Lecture 5: The PMA Case Study

CS350

Marco Patrignani

Lecture Goals

- present existing FA compilers that rely on a specific security architecture
- see how to formalise advanced security architecture notions
- see an advanced trace-based backtranslation
- reason about advanced FAC proofs

- Patrignani, Devriese, Piessens: On Modular and Fully-Abstract Compilation. In CSF'16
- Patrignani, Agten, Strackx, Jacobs, Clarke, Piessens: Secure Compilation to Protected Module Architectures. In TOPLAS'15

PMA: High Level (SGX-like)

- enclave: isolated memory region (coarse)
- enclaves are split in code and data
- jump to enclaves through entry points

From ↘ To	Protected			Unprotected
	Entry Point	Code	Data	
Protected	r x	r x	r w	r w x
Unprotected	x			r w x

PMA: Formally

to the board

- protection domains
- structuring ACP
- register allocation and flags

JavaJr: High Level

- Java-like (oo, no reflection, strongly typed, exceptions)
- deep encapsulation: only private fields
- public & private methods
- no inner classes, no cross-package inheritance

- Alan Jeffrey and Julian Rathke. Java Jr.: fully abstract trace semantics for a core Java language. In ESOP'05

JavaJr: Formally

to the board

- exceptions

Assumption 1: Correct Compilation

- $(\!|\cdot|\!) : \mathsf{P} \to \mathbf{P}$ (and for s, e, v, ...)
- $(\!|\cdot|\!)$ is correct

$$\forall \mathsf{s}, (\!|\mathsf{s}\gamma|\!) \hookrightarrow^* (\!|\mathsf{v}|\!) \Rightarrow \mathsf{s}\gamma \hookrightarrow^* \mathsf{v}$$

Desirable Security Properties

- confidentiality and integrity of field contents, of object names and of method bodies
- no control flow alteration apart from when using exceptions
- non reachability of stuck (error) program states

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All of them can be encoded through program equivalence

Compiler Vulnerabilities

1. stack access
2. information leakage through registers and flags
3. boolean values
4. current object type
5. argument type
6. guessable references
7. excessive exceptions catching

Vulnerability #1

```
1  package p;
2  class CL {
3    private sec : Int = 0;
4
5    public doCallback( cb :
         External ) : Int {
6      var x : Int = sec;
7      cb.callback();
8      return 0;
9    }
10 }
11 object oL : CL
```

```
1  package p;
2  class CR {
3    private sec : Int = 1;
4
5    public doCallback( cb :
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- location of x matters

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```

- location of x matters
- Sol: need a protected stack

Vulnerability #2

```
1  package p;
2  class CL {
3    public testVariable() :
         Int {
4      var x : Int = 0;
5      if ( x == 0 ) {
6        return 0;
7      } else {
8        return 0;
9      }
10   }
11 }
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- flags and register leak information
- Sol: reset flags and unused registers

Vulnerability #3

```
1  package p;
2  class CL {
3    public identBool( x :
         Bool ) : Bool {
4      if( x == true ){
5        return true;
6      }
7      return false;
8    }
9  }
10 object oL : CL
```

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```

- ground values have a fixed **value**
- Sol: dynamic typecheck

Vulnerability #4

```
1  package p;
2  class PairL {
3    private fst, snd : Obj =
         null;
4    public getFirst(): Obj {
5      return this.fst;
6    }
7  }
8  class SecretL {
9    private sec : Int = 0;
10 }
11 object oL : SecretL
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```

- invoke `getFirst` on `oL`/`oR`

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- invoke `getFirst` on `oL`/`oR`
- Sol: dynamic typecheck the current object

Vulnerability #5

```
1  package p;
2  class ProxyPair {
3    public takeFirst( v :
         Pair ): Obj {
4      return v.getFirst();
5    }
6  }
7  class SecretL {
8    private sec : Int = 0;
9  }
10 object oL : SecretL
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- invoke `takeFirst` on `oL`/`oR`
- Sol: dynamic typecheck all arguments

Vulnerability #6

```
1  package p;
2  class SecretL {
3    private sec : Int = 0;
4    public createSecret() :
         Secret {
5
6
7      return new Secret();
8    }
9  }
10 object oL1 : SecretL
11 object oL2 : SecretL
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```
1  package p;
2  class SecretR {
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- witness address of returned `Secret`

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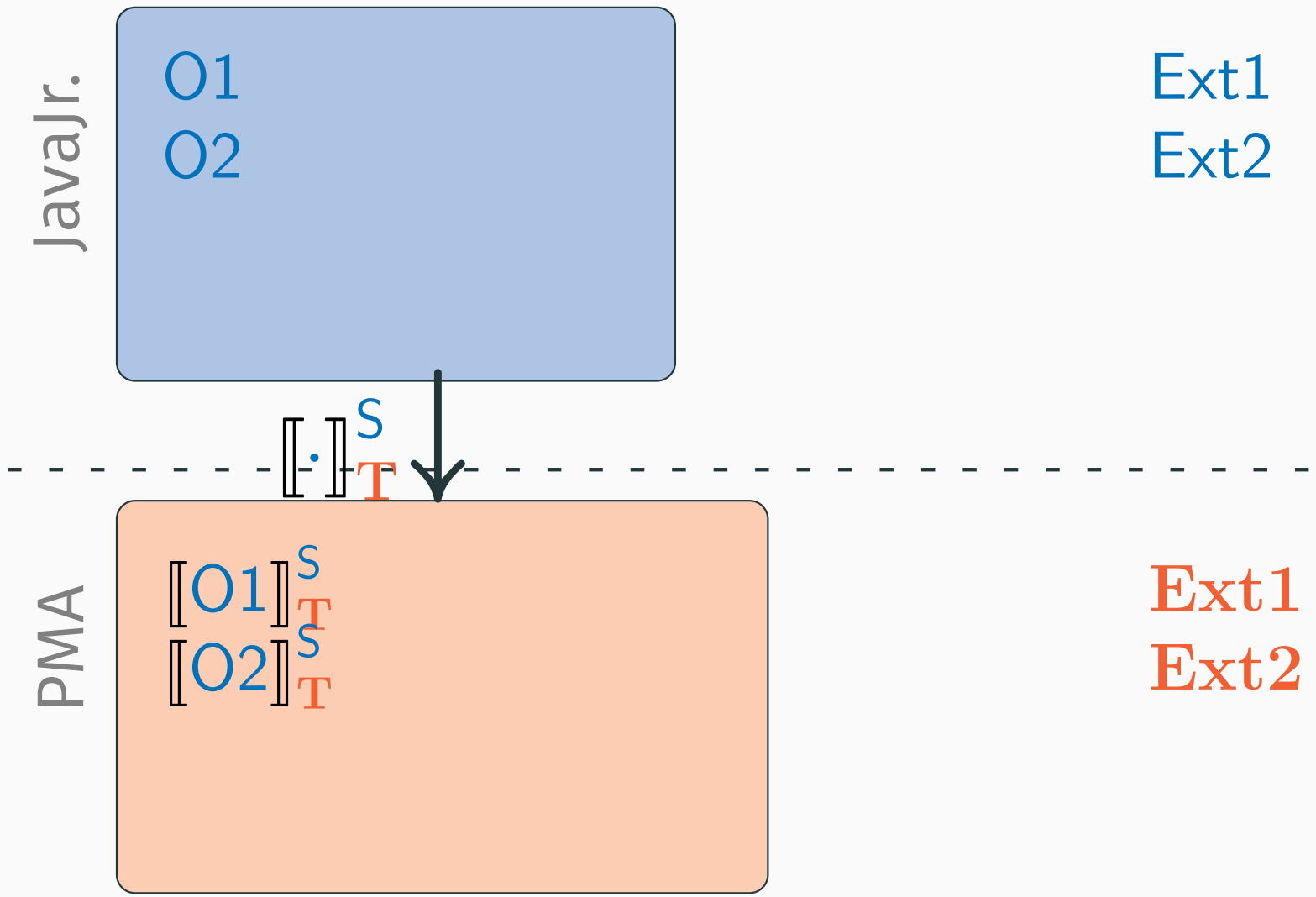
- witness address of returned `Secret`
- Sol: mask objects through proxies

Memory Allocation Issues



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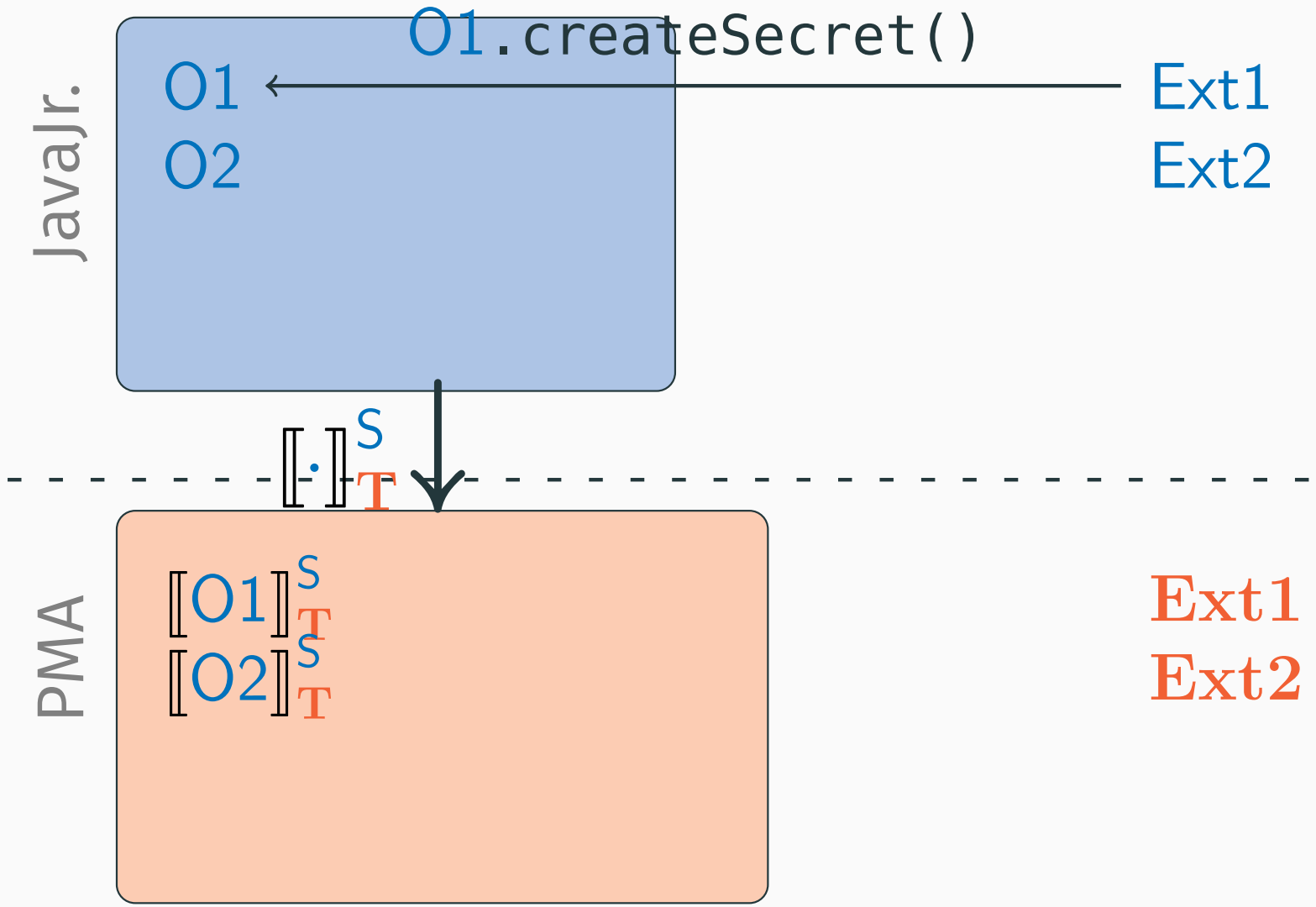

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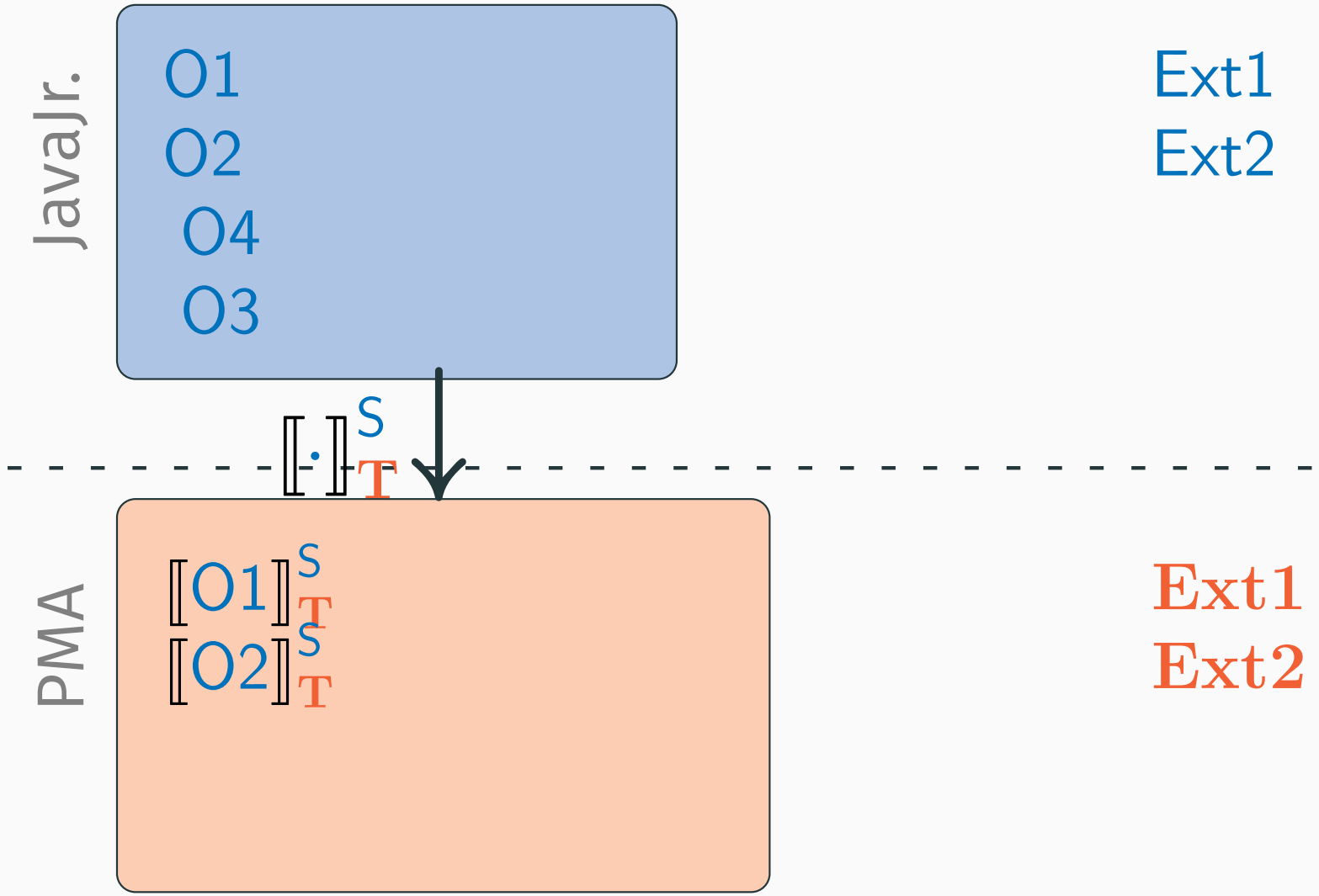

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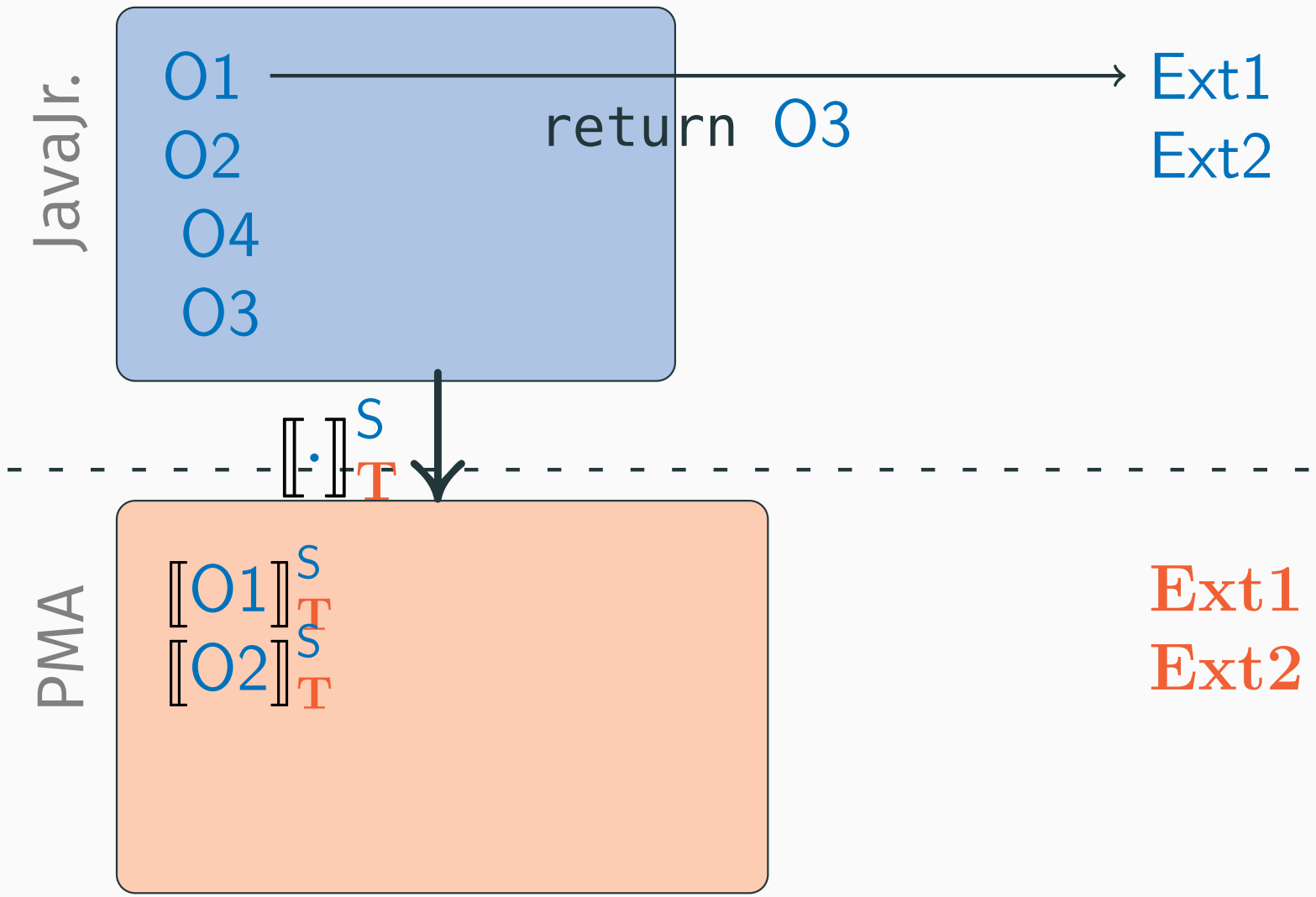

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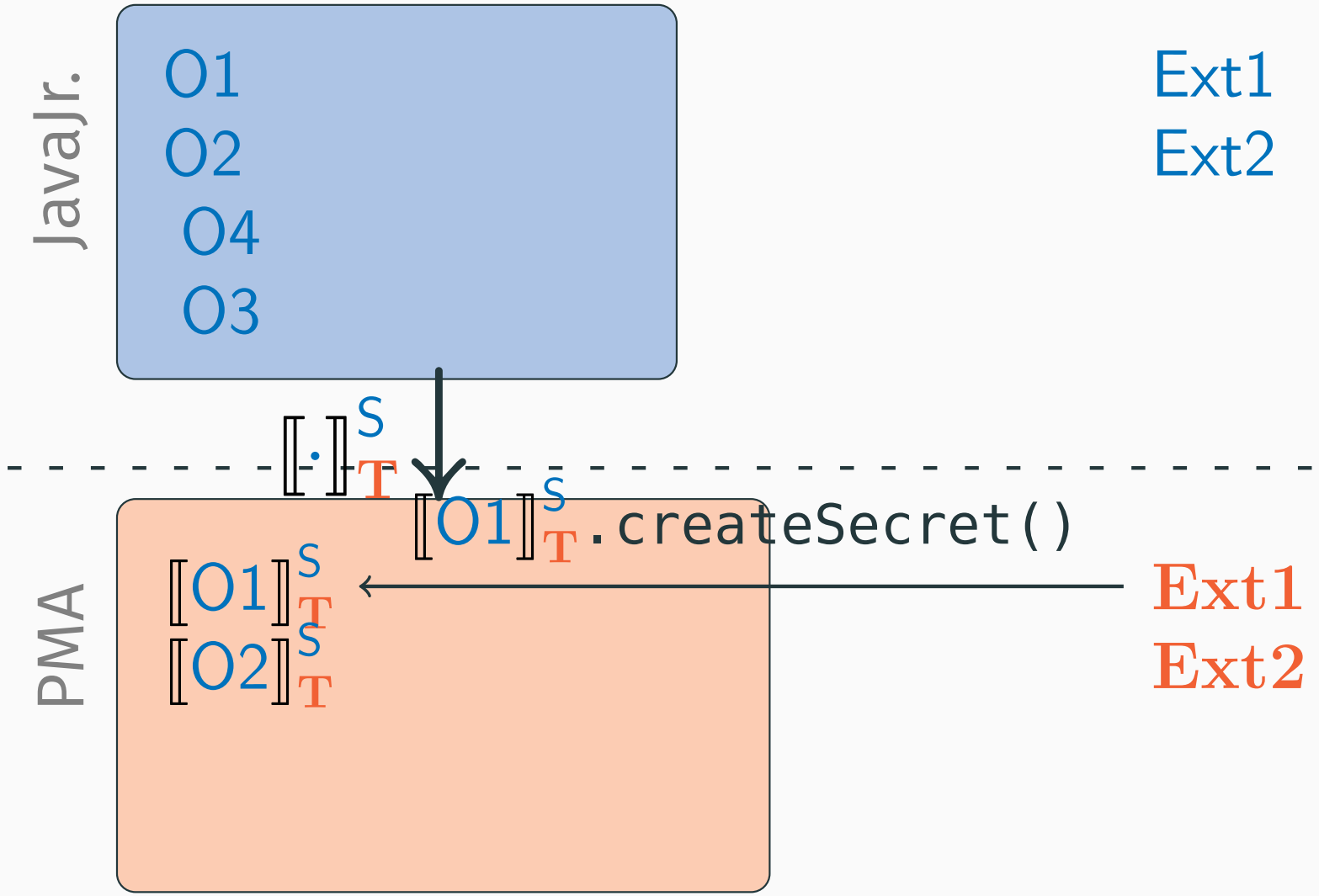

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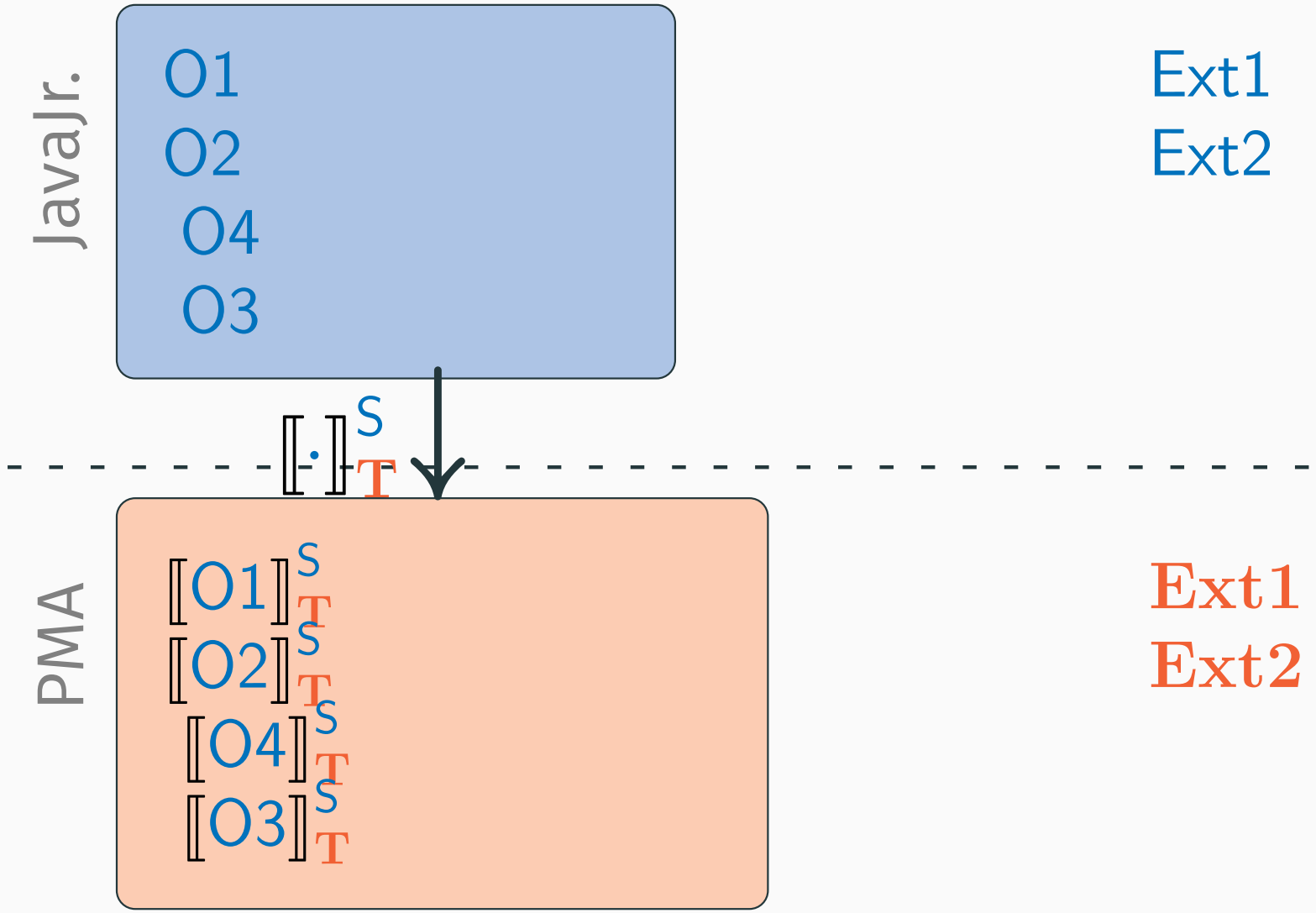

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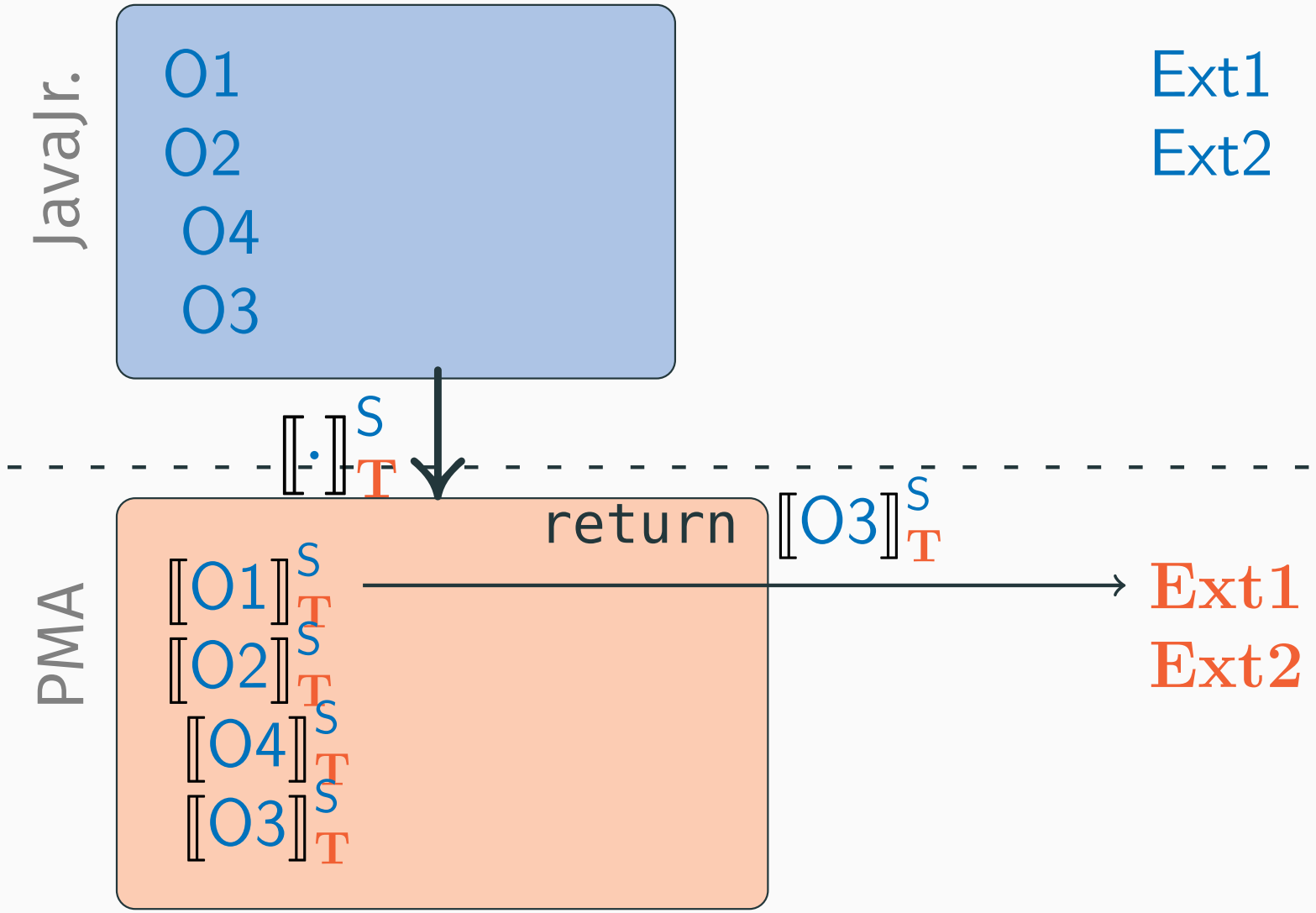

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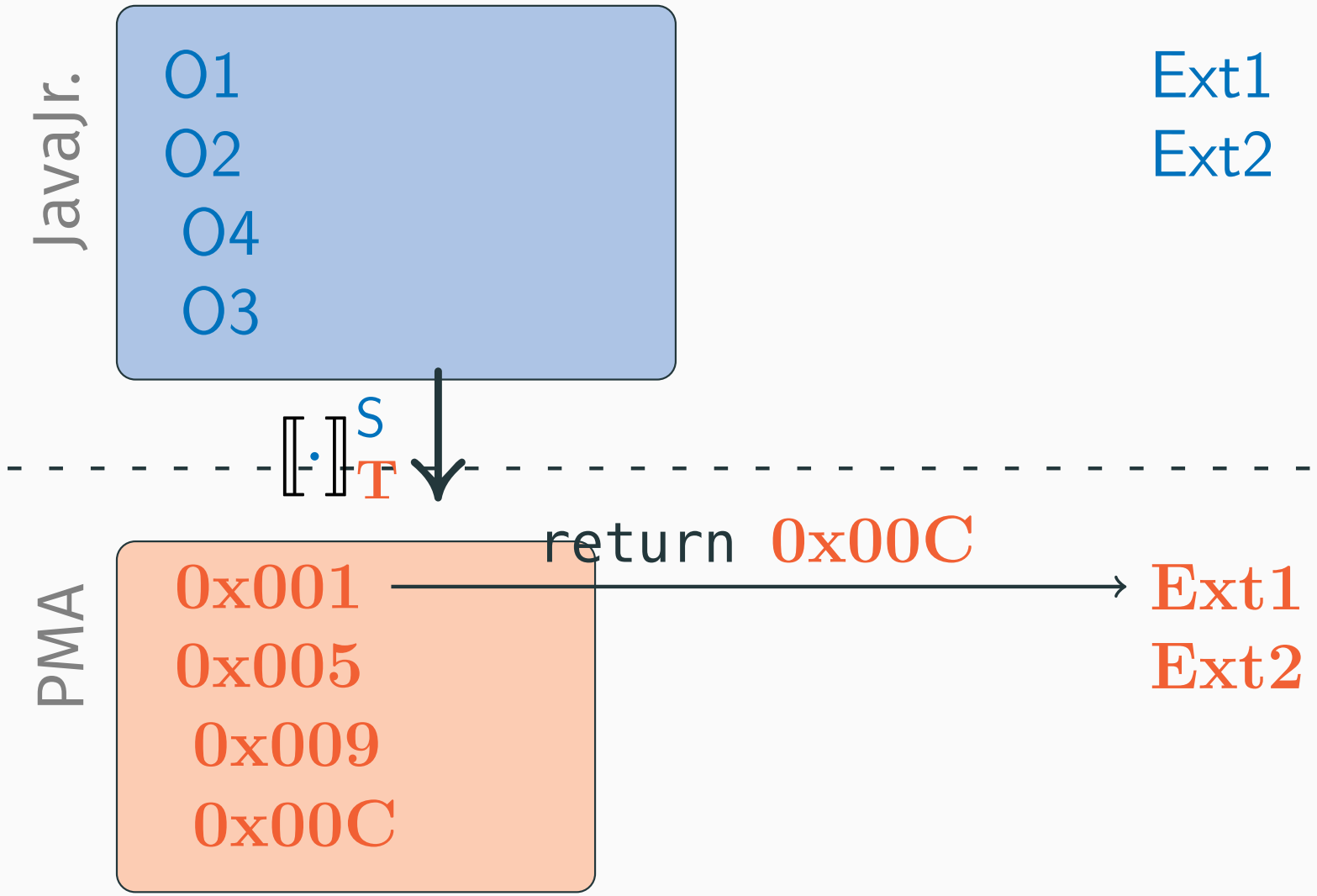

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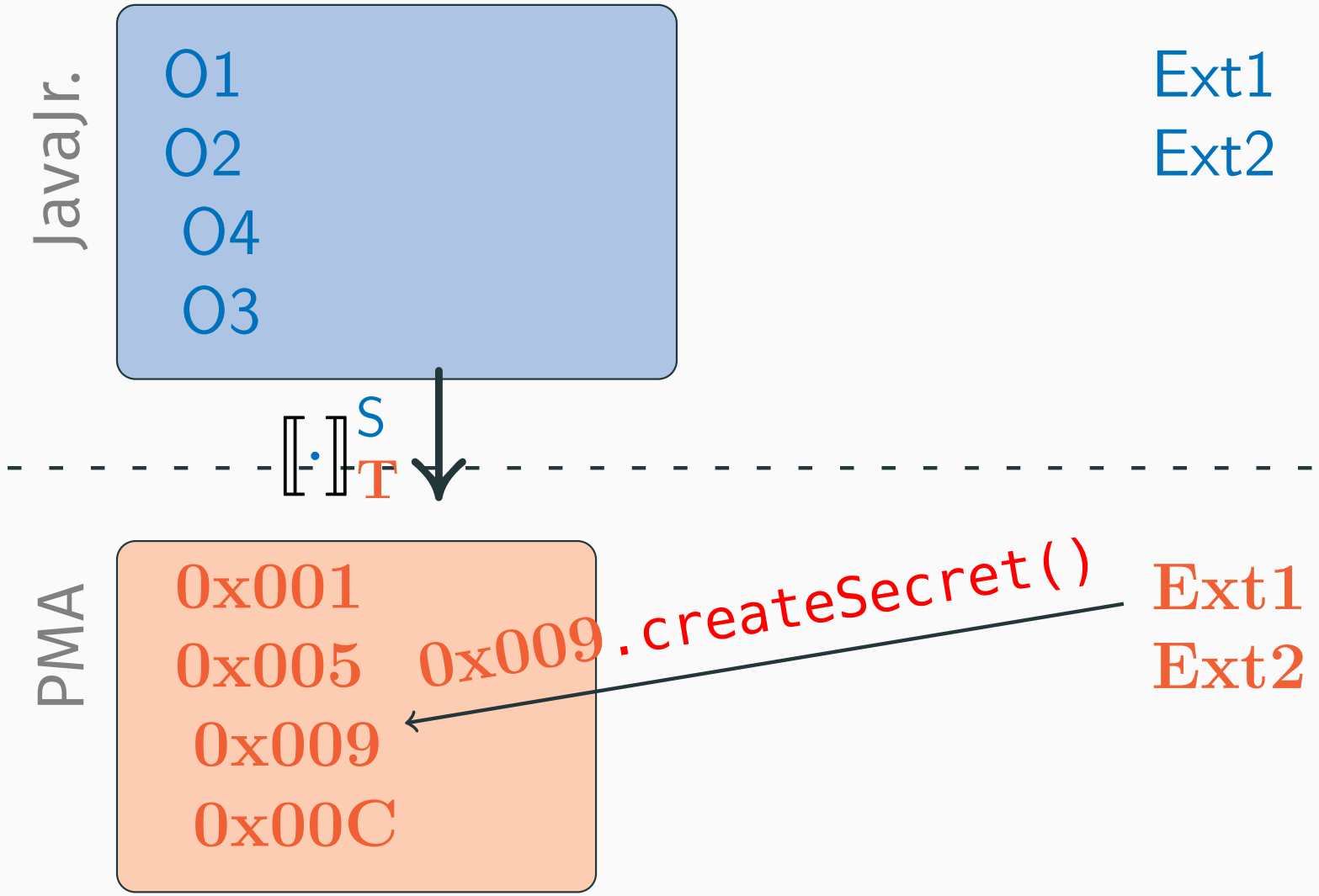

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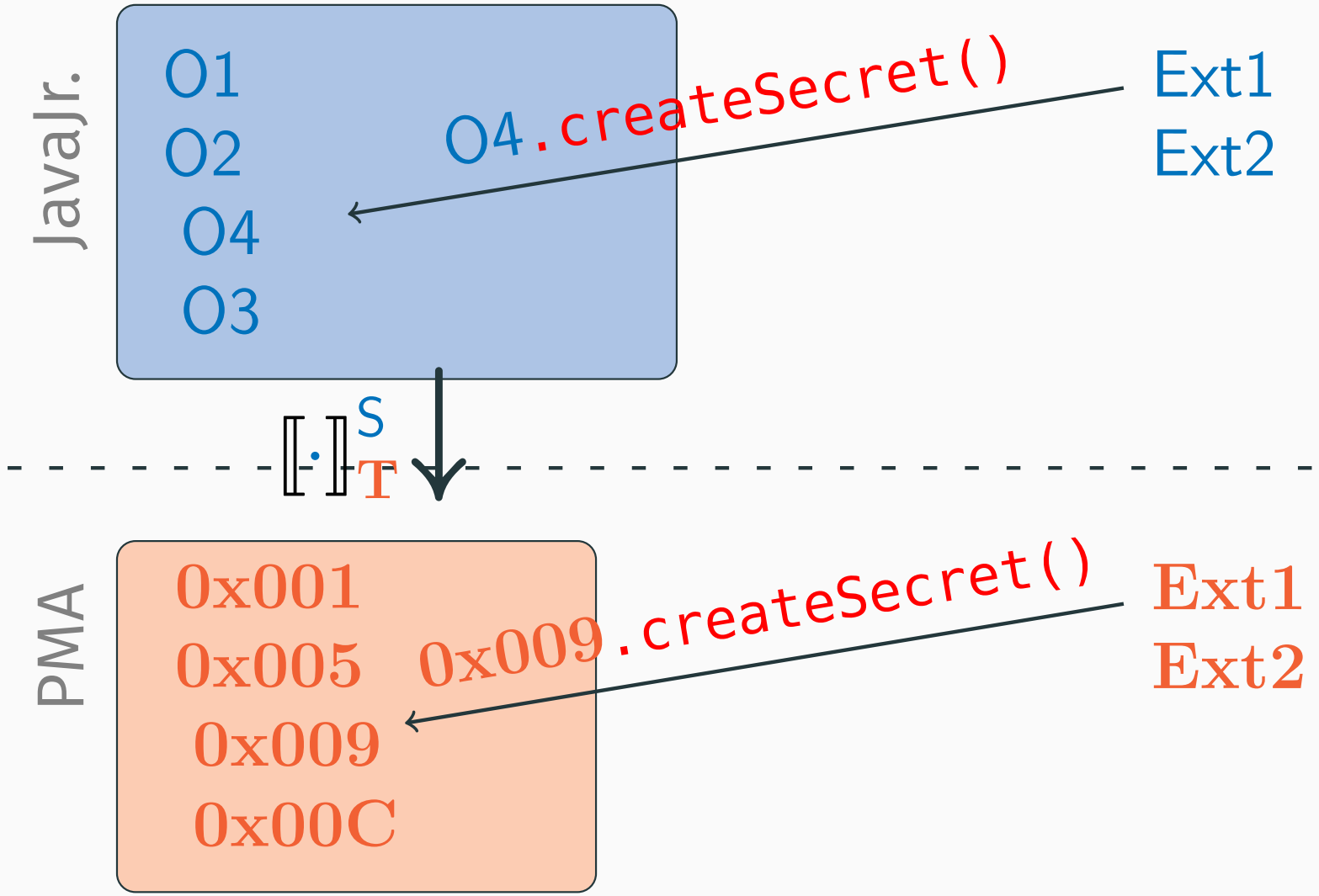

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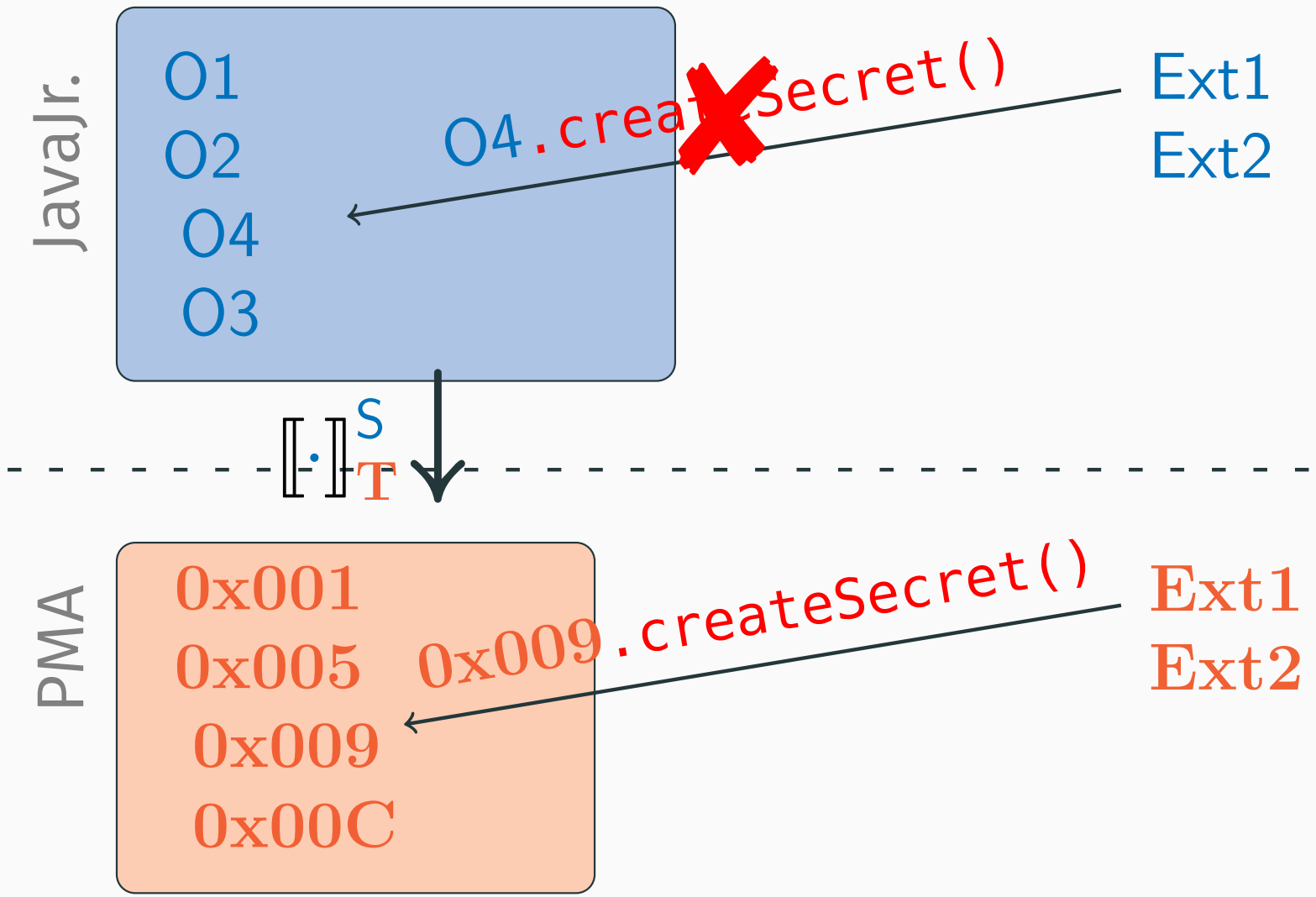

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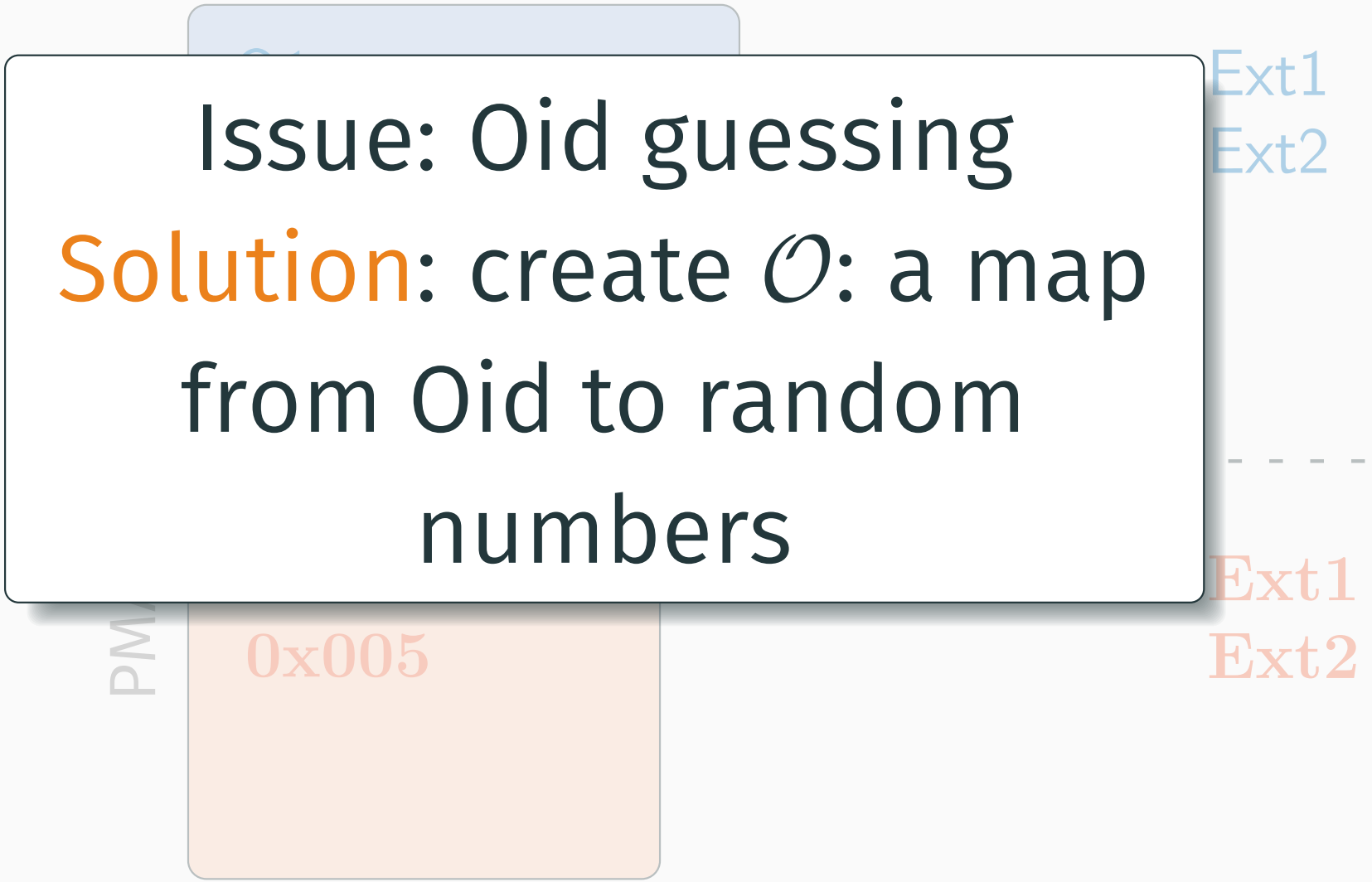

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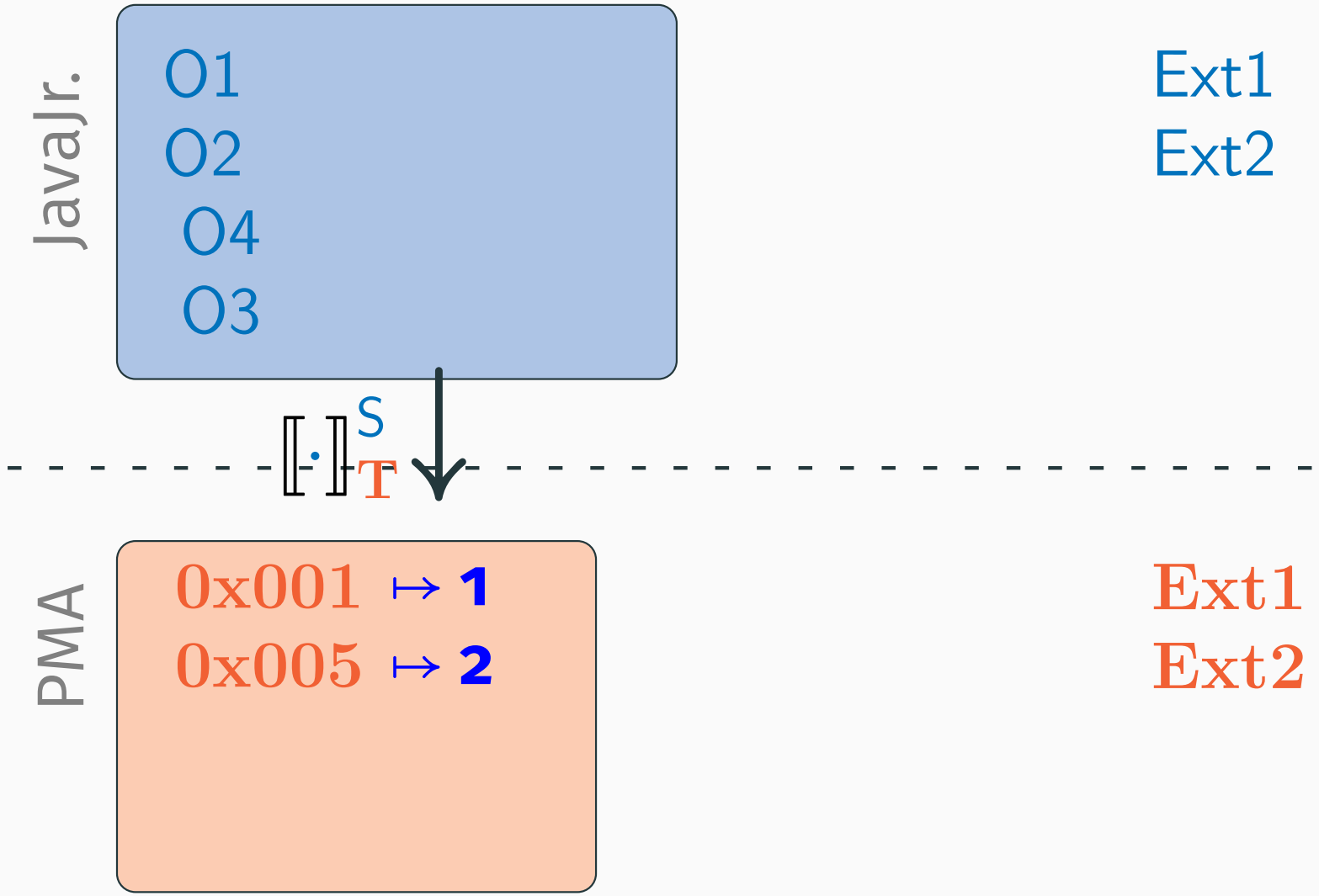

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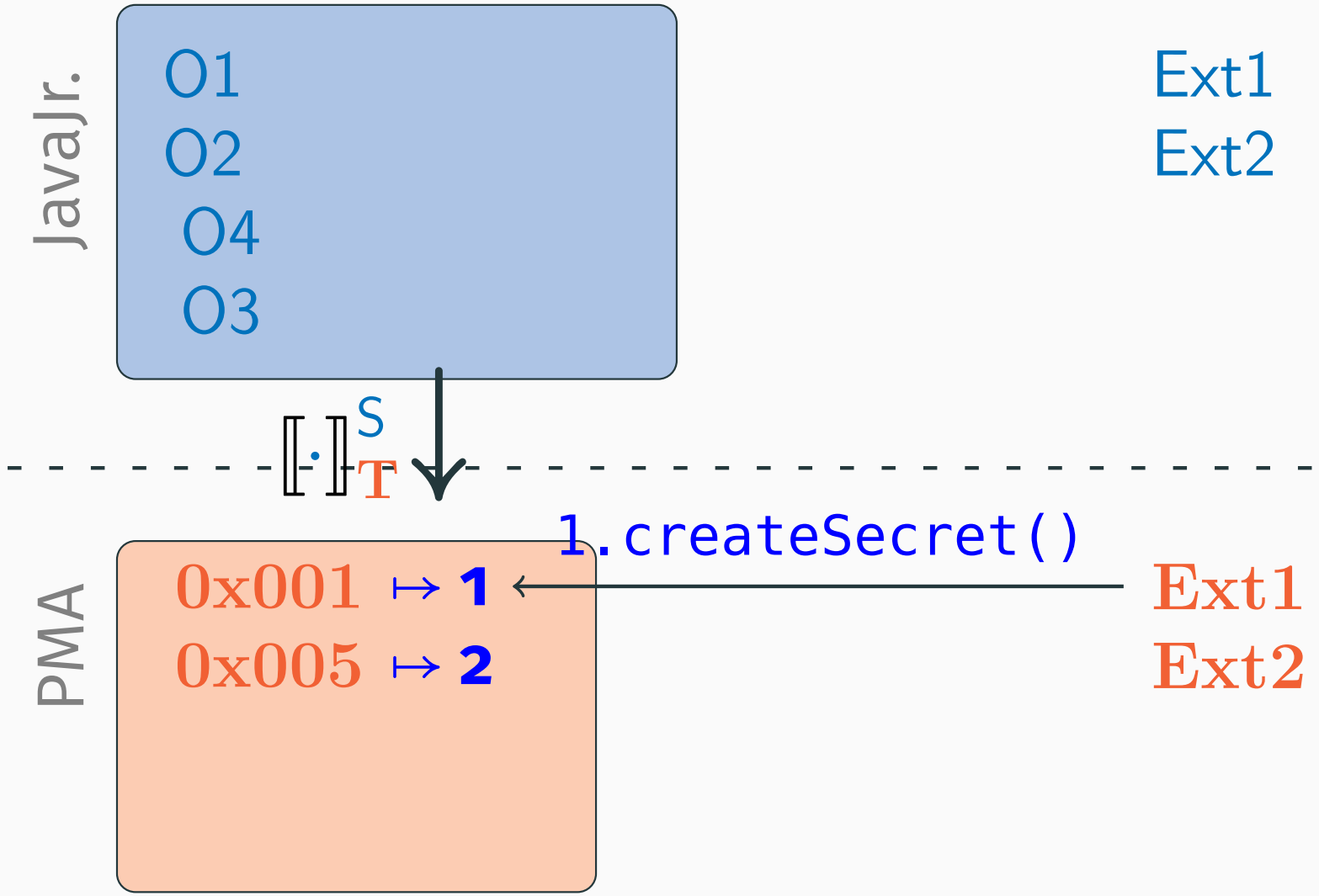

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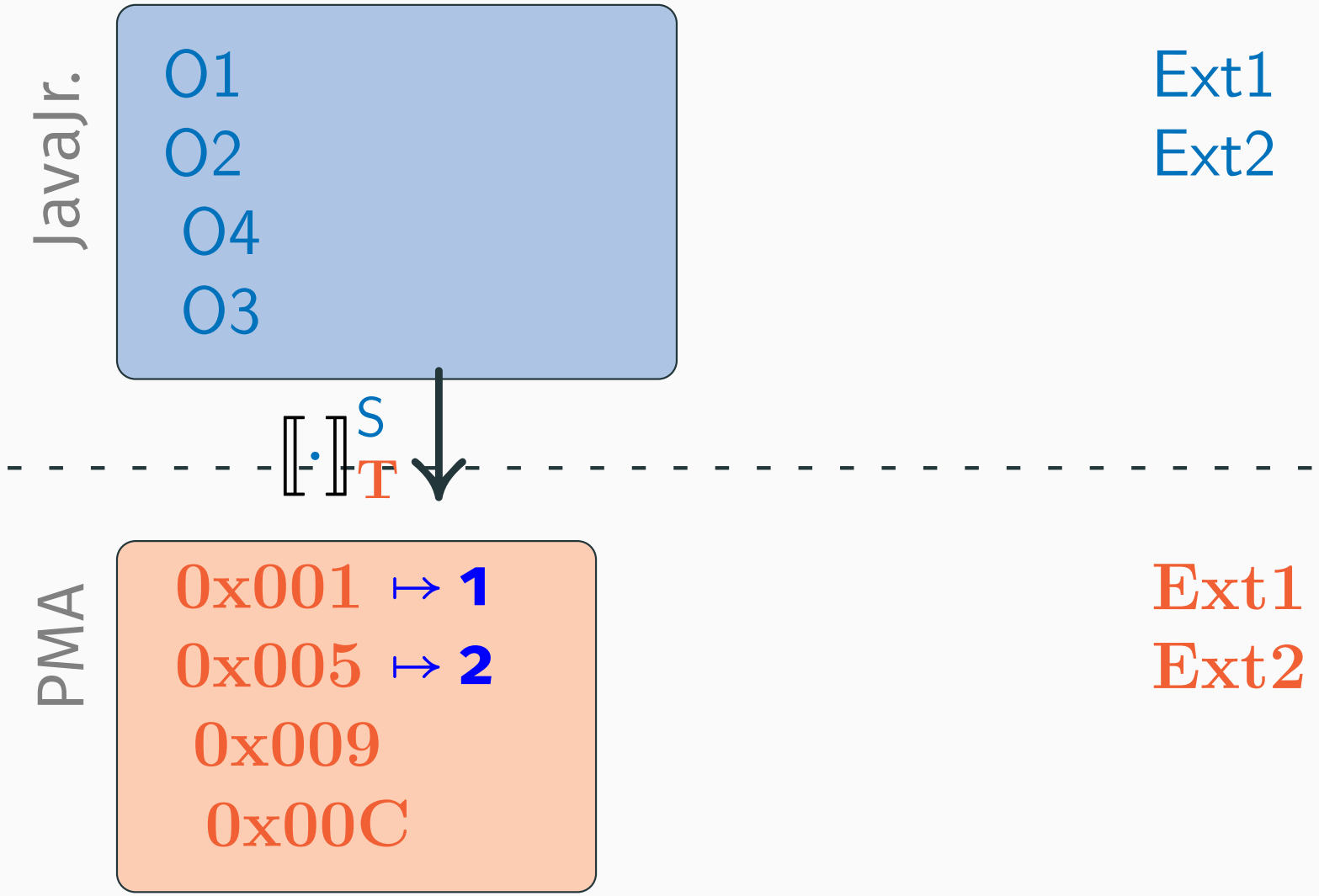

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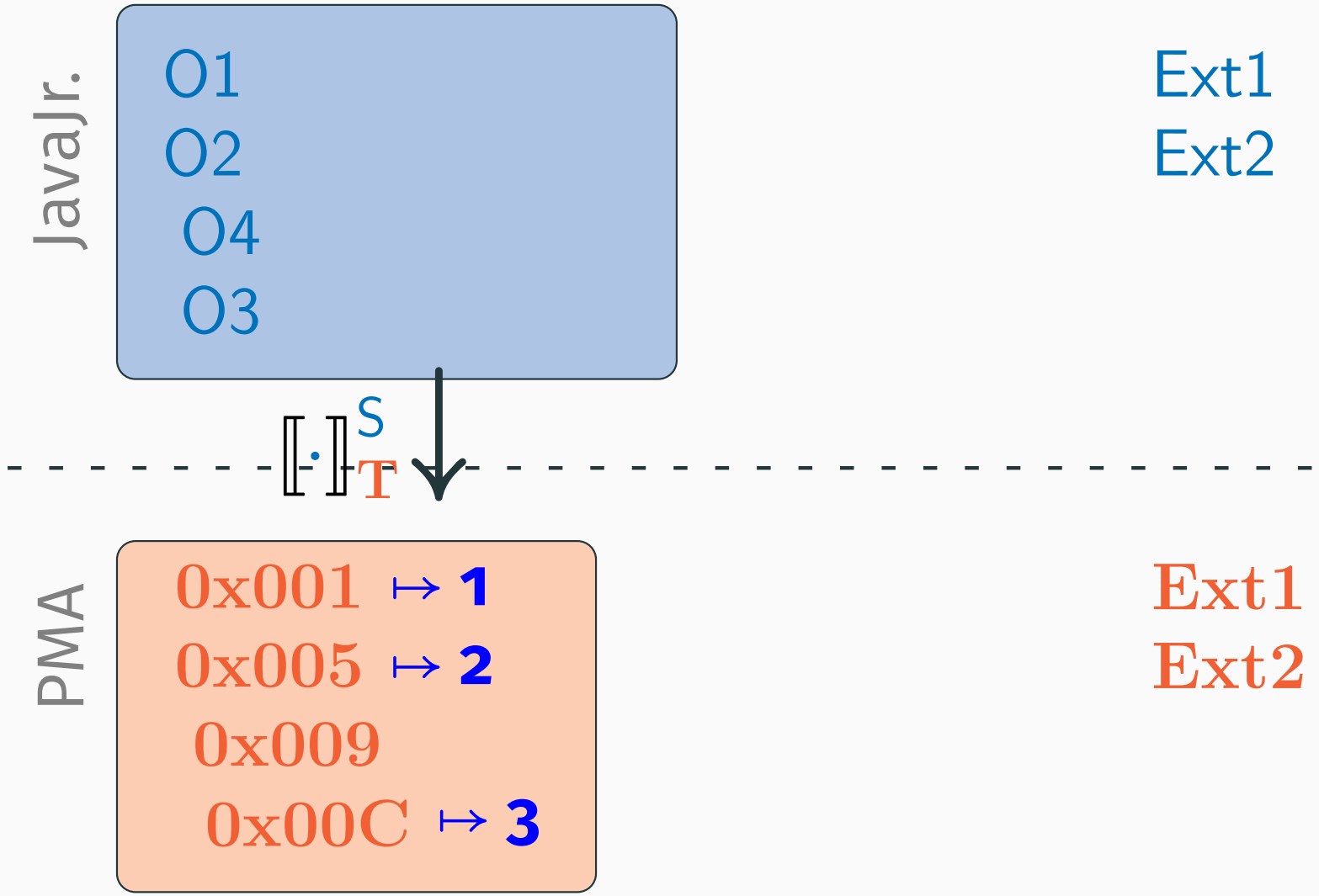

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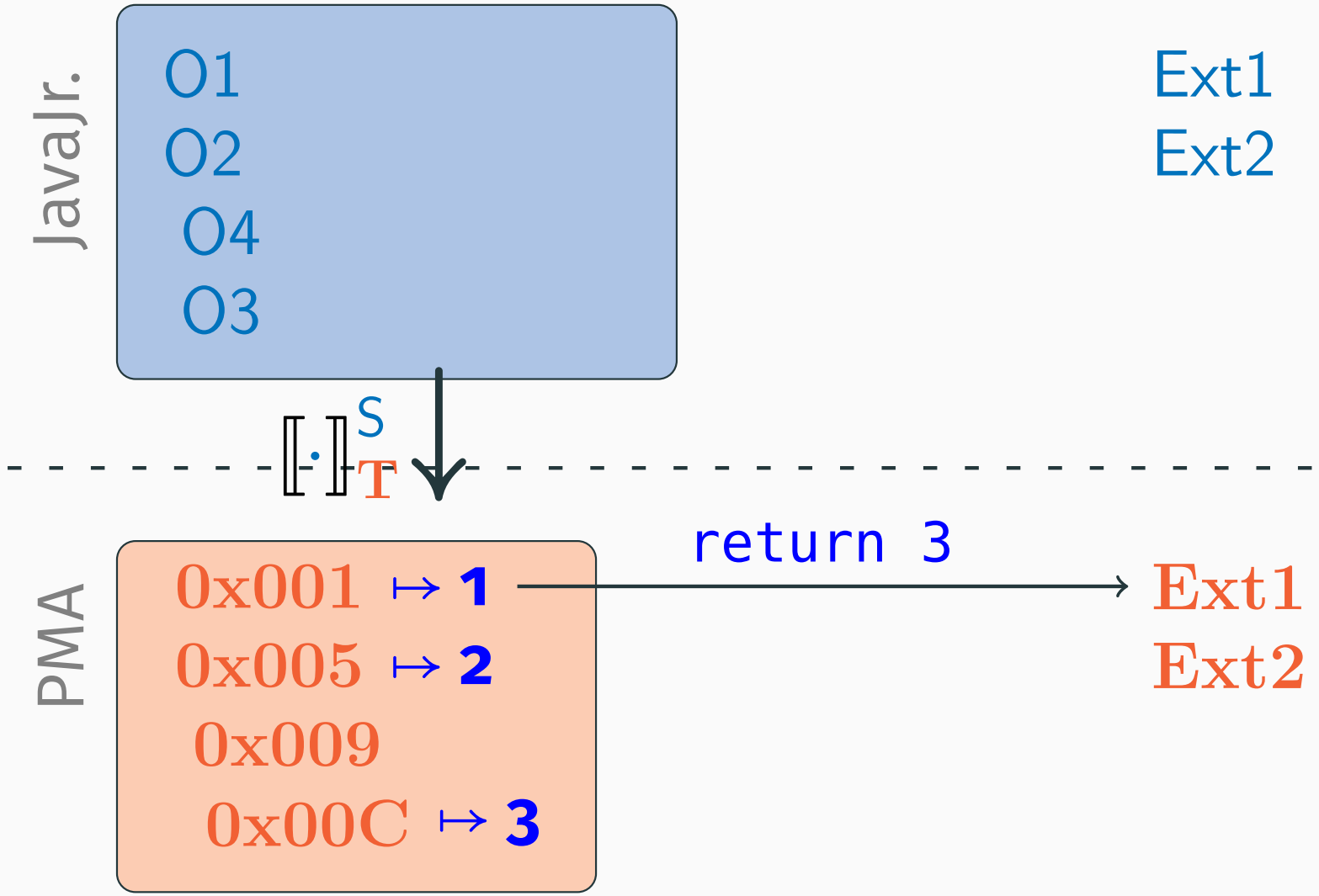

Secure Compiler Structure

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$[\![\cdot]\!] : \mathsf{P} \to \mathbf{P}$ must:

- generate correct code (through $(\!|\cdot|\!)$)
- place it inside an enclave
- wrap it at entry and exit points with checks

Entry and Exit Points

Method p entry point		Preamble to returnback entry point	
1	Load receiver $v = \mathcal{O}(\mathtt{r}_4)$	a	Push current object $v = \mathtt{r}_4$, return address a and return type m
2	Check that v's class defines method p	b	Reset flags and unused registers
3	Load parameters $\overline{v}$ from $\mathcal{O}$	c	Replace object identities with indexes in $\mathcal{O}$
4	Dynamic typecheck on $\overline{v}$	d	Jump to callback address (*run external code*)
5	Perform dynamic dispatch (*run method p code*)		
Exit point		Returnback entry point	
6	Reset flags and unused registers	e	Pop return type m and check it
7	Replace object identities with indexes in $\mathcal{O}$	f	Dynamic typecheck
		g	Pop return address a, current object v and resume execution

Properties of the Compiler

$$\forall \mathsf{P}_1, \mathsf{P}_2 . \mathsf{P}_1 \simeq_{ctx} \mathsf{P}_2 \iff [\![\mathsf{P}_1]\!] \simeq_{ctx} [\![\mathsf{P}_2]\!]$$

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- correctness of $[\![\cdot]\!]$ ($\Rightarrow$) should follow from the correctness of $(\!|\cdot|\!)$
- security of $[\![\cdot]\!]$ ($\Leftarrow$) requires BT
- the gap between PMA and JavaJr is too big: trace-based BT

Traces for PMA

In this case:

- capture specific component-context interactions
- alternation of call/return

Traces for PMA

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- capture specific component-context interactions
- alternation of call/return

Generally:

- capture arbitrary component-context interactions
- alternation of call/return plus read and write to shared memory

Traces for PMA: formally

to the board

- reliance on operational semantics
- problems of read/write

$$
\begin{array}{ll}
\textit{labels} & \lambda ::= \alpha \mid \tau \\
\textit{actions} & \alpha ::= \gamma! \mid \gamma? \mid \surd \\
\textit{observables} & \gamma ::= \mathbf{call\ a\ \overline{w}} \mid \mathbf{ret\ a\ w, id}!
\end{array}
$$

Instead of creating the BT now, we look at the multimodule case and show only that BT

Multiple Isolation in PMA

- multiple programmers may not trust each others
- each programmer gets an enclave

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<table>
<tr><th rowspan="2">From \ To</th><th rowspan="2">Unprotected</th><th colspan="3">Protected</th></tr>
<tr><th>Entry Point</th><th>Code</th><th>Data</th></tr>
<tr><td>Unprotected</td><td>r w x</td><td>x</td><td></td><td></td></tr>
<tr><td rowspan="3">Protected</td><td rowspan="3">r w x</td><td colspan="3">Same id</td></tr>
<tr><td>r x</td><td>r x</td><td>r w</td></tr>
<tr><td colspan="3">Different id</td></tr>
<tr><td>x</td><td></td><td></td></tr>
</table>

Multiple Isolation in PMA: Formally

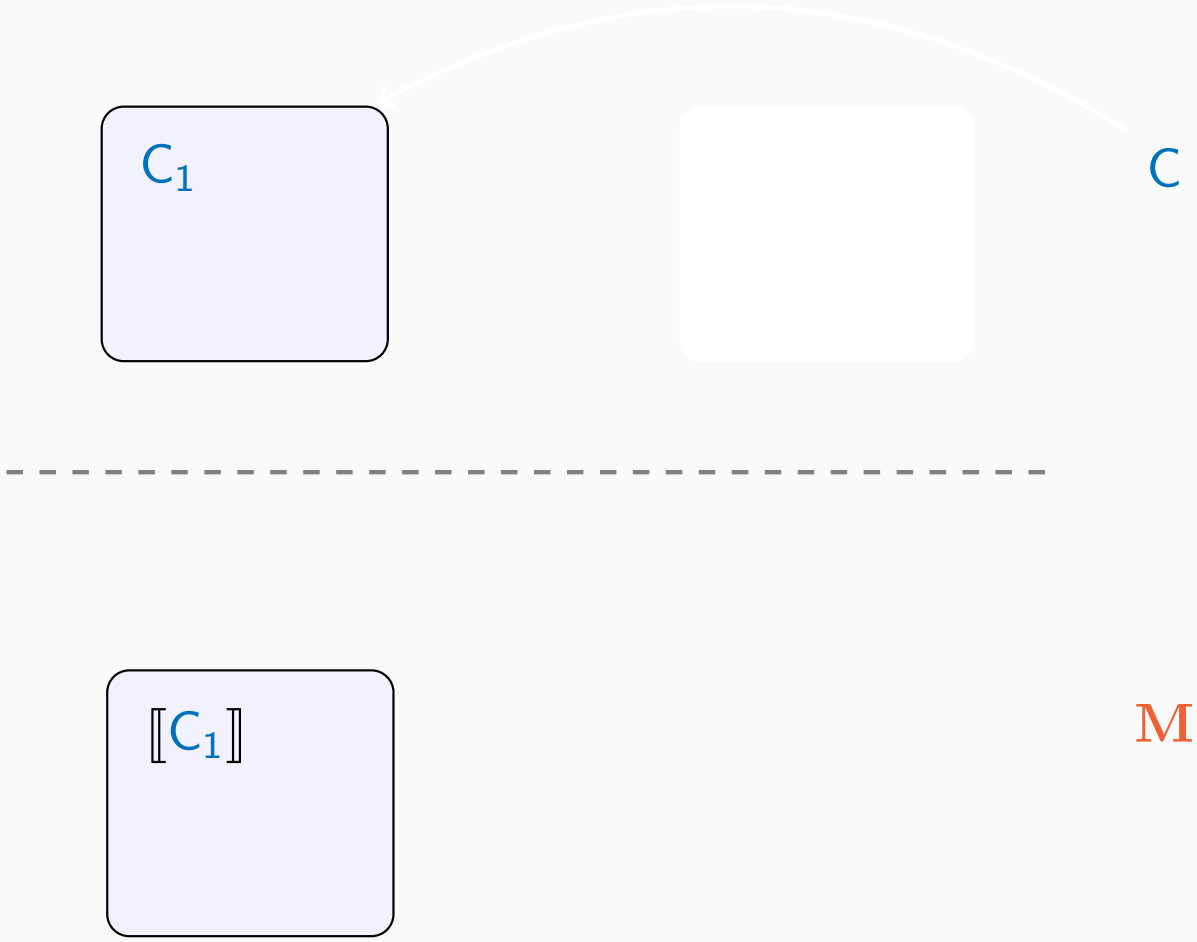
to the board

- multiple domains
- randomisation
- contextual preorders

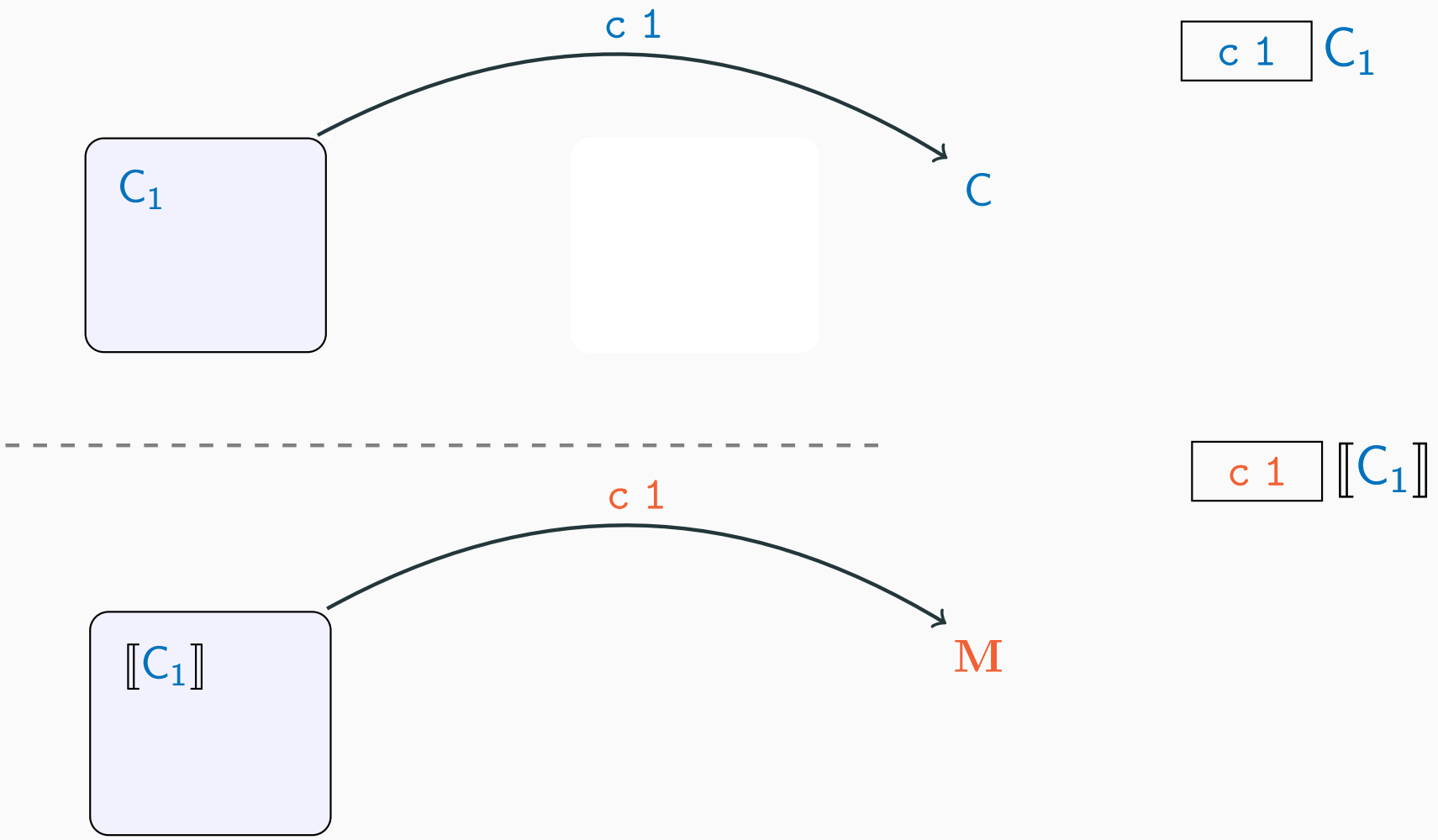
Linking Vulnerabilities

1. Call stack shortcutting;
2. Types of objects in other modules;
3. Existence of objects in other modules.

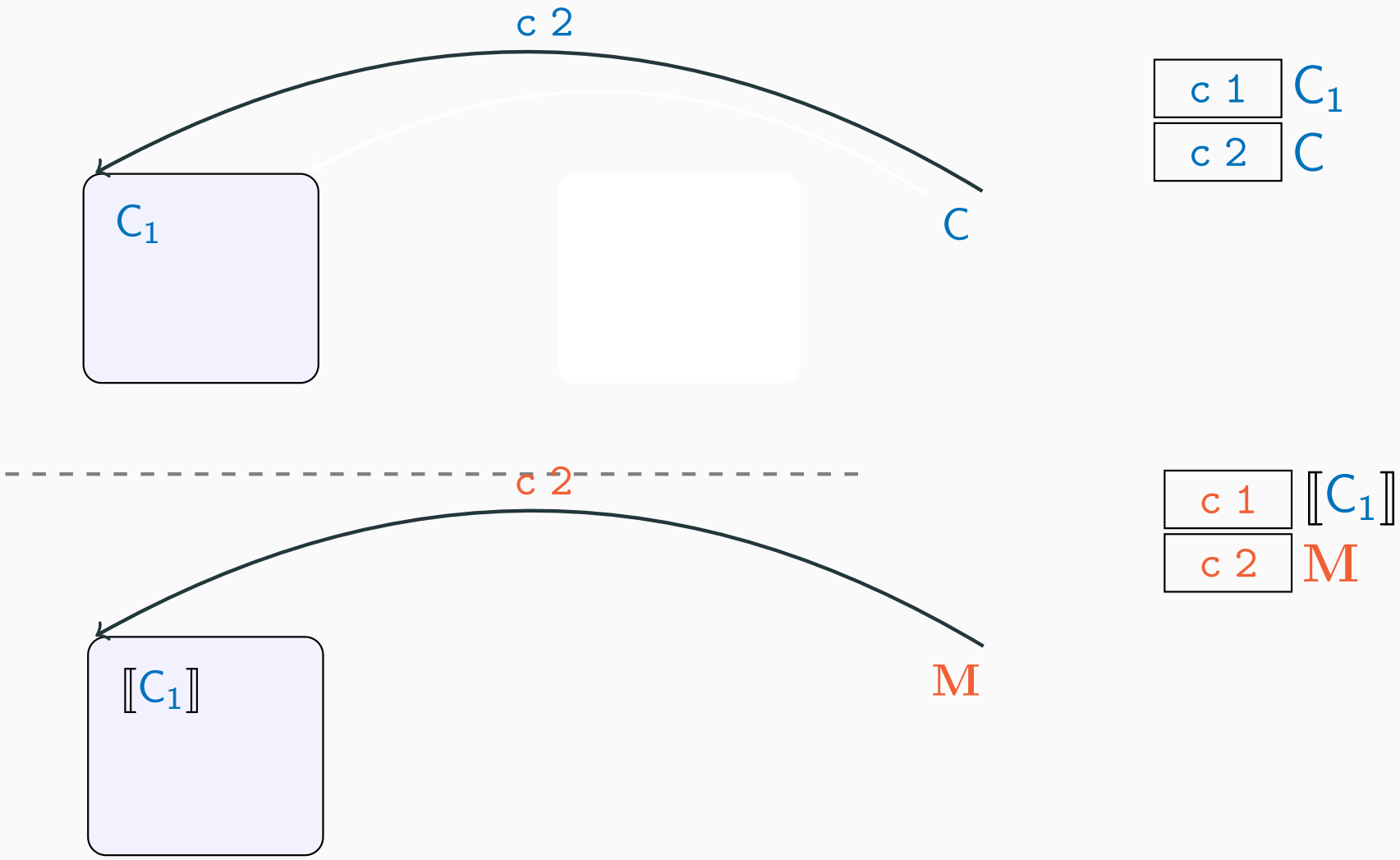
Calls - 1 Component



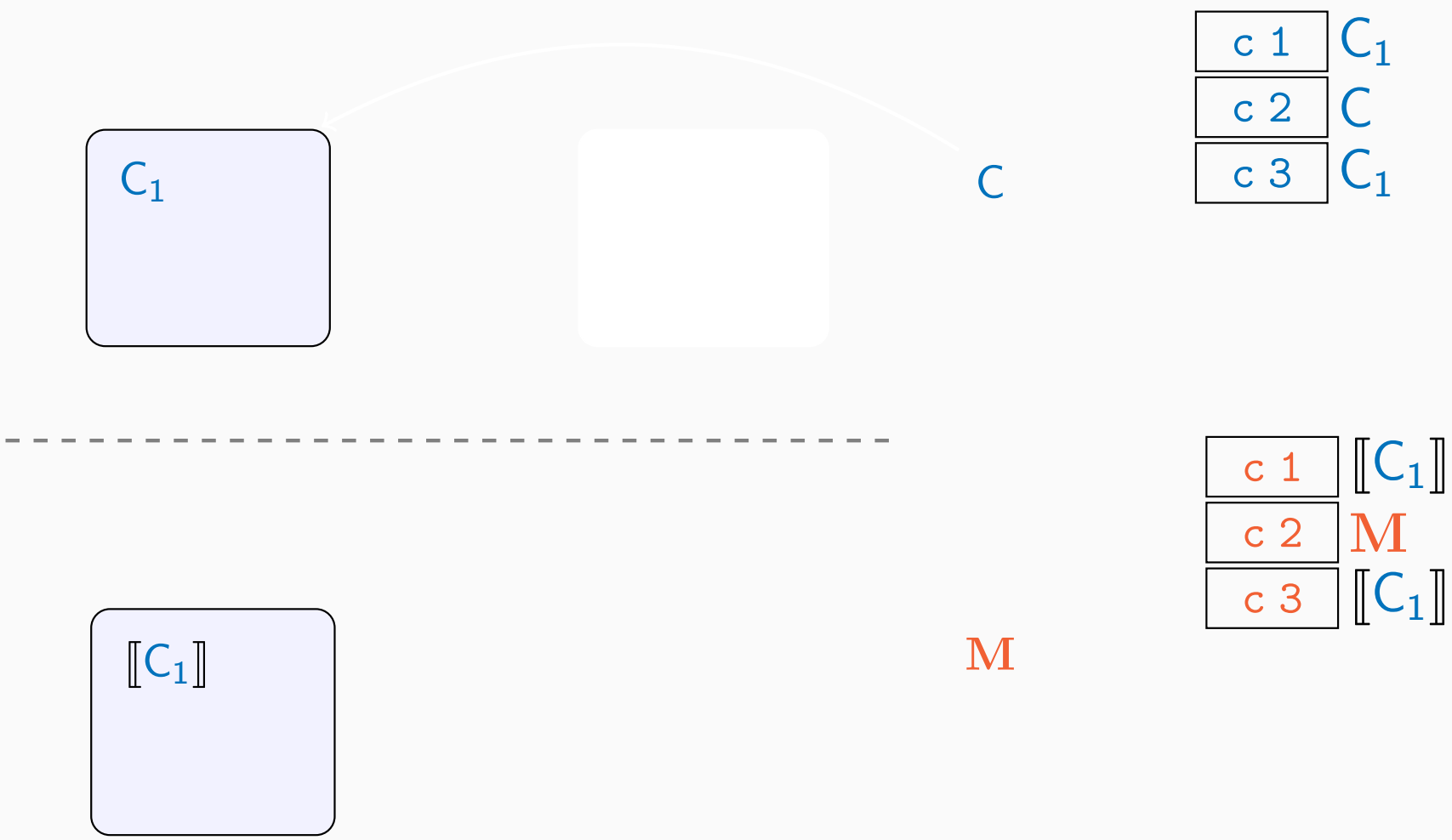
Calls - 1 Component



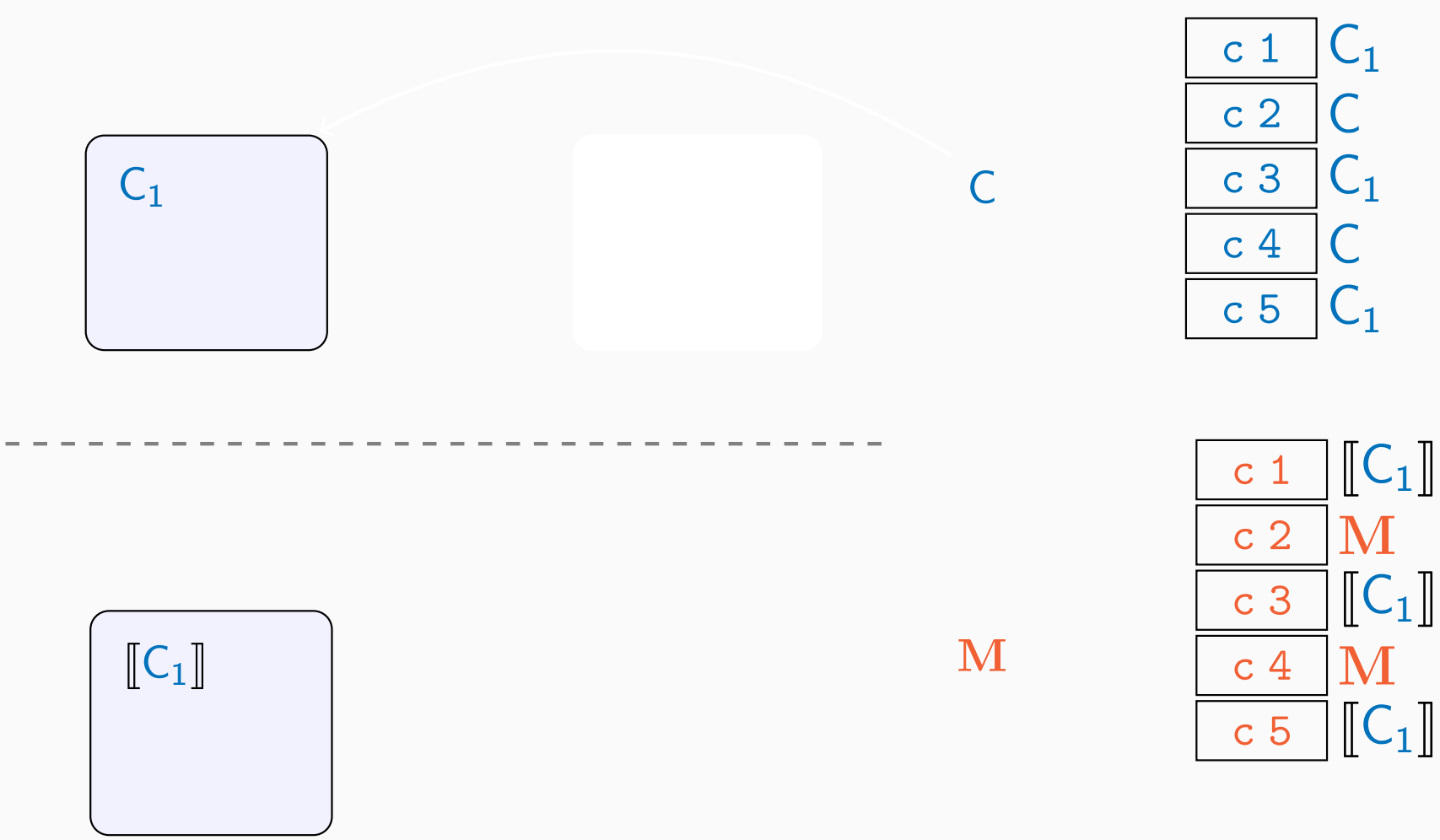
Calls - 1 Component



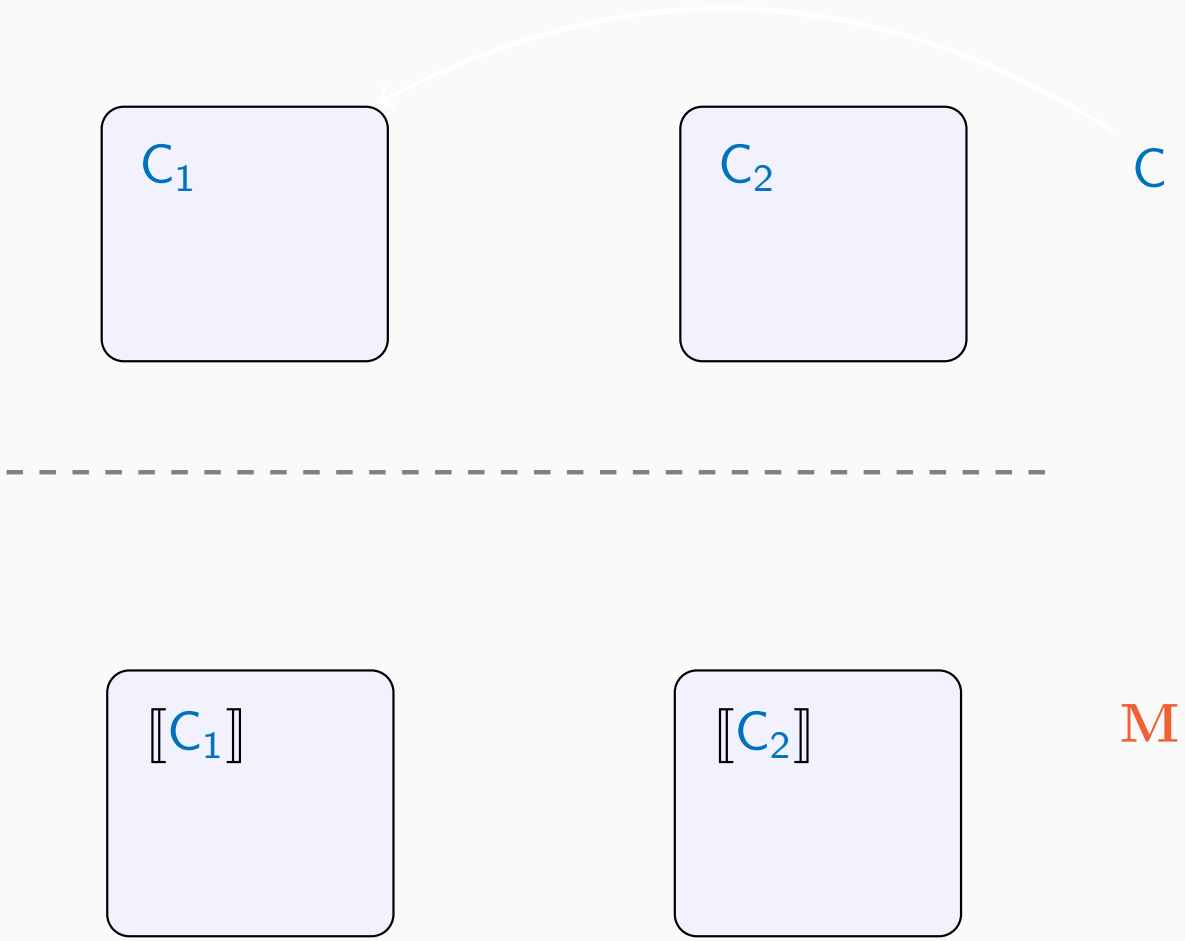
Calls - 1 Component



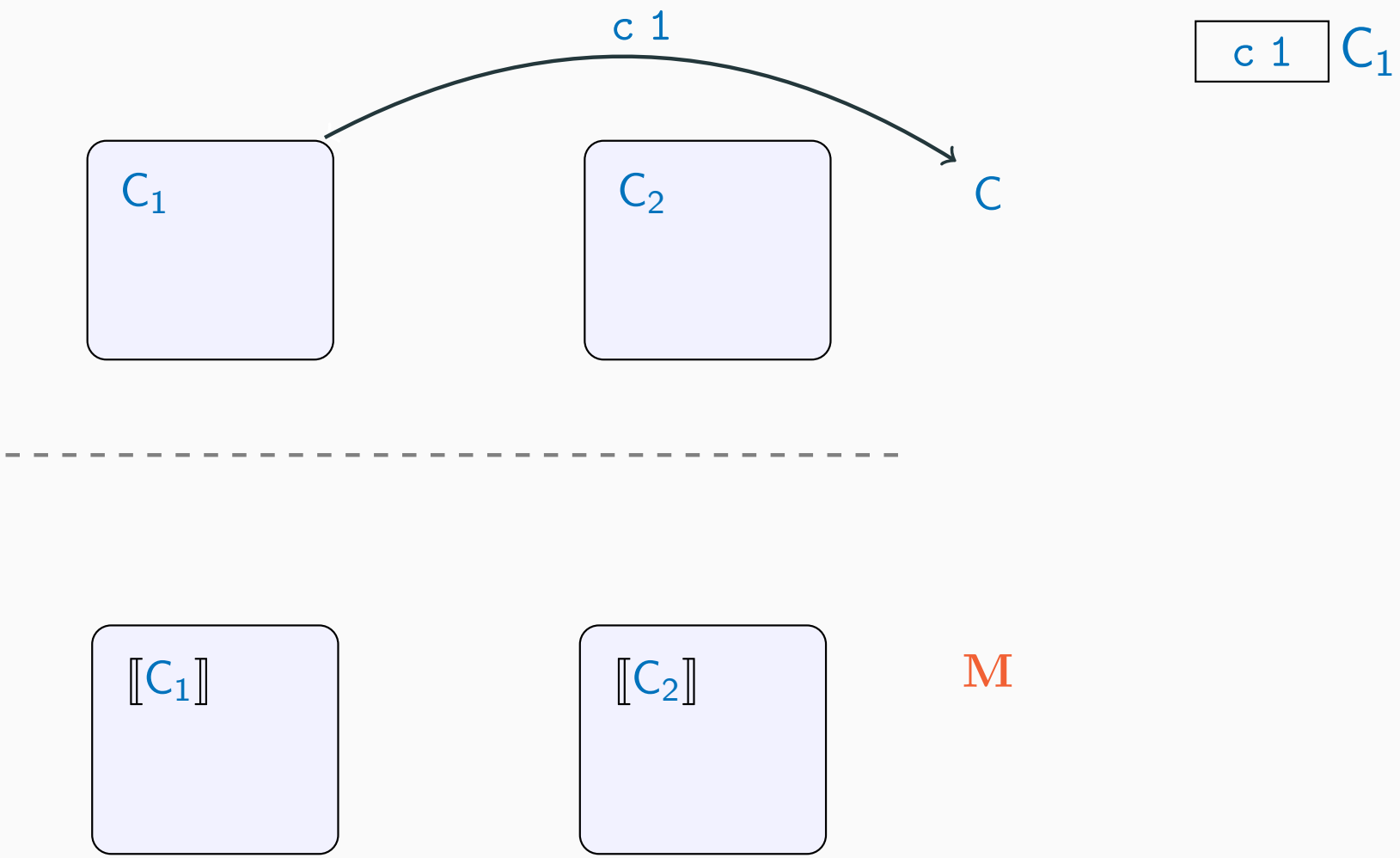
Calls - 1 Component



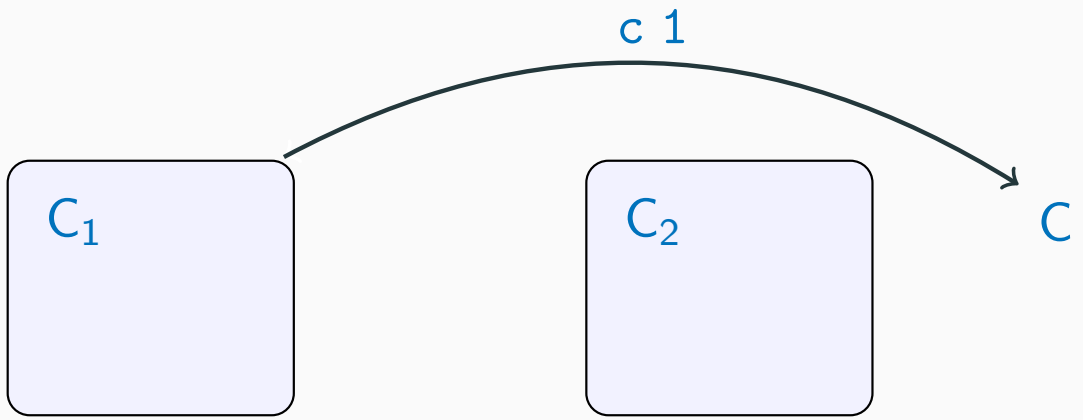
Call Stack Shortcutting



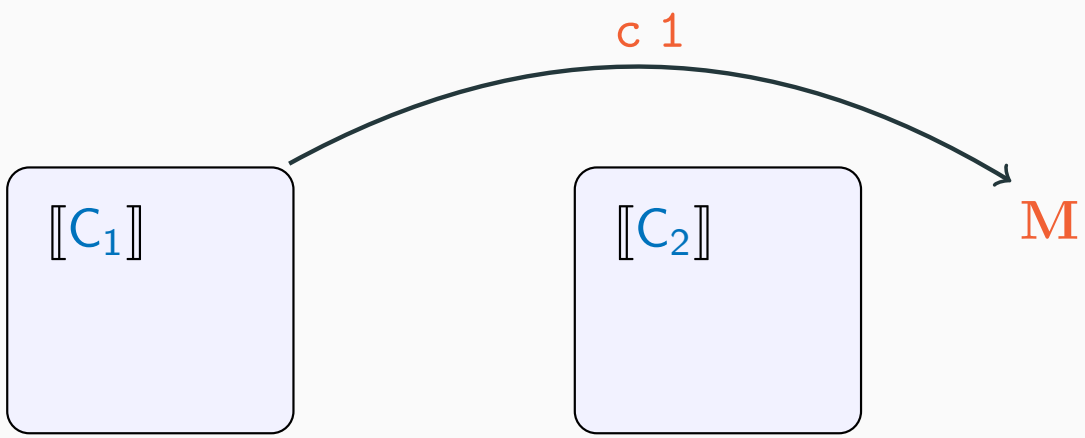
Call Stack Shortcutting



Call Stack Shortcutting

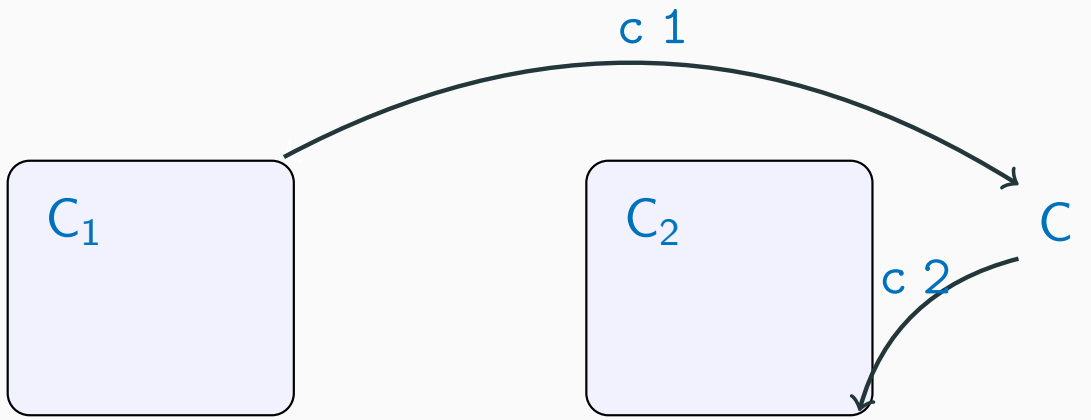


c 1 C_1

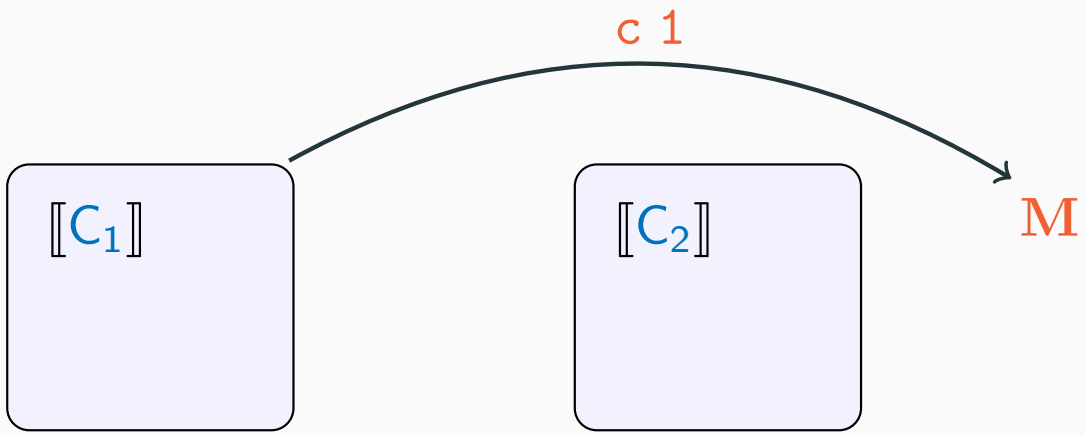


c 1 $[\![C_1]\!]$

Call Stack Shortcutting

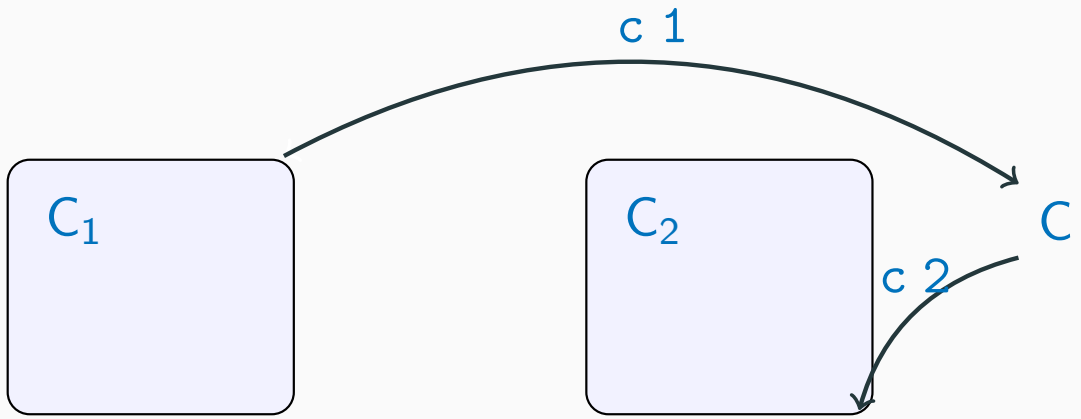


c 1	C_1
c 2	C

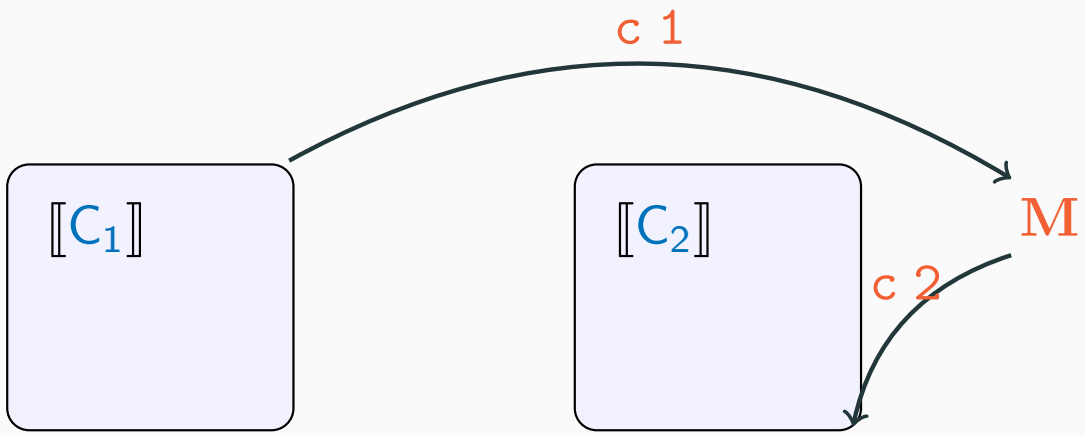


c 1	$[\![C_1]\!]$

Call Stack Shortcutting

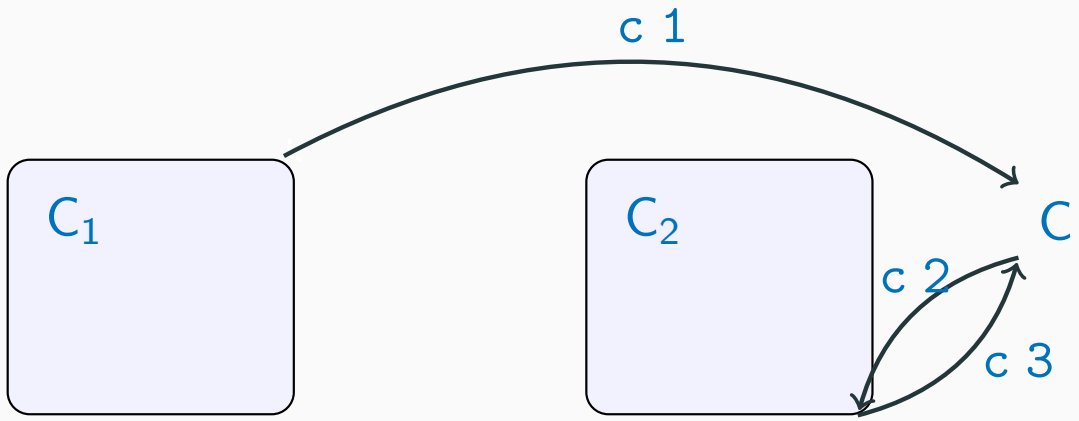


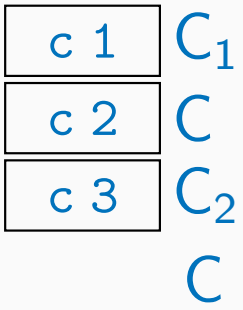
c 1	C_1
c 2	C

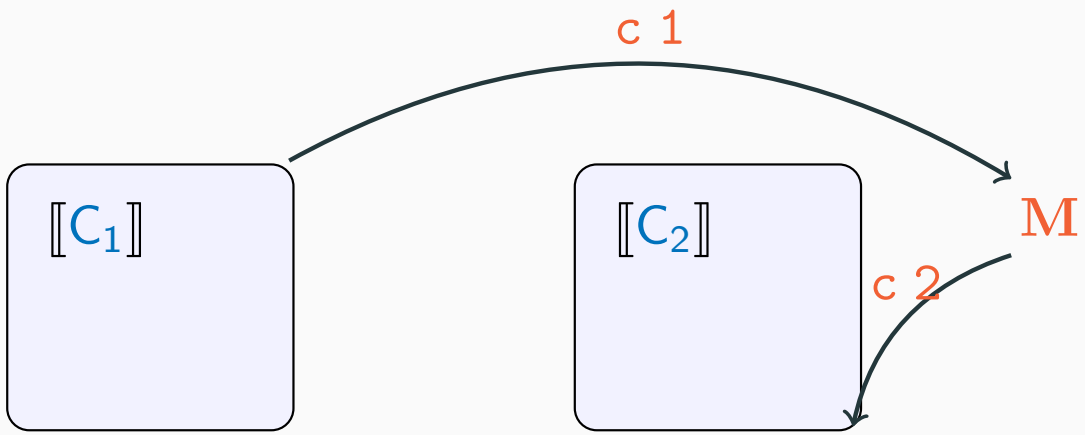


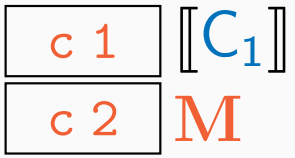
c 1	$[\![C_1]\!]$
c 2	M

Call Stack Shortcutting

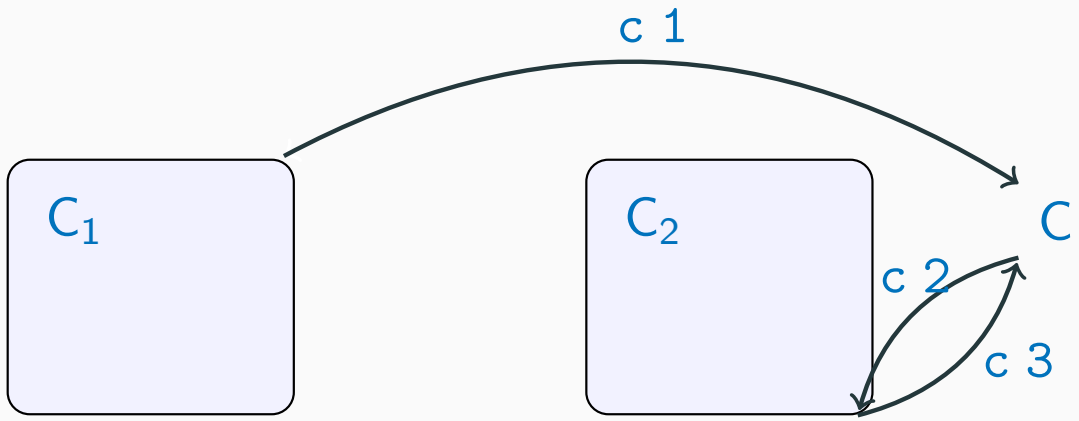




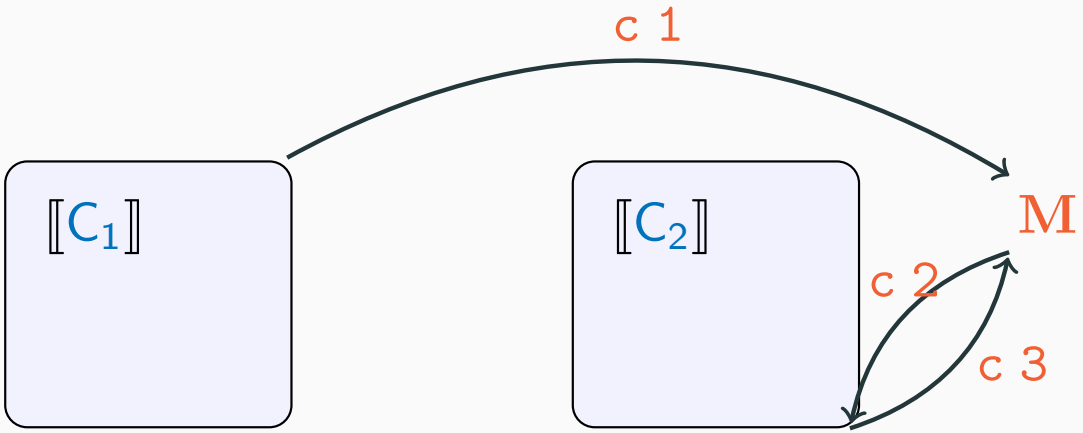




Call Stack Shortcutting

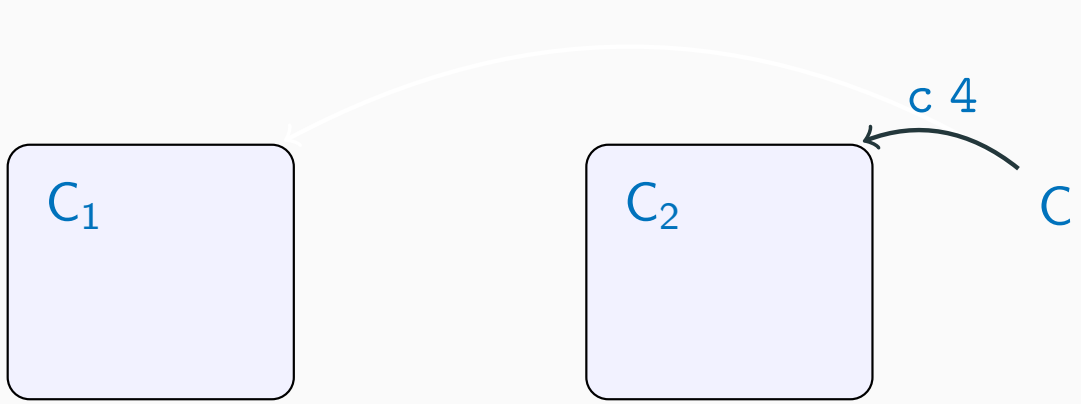


c 1	C_1
c 2	C
c 3	C_2
	C

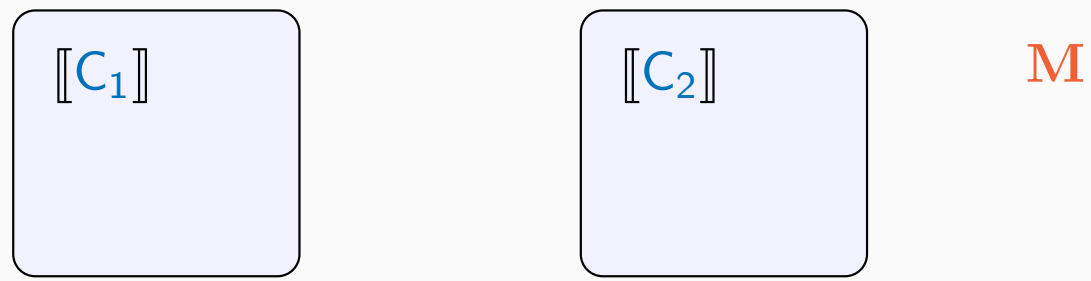


c 1	$[\![C_1]\!]$
c 2	M
c 3	$[\![C_2]\!]$
	M

Call Stack Shortcutting

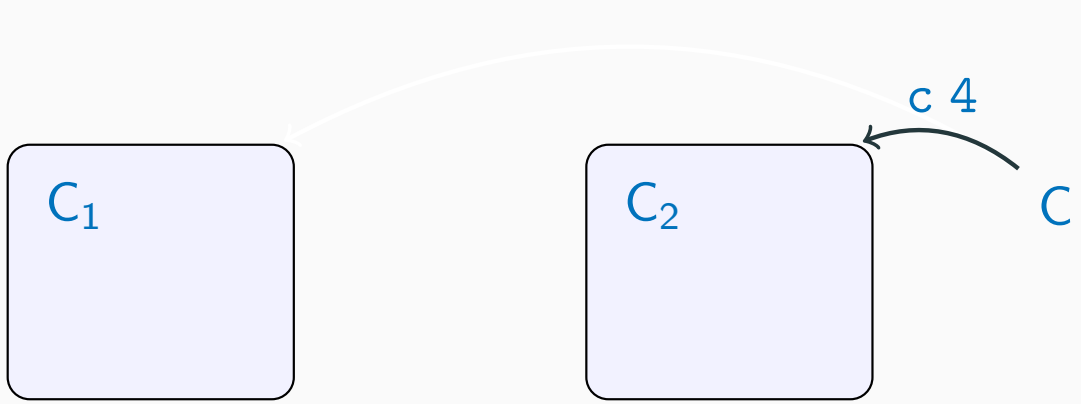


c 1	C_1
c 2	C
c 3	C_2
c 4	C

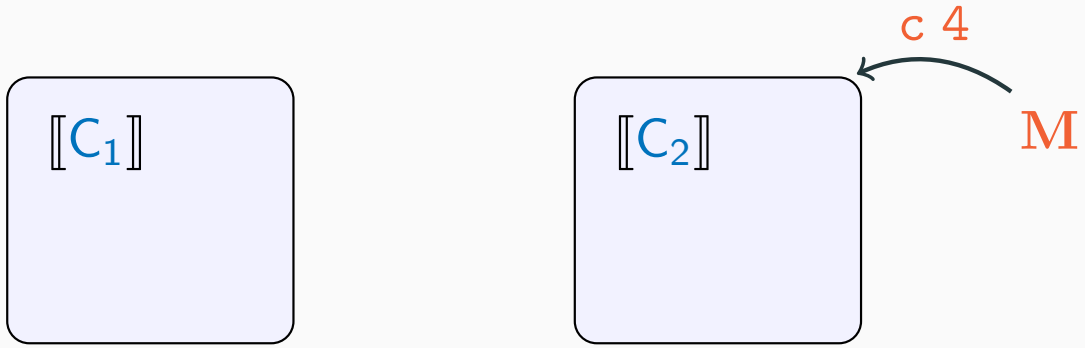


c 1	$[\![C_1]\!]$
c 2	M
c 3	$[\![C_2]\!]$
	M

Call Stack Shortcutting

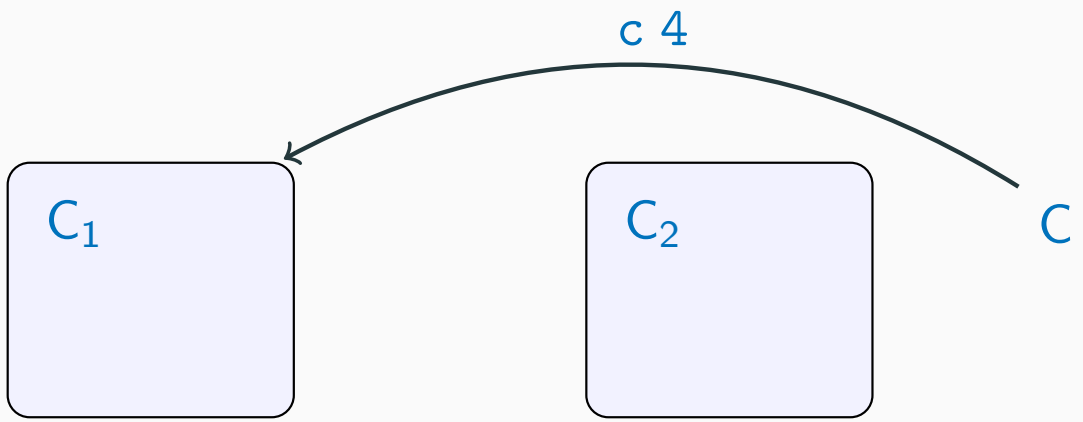


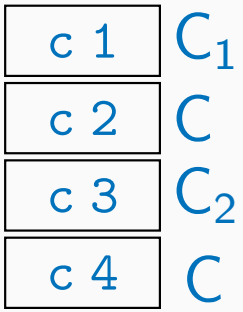
c 1	C_1
c 2	C
c 3	C_2
c 4	C

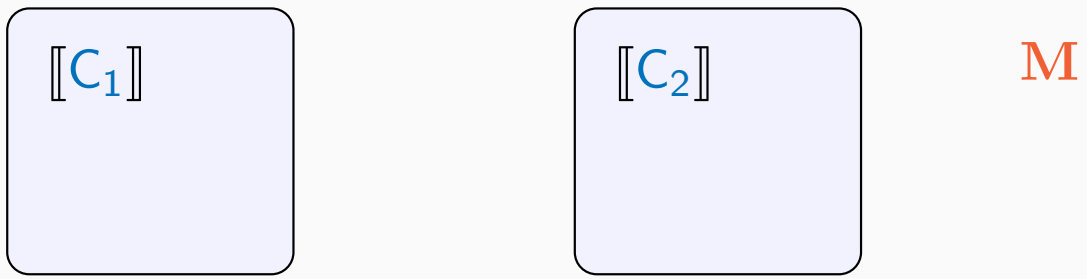


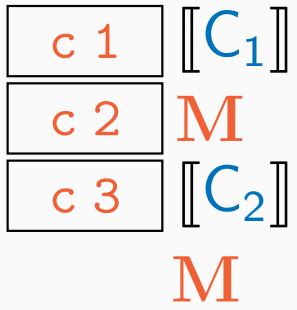
c 1	$[\![C_1]\!]$
c 2	M
c 3	$[\![C_2]\!]$
c 4	M

Call Stack Shortcutting

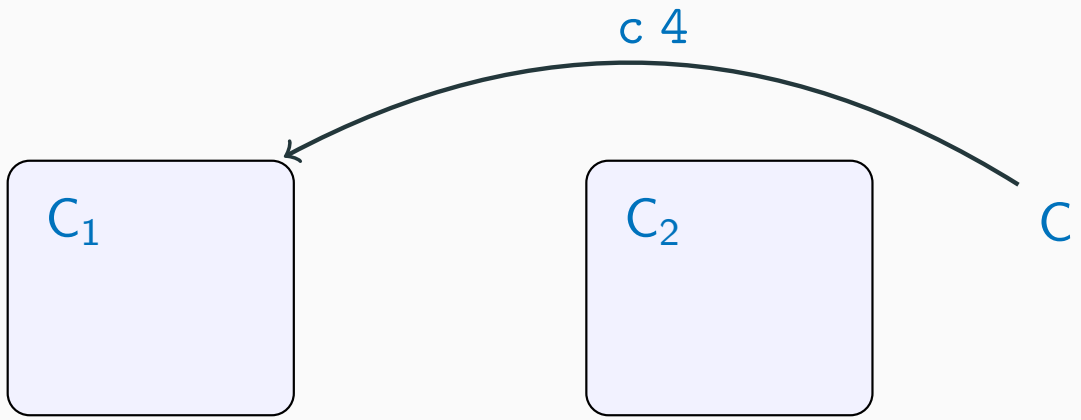




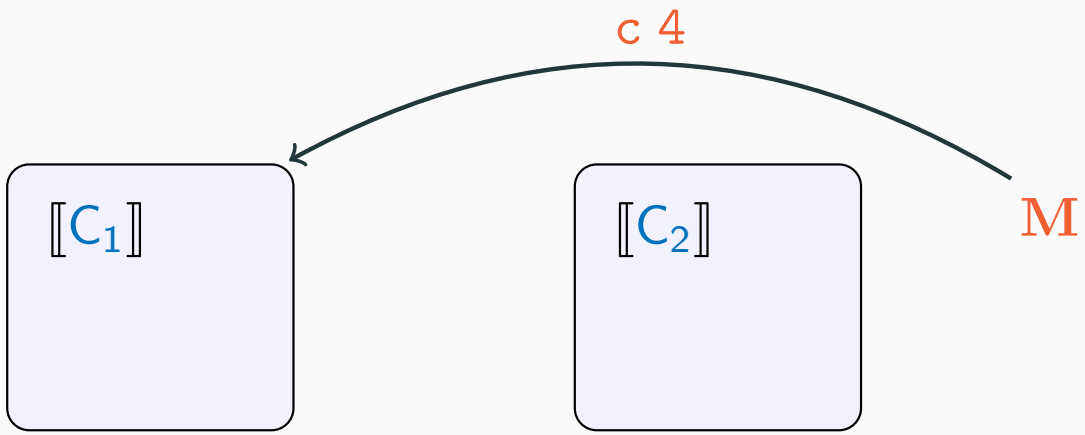




Call Stack Shortcutting

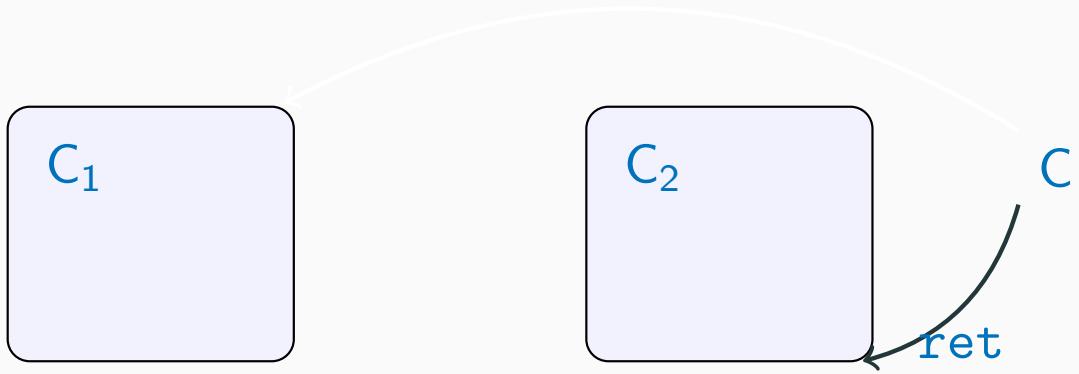


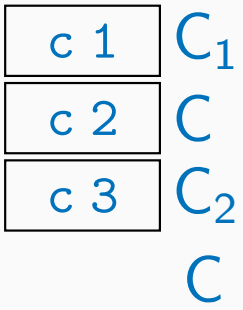
c 1	C_1
c 2	C
c 3	C_2
c 4	C

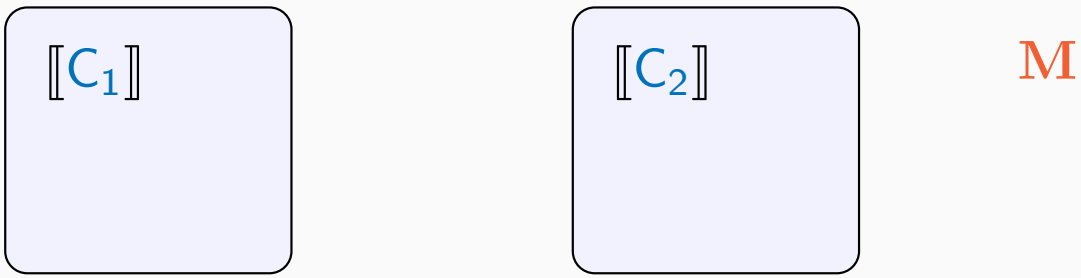


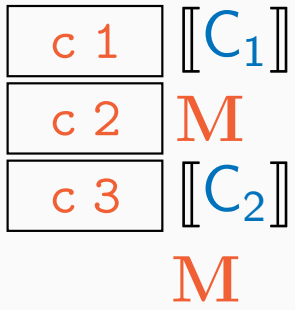
c 1	$[\![C_1]\!]$
c 2	M
c 3	$[\![C_2]\!]$
c 4	M

Call Stack Shortcutting

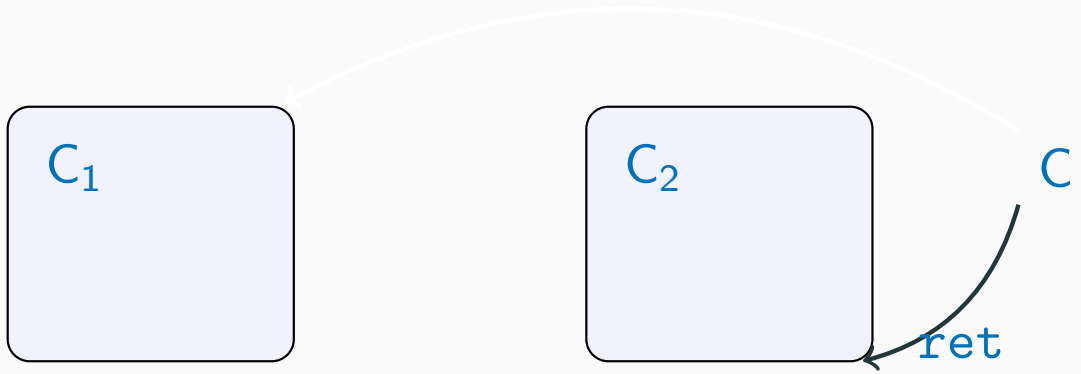


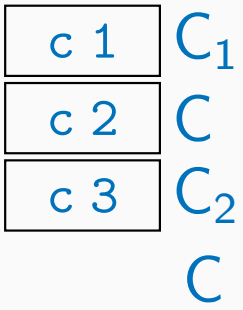


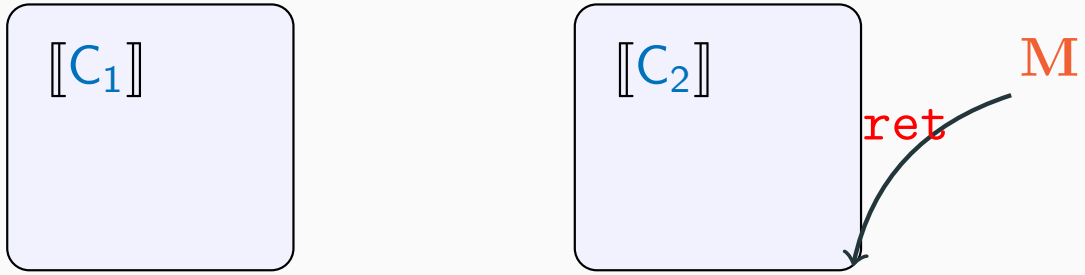


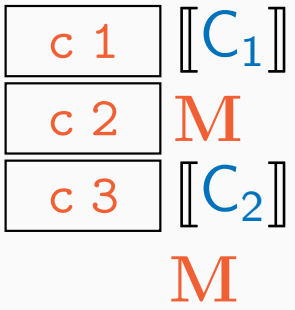


Call Stack Shortcutting

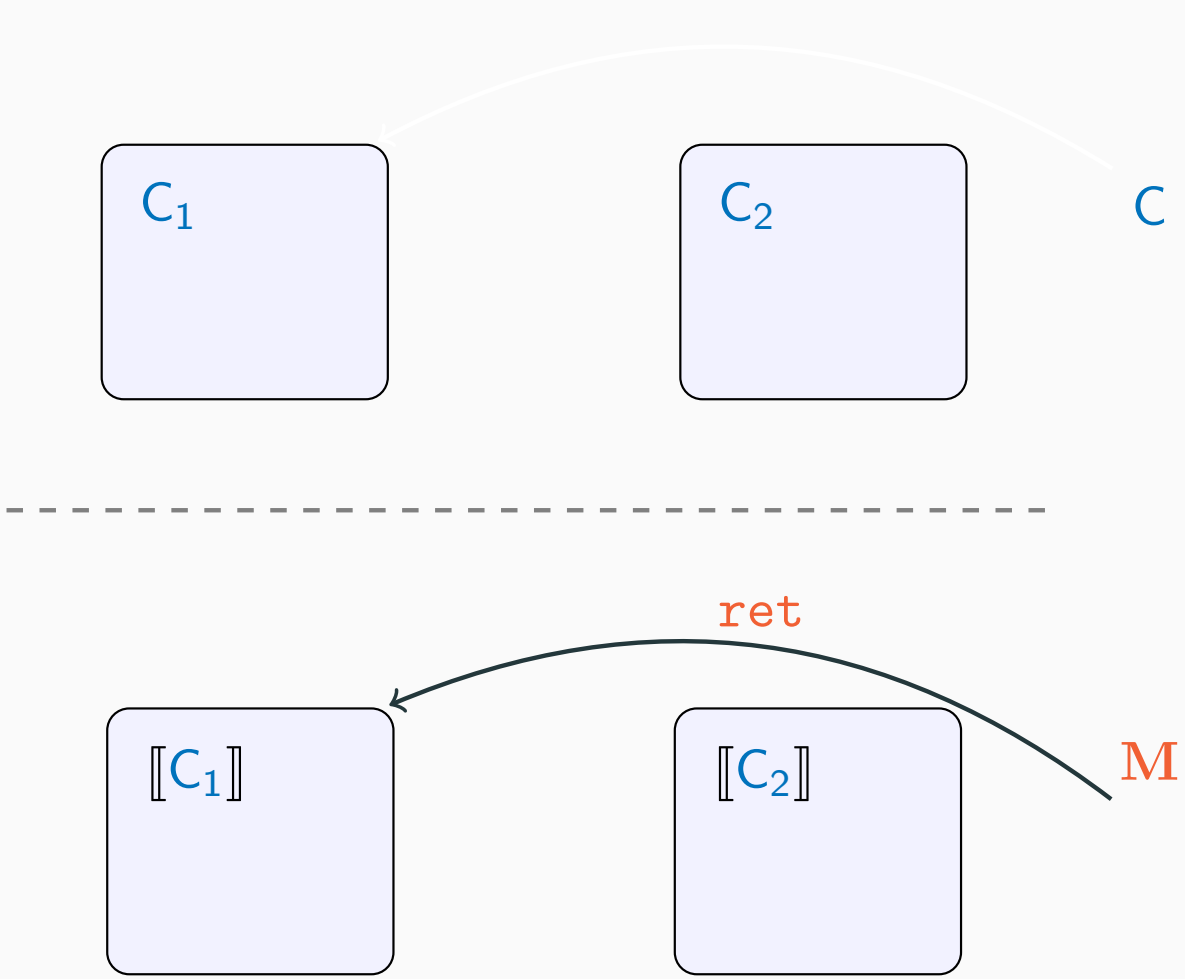


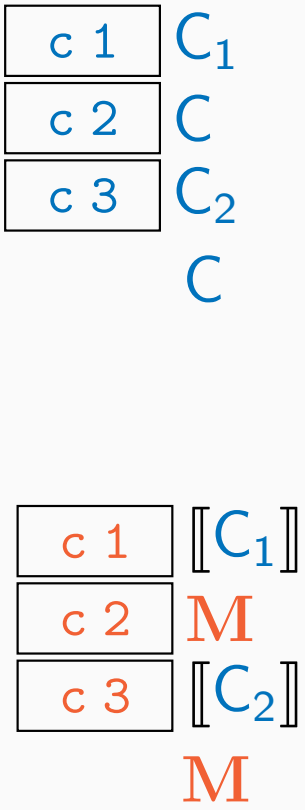




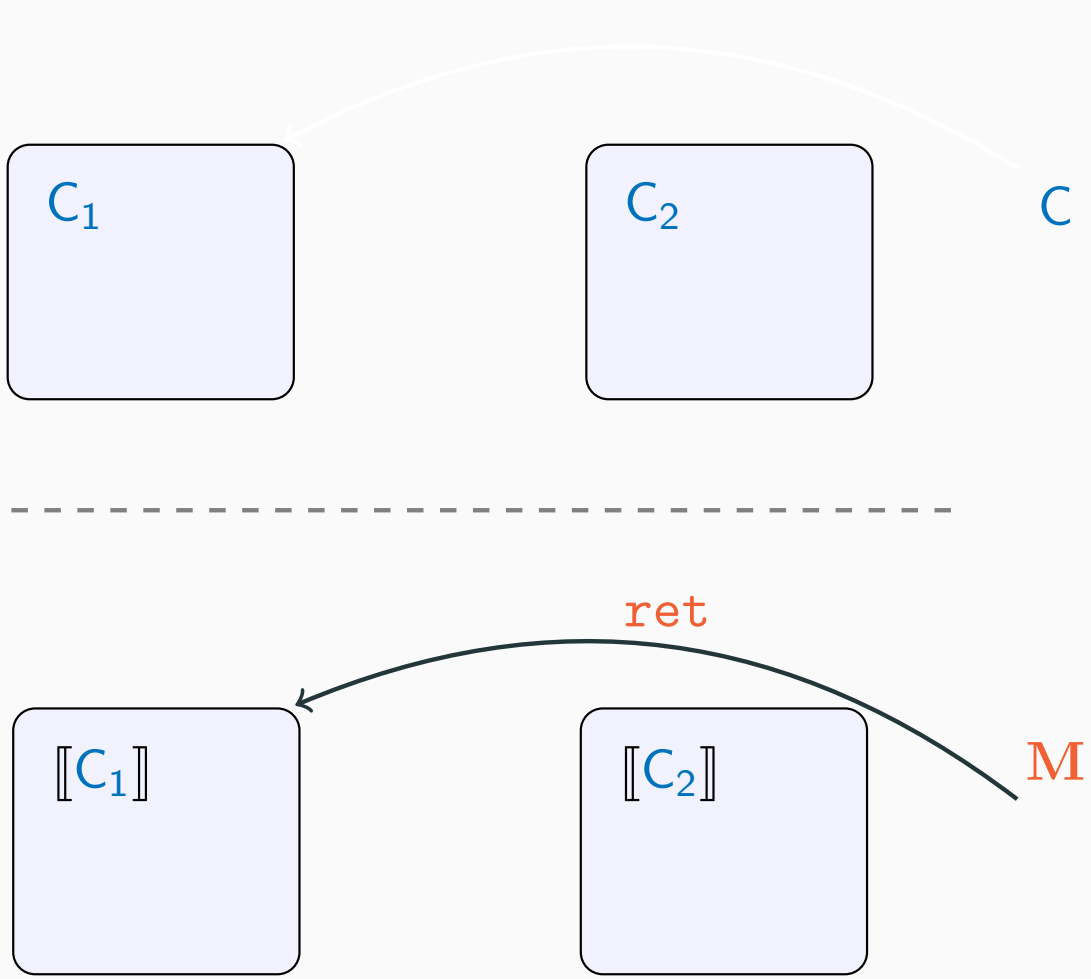


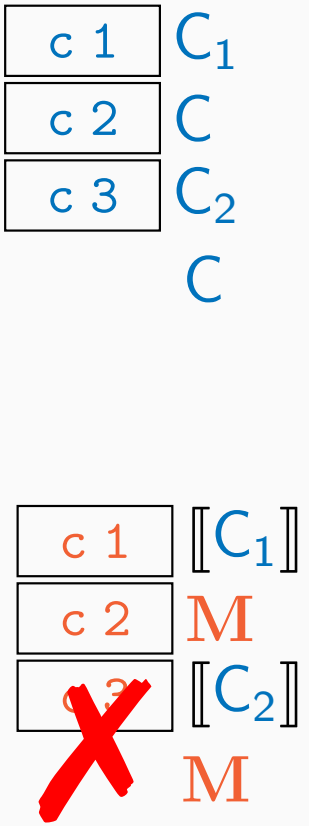
Call Stack Shortcutting



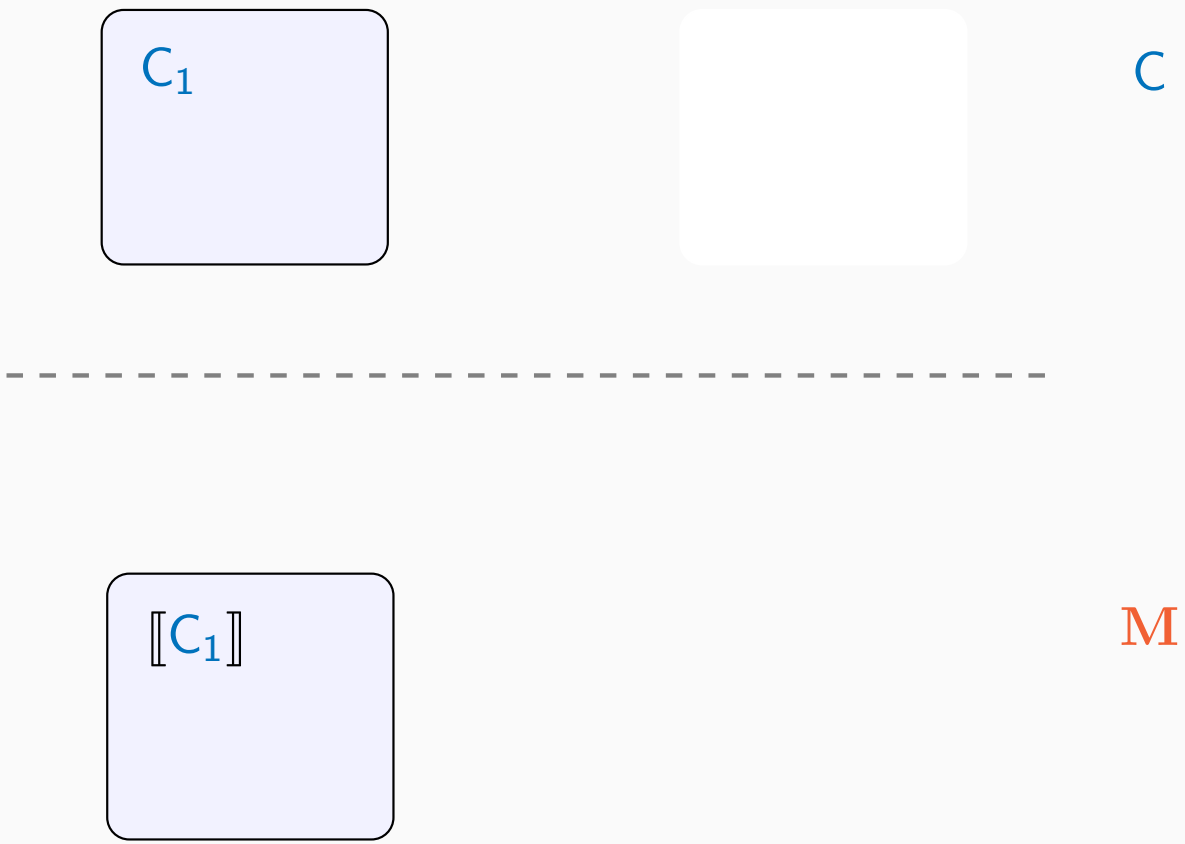


Call Stack Shortcutting

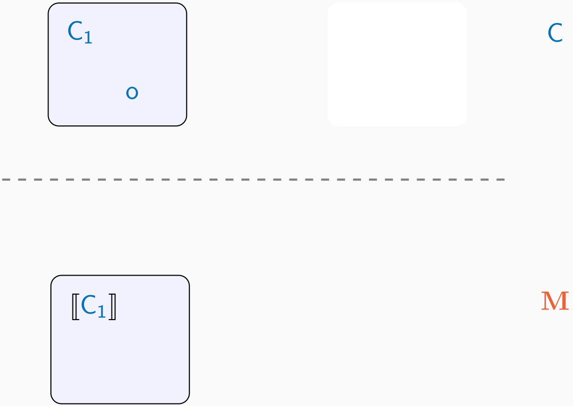




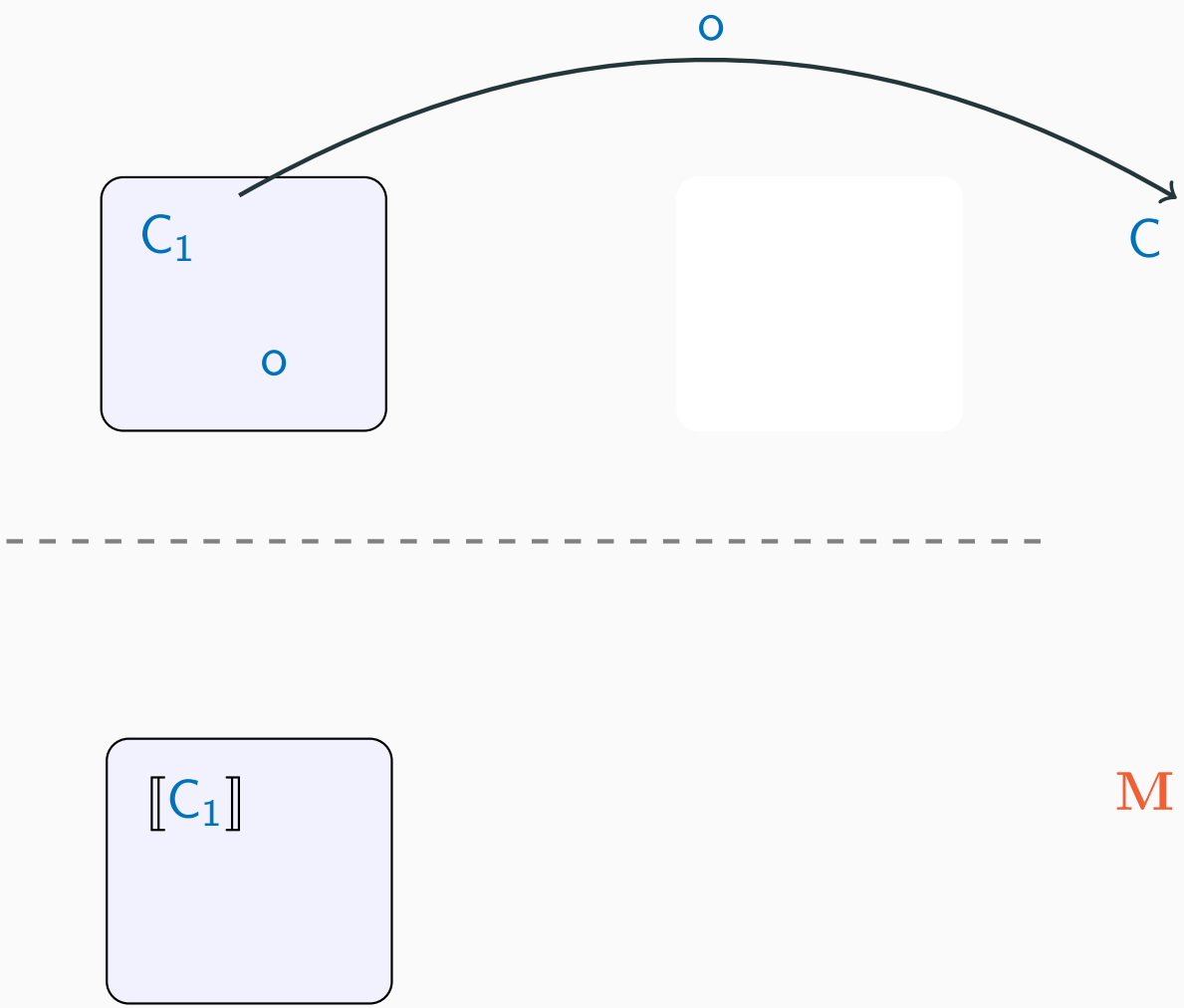
Object Guessing - 1 Component



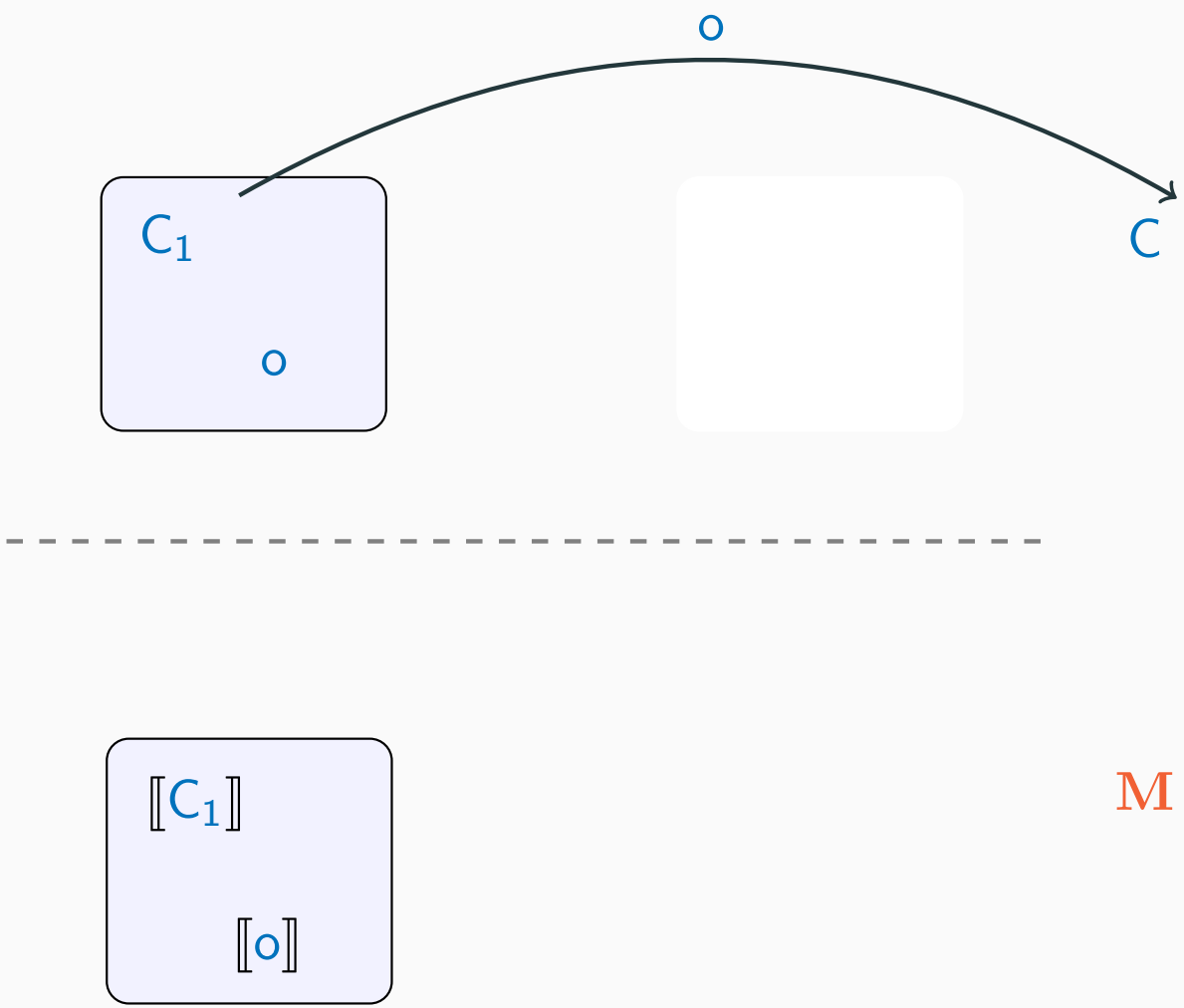
Object Guessing - 1 Component



Object Guessing - 1 Component



Object Guessing - 1 Component



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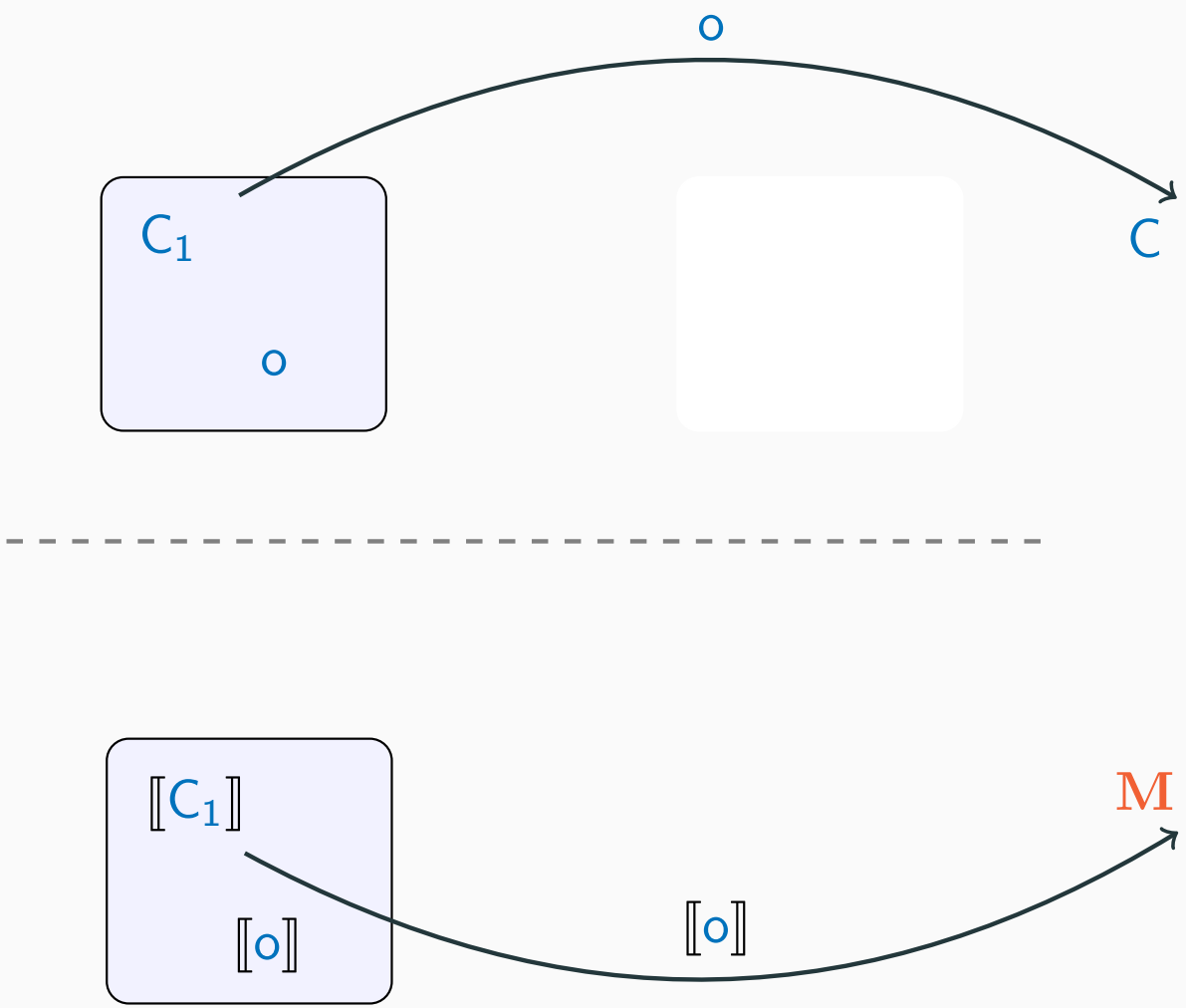

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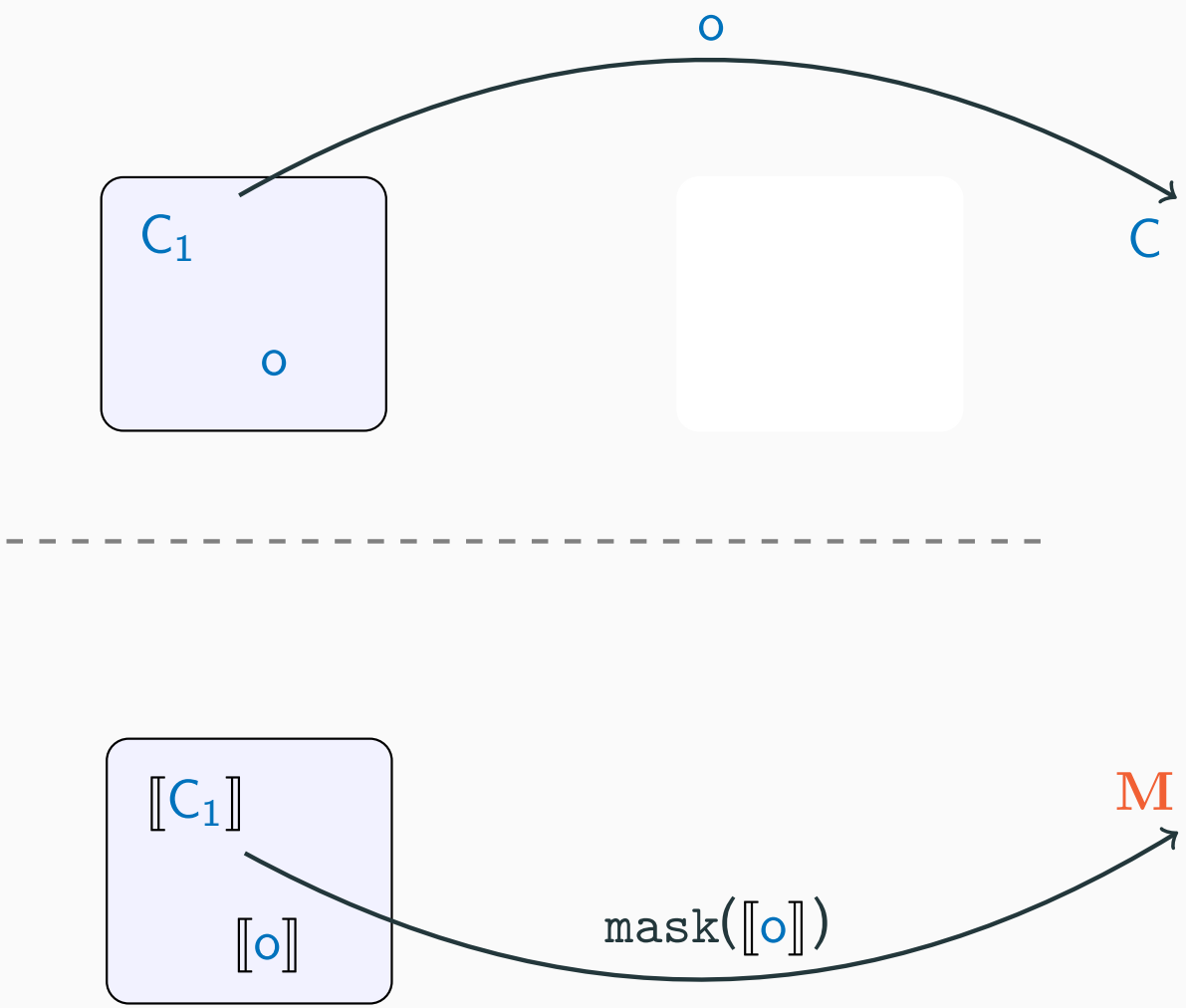

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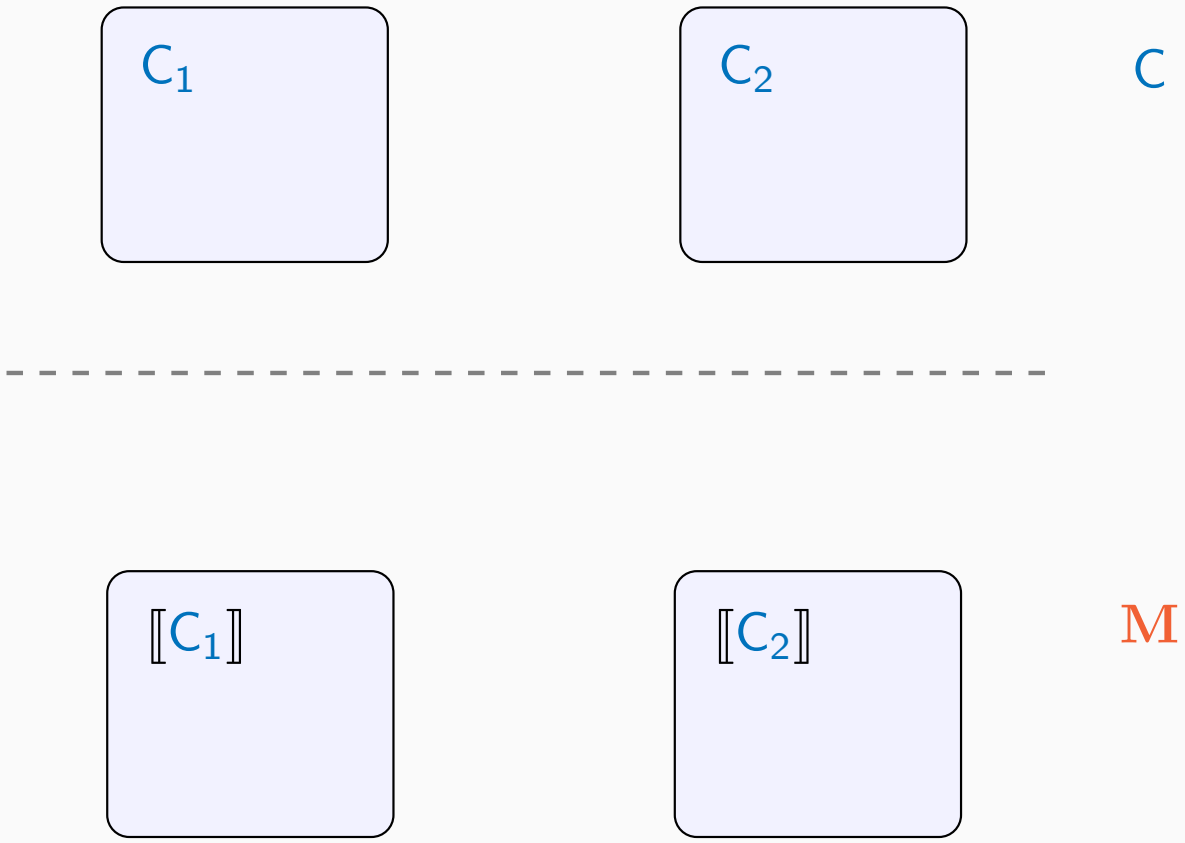
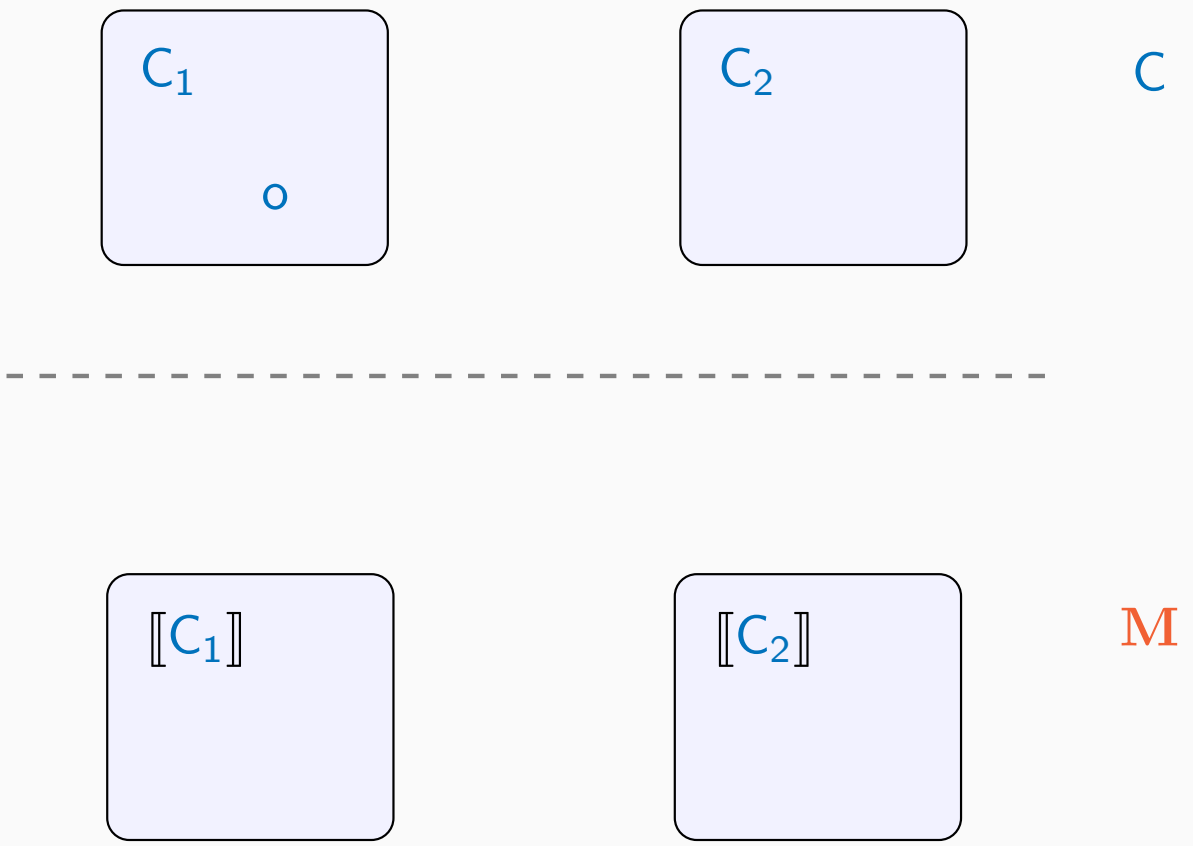
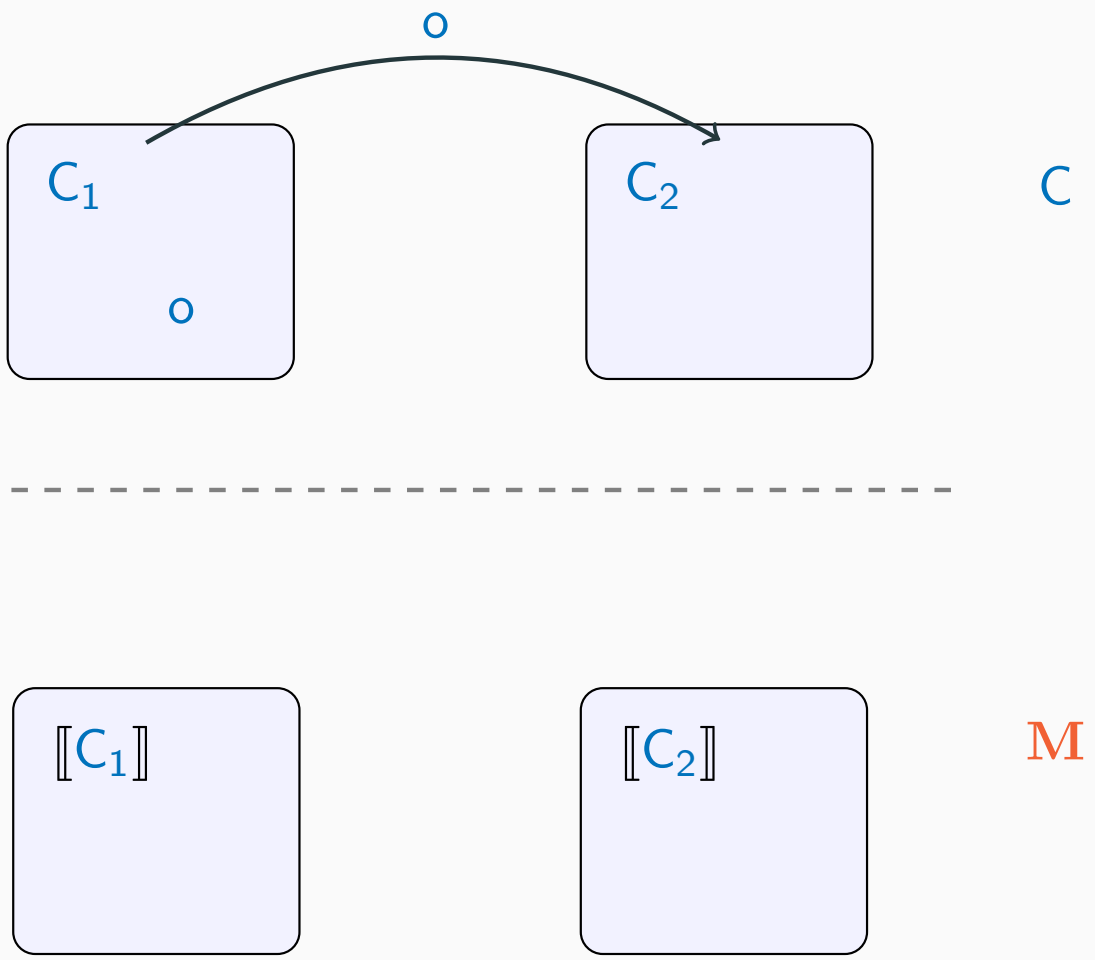


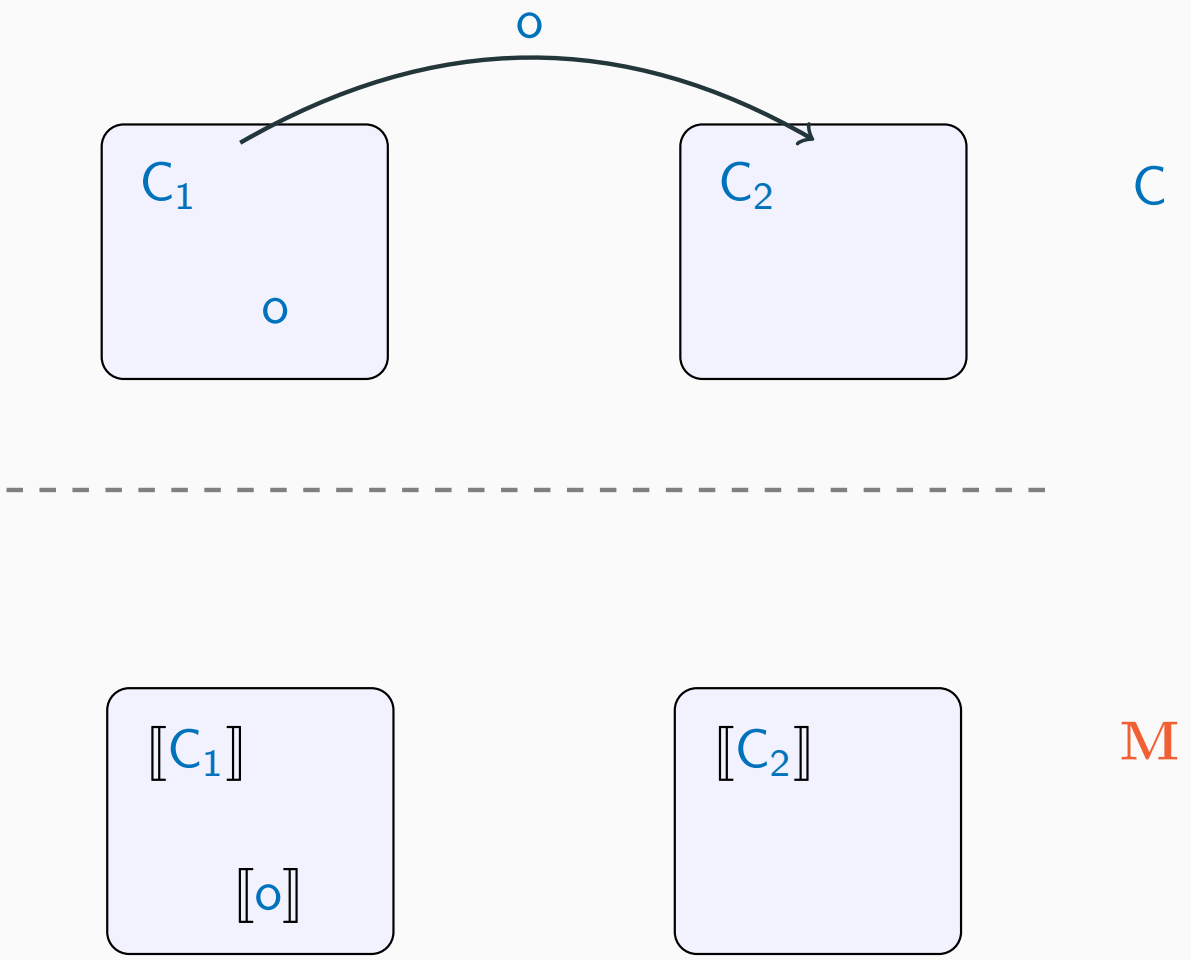
Object Guessing



Object Guessing



Object Guessing



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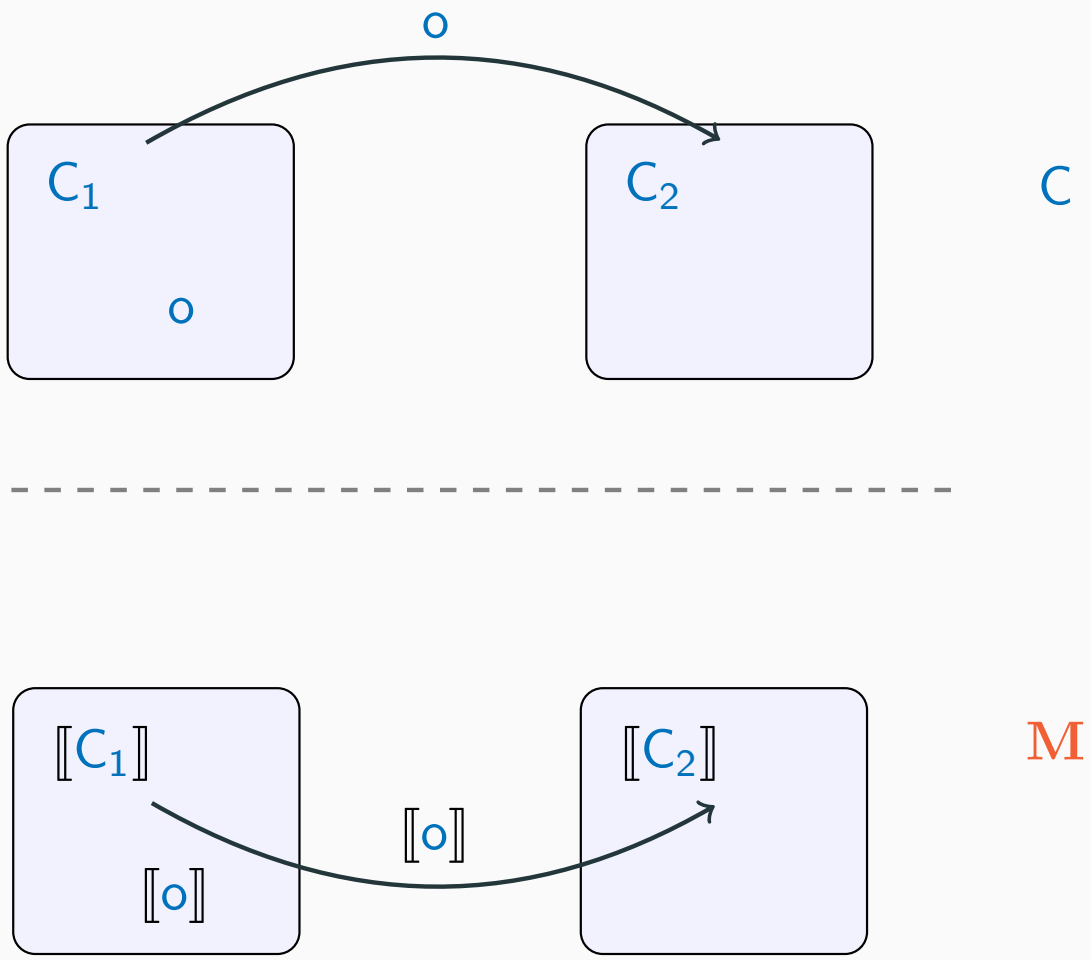

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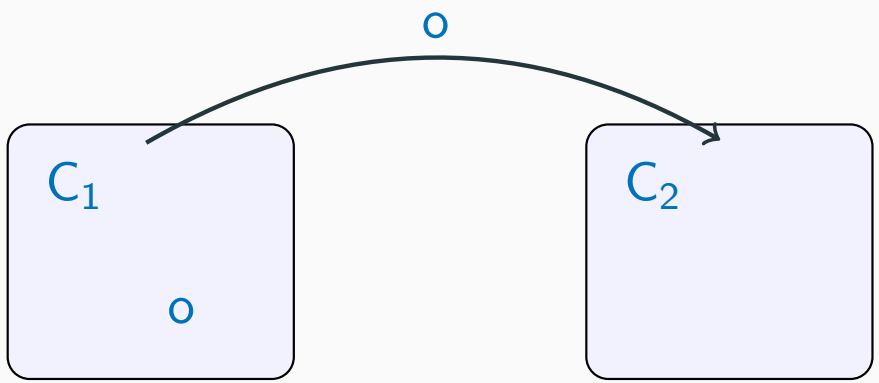
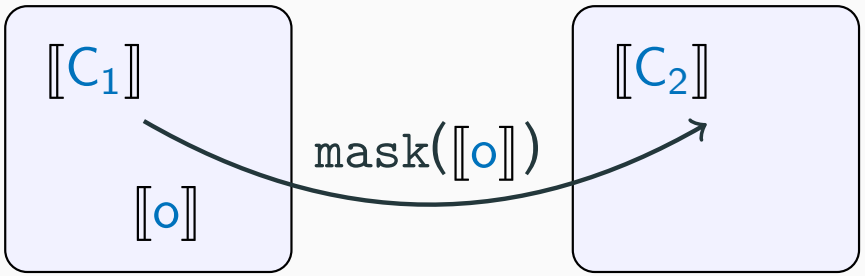
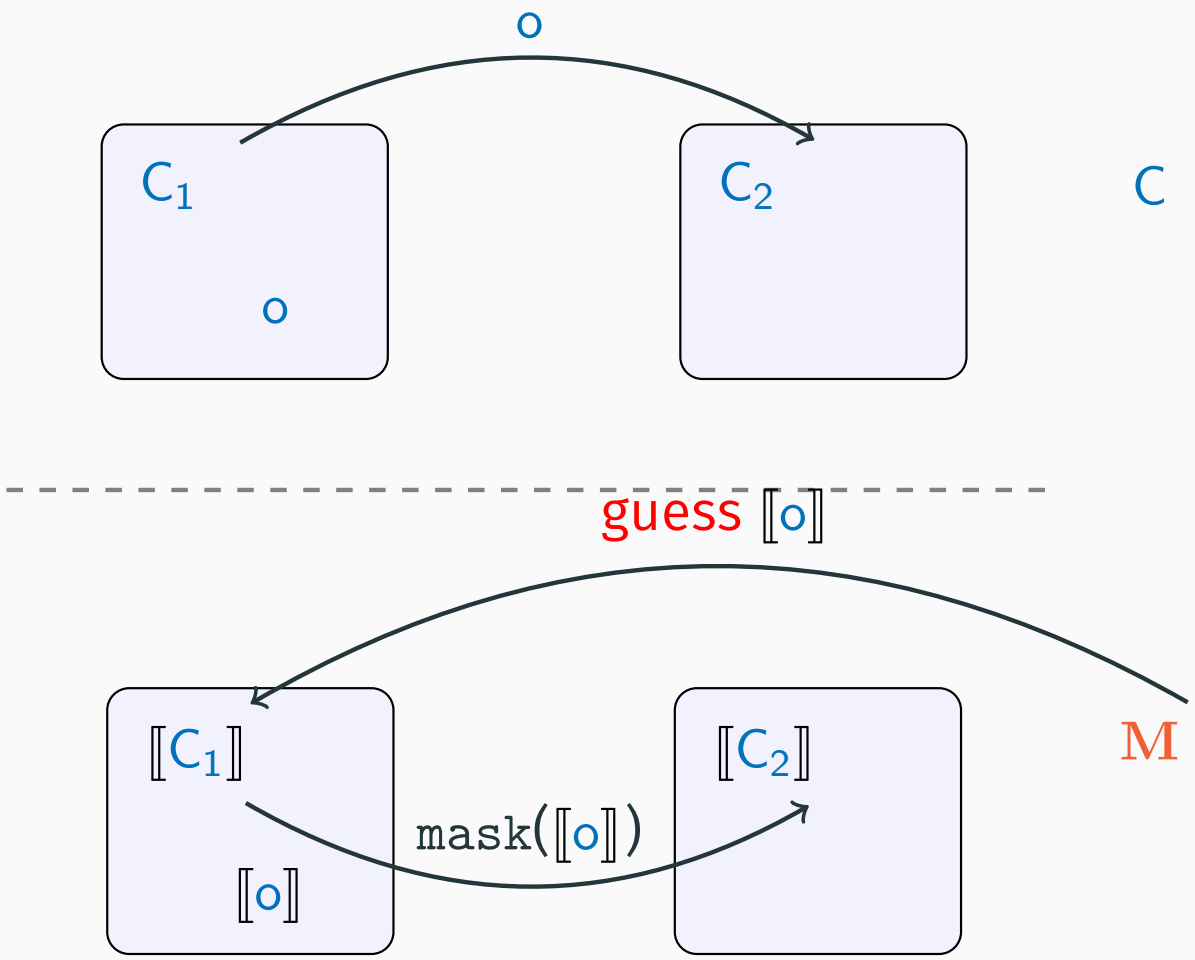


C

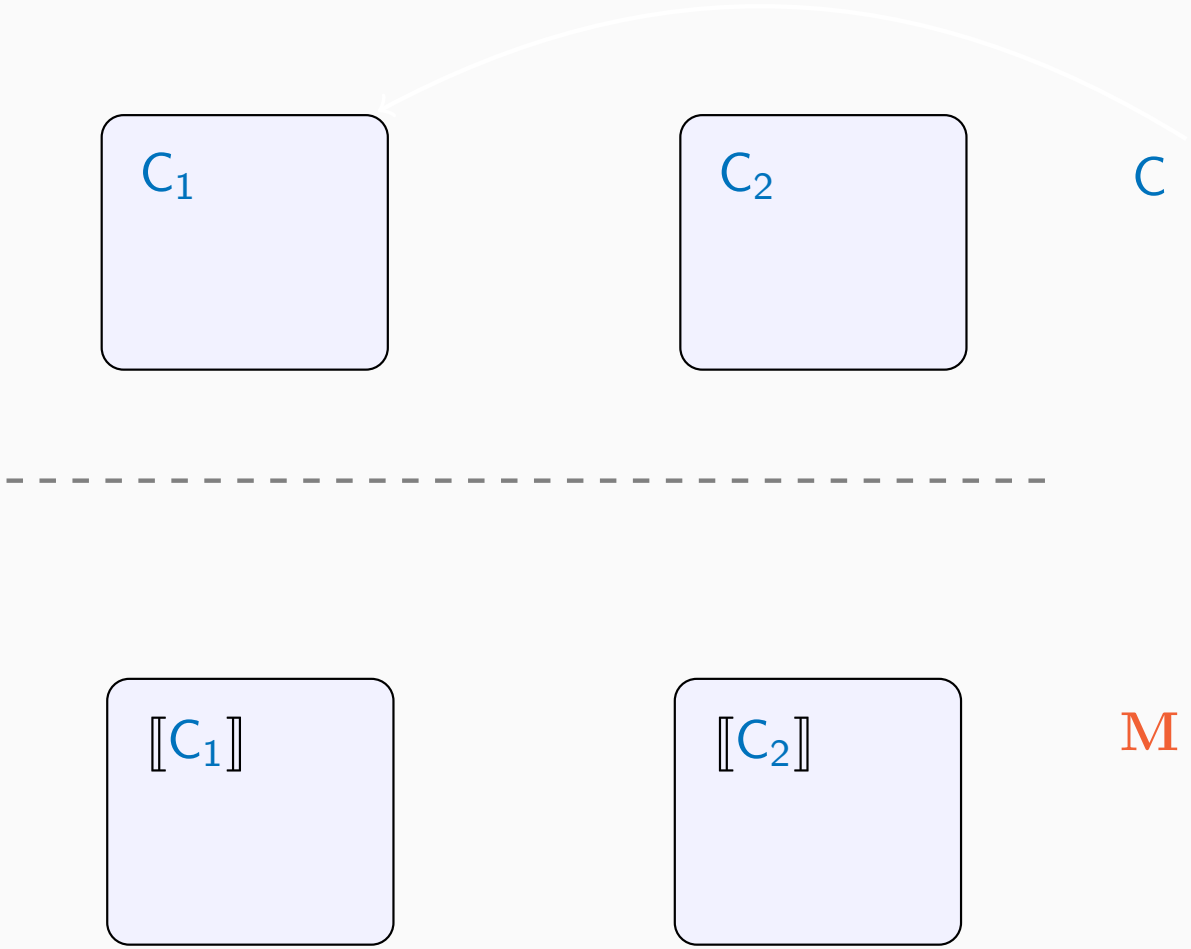


M

Object Guessing



Object Faking



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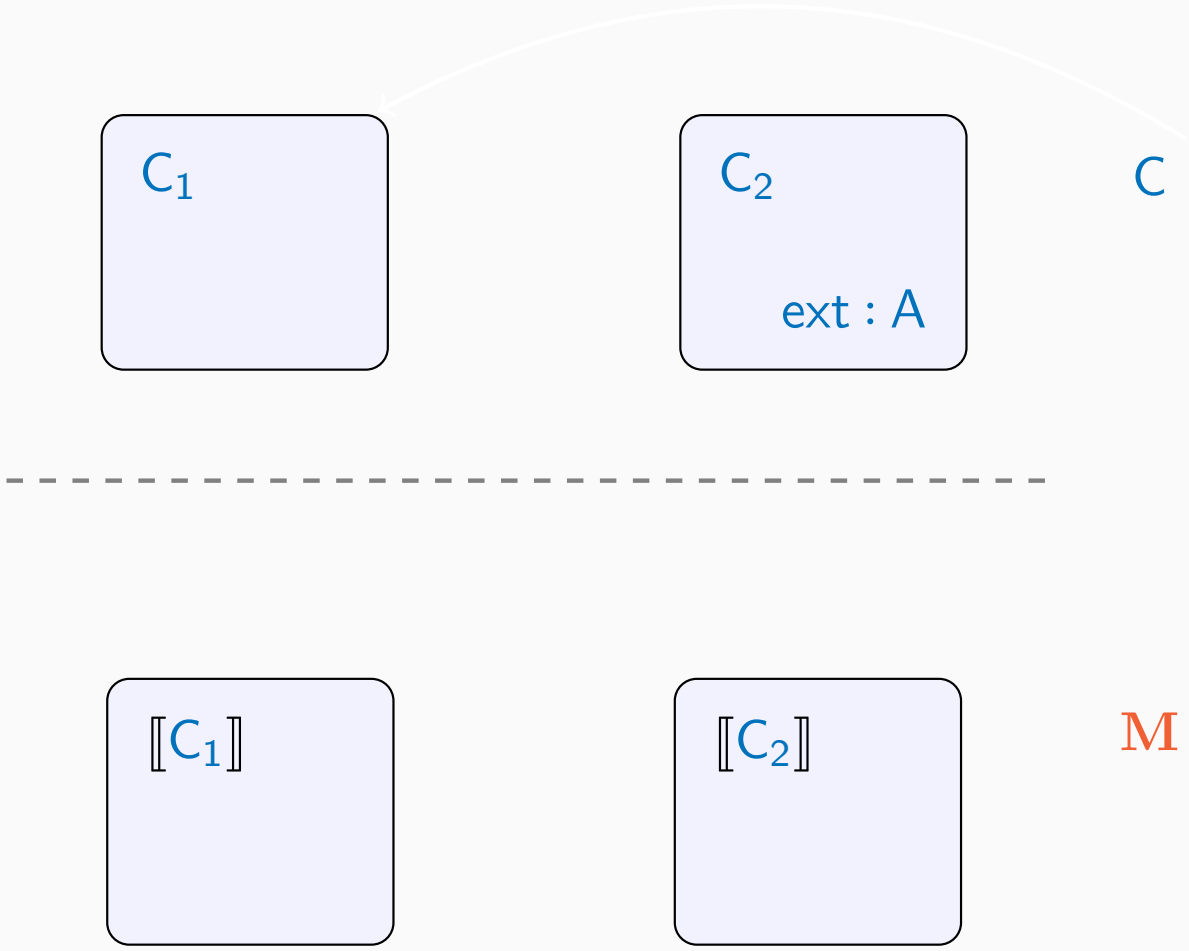

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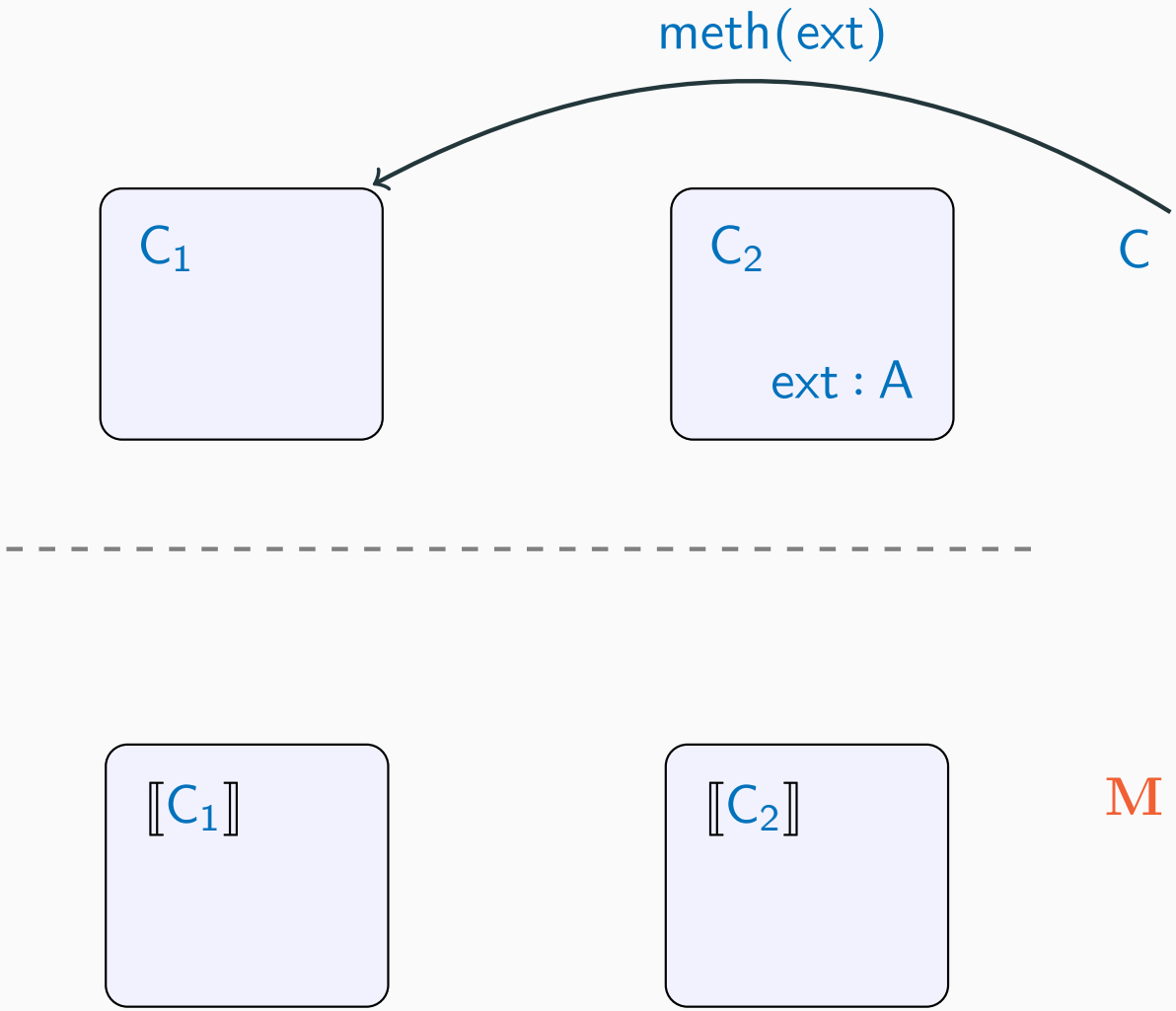
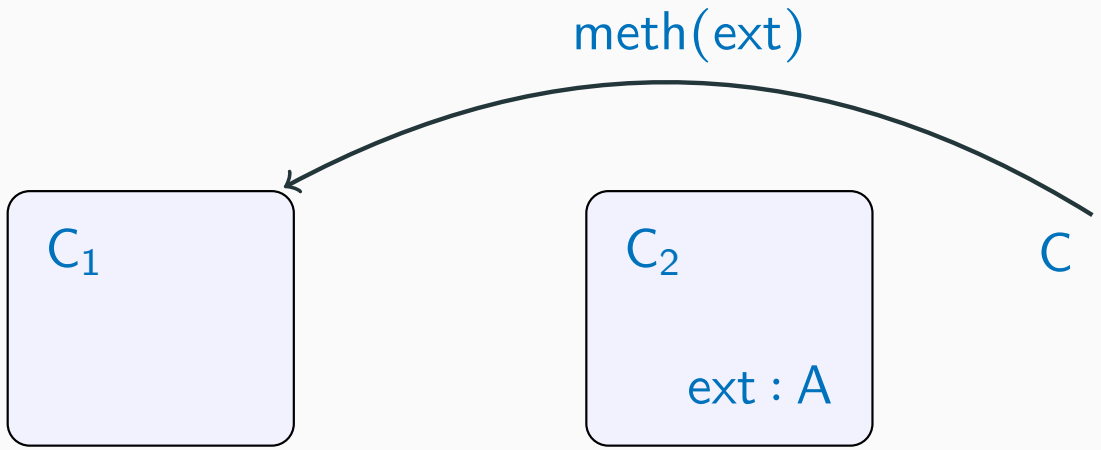
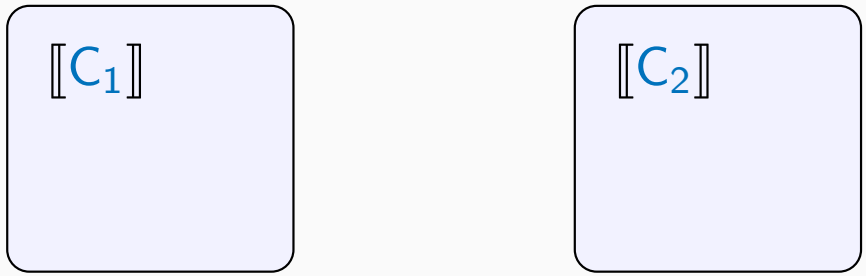


Object Faking



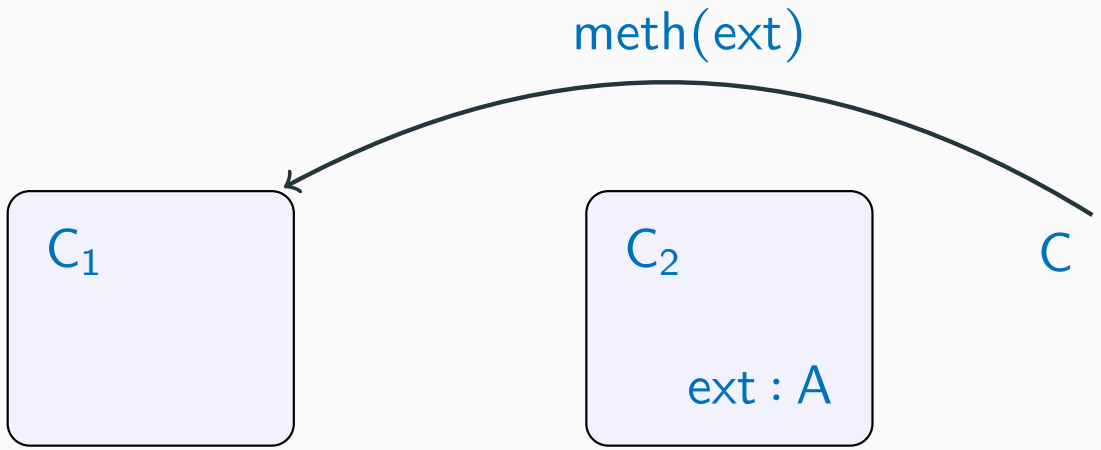
ext = `null`

or obj : A



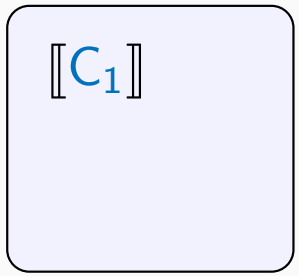
M

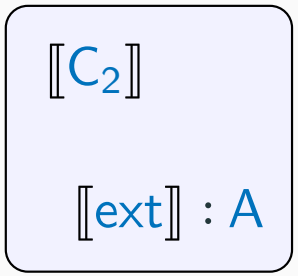
Object Faking



ext = `null`

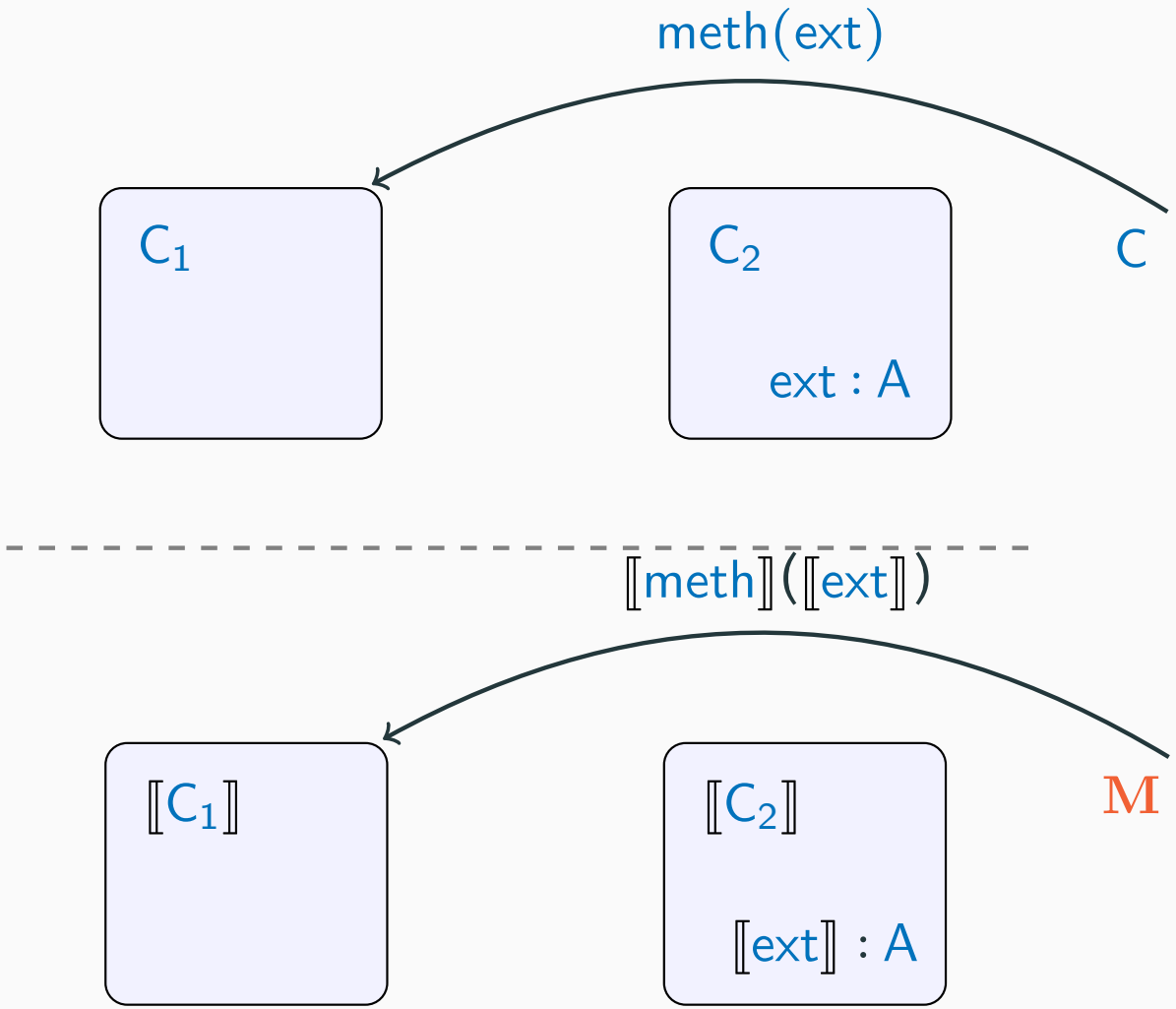
or obj : A





M

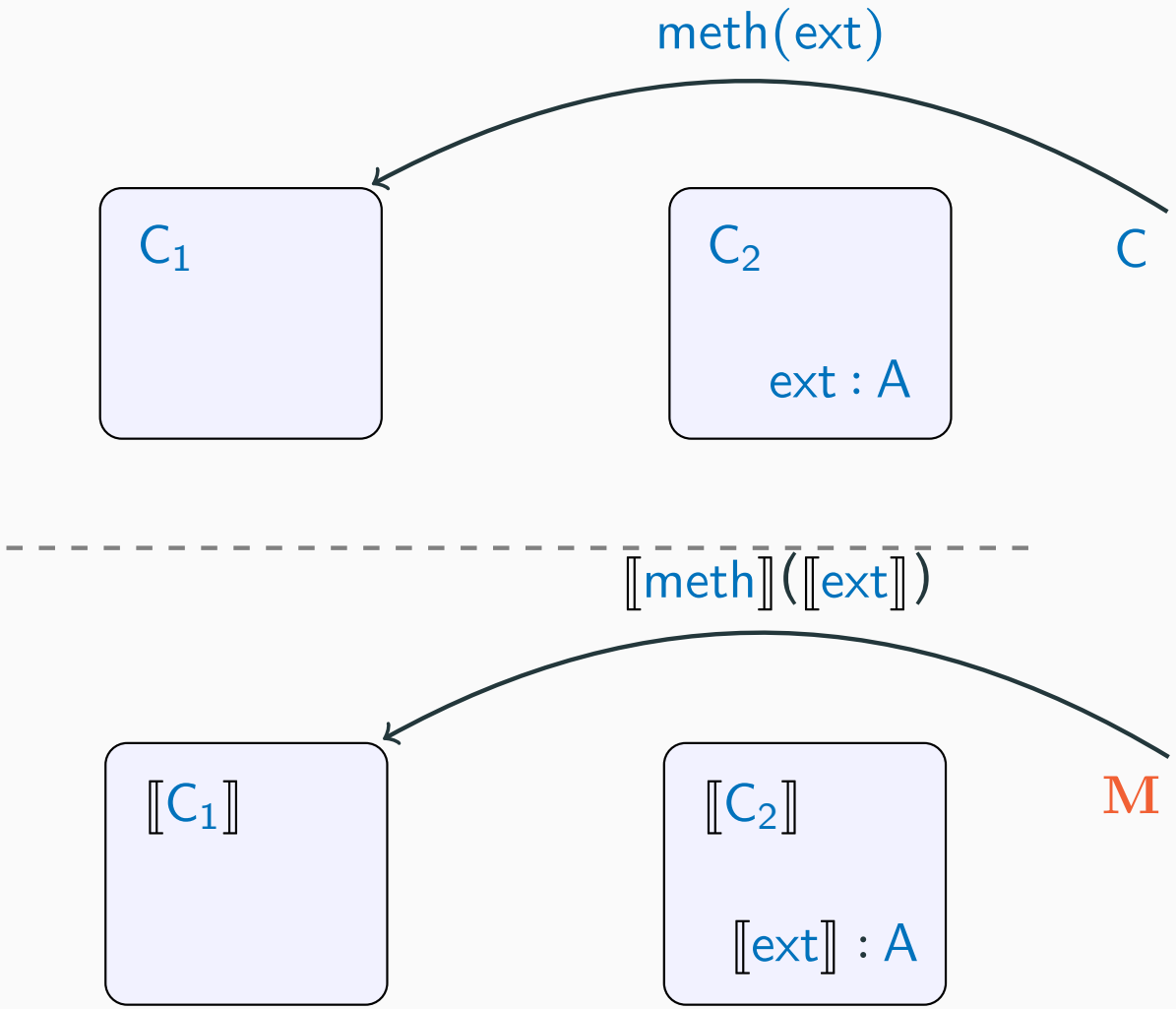
Object Faking



ext = `null`

or obj : A

Object Faking



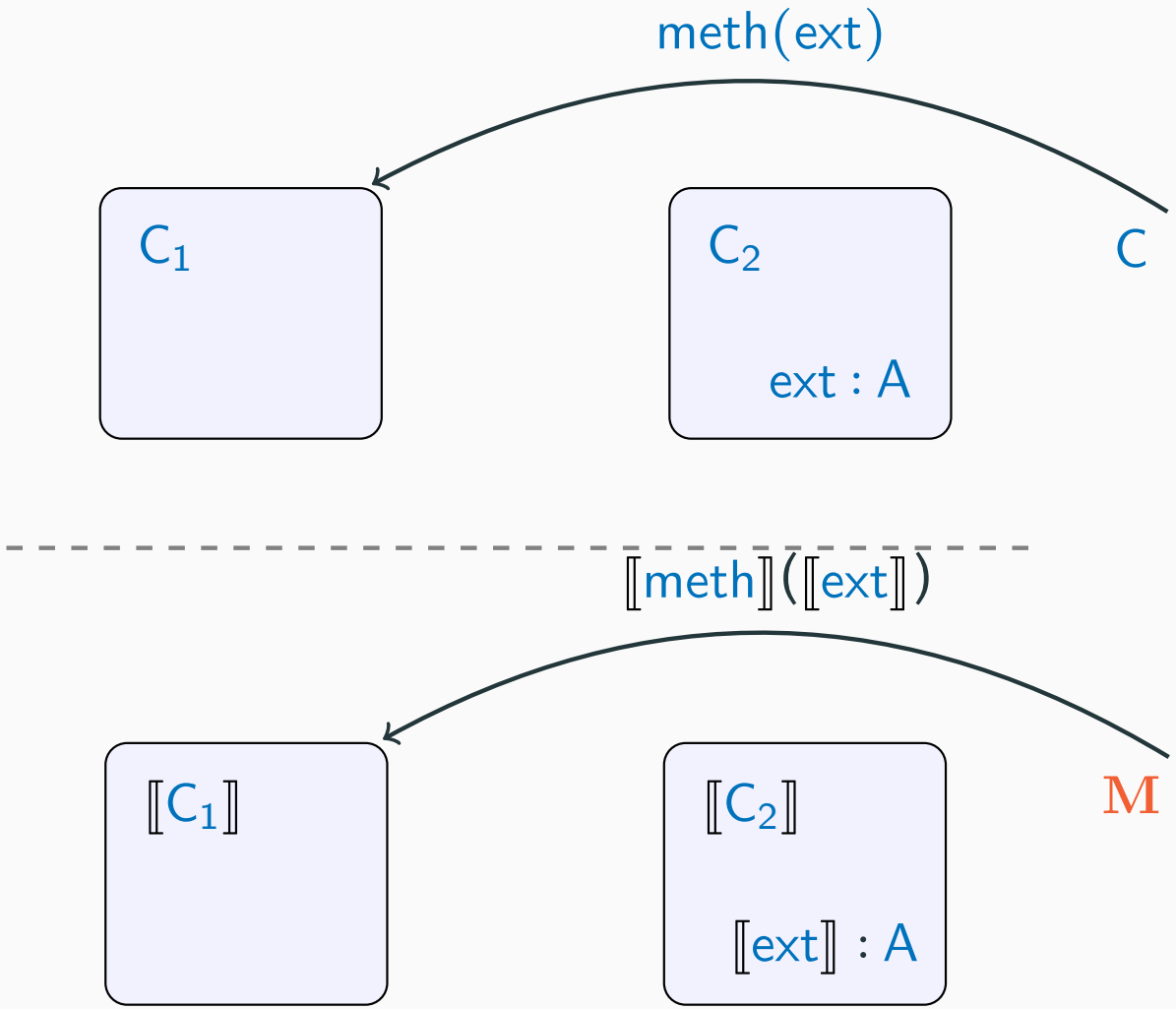
ext = `null`

or obj : A

⟦ext⟧ = ⟦`null`⟧

or obj : A

Object Faking



ext = `null`

or obj : A

⟦ext⟧ = ⟦`null`⟧

or obj : A

or obj : B $\not<:$ A

or garbage

Compiler Structure and Assumptions

- operates on components $\mathcal{C} = \overline{P}$

Compiler Structure and Assumptions

- operates on components $\mathcal{C} = \overline{P}$
- relies on linking table:

$$
\begin{array}{lr}
\textit{symbol tables} & \mathbf{t} ::= \overline{\mathbf{EM}}; \overline{\mathbf{EO}}; \overline{\mathbf{RM}}; \overline{\mathbf{RO}} \\
\textit{exported methods} & \mathbf{EM} ::= \mathsf{m} : \mathsf{M}_\mathsf{t} \mapsto \mathbf{a} \\
\textit{exported objects} & \mathbf{EO} ::= \mathsf{o} : \mathsf{c} \mapsto \mathbf{n} \\
\textit{required methods} & \mathbf{RM} ::= \mathsf{m} : \mathsf{M}_\mathsf{t} \mapsto \iota; \sigma \\
\textit{required objects} & \mathbf{RO} ::= \mathsf{o} : \mathsf{c} \mapsto \sigma
\end{array}
$$

Secure Compiler Structure

Same structure as before plus:

- The System Module Sys
- Different entry/exit point checks
- Secure linker

The System Module Sys

- all calls and returns go through it
  - implements: forwardCall and forwardReturn
  - implements testObj and registerObj
- maintains a global call stack
- registers all objects passed
- relies on caller-callee authentication
  - semantics sets a register to module id on call/return

Entry/exit Point checks

- check that calls comes from Sys
  - relies on caller-callee authentication
- performs dynamic typechecks on arguments
  - reiled on testObj from Sys
- masks and unmasks objects (as before)
- reset flags and registers (as before)

Secure Linker

- creates Sys
- initialises Sys with static global objects

Properties of the Compiler

- FA is not enough: need MFAC

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- FA is not enough: need MFAC

Definition (Modular full-abstraction)

$$\forall \mathcal{C}_1, \mathcal{C}_2, \mathcal{C}_3, \mathcal{C}_4.\ \forall \mathbf{P}.[\![\mathcal{C}_2]\!] \simeq_{ctx} \mathbf{P},\ \forall \mathbf{P}'.[\![\mathcal{C}_4]\!] \simeq_{ctx} \mathbf{P}',$$
$$\mathcal{C}_1;\mathcal{C}_2 \simeq_{ctx} \mathcal{C}_3;\mathcal{C}_4 \iff$$
$$\texttt{link}([\![\mathcal{C}_1]\!], \mathbf{P}) \simeq_{ctx} \texttt{link}([\![\mathcal{C}_3]\!], \mathbf{P}').$$

Trace-based Backtranslation

- $\langle\!\langle \mathcal{C}_1, \mathcal{C}_2, \overline{\alpha_1}, \overline{\alpha_2} \rangle\!\rangle = \mathbb{C}$
- $\overline{\alpha_1} \equiv \overline{\alpha}\alpha_1!$
- $\overline{\alpha_2} \equiv \overline{\alpha}\alpha_2!$
- $\alpha_1! \neq \alpha_2!$
- $\overline{\alpha}$ is the *common prefix*
- $\alpha_1!$ and $\alpha_2!$ are the *different actions* at index i.

Skeleton

$\texttt{skeleton}(\mathcal{C}_1, \mathcal{C}_2) : \mathbb{C}$

- implements classes and objects that $\mathcal{C}_1$ and $\mathcal{C}_2$ import
- creates helper functions and objects:
  - tables where all globally-known objects are stored
  - a variable to keep track of the action being emulated

Common Prefix

$\texttt{emulate}\,(\overline{\alpha}, \mathbf{t}) : \mathsf{e@M}$

- $\mathbf{t}$ = linking table
- $\mathbf{call\ a\ \overline{w}?}$: call method m compiled at address $\mathbf{a}$ with $\langle\!\langle \overline{\mathbf{w}} \rangle\!\rangle$
  lookup type of $\langle\!\langle \mathbf{w} \rangle\!\rangle$ in $\mathbf{t}$
  $\langle\!\langle \mathbf{w} \rangle\!\rangle$ is trivial if $\mathbf{w}$ is of ground type
  if $\mathbf{w}$ is an object, it is found in a table with its type and $\mathbf{id}$.
- $\mathbf{ret\ a\ w?}$
  Return the backtranslation of $\mathbf{w}$
- $\mathbf{call\ a\ \overline{w}}$ and $\mathbf{ret\ a\ w!}$
  Update the internal state of $\mathbb{C}$
  E.g., add all newly allocated objects received via $\overline{\mathbf{w}}$ or $\mathbf{w}$ to the table

Differentiator

$\texttt{diff}\,(\alpha_1!, \alpha_2!, i) : \mathsf{e@M}, \mathsf{e@M}$

- case analysis on all differences:

Differentiator

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- case analysis on all differences:
  - different length

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  - different method called

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$\texttt{diff}\,(\alpha_1!, \alpha_2!, i) : \mathsf{e@M}, \mathsf{e@M}$

- case analysis on all differences:
  - different length
  - different actions
  - different method called
  - different return
  - different current object
  - different argument