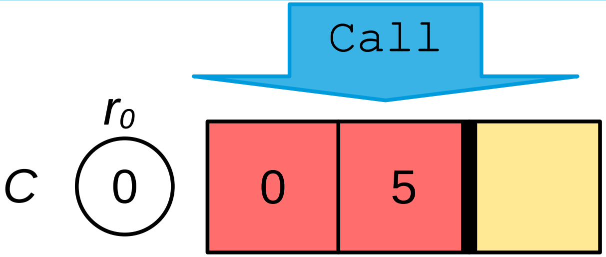
Caller Confidentiality = Non-interference



$\forall\, C$

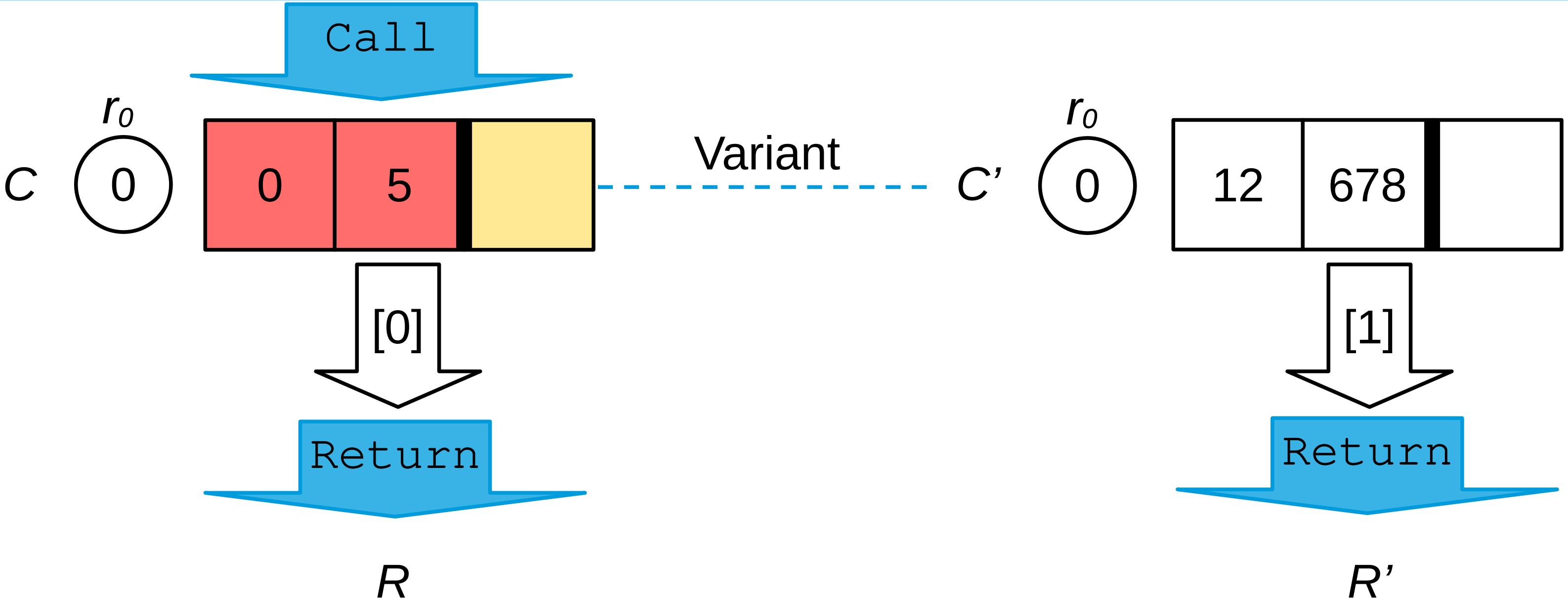
Caller Confidentiality = Non-interference

$\forall\ C\ C' \quad .\ (k \in sealed(C) \vee C[k] = C'[k]) \rightarrow$

Caller Confidentiality = Non-interference

$\forall\, C\, C' \quad .\, C \sim C' \rightarrow$

Caller Confidentiality = Non-interference



$$\forall\, C\, C'\, R\, R'.\; C \sim C' \to C \overset{t}{\Longrightarrow}{}^{*} R \to C' \overset{t'}{\Longrightarrow}{}^{*} R' \to$$

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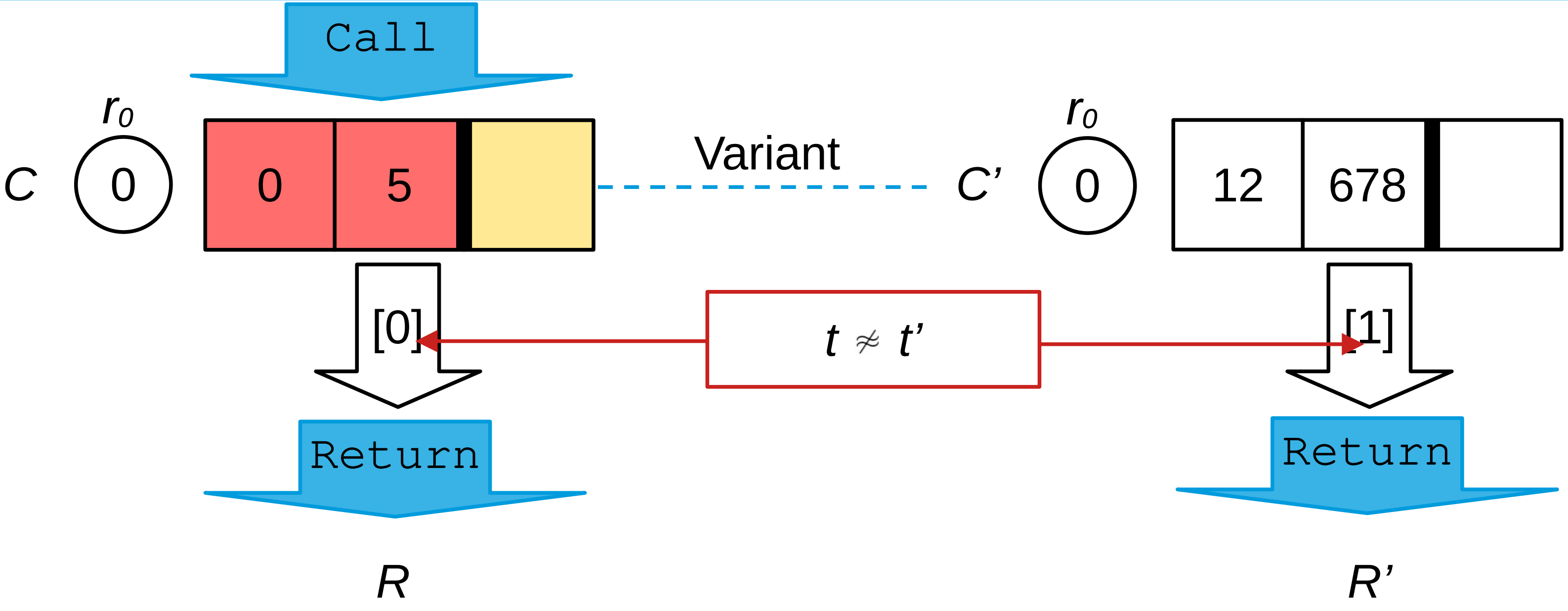

$$\forall\, C\, C'\, R\, R'.\; C \sim C' \to C \xRightarrow{t}{}^{*} R \to C' \xRightarrow{t'}{}^{*} R' \to t \approx t'$$

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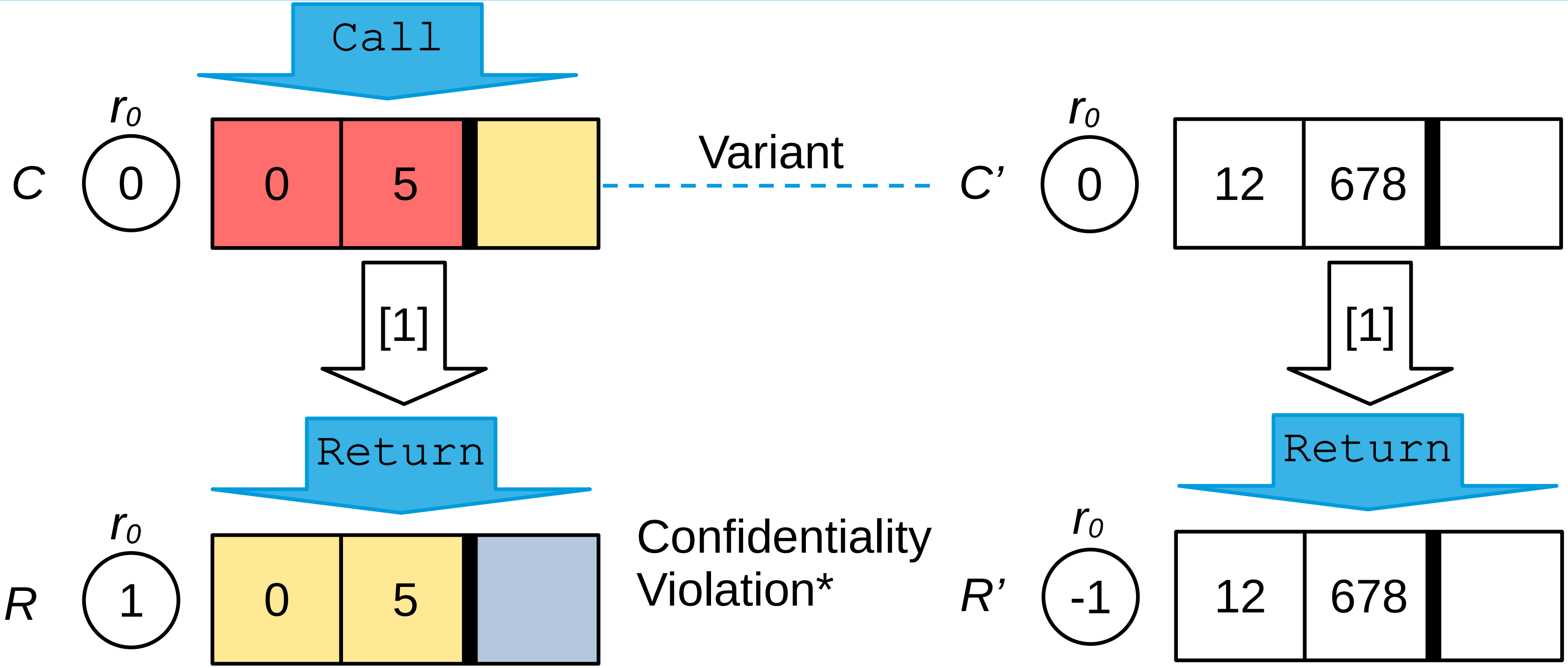

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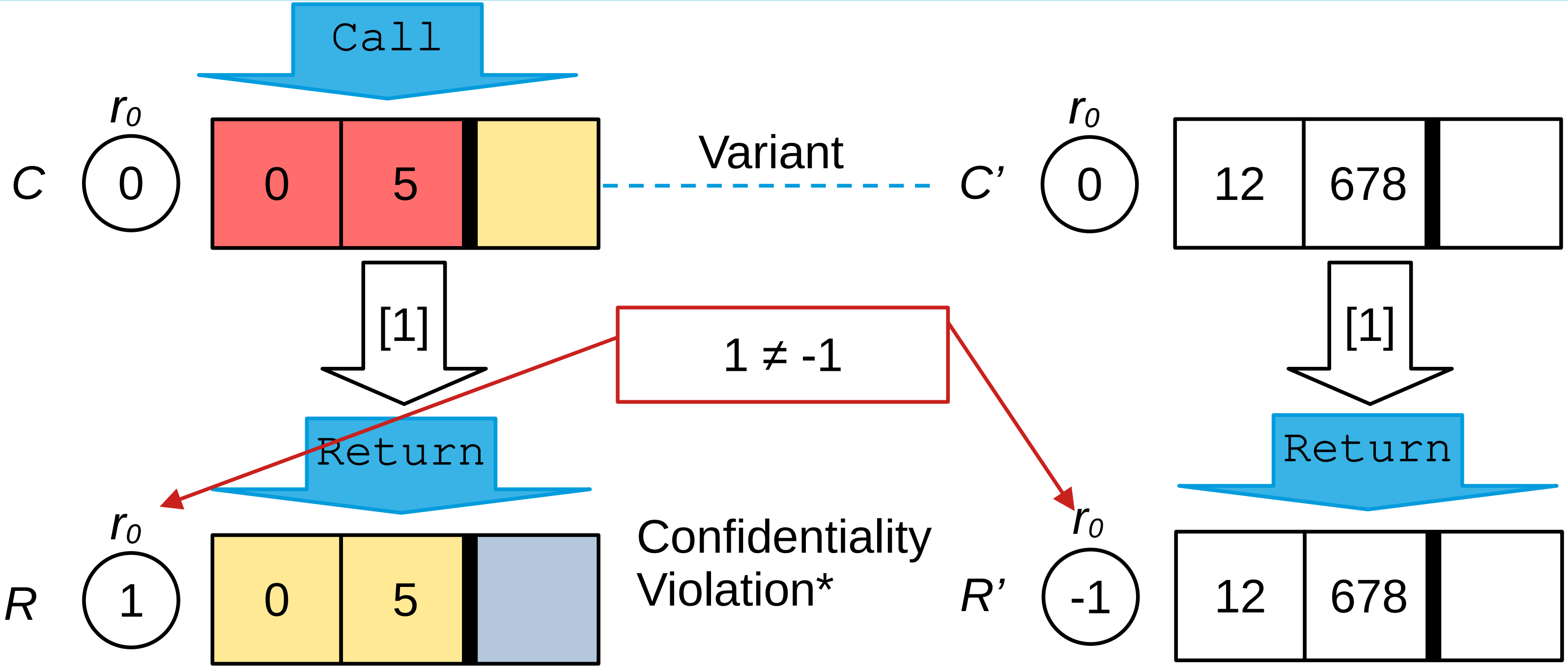

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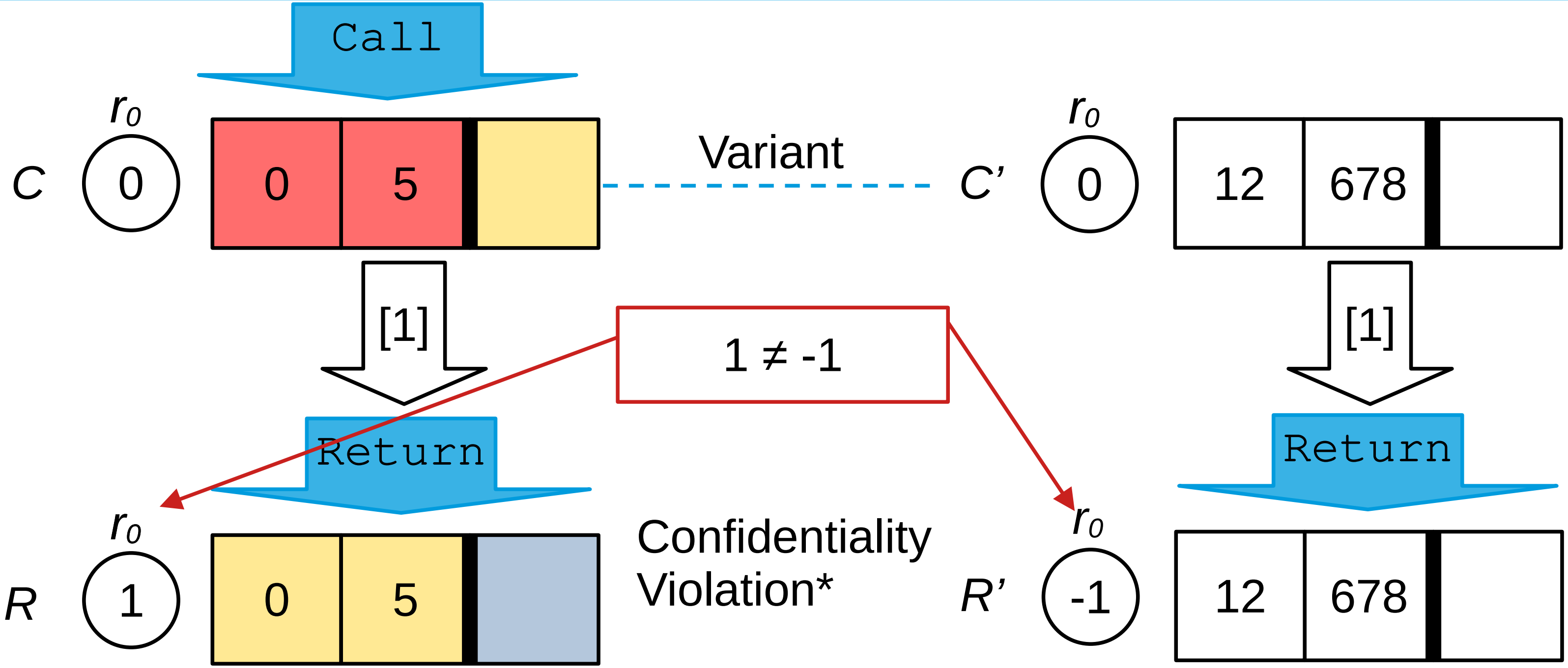

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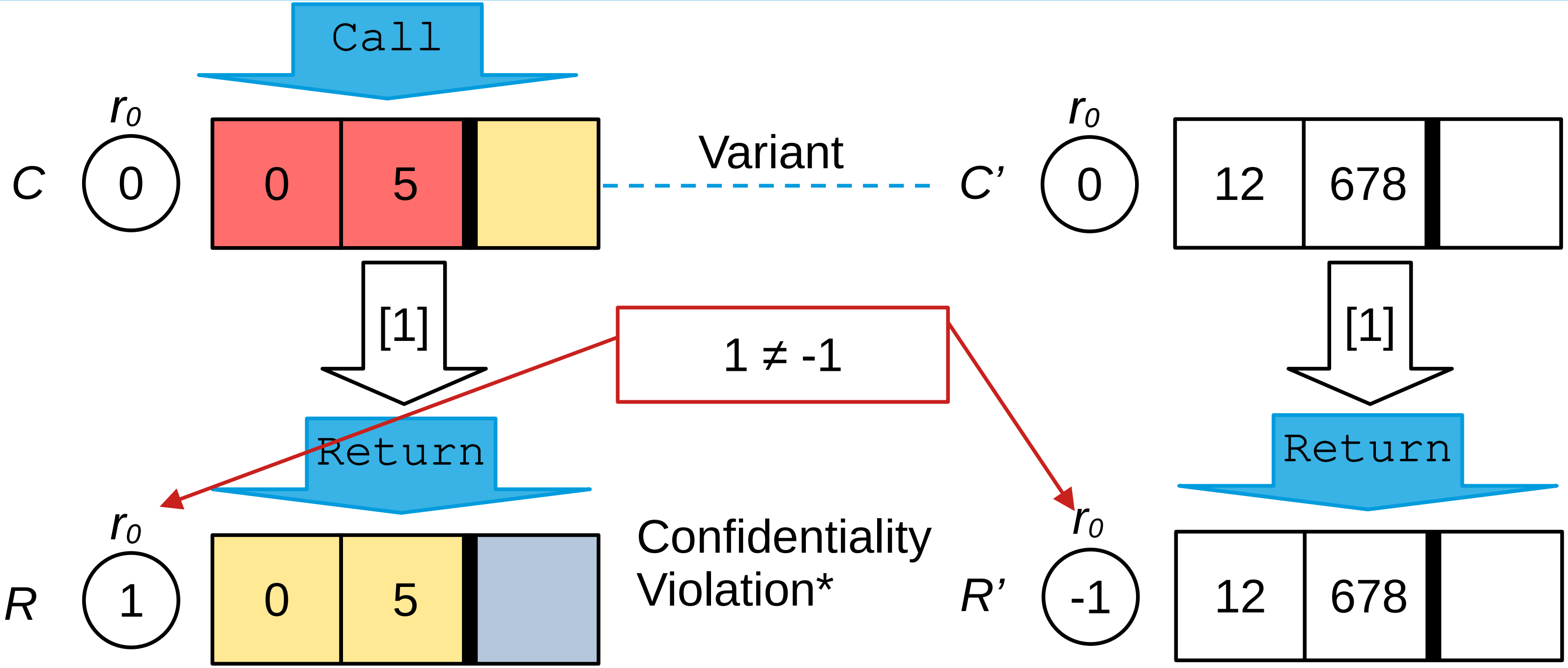
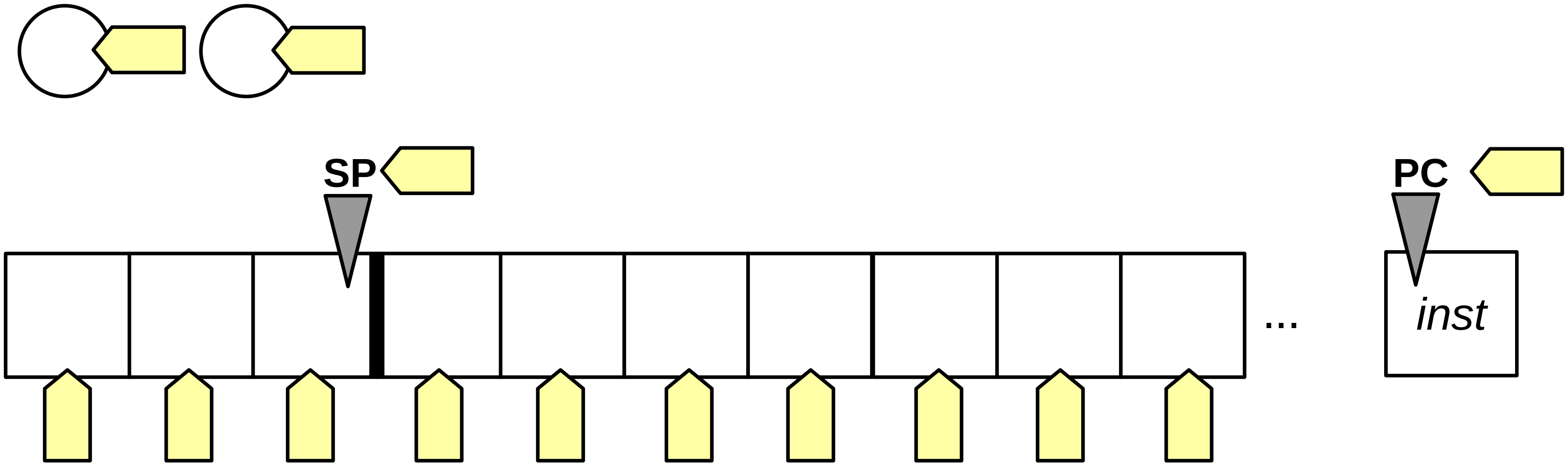
$$t \approx t' \wedge (\forall\, k .\; C[k] \neq R[k] \vee C'[k] \neq R'[k] \rightarrow R[k] = R'[k])$$

Caller Confidentiality = Non-interference



$$\forall\, C\ C'\ R\ R' .\ C \sim C' \rightarrow C \overset{t}{\Longrightarrow}{}^{*} R \rightarrow C' \overset{t'}{\Longrightarrow}{}^{*} R' \rightarrow$$
$$t \approx t' \wedge (\forall\, k .\ consistent(C,C',R,R',k))$$

Programmable Interlocks for Policy Enforcement: **PIPE**



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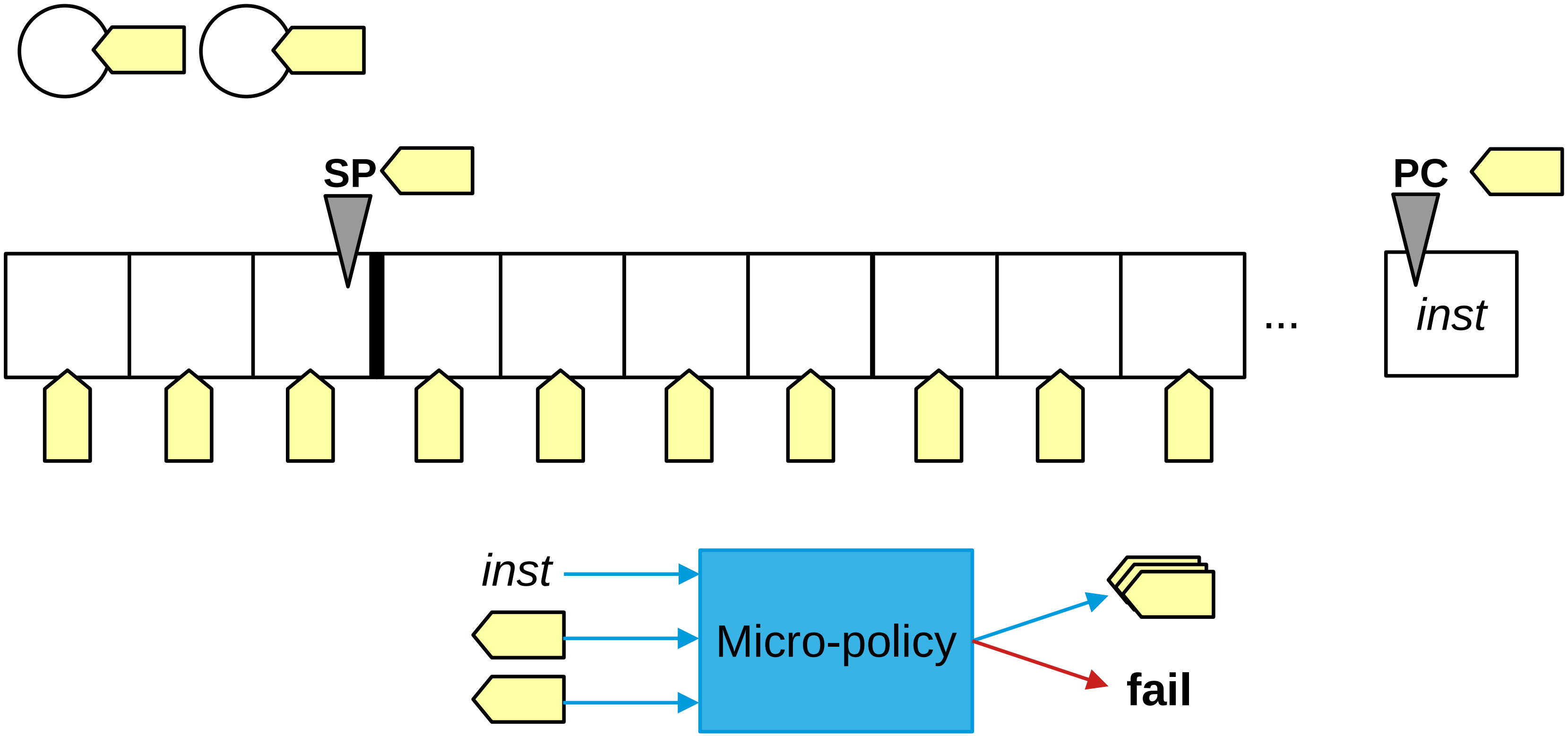
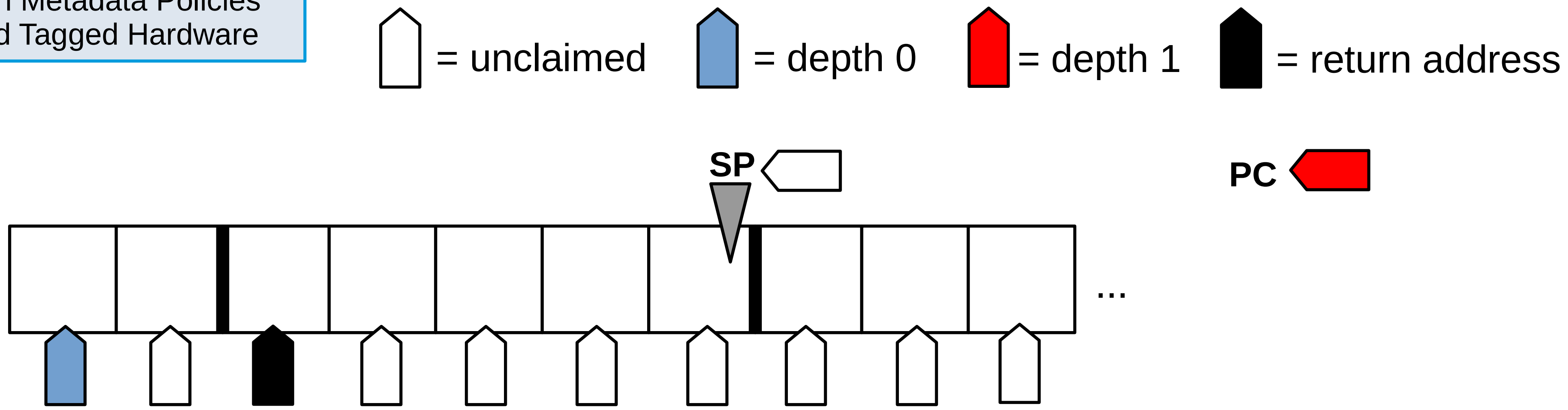


Lazy Depth Isolation

Roessler and DeHon, 2018
Protecting the Stack
with Metadata Policies
and Tagged Hardware



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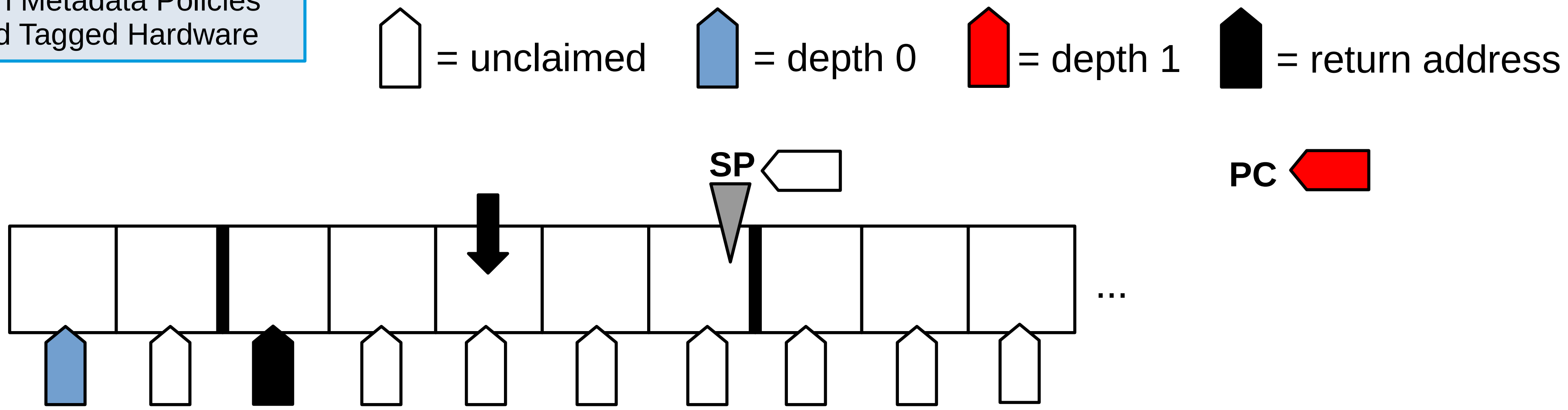

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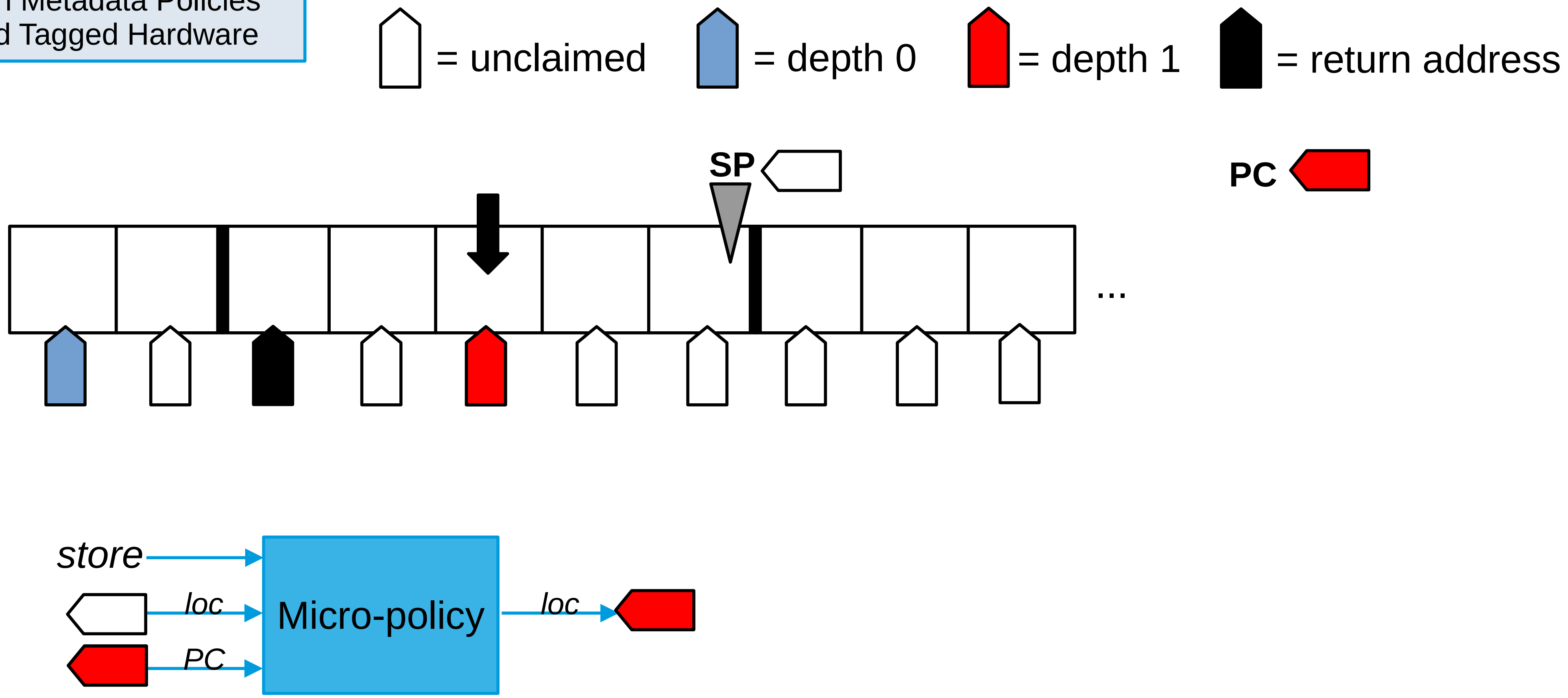

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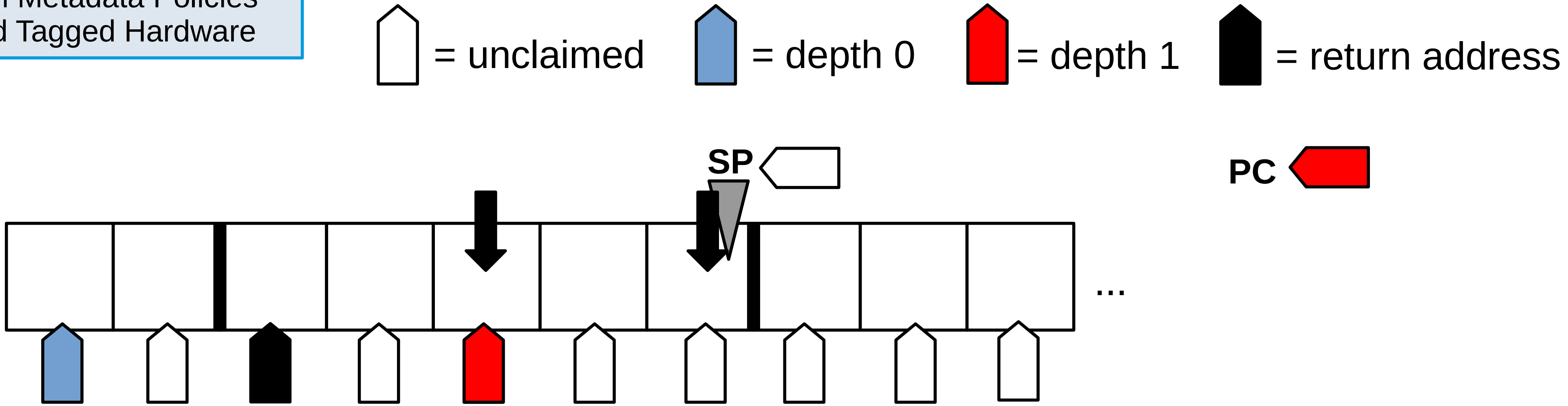

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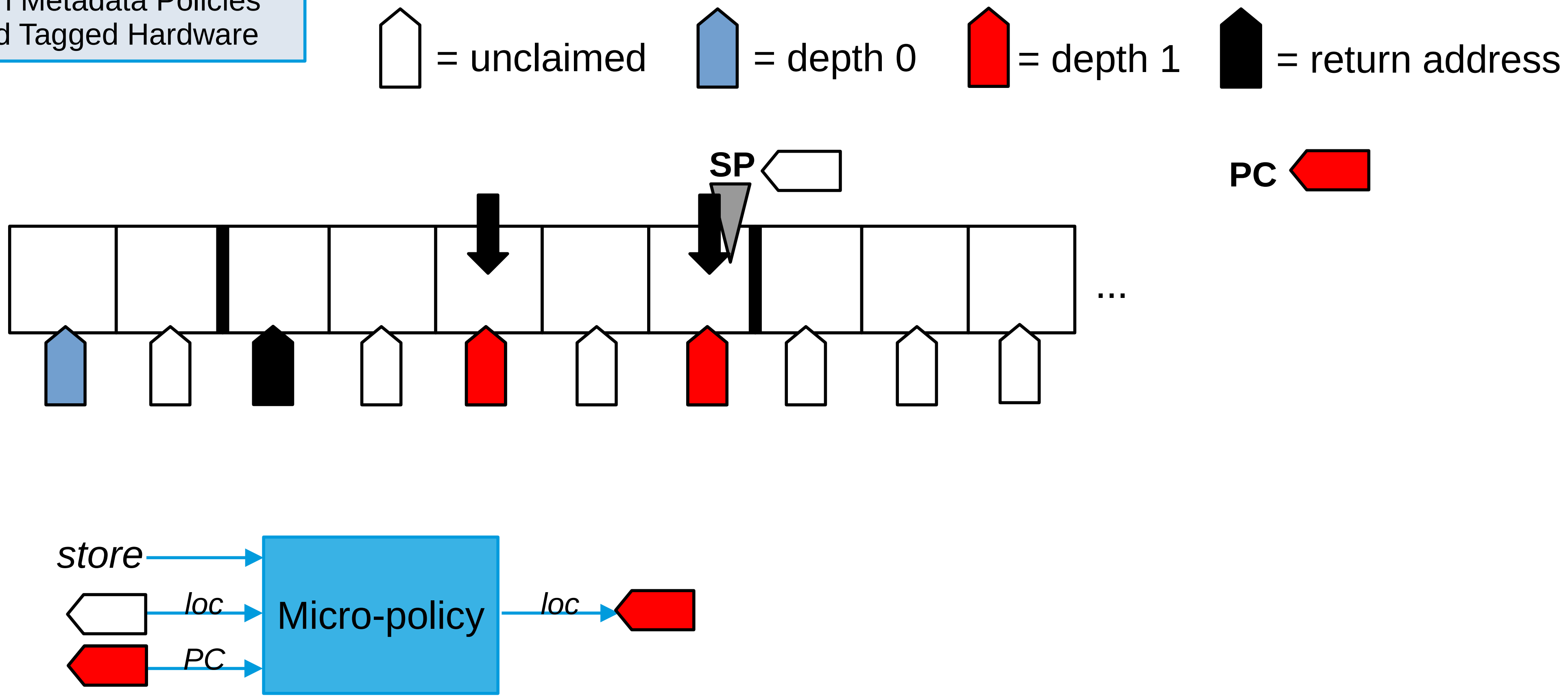

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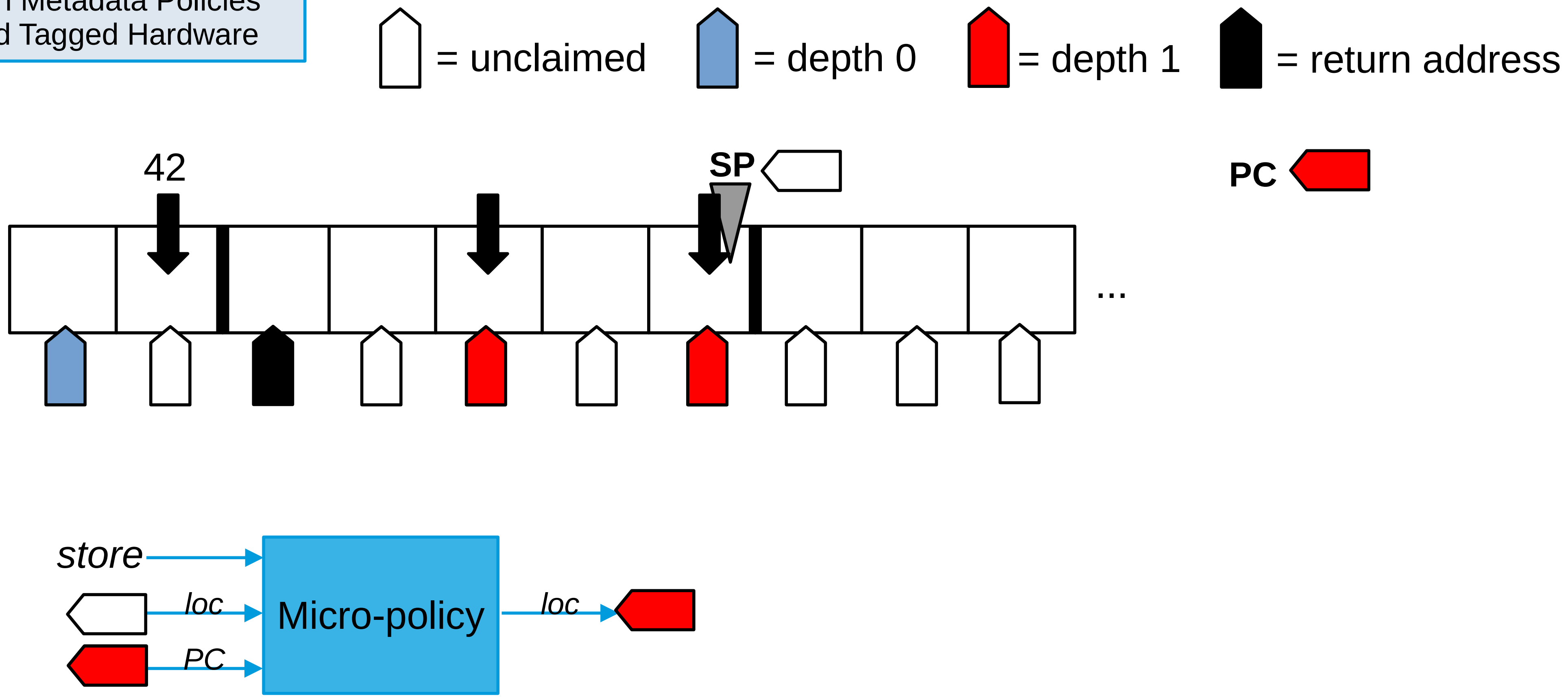

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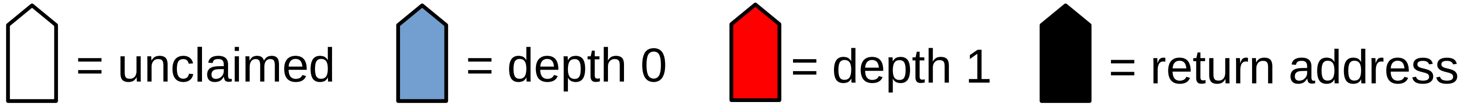

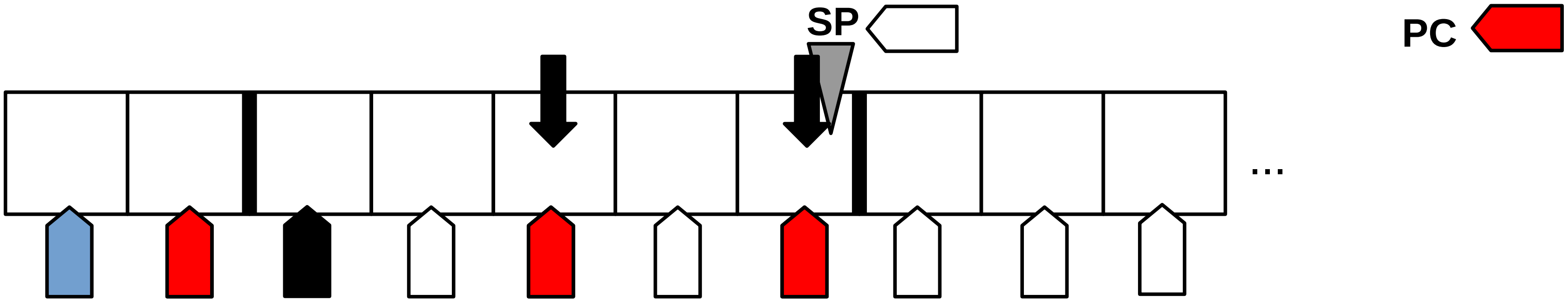

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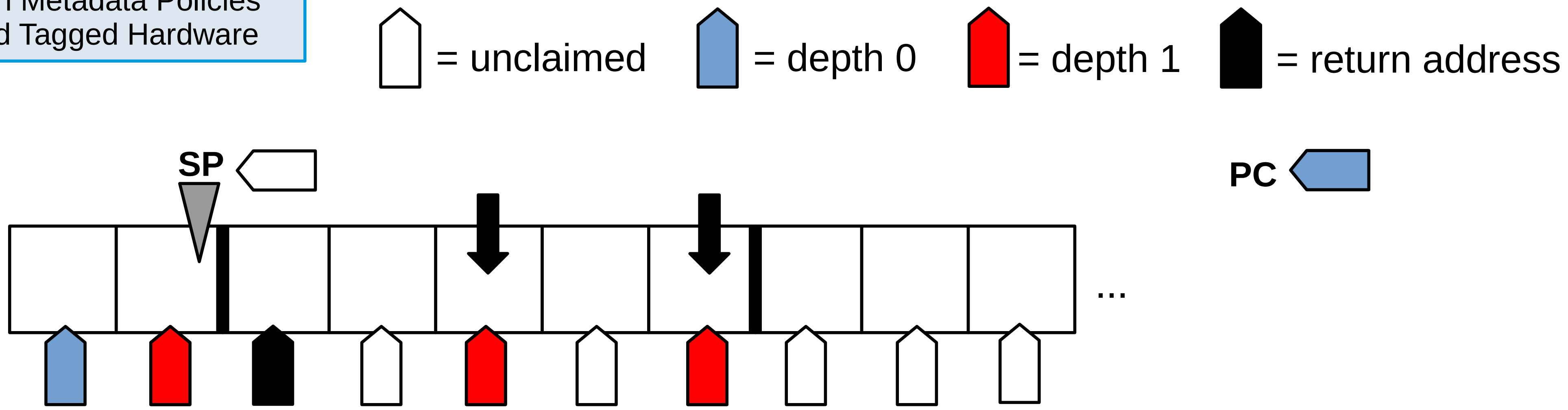

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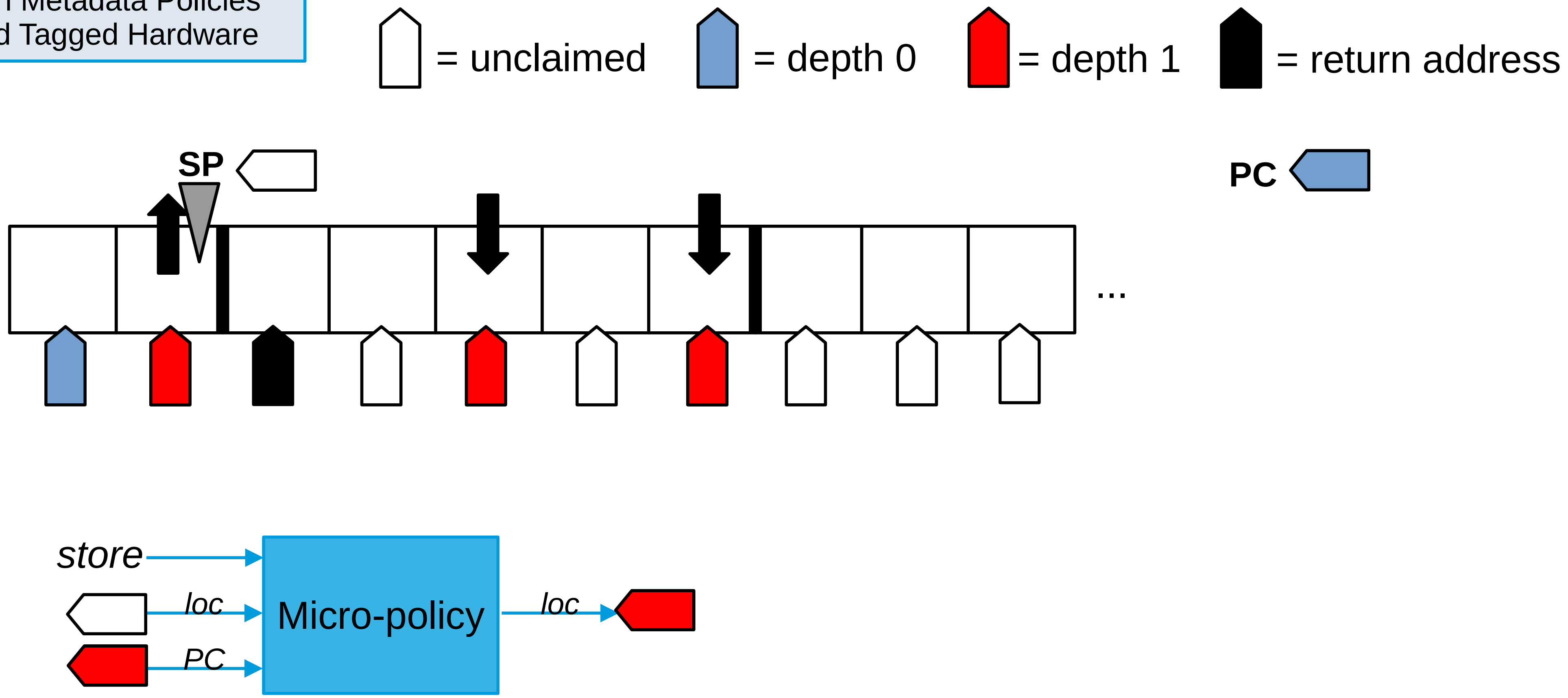

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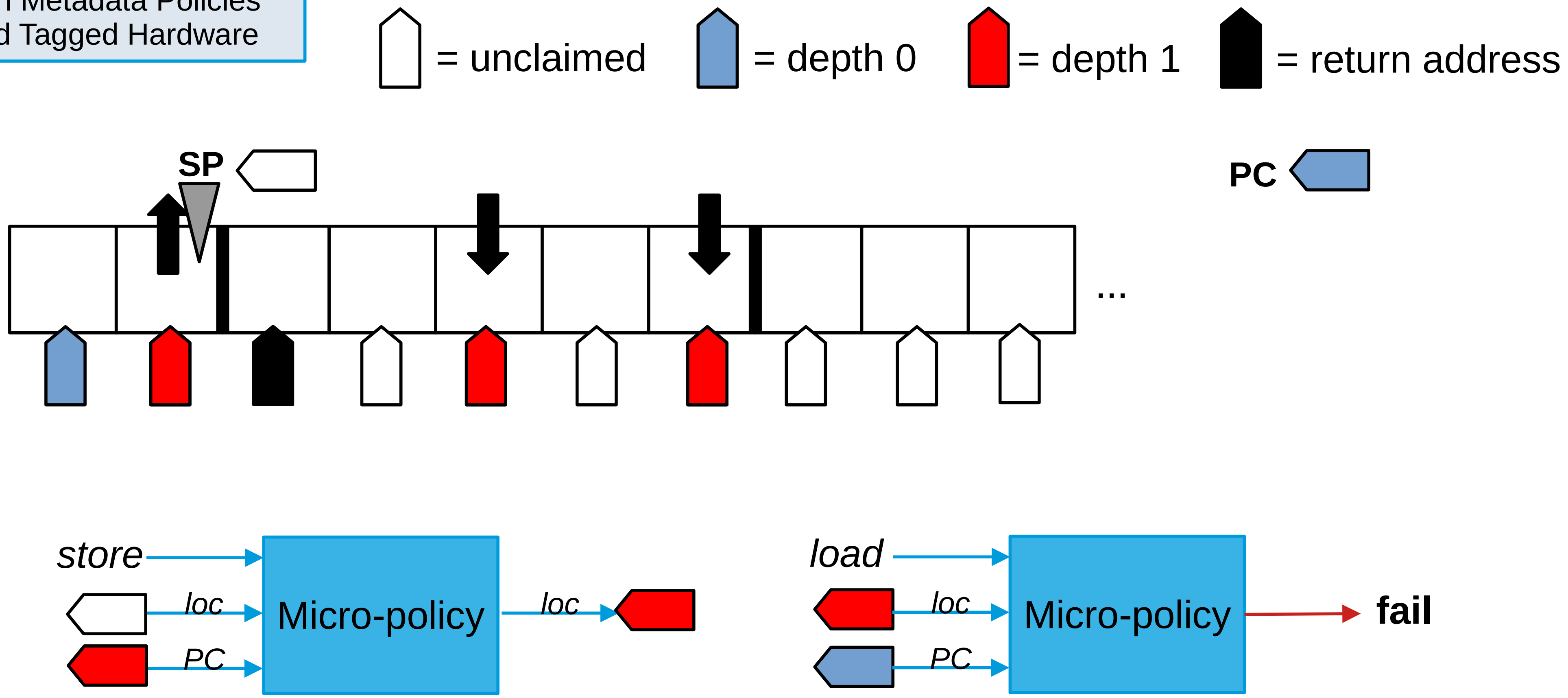
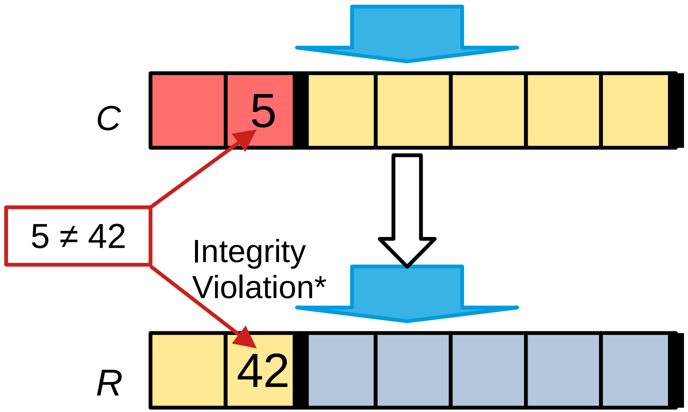
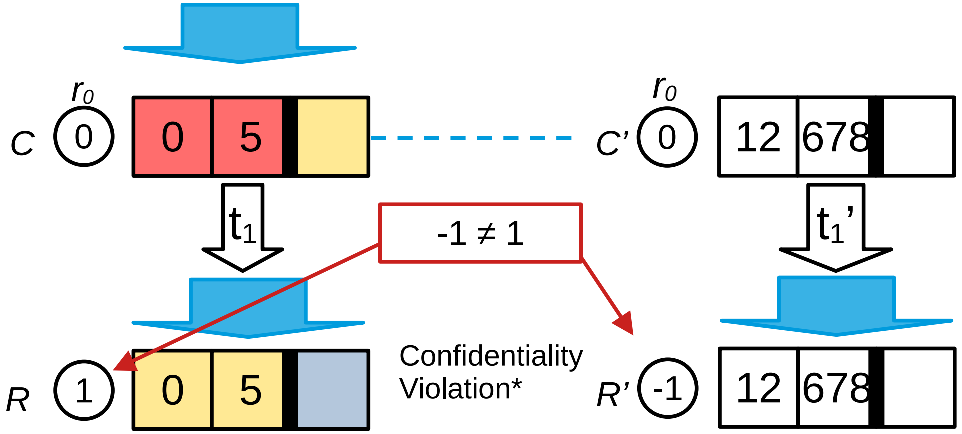


Properties, Observationally





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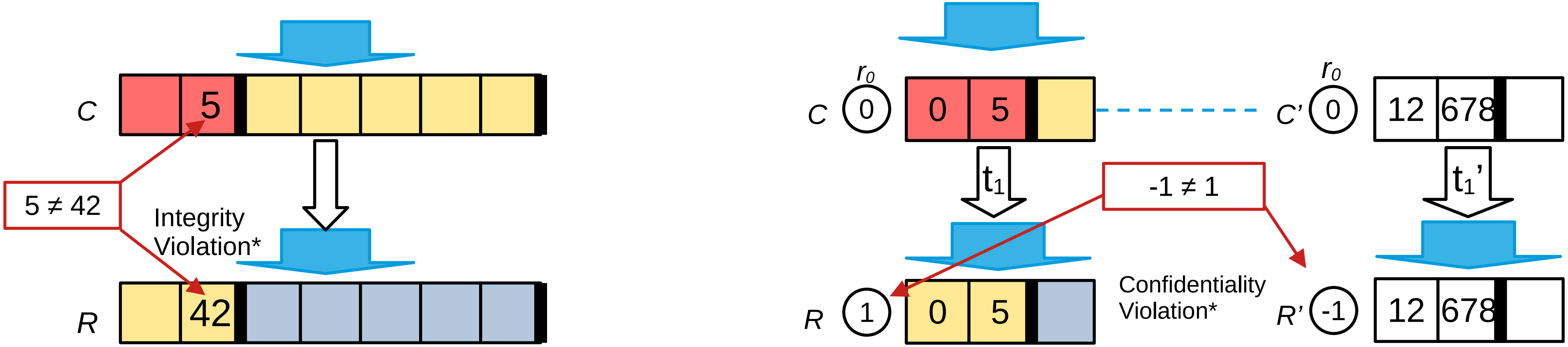
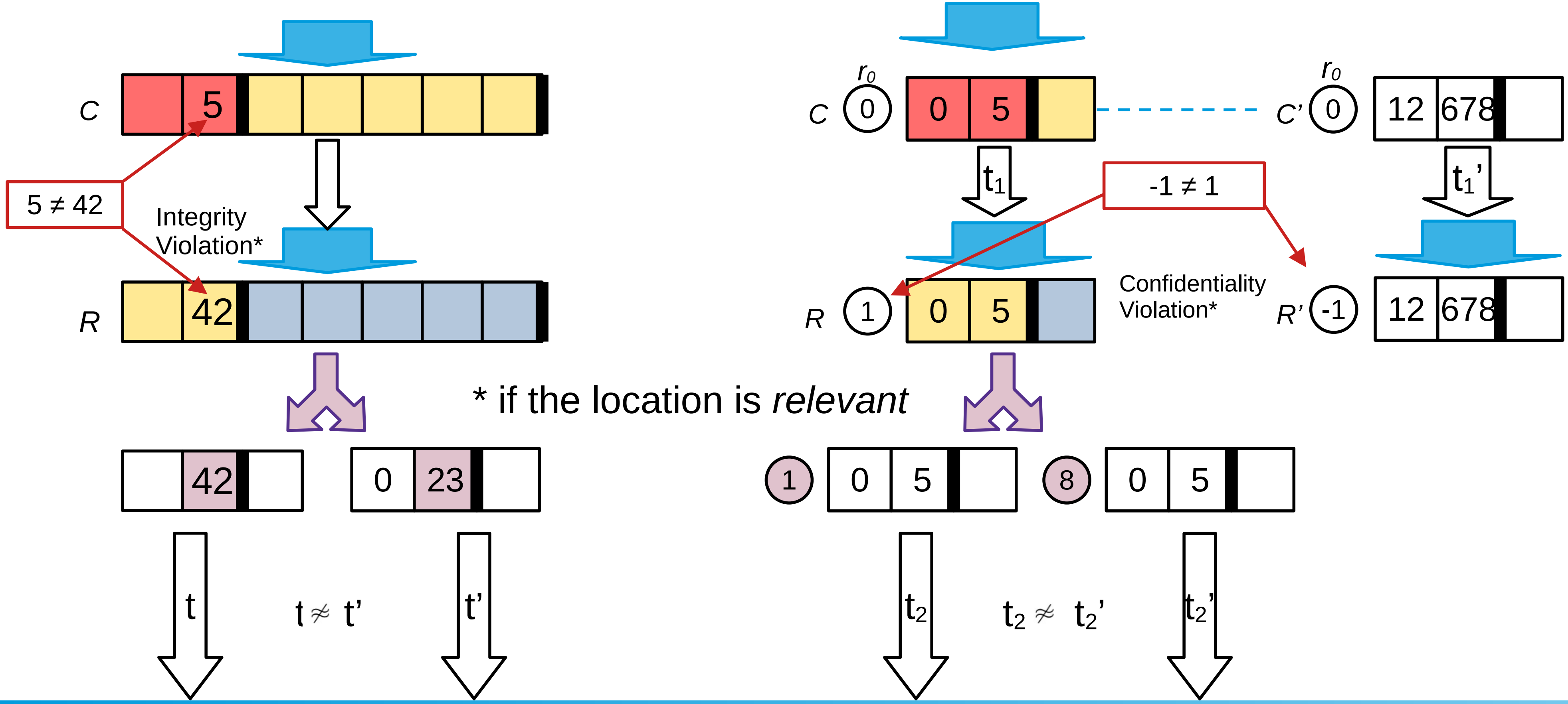


* if the location is *relevant*

Properties, Observationally



* if the location is *relevant*

Properties, Observationally

$$\textit{irrelevant}(R, K) \triangleq \forall R' . (\forall k \notin K . C[k] = C'[k]) \rightarrow$$

$$R \xRightarrow{t}{}^{*} \perp \rightarrow R' \xRightarrow{t'}{}^{*} \perp \rightarrow$$

$$t \approx t'$$

Caller Integrity $\triangleq$

$$\forall C\ R\ k . k : \textit{sealed}(C) \rightarrow \textit{irrelevant}(R, \{ k \mid C[k] \neq R[k] \})$$

Caller Confidentiality $\triangleq$

$$\forall C\ C'\ R\ R' . C \sim C' \rightarrow C \xRightarrow{t}{}^{*} R \rightarrow C' \xRightarrow{t'}{}^{*} R' \rightarrow$$

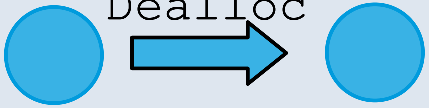
$$t \approx t' \wedge \textit{irrelevant}(R, \{ k \mid \neg\, \textit{consistent}(C, C', R, R', k) \})$$


Security-relevant Operations
Update
Security Context
Inform
Hyperproperties

Language Features via Security Semantics

Security-relevant Operations → *Update* → Security Context → *Inform* → Hyperproperties

```
Call
Tailcall
Return
Alloc
Dealloc
```



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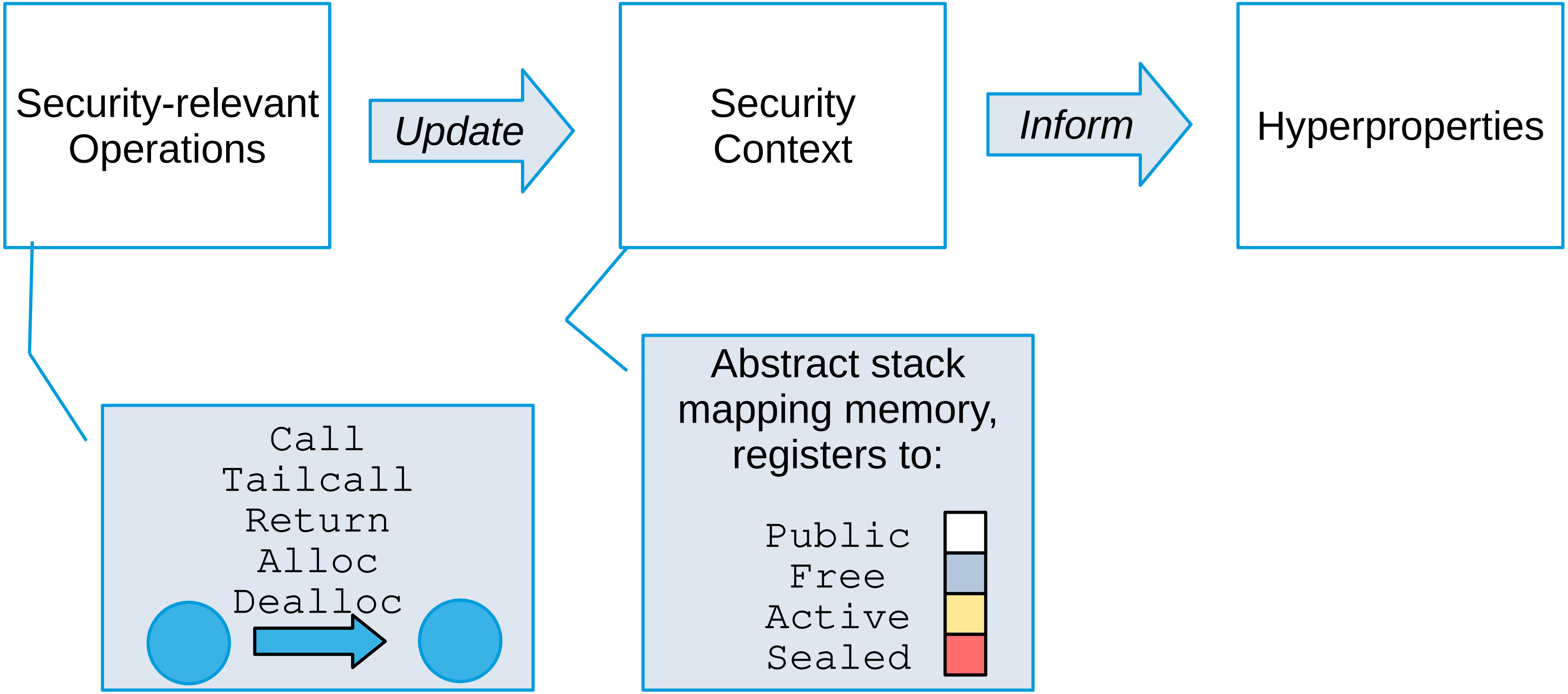

Language Features via Security Semantics

Security-relevant Operations → *Update* → Security Context → *Inform* → Hyperproperties

Call
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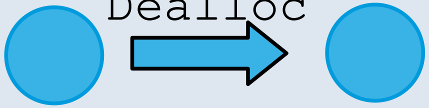

Abstract stack mapping memory, registers to:

Public
Free
Active
Sealed

Given security context at call:

WBCF
Integrity
Confidentiality

Language Features

Callee-save Registers

Pass-by-reference

“Public” (address-taken) variables

Tailcalls

Arguments Spilled to Memory

Memory Shared by Capability

Ongoing Work:

Exceptions

Concurrency

Property-based Testing w/ QuickChick

Random Program

Integrity Test

Conf. Test

\+

(Eager) Depth Isolation

Depth Isolation w/ Lazy Tagging

“Activation Isolation” w/ Lazy Tagging

Property-based Testing w/ QuickChick

Random Program

Integrity Test

Conf. Test

✗/? ✗/?

+

(Eager) Depth Isolation ✓

Depth Isolation w/ Lazy Tagging ✗

“Activation Isolation” w/ Lazy Tagging ✓

Property-based Testing w/ QuickChick

Random Program +

Integrity Test → ✗ / ?

Conf. Test → ✗ / ?

- (Eager) Depth Isolation ✓
- Depth Isolation w/ Lazy Tagging ✗
- "Activation Isolation" w/ Lazy Tagging ✓

Injected Bugs ✗

Future Work

- Testing Other Mechanisms
  - Cerise, CHERI-based calling convention
  - Software bounds checking
- Expanding model
  - Exceptions
  - Concurrency
- Mechanized Proofs

Summary

- Theory of Stack Safety: Integrity, Confidentiality, and/or WBCF
- Security Semantics: useful factorization over language features
- Observation-based properties to describe sophisticated enforcement mechanism
- Testing identifies flawed micro-policies