The Tome of Secure Compilation

Fully-Abstract Compilation to Protected Modules Architectures

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Fully-Abstract Compilation to Protected Modules Architectures 1

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The Tome of Secure Compilation

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...

1

Fully-Abstract Compilation to Protected Modules Architectures

Protected Modules Architectures

What is PMA?

Protected Modules Architectures

A security architecture

What is PMA?

Protected Modules Architectures

A security architecture

Isolation @ assembly

What is PMA?

A+I: Untyped Assembly + PMA

```
0x0001    call func. at 0xb53
0x0002    write r0 at 0x0b55
⋮
0x0b52    write r0 at 0x0b55
0x0b53    write r0 at 0x0001
0x0b54    call func. at 0x0002
0x0b55    ...
⋮
0xab00    jump to 0x0001
0xab01    return to 0x0b53
0xab02    ...
```

- memory space

A+I: Untyped Assembly + PMA

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Reasoning about A+I

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- interest in the behaviour of the module

Reasoning about A+I

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Problem
There is a lot of *the rest*

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Solution
Use *Trace semantics*

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There is a lot of *the rest*

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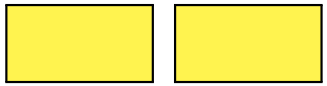
What is trace semantics?

- A trace is a sequence of actions: 

What is trace semantics?

- A trace is a sequence of actions: 

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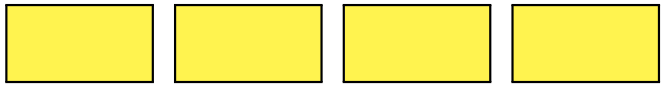
- A trace is a sequence of actions: 

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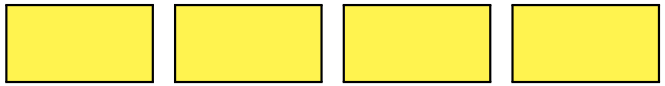
- A trace is a sequence of actions: 
- Actions describe an observable behaviour abstractly

 $= \begin{cases} \text{call a function} \\ \text{write something somewhere} \\ \ldots \end{cases}$

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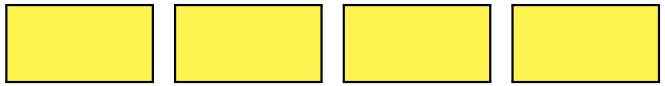
- A trace is a sequence of actions: 
- Actions describe an observable behaviour abstractly

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- The behaviour of some code is a set of traces

Trace semantics for A+I

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- abstract its behaviour *from the module perspective*:

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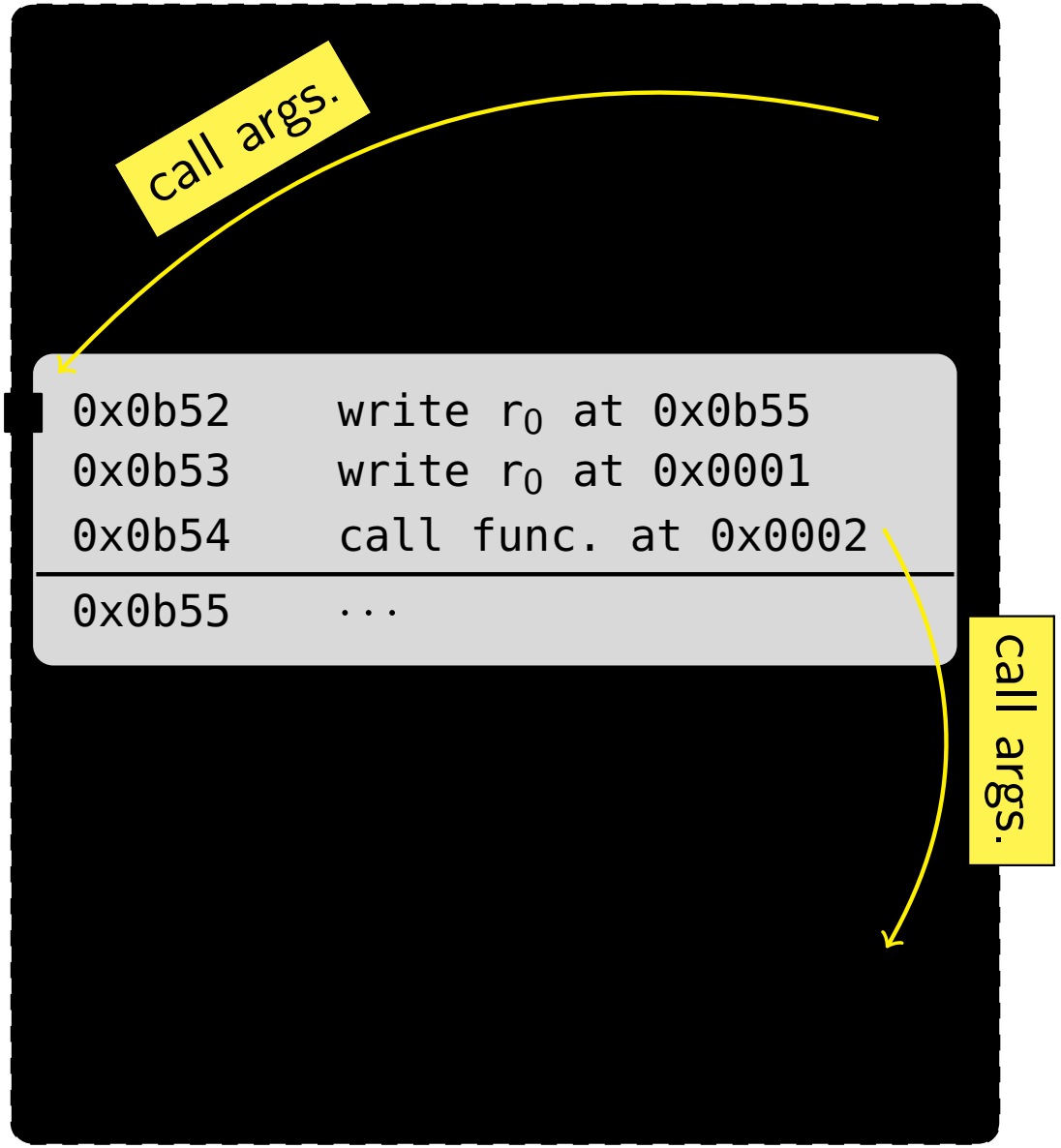
Trace semantics for A+I



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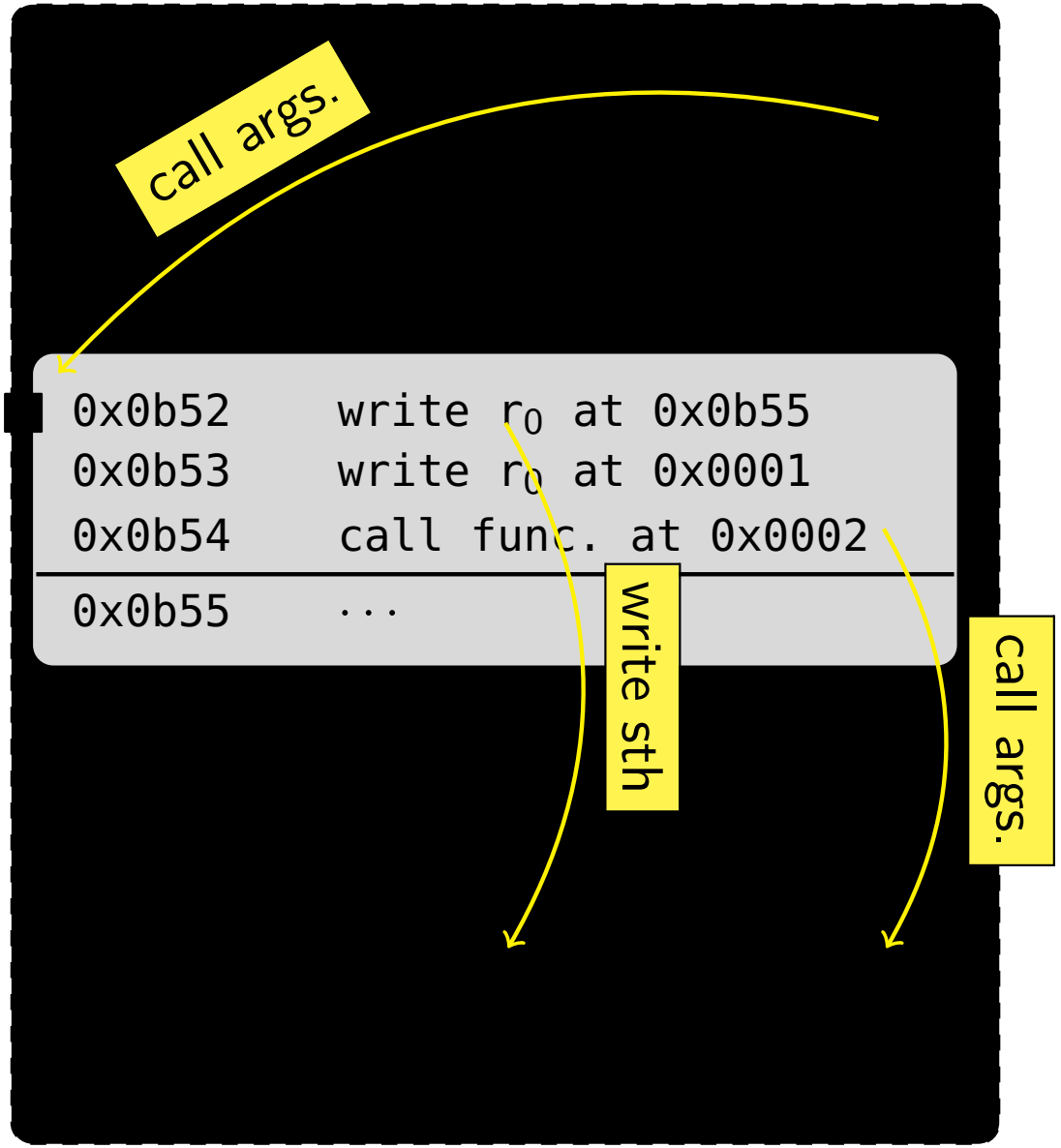

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  2. read/write outside

Trace semantics for this example

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Trace of this example:

call 0x0b52 (args) · write 0x0001 (arg) · call 0x0002 (args)

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Trace of this example:

call 0x0b52 (args)**?** · write 0x0001 (arg) · call 0x0002 (args)**!**

Correctness of the Trace semantics

- formalise the trace semantics

Correctness of the Trace semantics

$$\mathsf{TR} = \left\{ \alpha = \left\{ \begin{array}{c} \rightarrow \\ \texttt{call}\ a\ (\overline{v}) \\ \texttt{ret}\ v \\ \texttt{write}(a, v) \\ \texttt{read}(a, v) \\ \overset{\alpha}{\Longrightarrow} \end{array} \right\} \right\}$$

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$$\mathsf{Traces}^{\mathsf{S}}_{\mathsf{A+I}}(P) = \{\overline{\alpha} \mid P \overset{\overline{\alpha}}{\Longrightarrow} P'\}$$

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- formalise the trace semantics
- define traces of a program
- prove the semantics to be as precise as what *the rest* captured
- this defines "what the rest captures" (i.e., contextual equivalence)

Trace Semantics with Equivalence Classes

Equivalence classes!!

Secure Compilation

What is secure compilation?

Compilation

What is compilation?

Compilation

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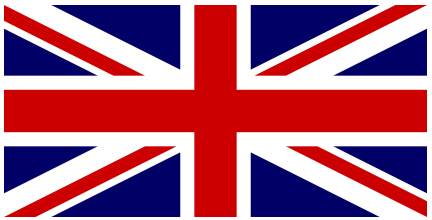

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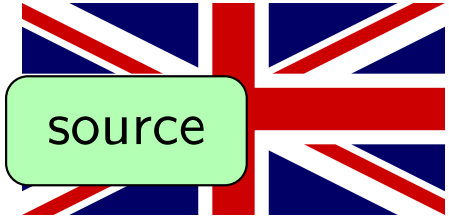

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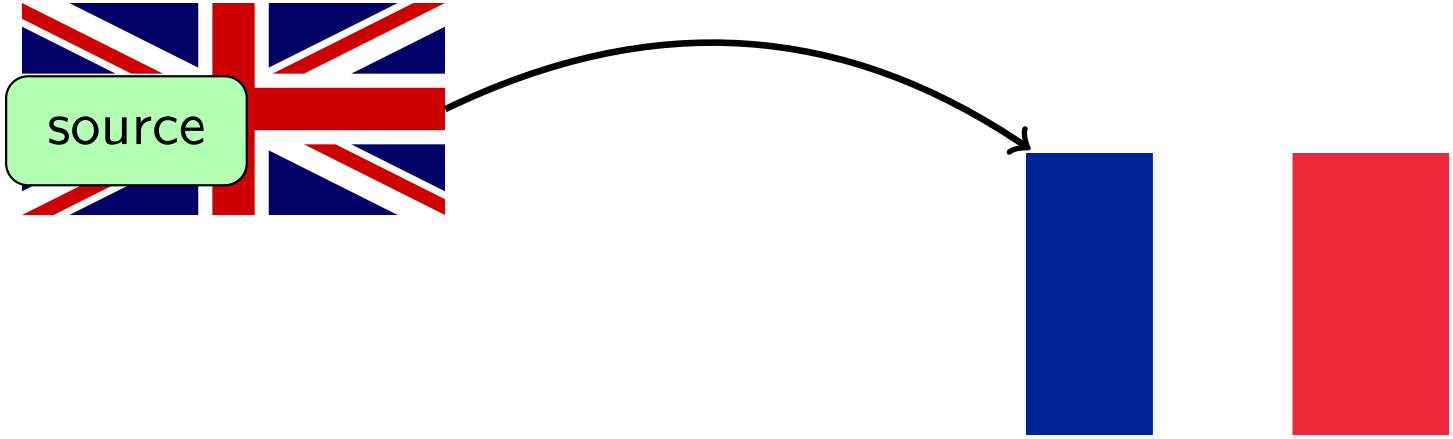

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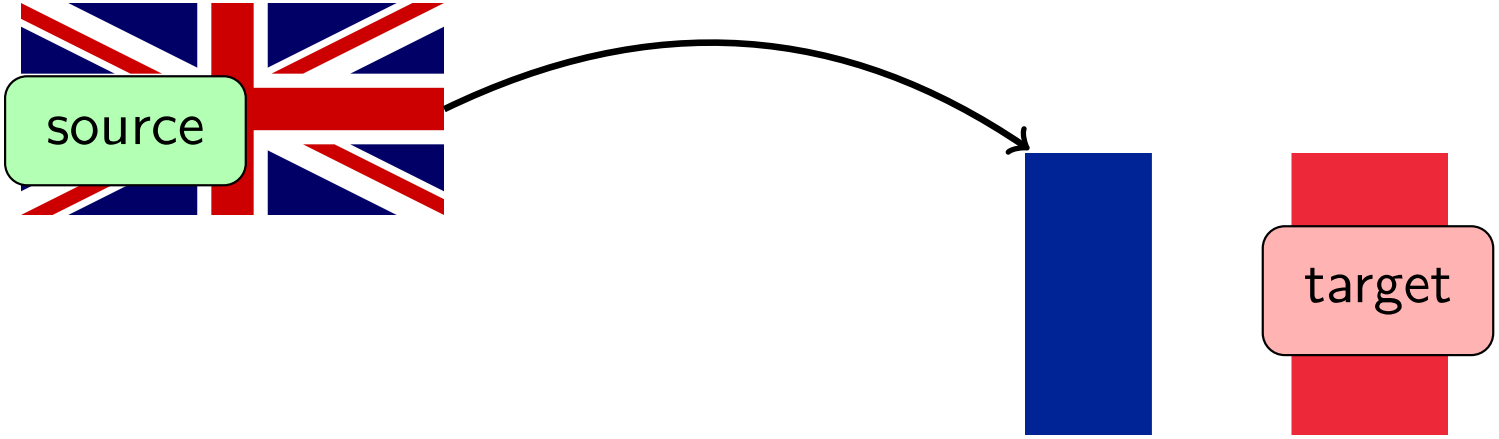

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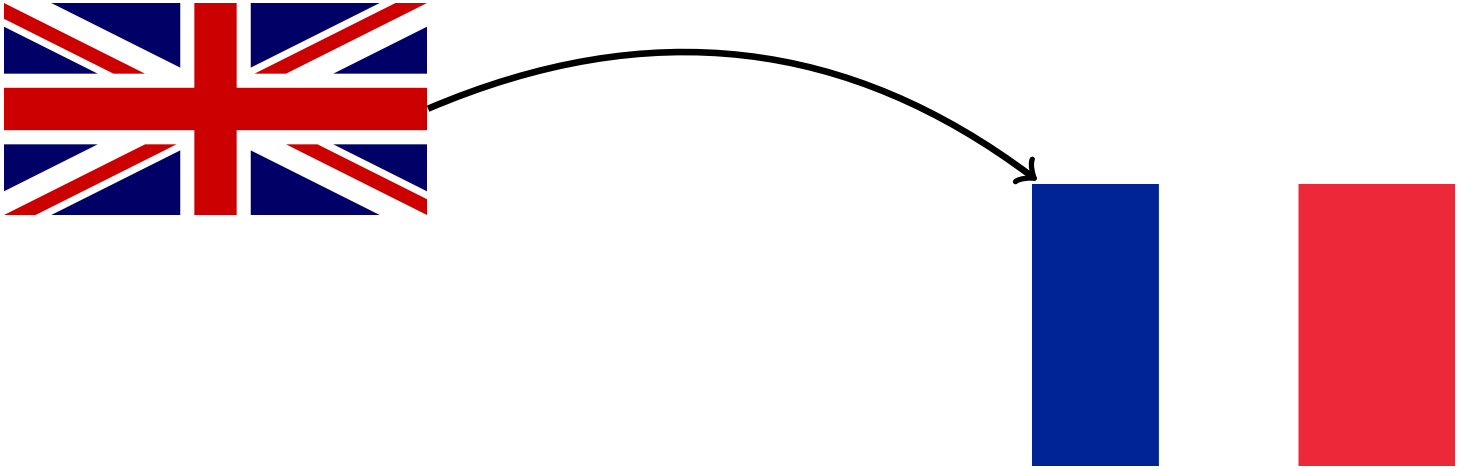

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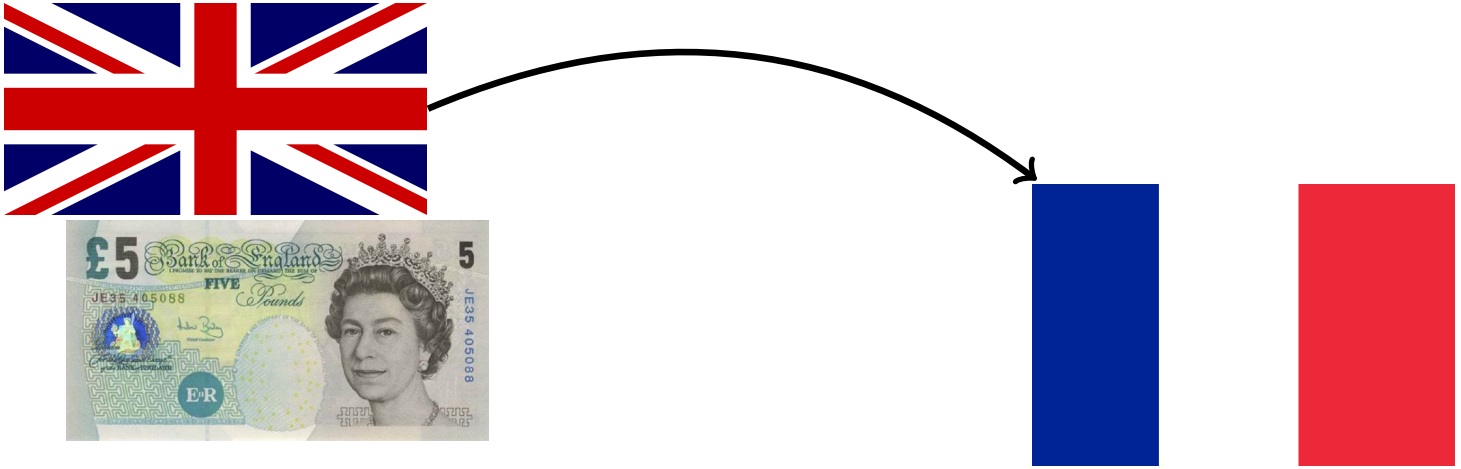

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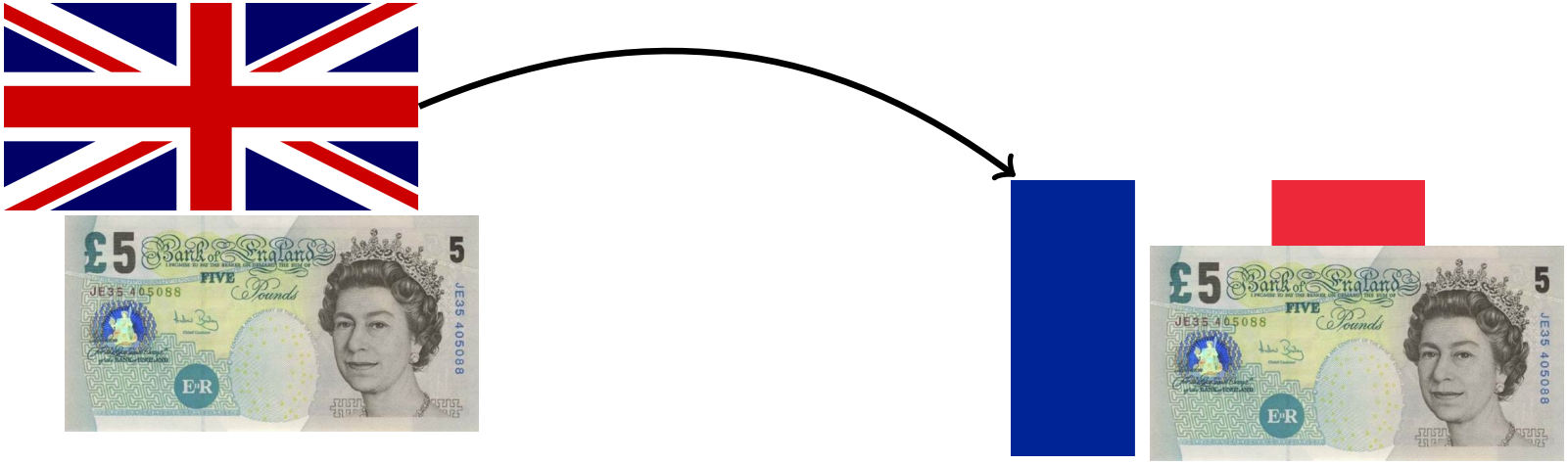

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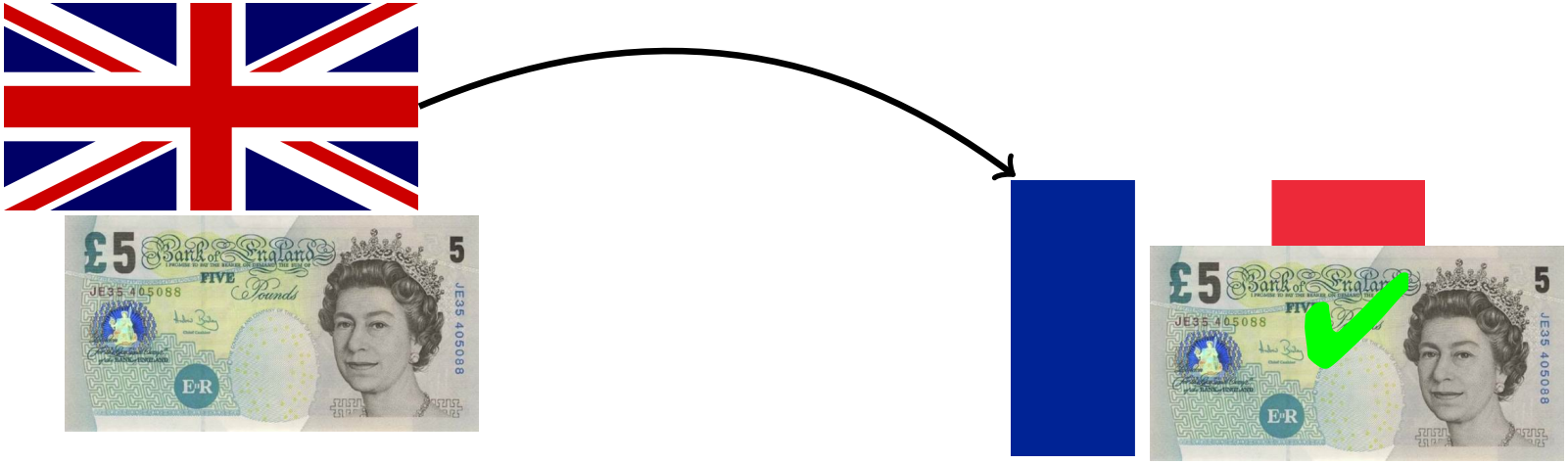

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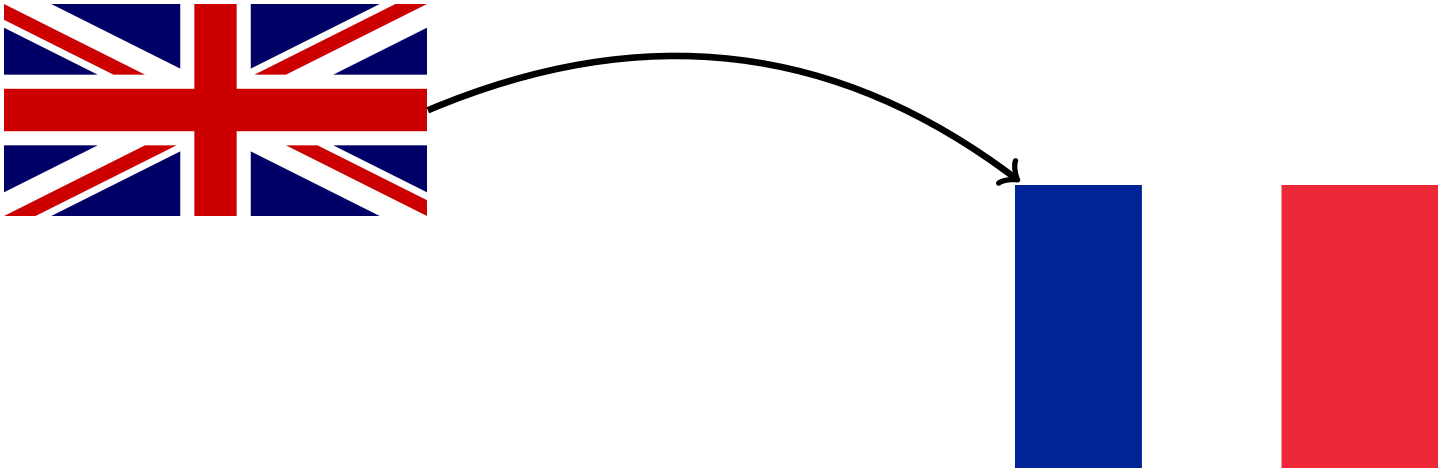

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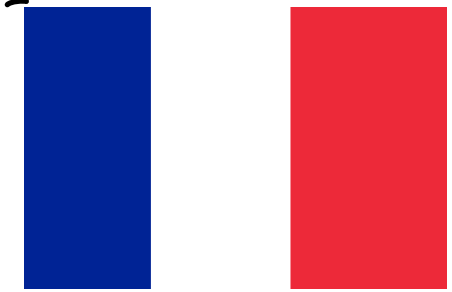

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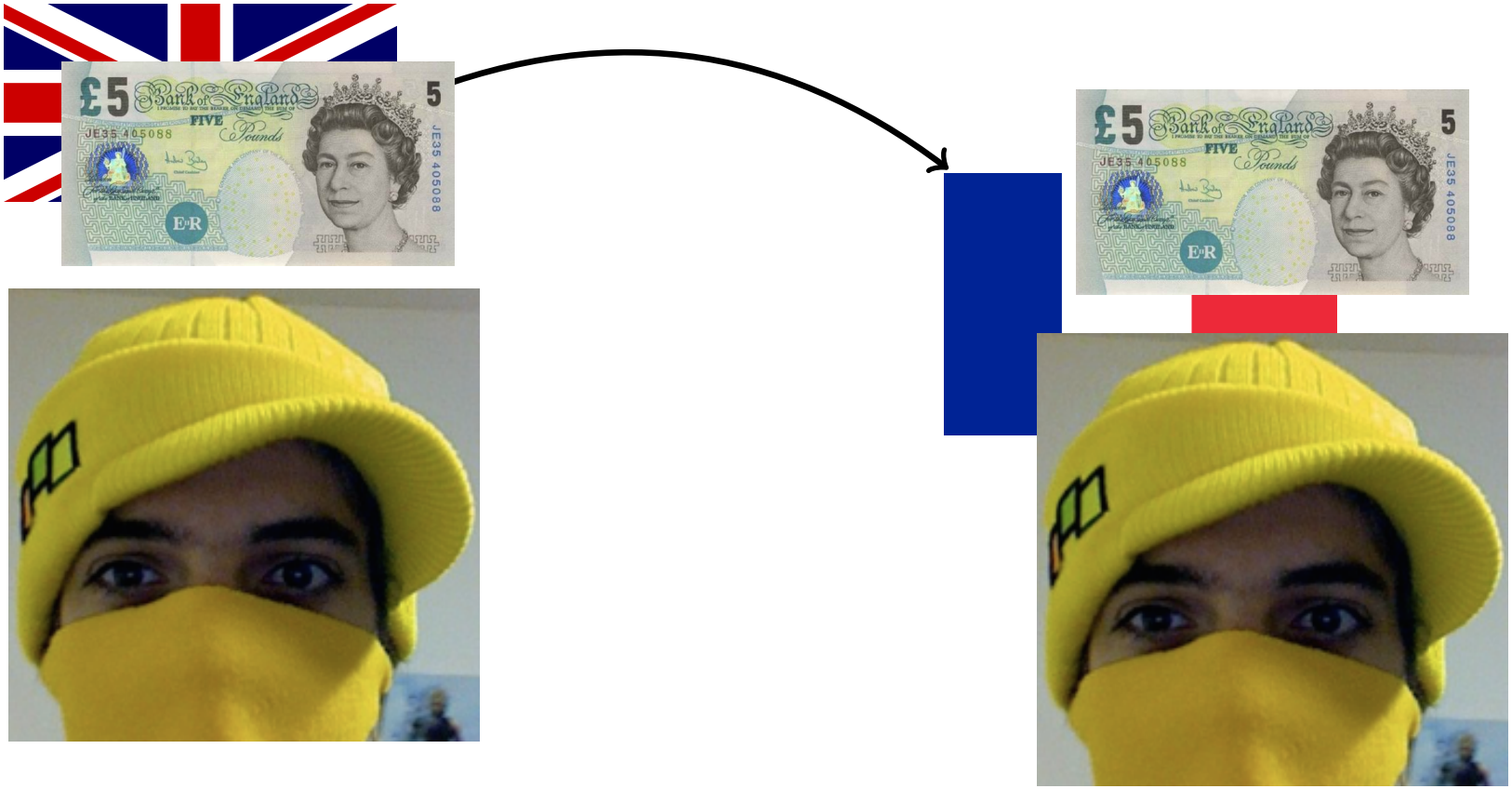

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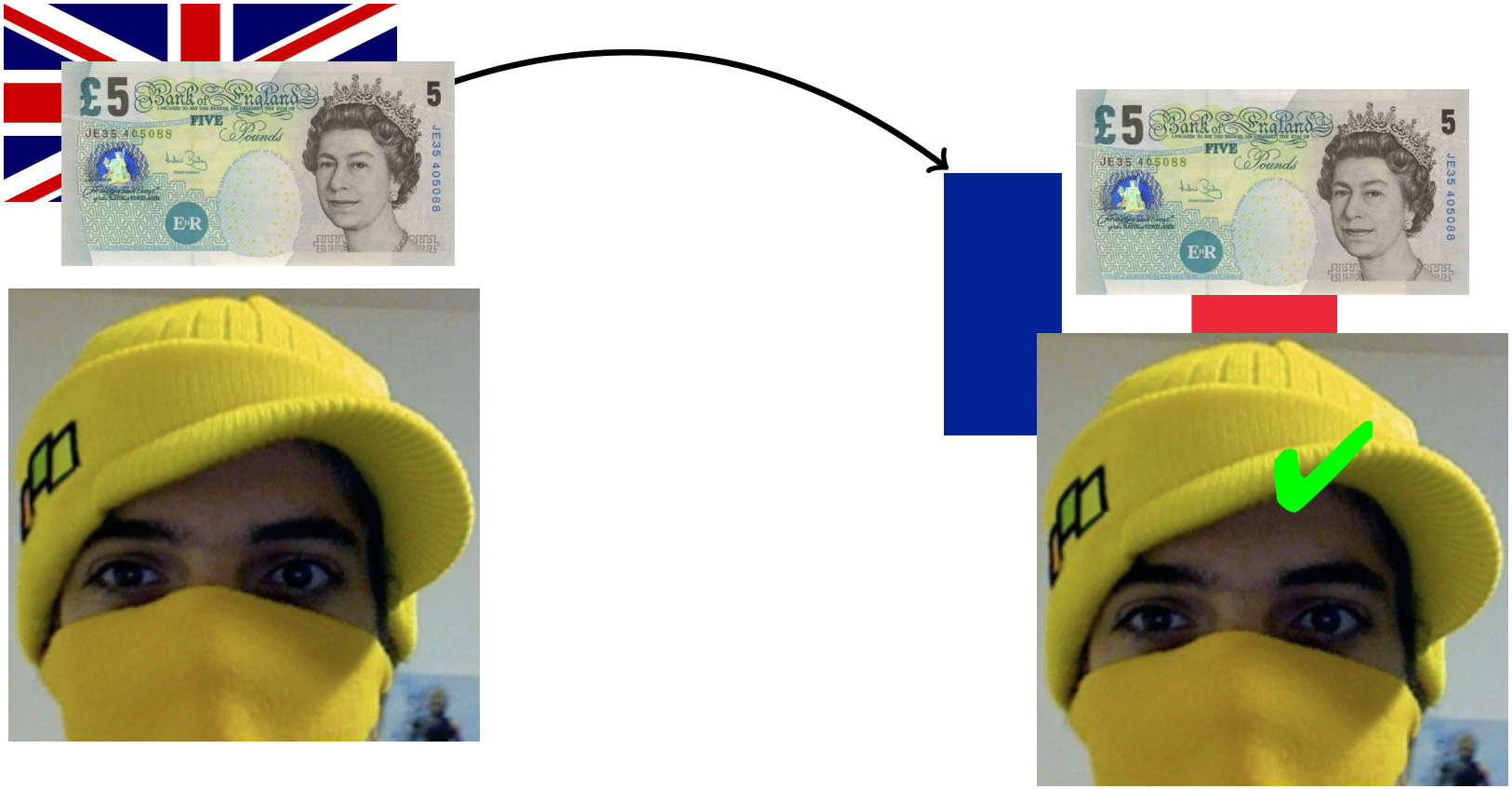

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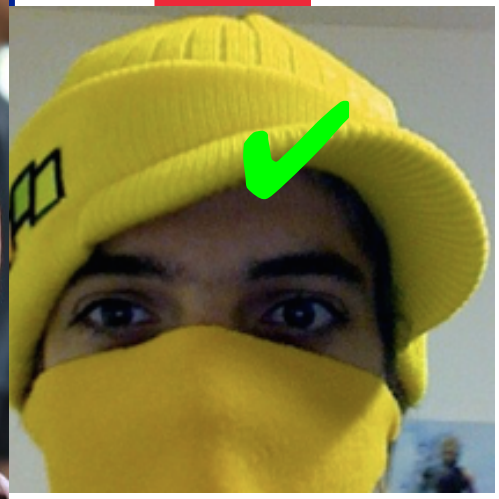
Source security properties

Hold @ target



Secure Compilation

What is secure compilation?

J+E: Java-like Language

- component-based
- private fields
- programming to an interface
- exceptions

```
1  package PI;
2    interface Account {
3      public createAccount() : Foo;
4    }
5    extern extAccount : Account;
6
7  package PE;
8    class AccountClass
9      implements PI.Account {
10     AccountClass() { counter = 0; }
11     public createAccount() : Account {
12       return new PE.AccountClass();
13     }
14
15     private counter : Int;
16   }
17   object extAccount : AccountClass;
```

J+E: Java-like Language

- component-based
- private fields
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- exceptions
- **Q:** What is secure in this code?

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- programming to an interface
- exceptions
- **Q:** What is secure in this code?

```
1  package PI;
2    interface Account {
3      public createAccount() : Foo;
4    }
5    extern extAccount : Account;
6
7  package PE;
8    class AccountClass
9      implements PI.Account {
10     AccountClass() { counter = 0; }
11     public createAccount() : Account {
12       return new PE.AccountClass();
13     }
14
15     private counter : Int;
16   }
17   object extAccount : AccountClass;
```

J+E: Java-like Language

- component-based
- private fields
- programming to an interface
- exceptions
- **Q:** What is secure in this code?
- **Q:** How do we securely compile this code?

```
package PI;
  interface Account {
    public createAccount() : Foo;
  }
  extern extAccount : Account;

package PE;
  class AccountClass
    implements PI.Account {
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      return new PE.AccountClass();
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J+E: Java-like Language

Dynamic dispatch

---

v-tables

Secure stack

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J+E: Java-like Language

- proxy to `createAccount`

Dynamic dispatch

---

v-tables

Secure stack

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J+E: Java-like Language

- proxy to `createAccount`

  `createAccount` body

  constructor

  Dynamic dispatch

---

  v-tables

  Secure stack

  `extAccount`
  `counter`

```
1  package PI;
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PMA for Secure Compilation

Source level

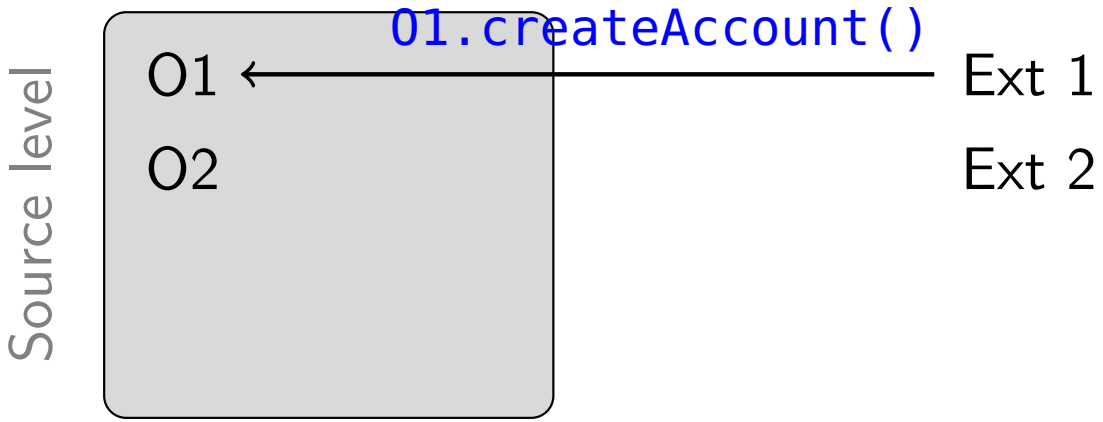
O1

O2

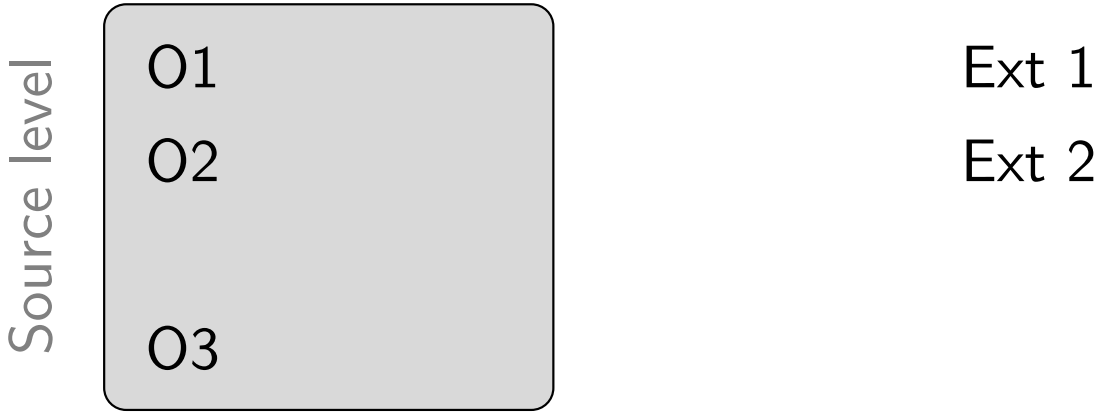
Ext 1

Ext 2

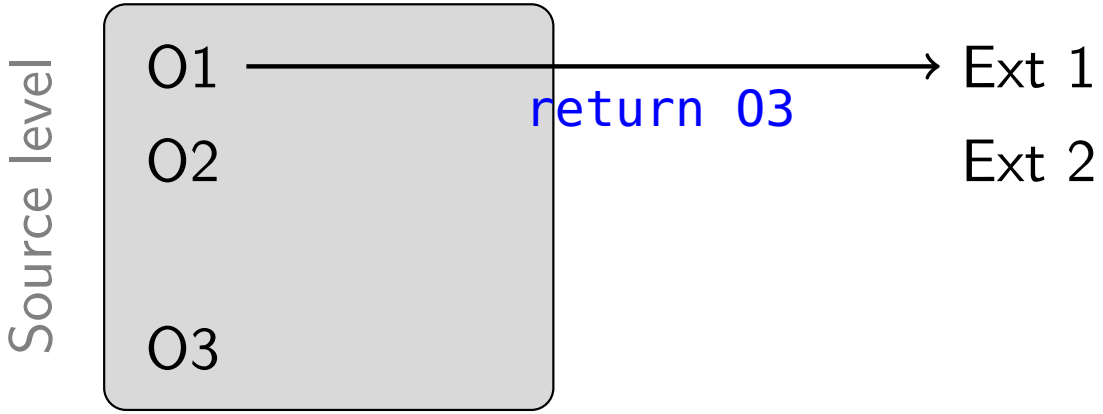
PMA for Secure Compilation



PMA for Secure Compilation



PMA for Secure Compilation



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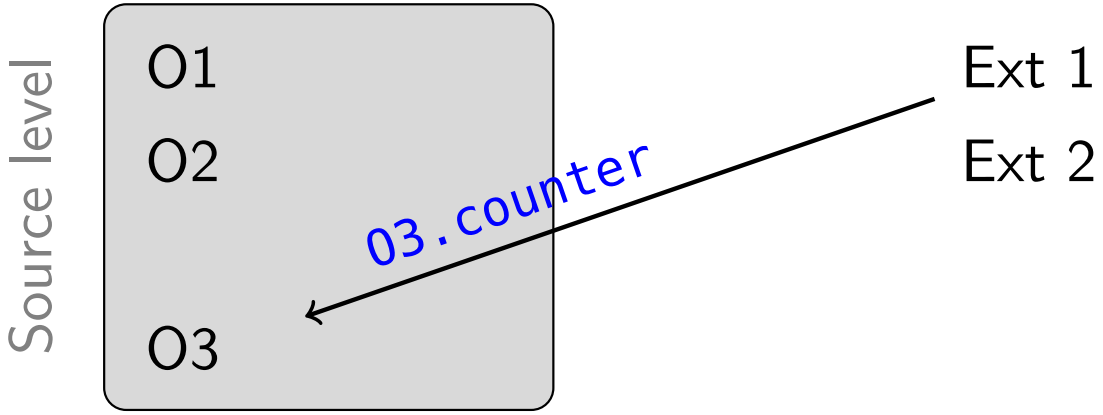

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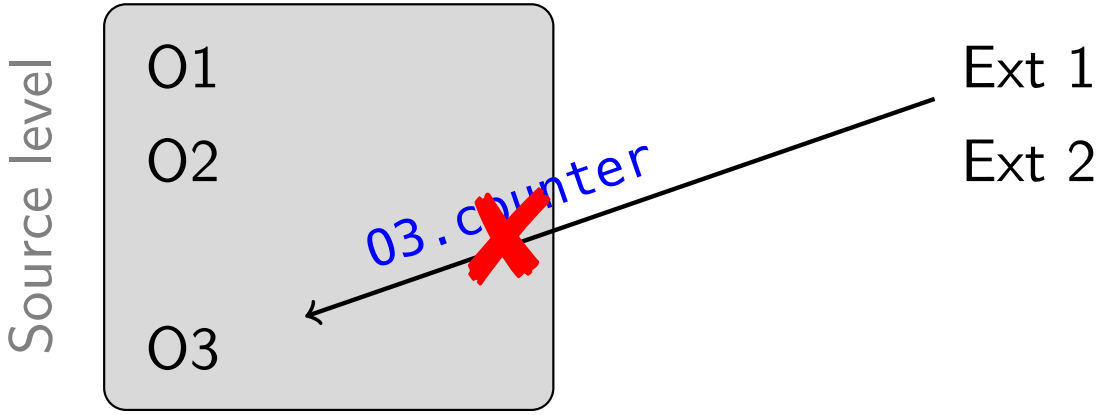

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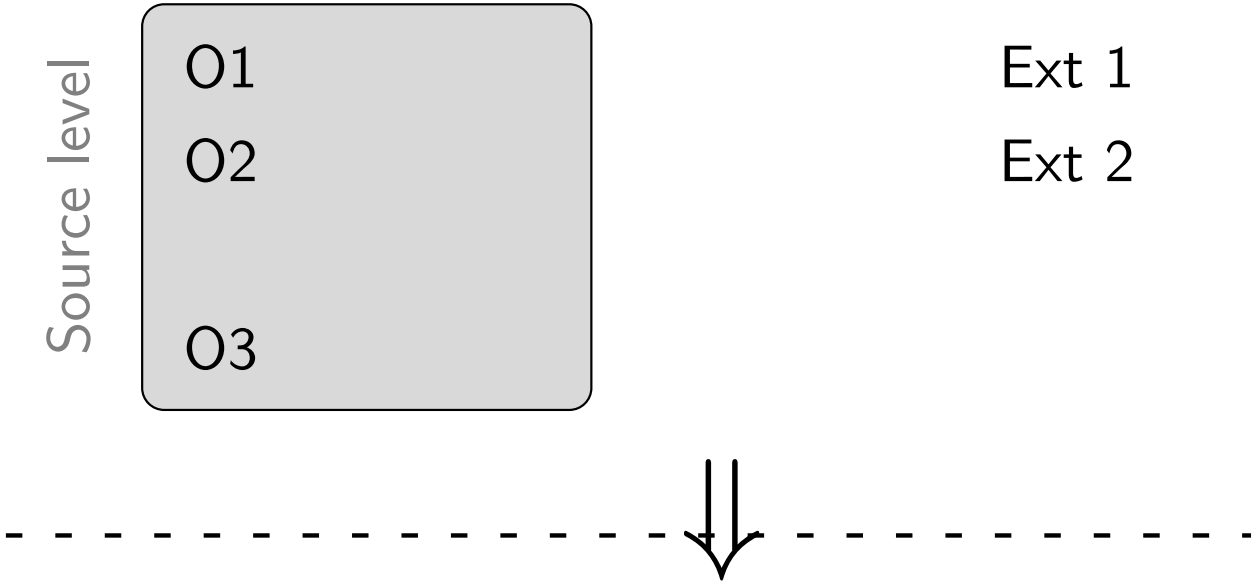
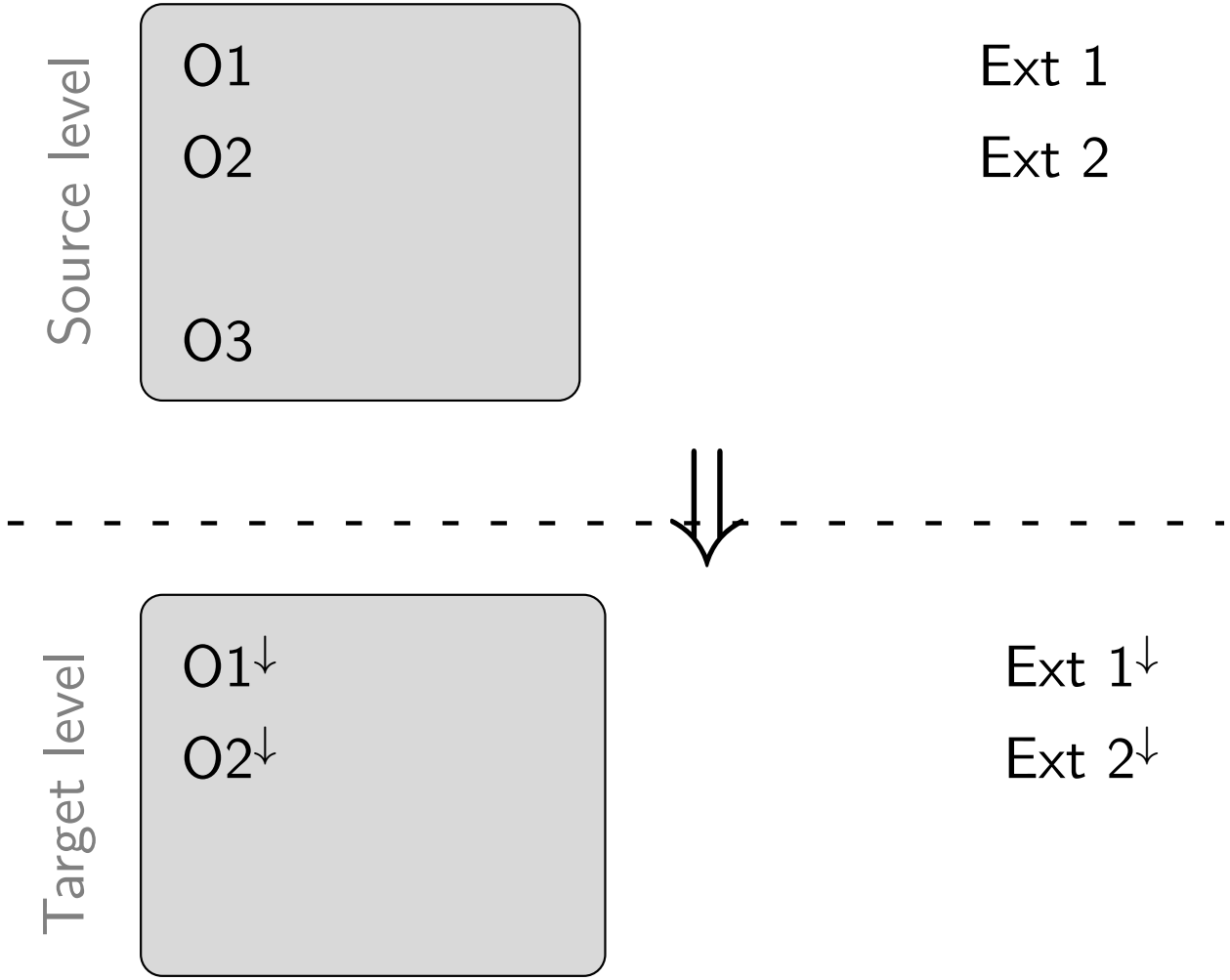


PMA for Secure Compilation



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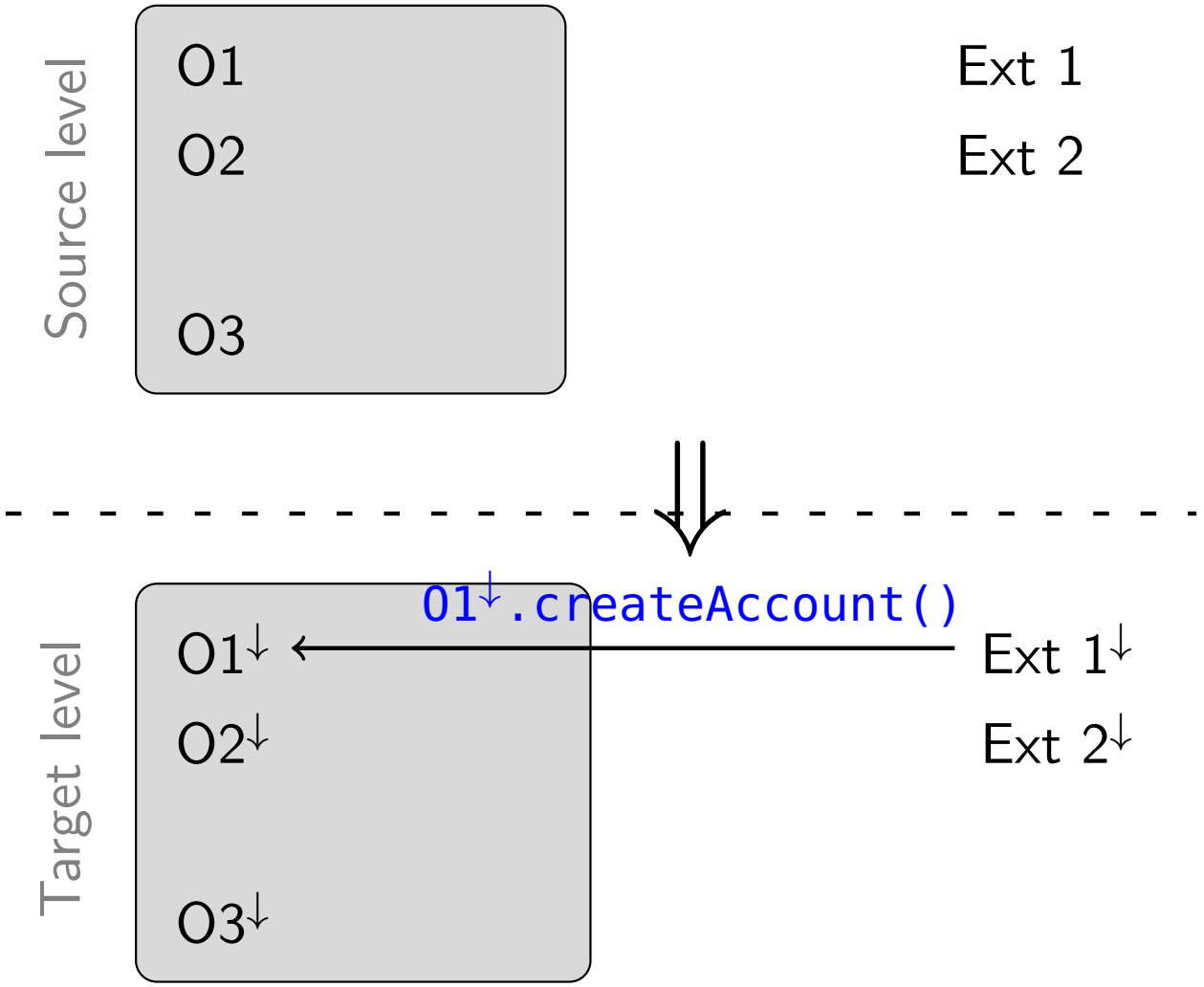

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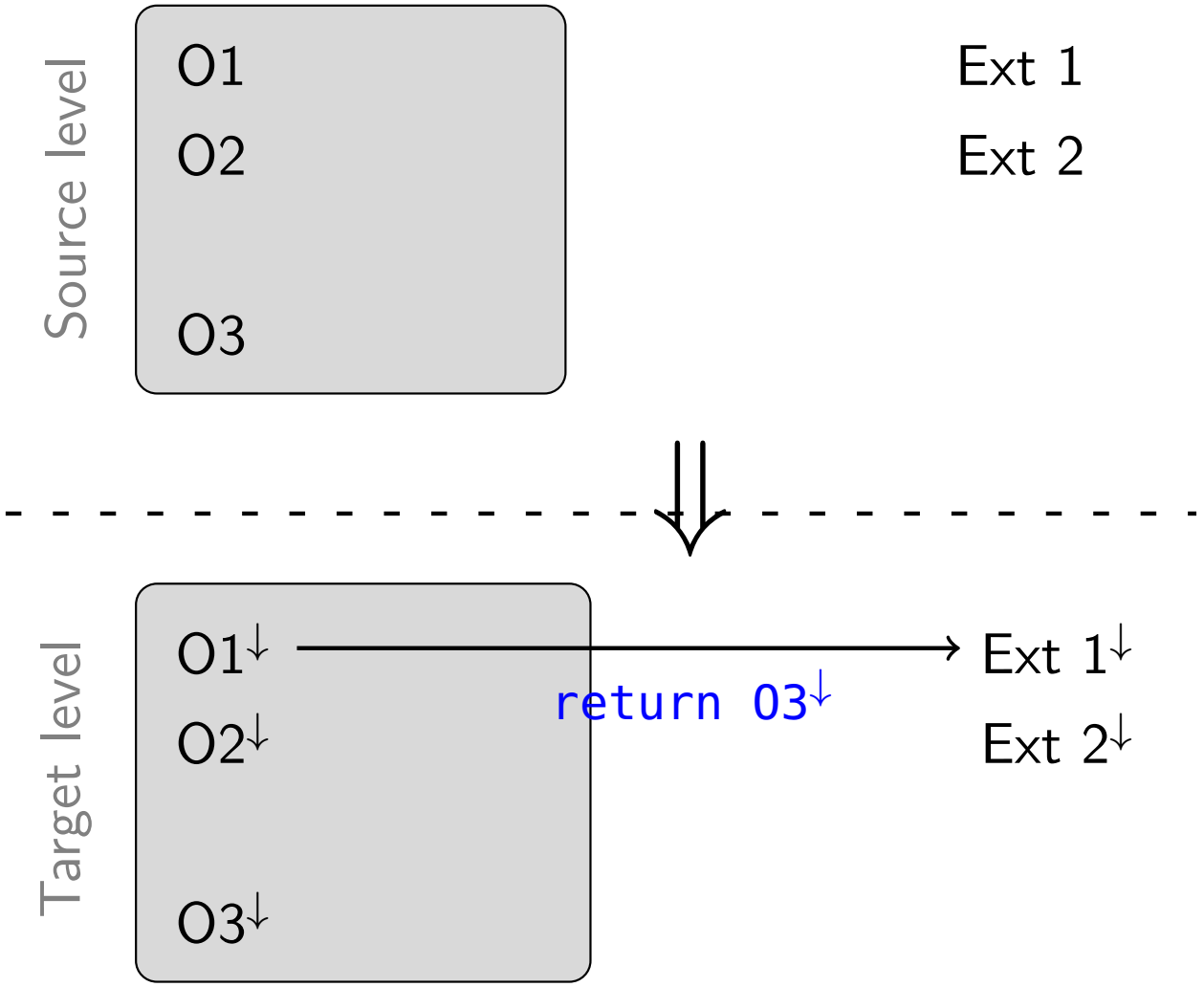
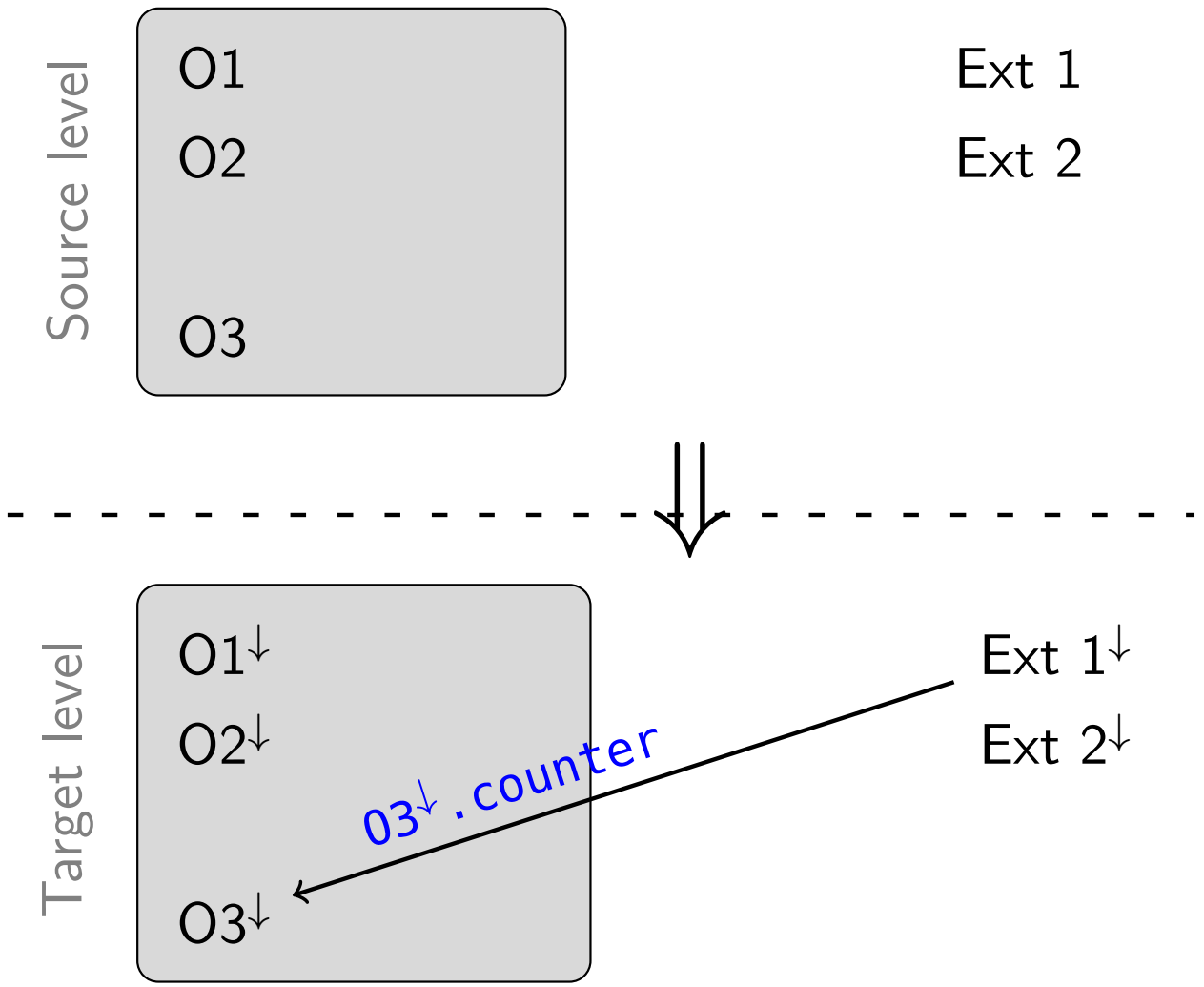
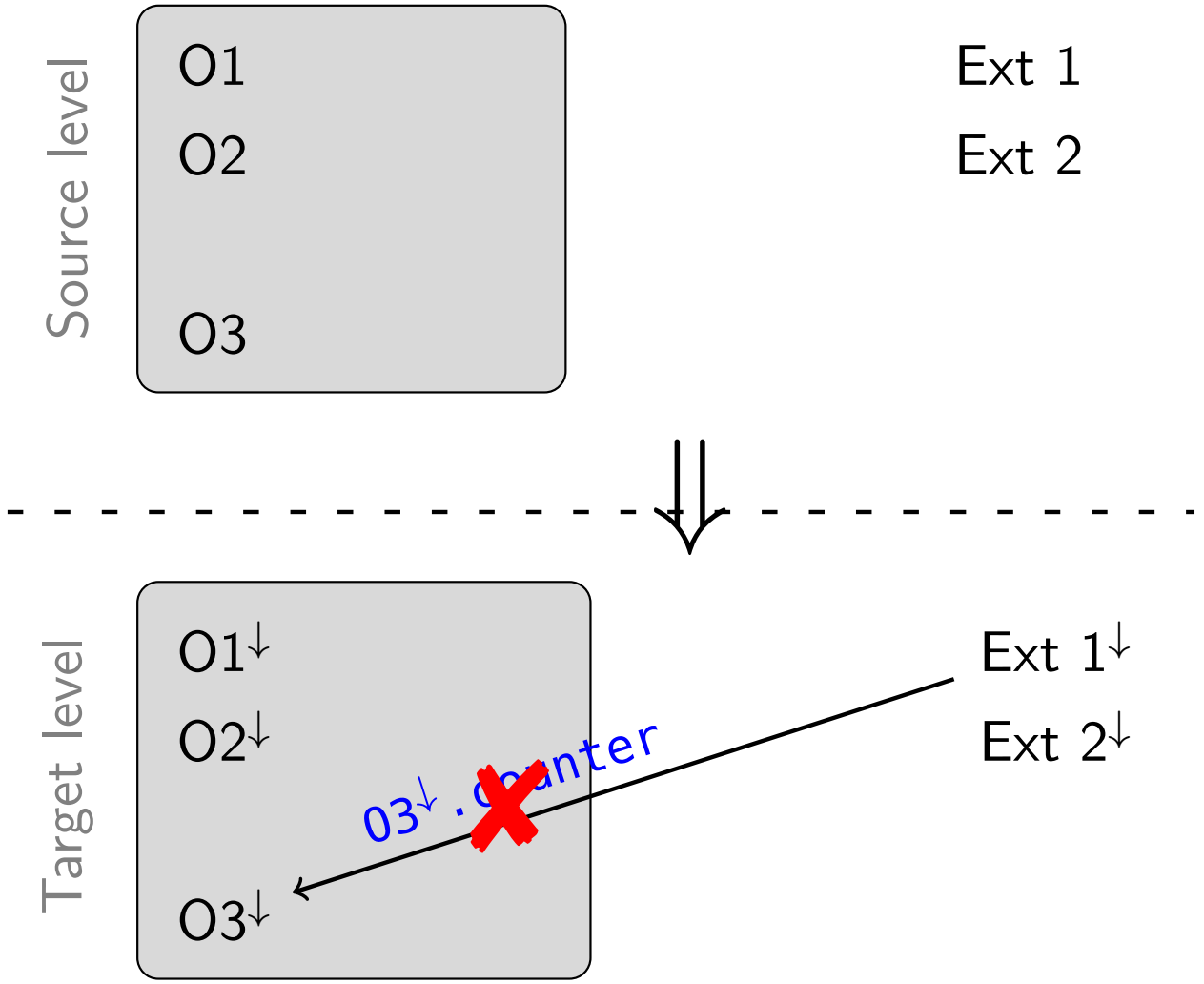


PMA for Secure Compilation

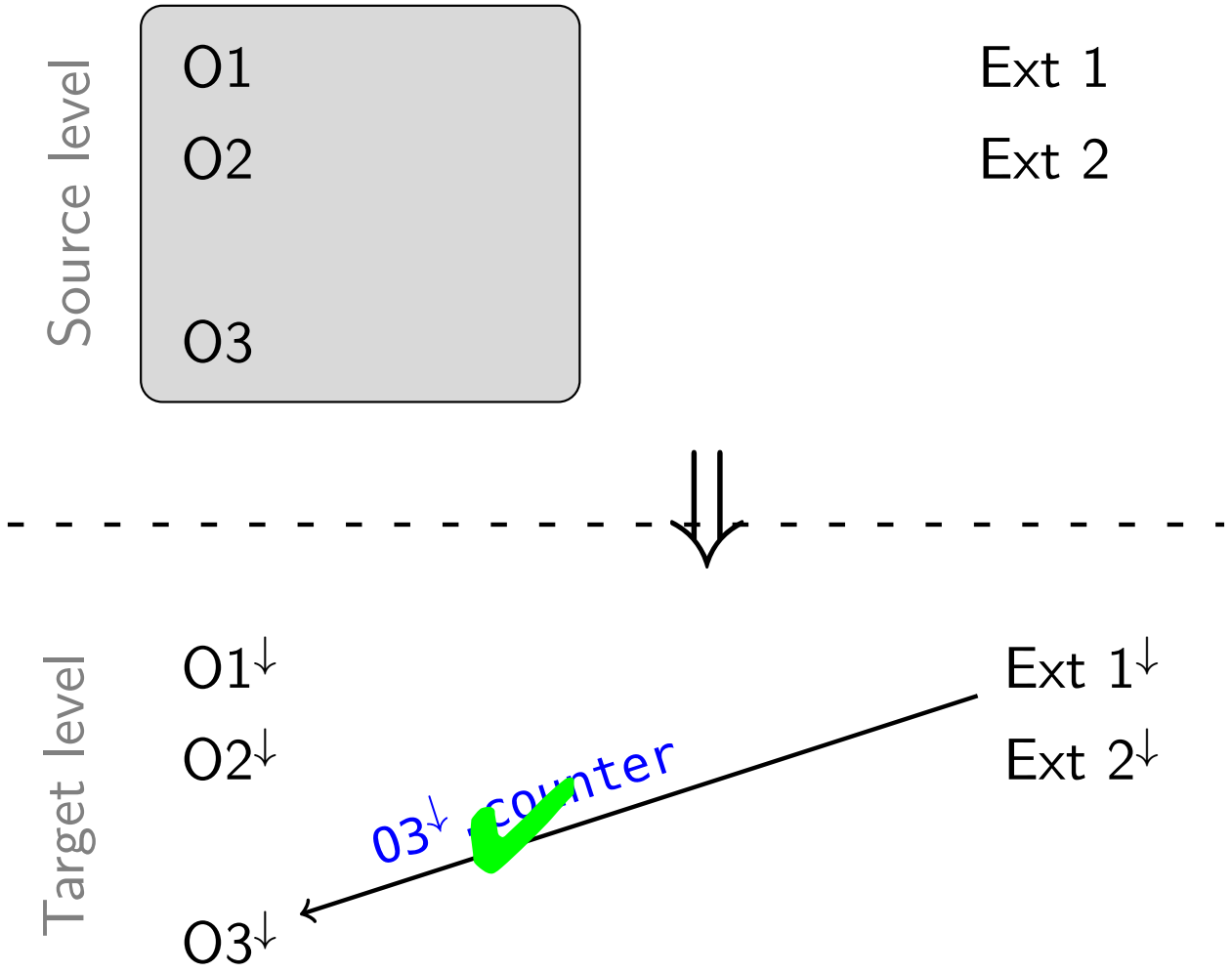


PMA for Secure Compilation



- Protect against low-level attackers

PMA for Secure Compilation



- Protect against low-level attackers
- Target code is vulnerable without PMA

Secure Compilation of Outcalls

Q: : Is that all?

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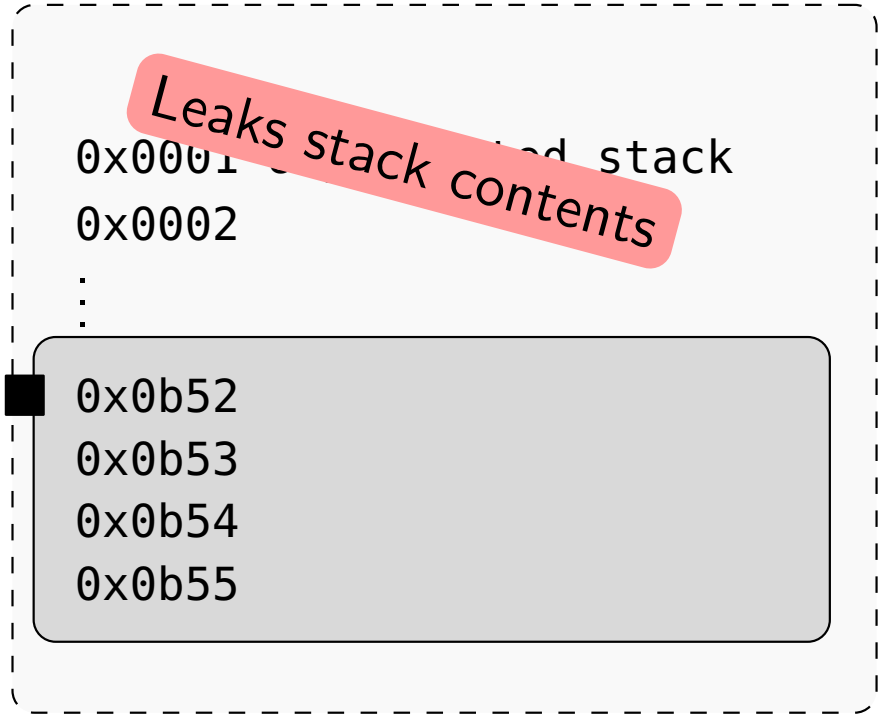
Secure Compilation of Outcalls

Q: : Is that all?

- protected stack



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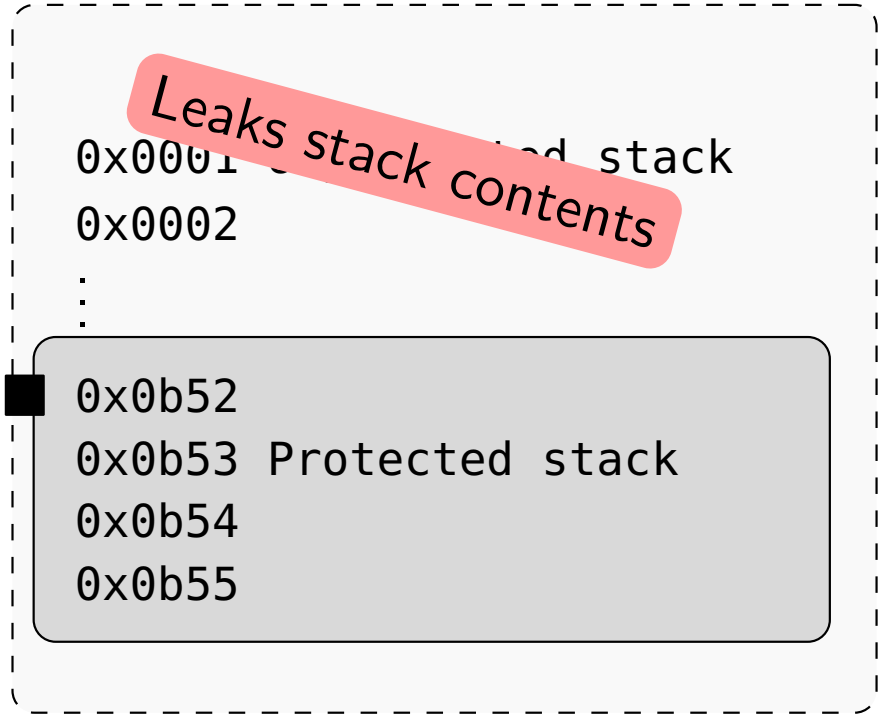
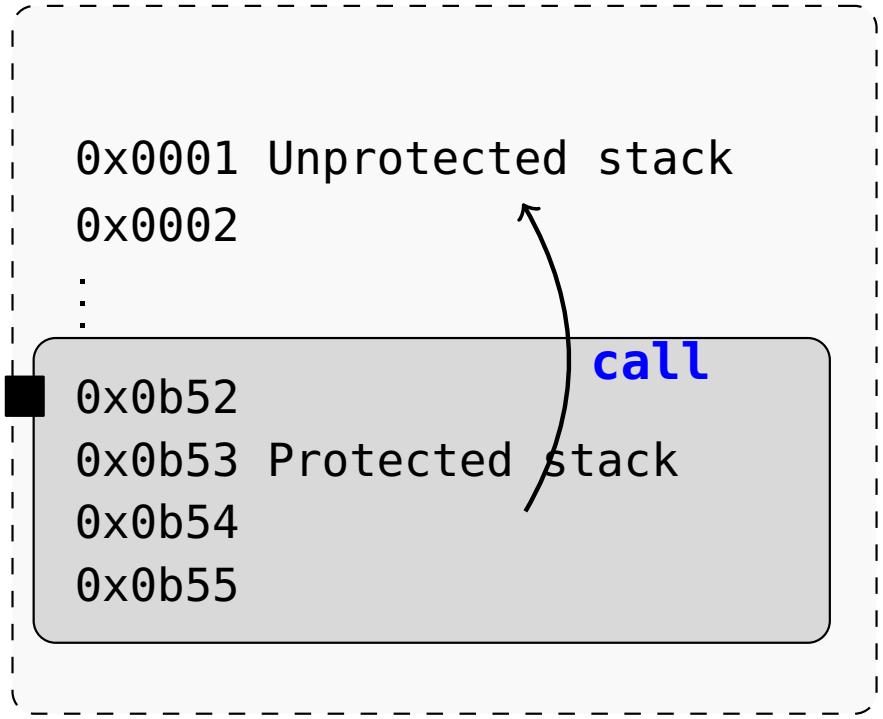


Secure Compilation of Outcalls

Q: : Is that all?

- protected stack
- returnback entry point



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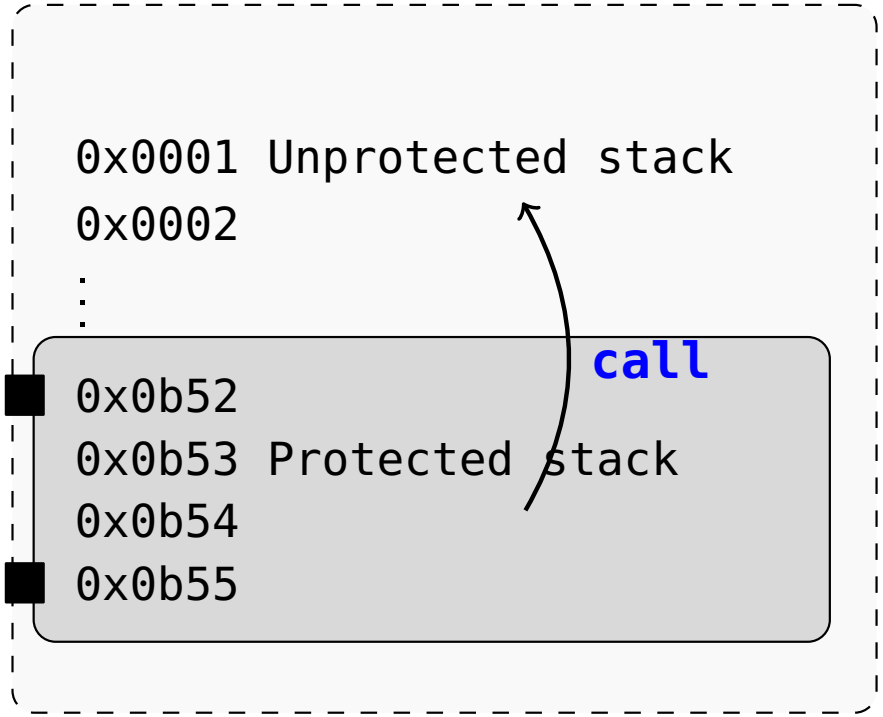

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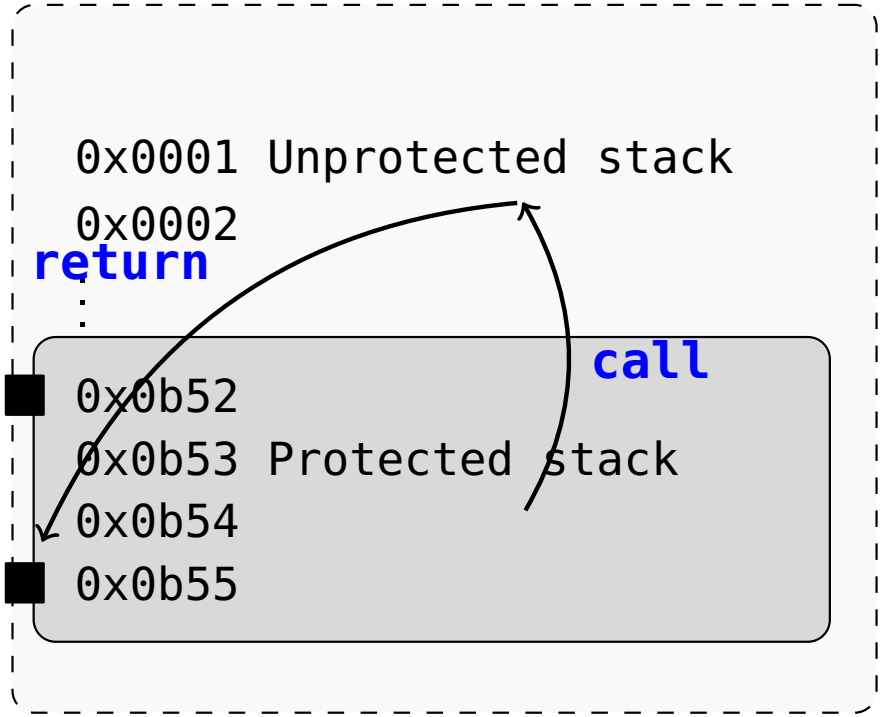

Secure Compilation of Outcalls

Q: : Is that all?

- protected stack
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- reset flags and registers

Secure Compilation of Outcalls

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- reset flags and registers

```
0x0001 Unprotected stack
0x0002
⋮
0x0b52
0x0b53 Protected stack
0x0b54 je ···
0x0b55
```

Secure Compilation of Outcalls

Q: : Is that all?

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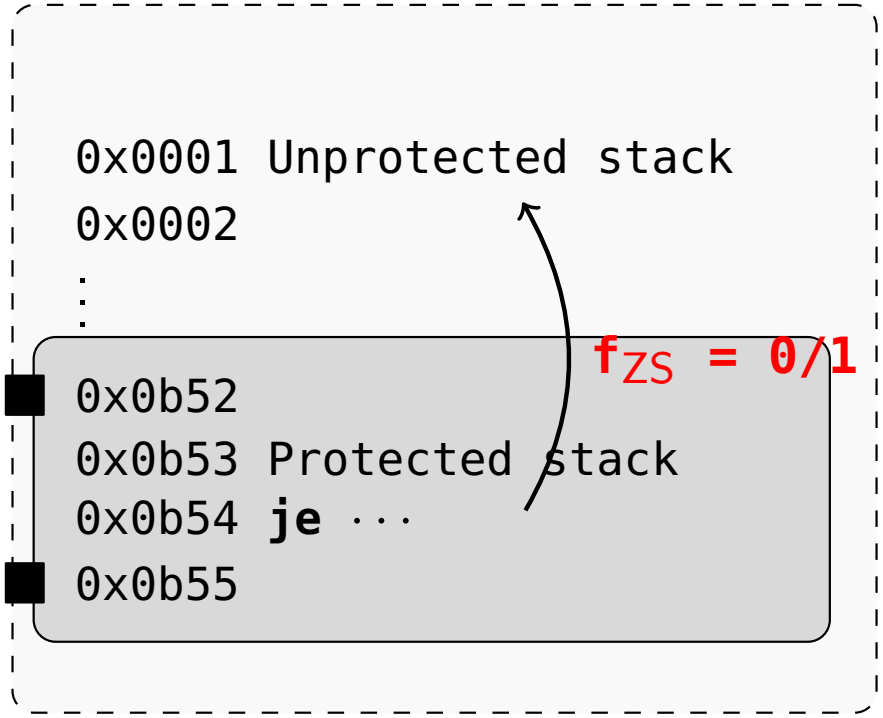
- returnback entry point
- reset flags and registers



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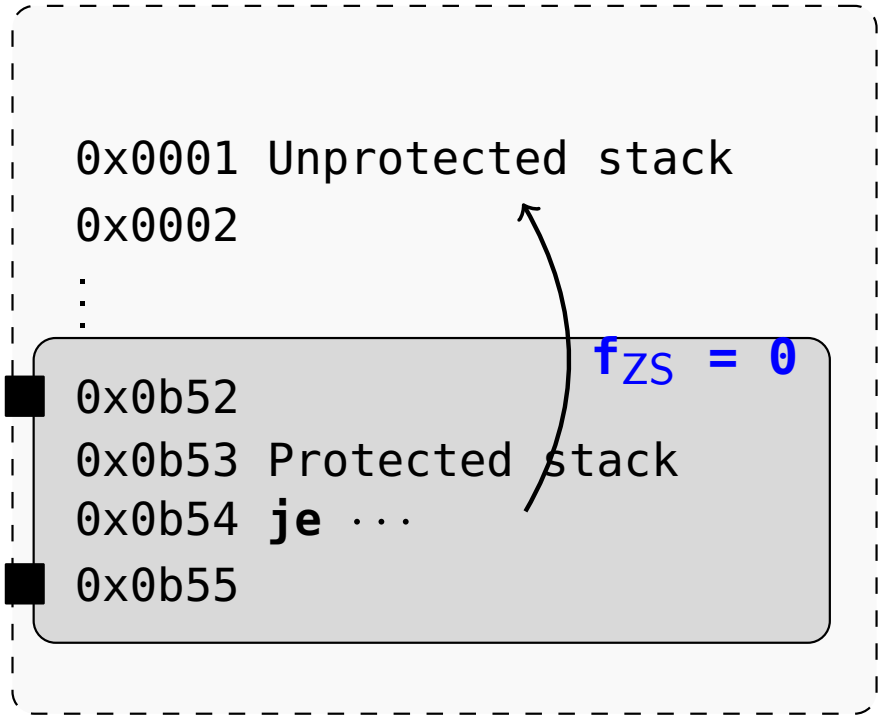

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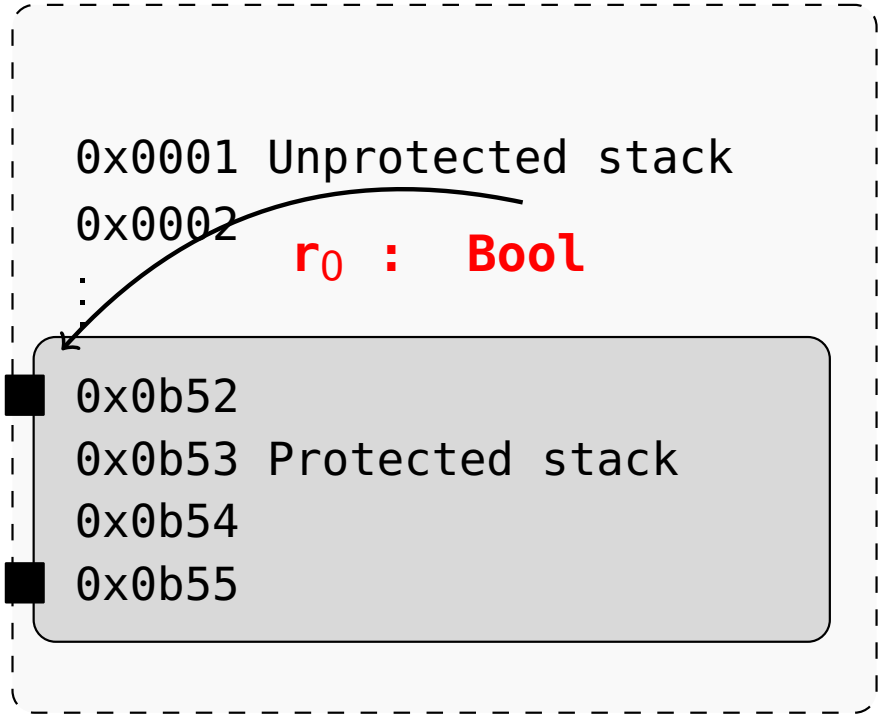

Secure Compilation of Outcalls

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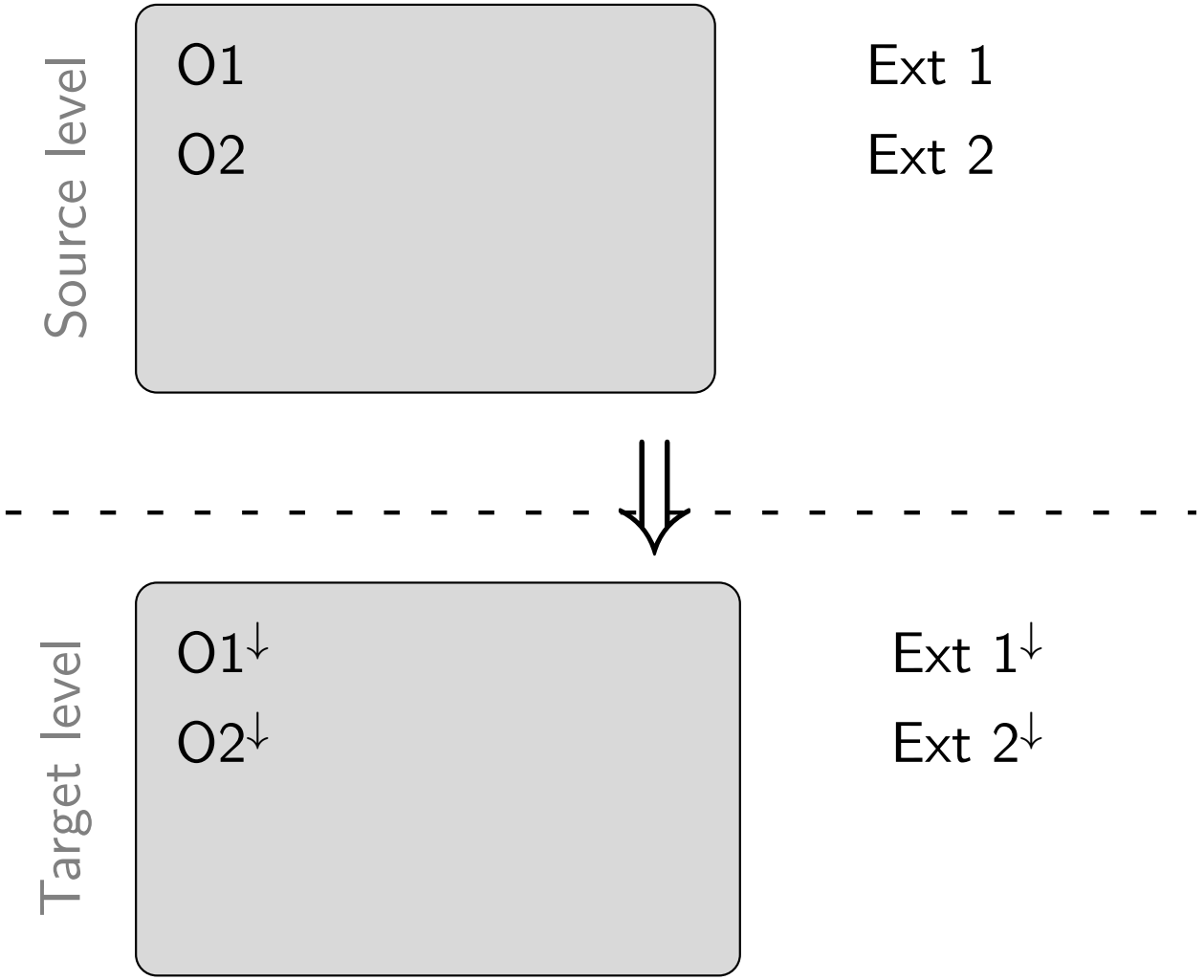
Dynamic Memory Allocation



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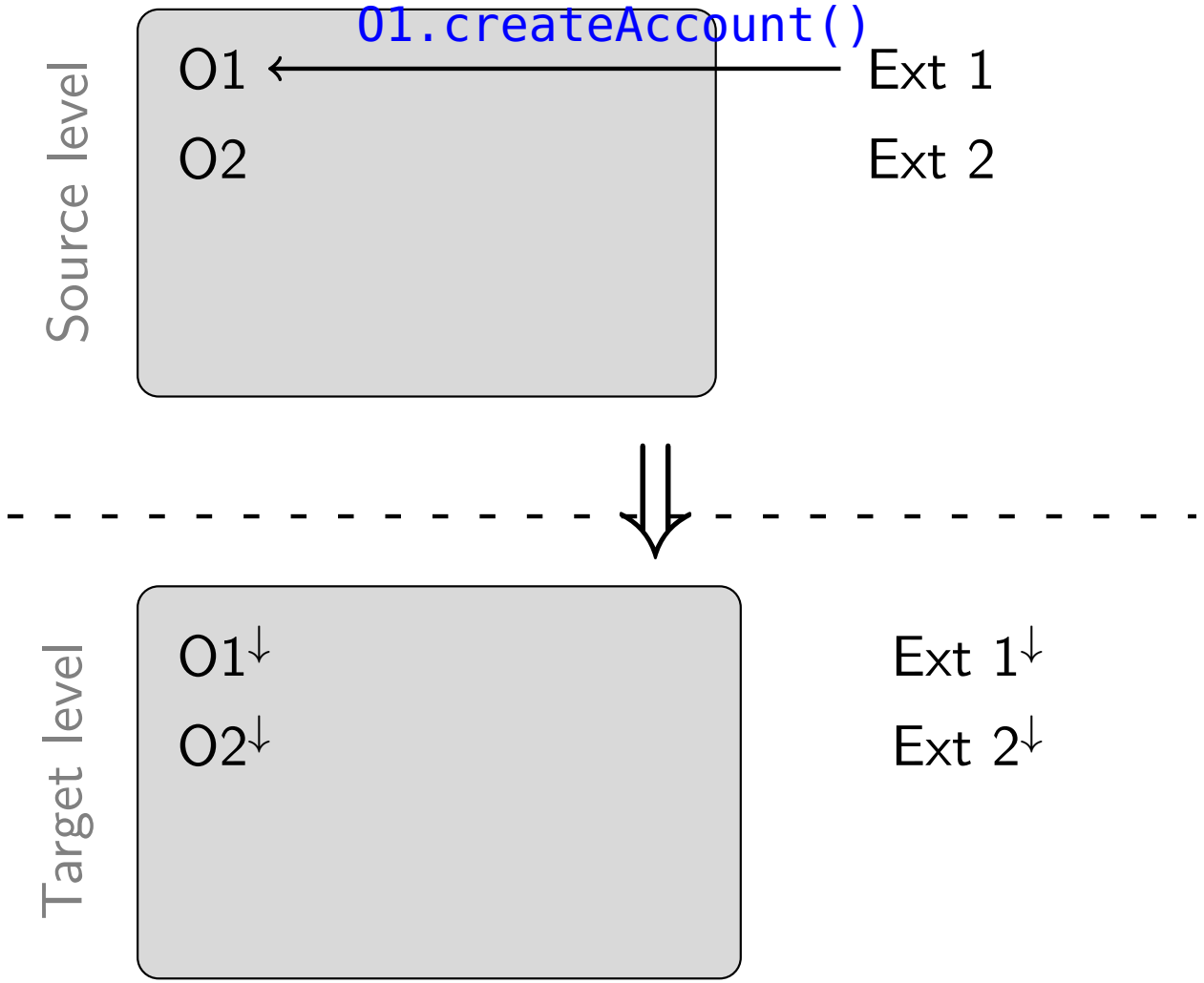
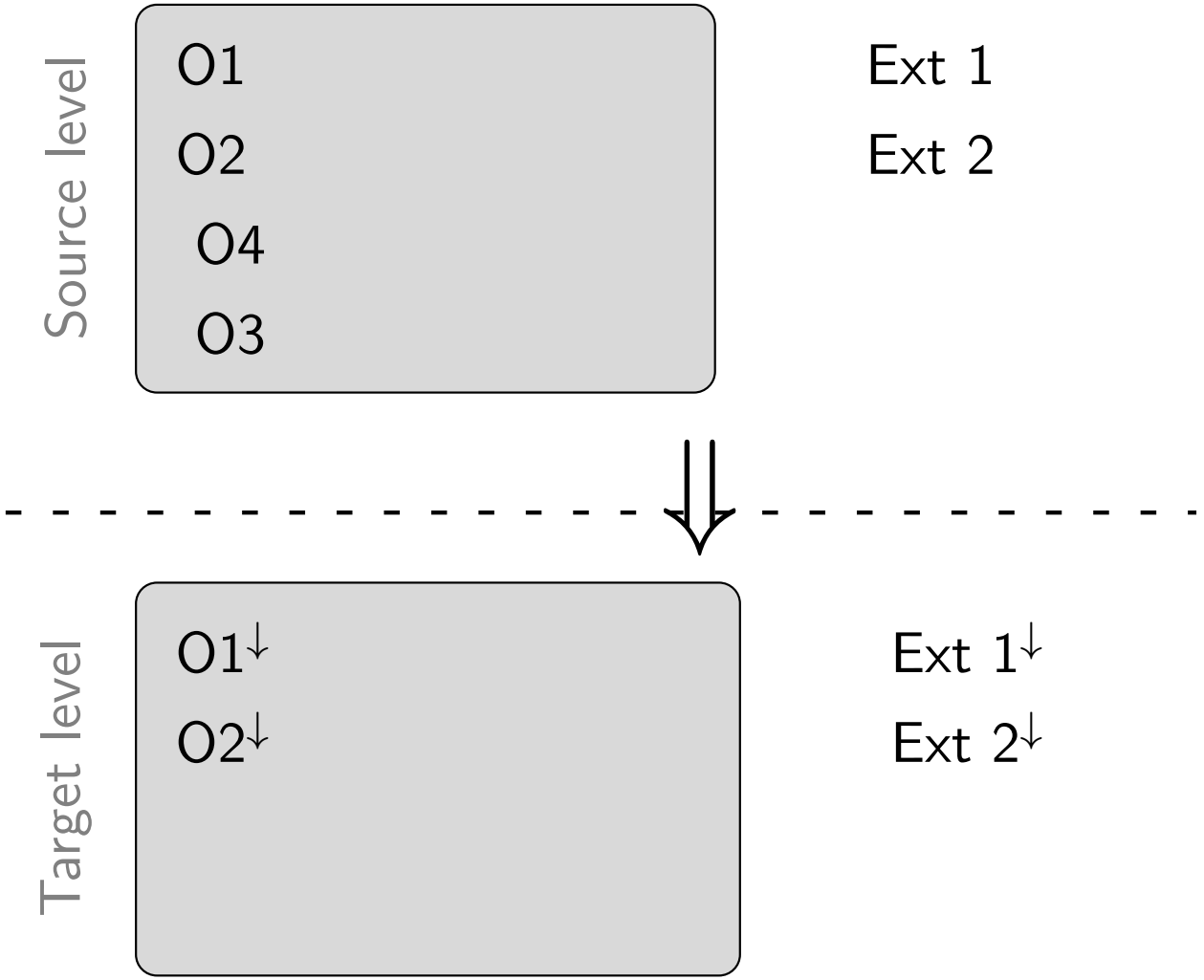


Dynamic Memory Allocation



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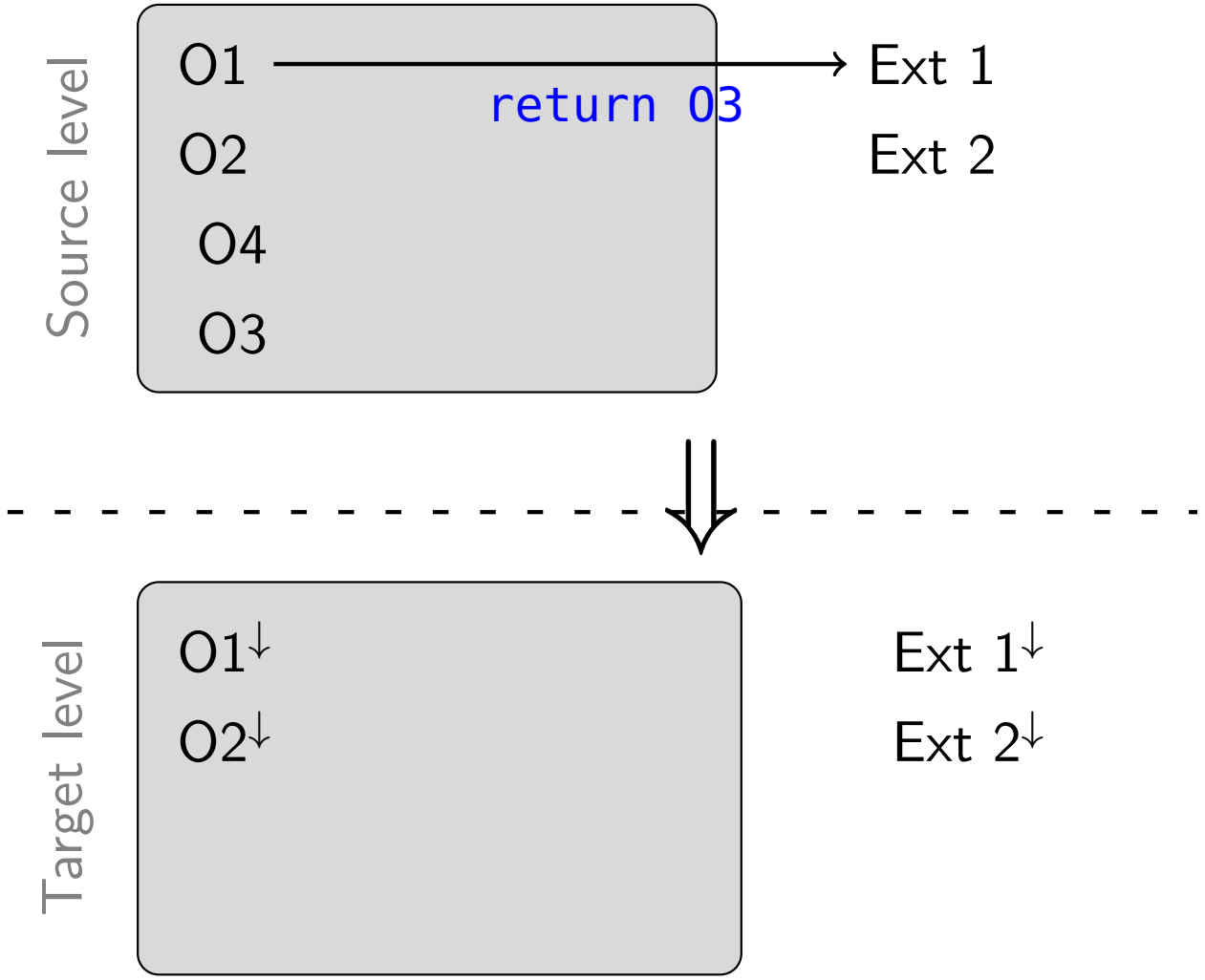

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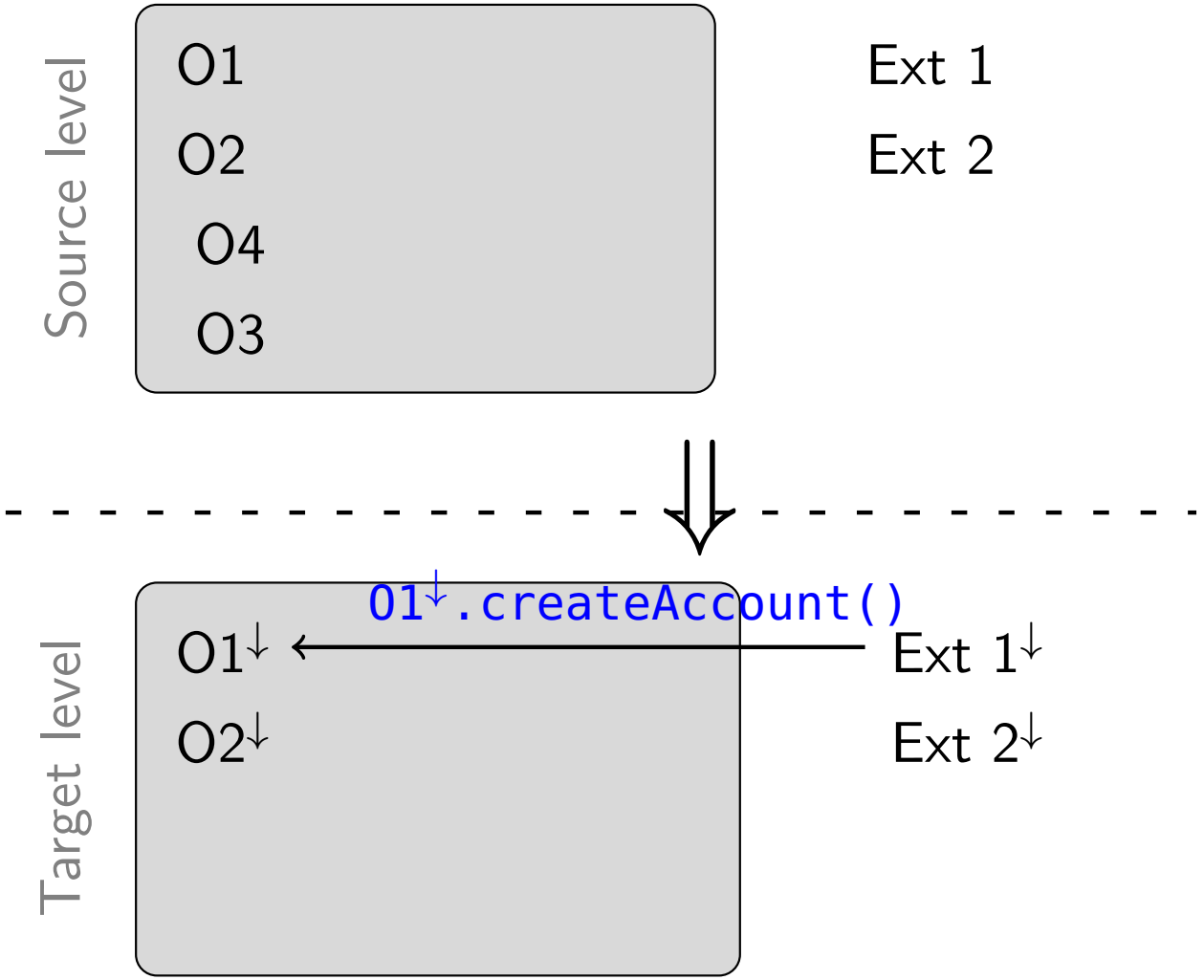

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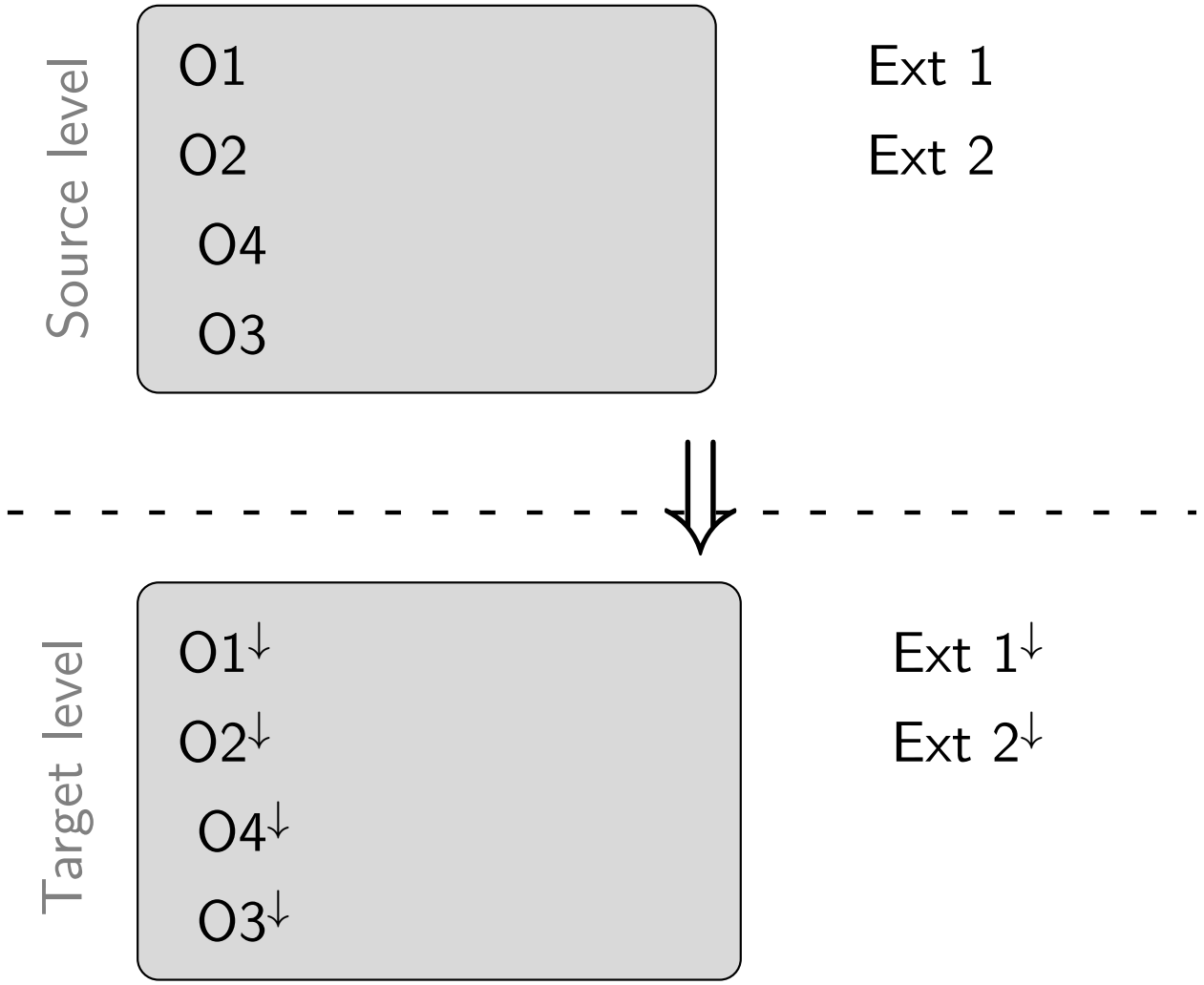

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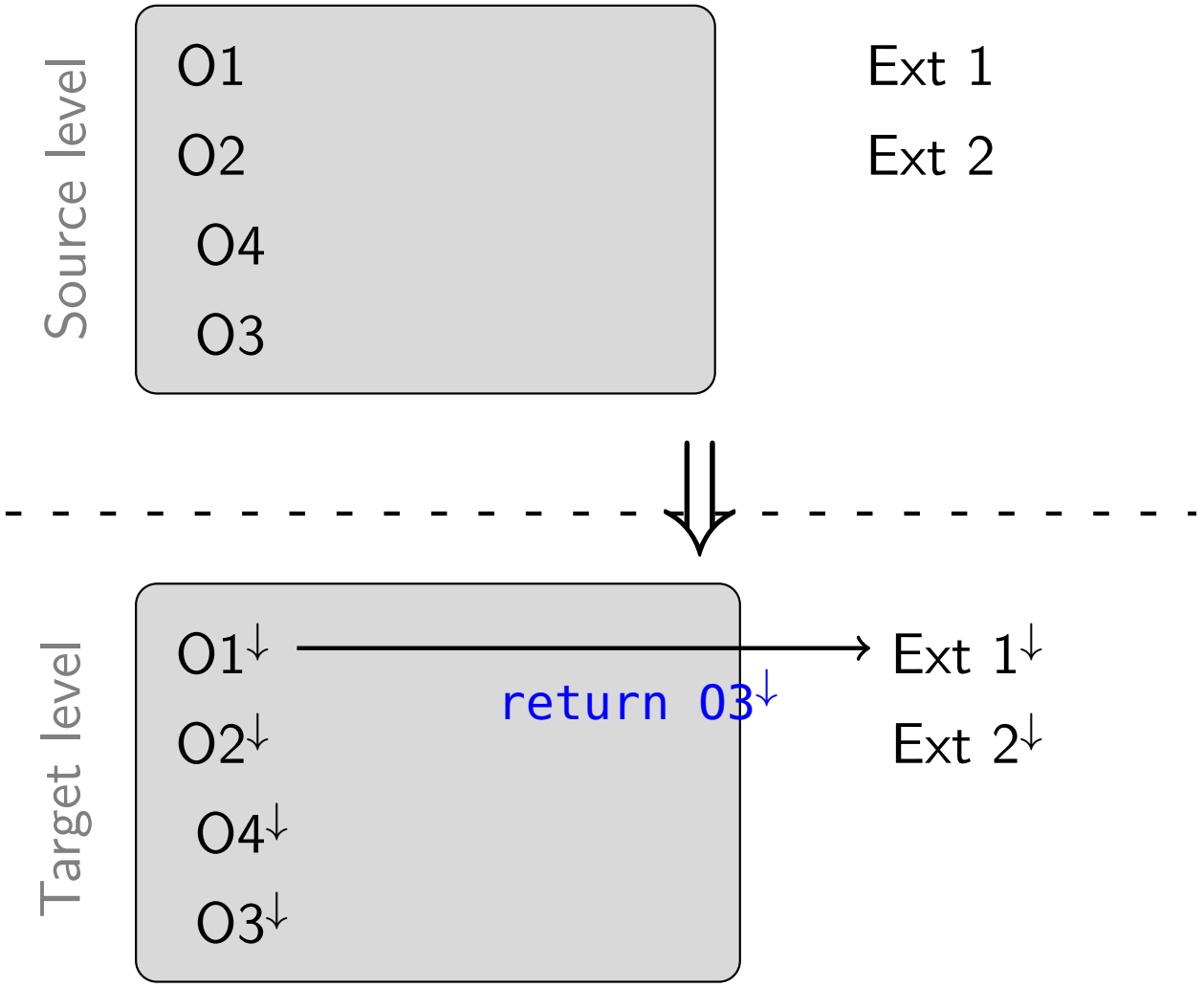

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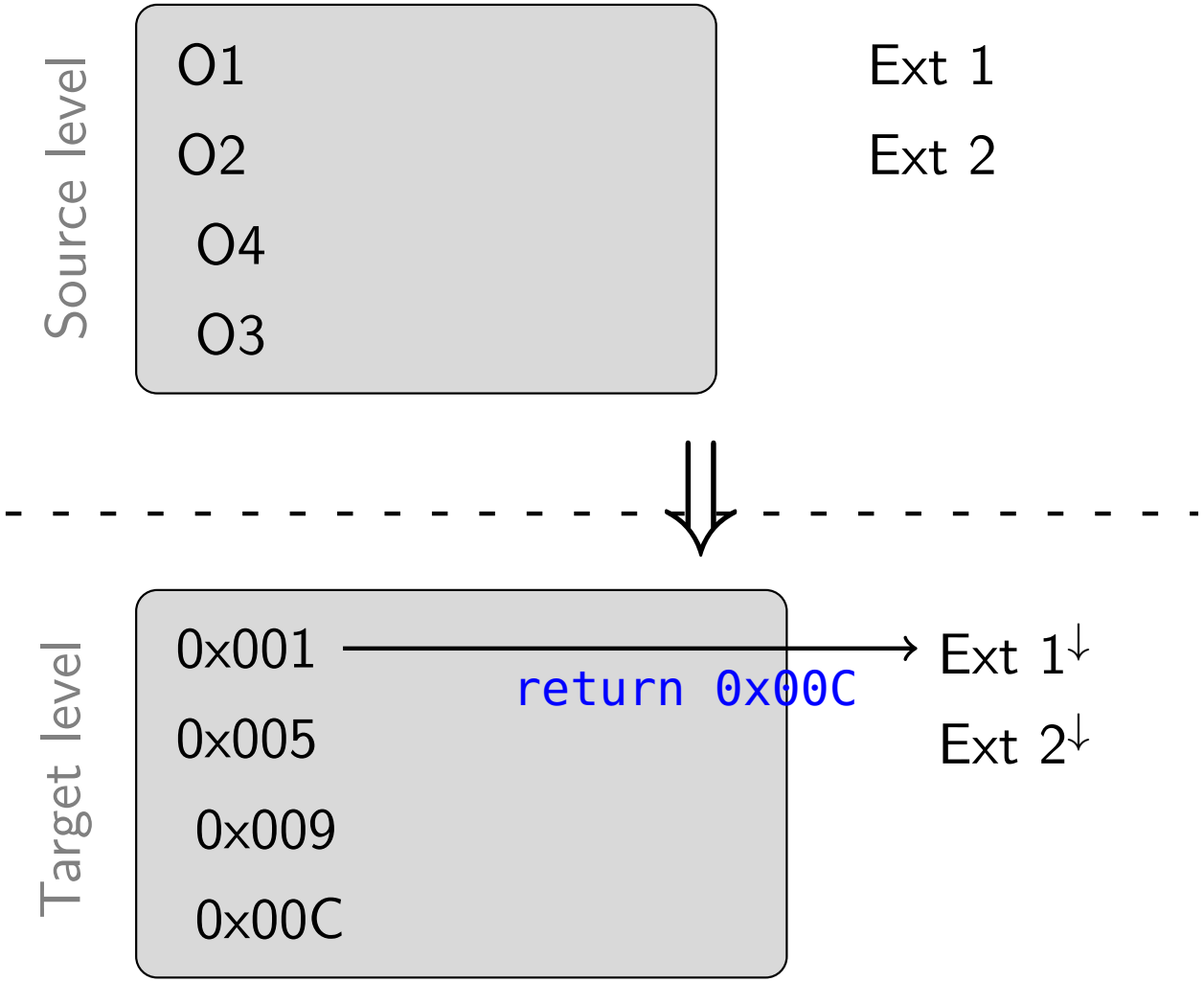

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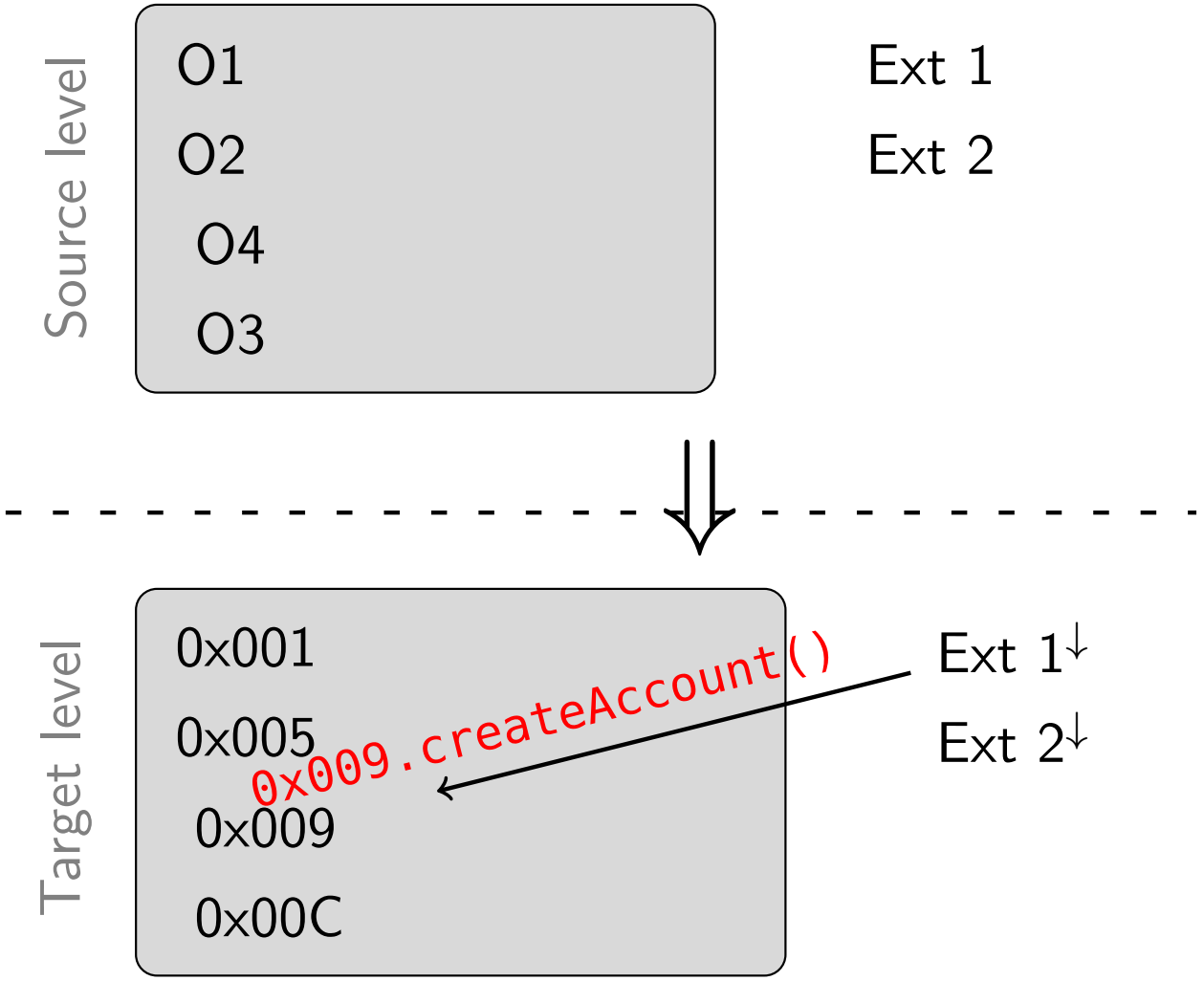

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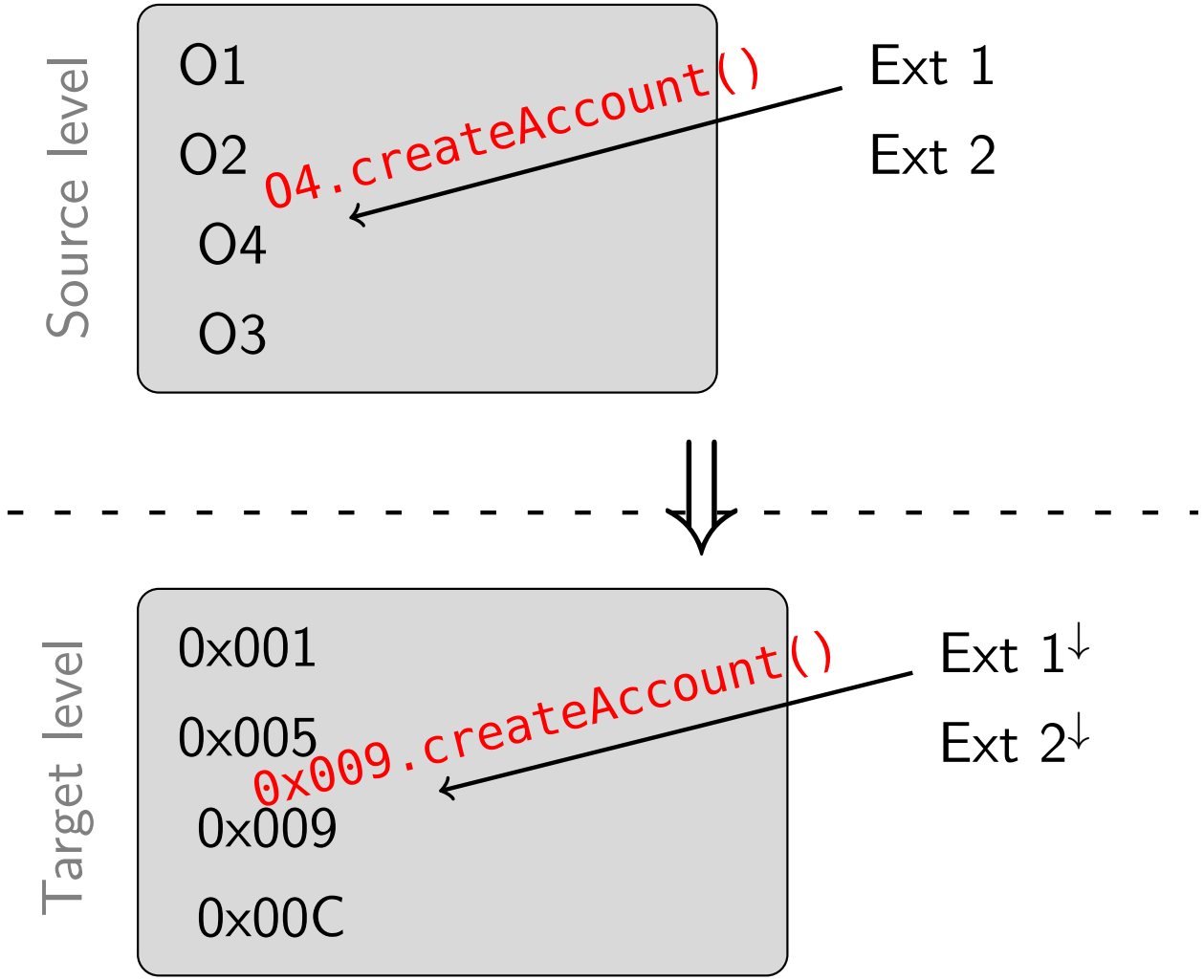
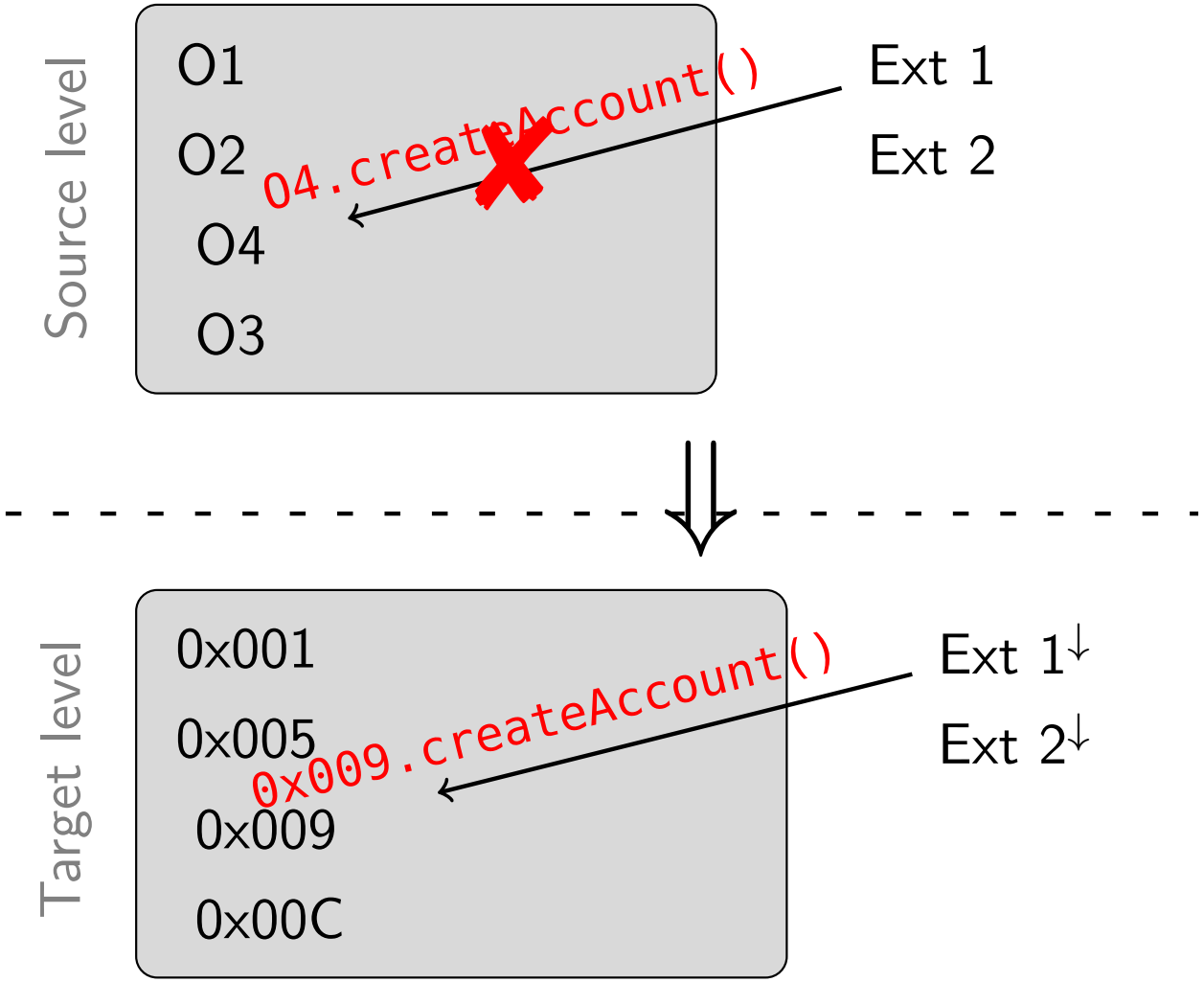
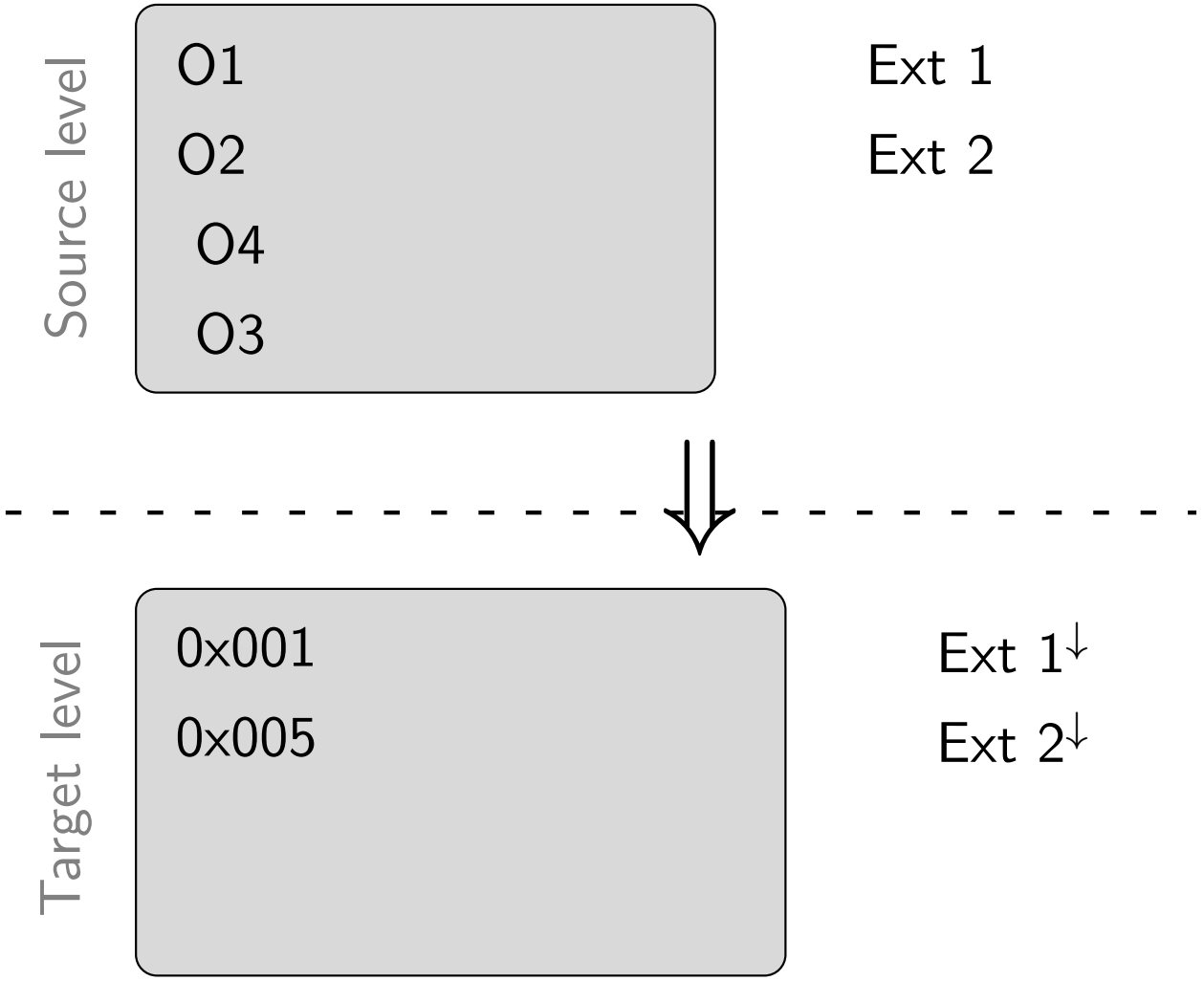


Dynamic Memory Allocation



- Object id guessing

Dynamic Memory Allocation



- Object id guessing
- map Oid to natural numbers

Dynamic Memory Allocation

Source level

O1
O2
O4
O3

Ext 1
Ext 2

$\Downarrow$

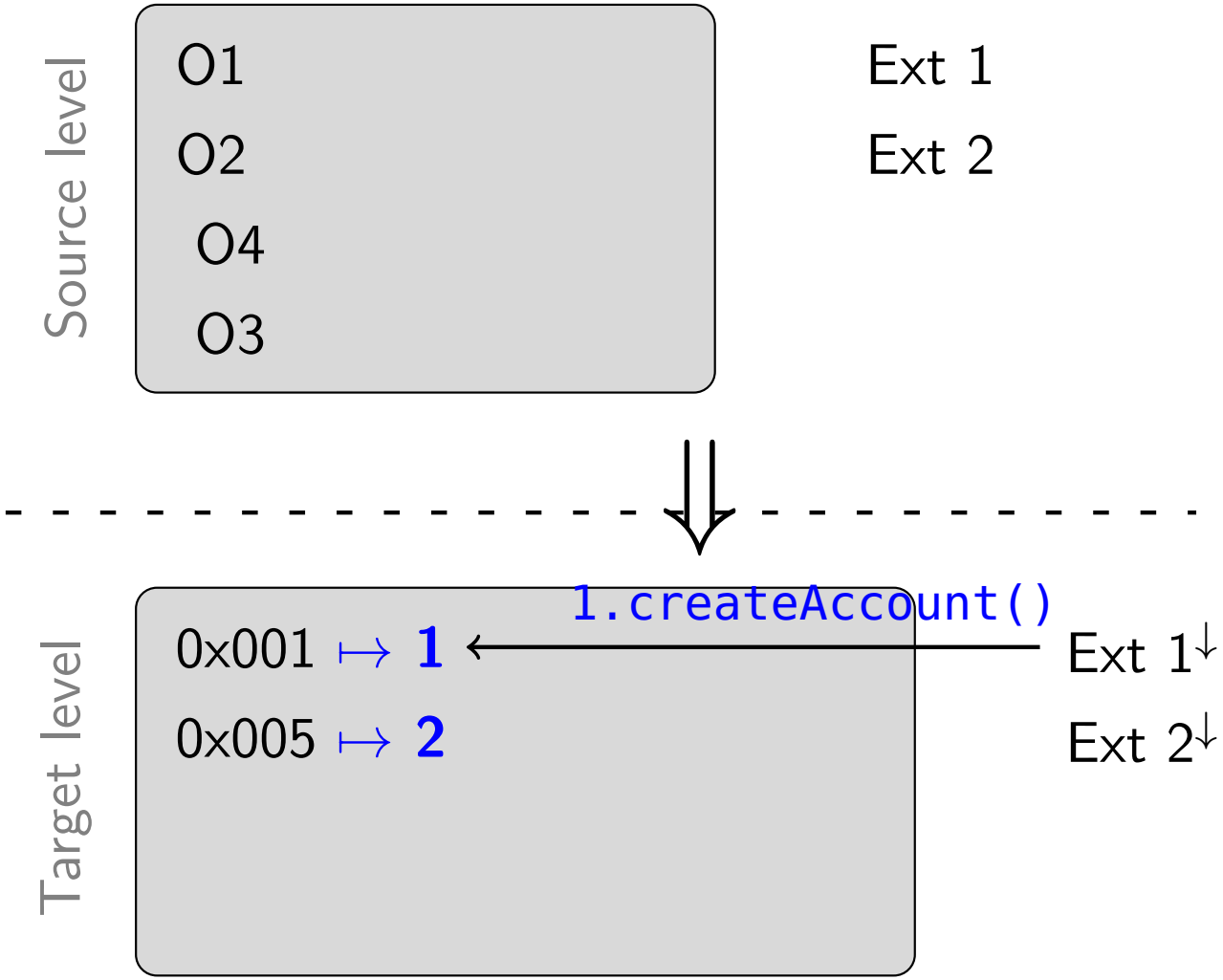
Target level

0x001 $\mapsto$ **1**
0x005 $\mapsto$ **2**

Ext $1^{\downarrow}$
Ext $2^{\downarrow}$

- Object id guessing
- map Oid to natural numbers

Dynamic Memory Allocation



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Dynamic Memory Allocation

Source level

O1
O2
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Ext 1
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Target level

0x001 $\mapsto$ **1**
0x005 $\mapsto$ **2**
0x009
0x00C

Ext $1^{\downarrow}$
Ext $2^{\downarrow}$

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Dynamic Memory Allocation

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O2
O4
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Ext 2

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Target level

0x001 $\mapsto$ **1**
0x005 $\mapsto$ **2**
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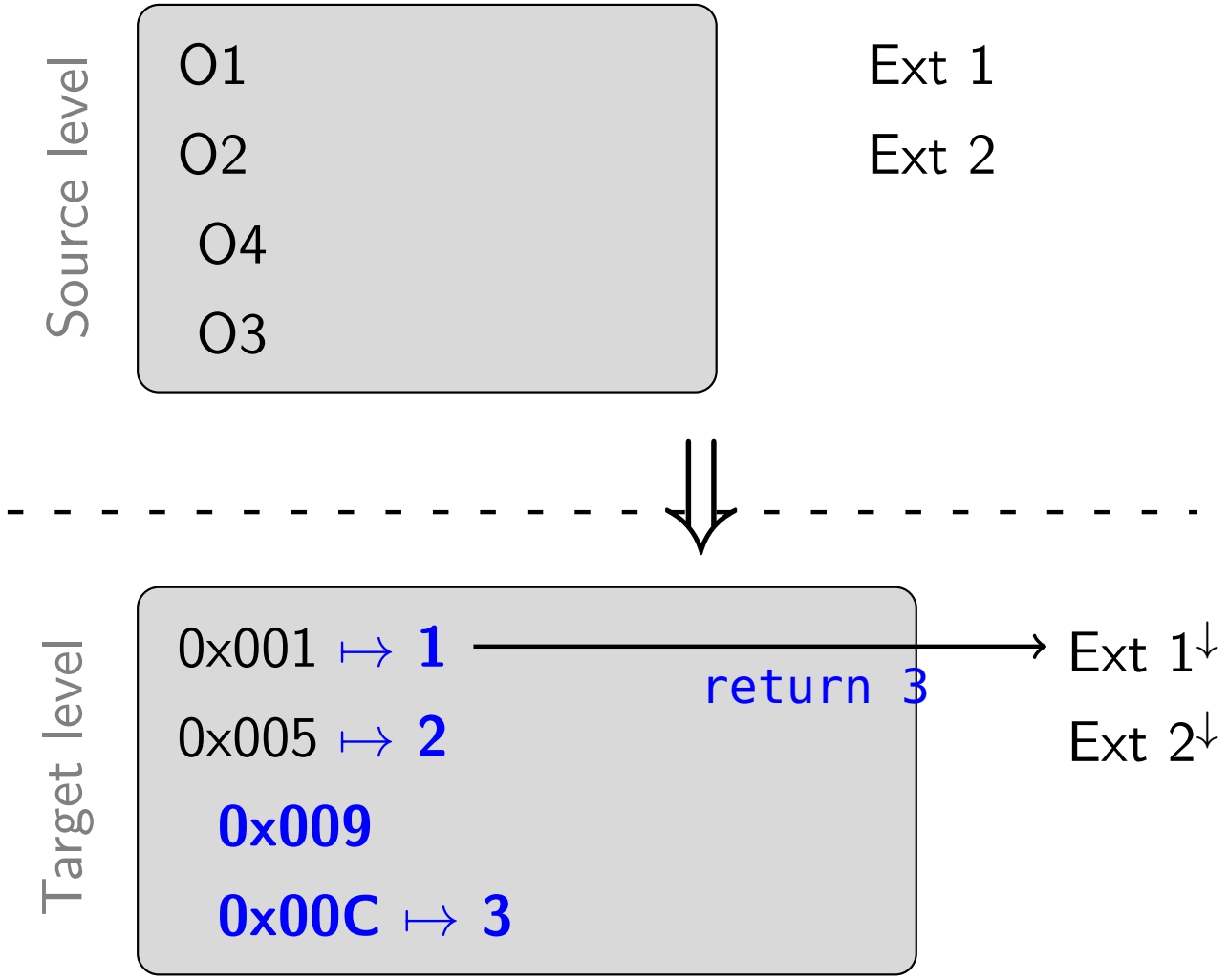
0x00C $\mapsto$ **3**

Ext $1^{\downarrow}$
Ext $2^{\downarrow}$

- Object id guessing
- map Oid to natural numbers
- add Oid to map

Dynamic Memory Allocation



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Ext $1^{\downarrow}$
Ext $2^{\downarrow}$

- Object id guessing
- map Oid to natural numbers
- add Oid to map
- lookup ($\mathbf{O}(1)$) when number is received

Dynamic Memory Allocation

Source level

O1 : Account
O2 : Pair
O4
O3

Ext 1
Ext 2

$\Downarrow$

Target level

0x001 $\mapsto$ **1**
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0x009
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Ext $1^{\downarrow}$
Ext $2^{\downarrow}$

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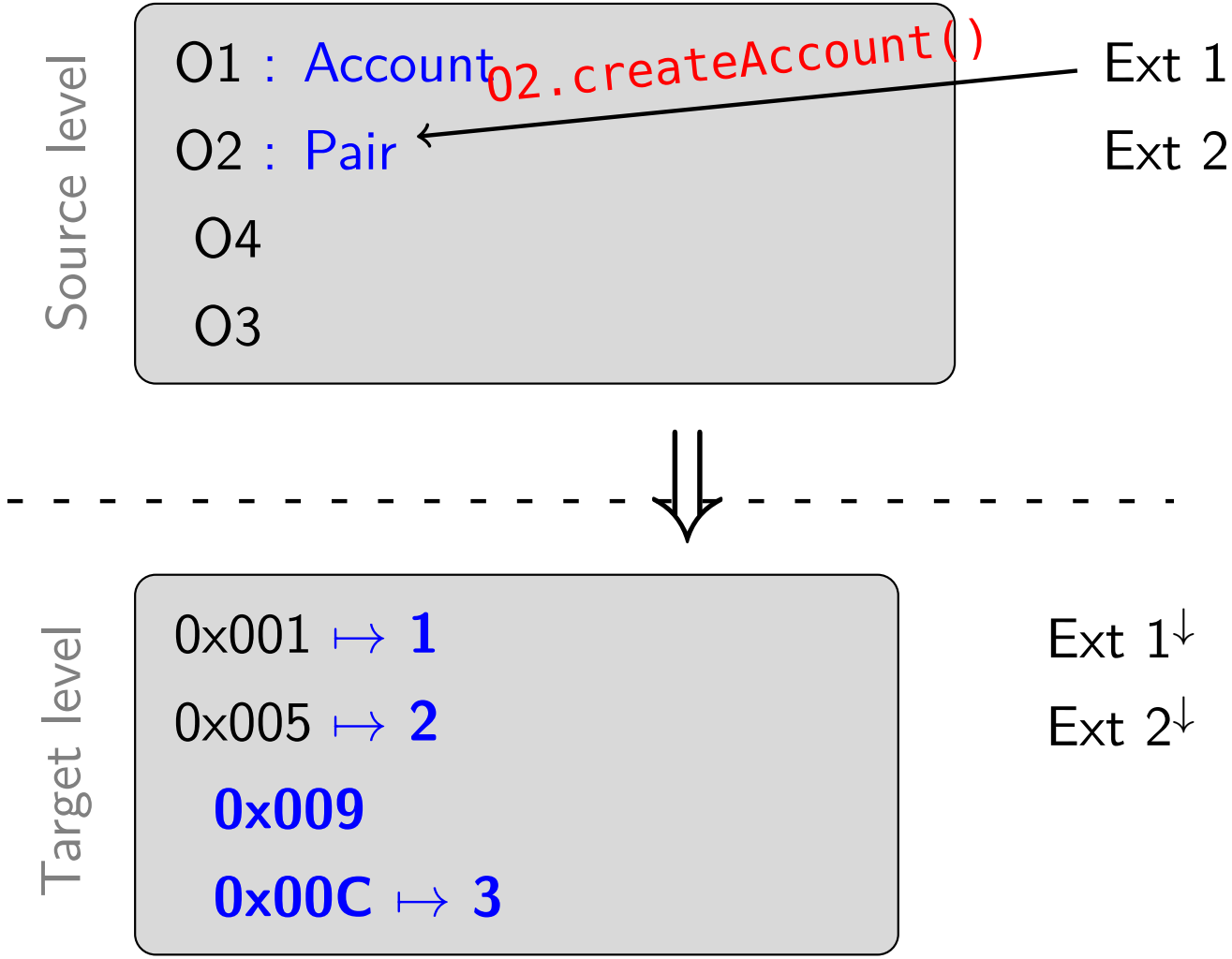

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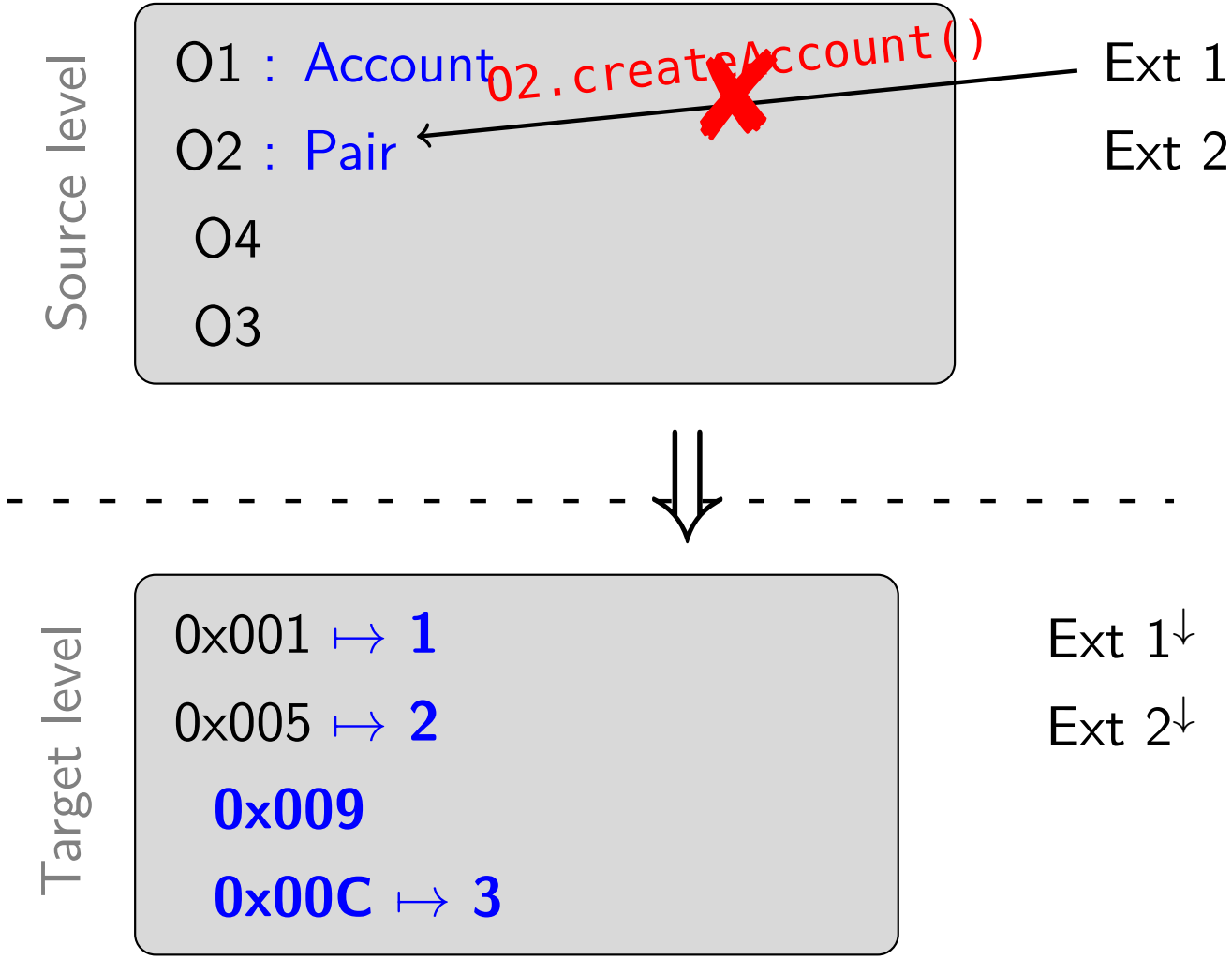

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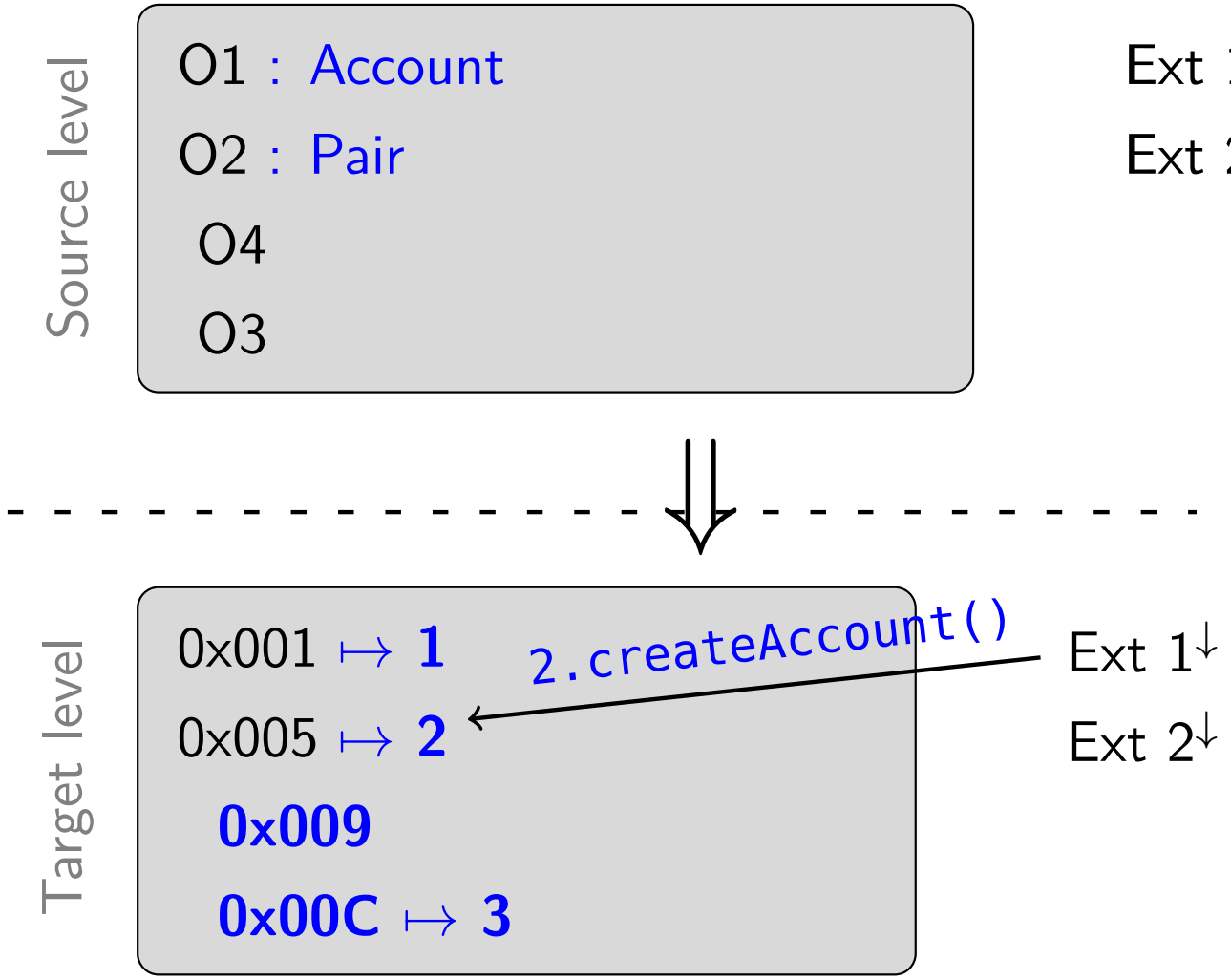

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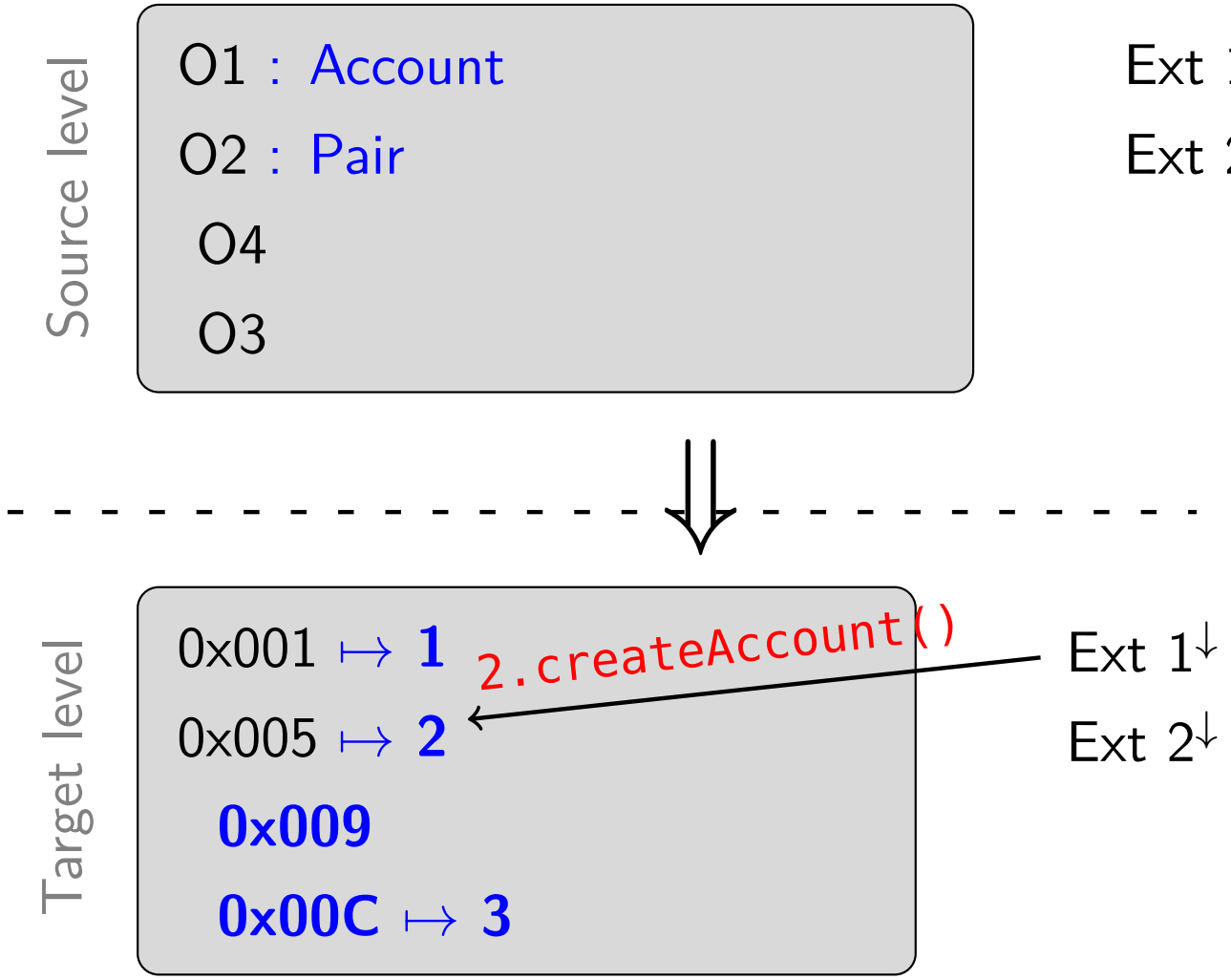
- lookup ($\mathbf{O}(1)$) when number is received
- dynamic typecheck for: current object

Dynamic Memory Allocation



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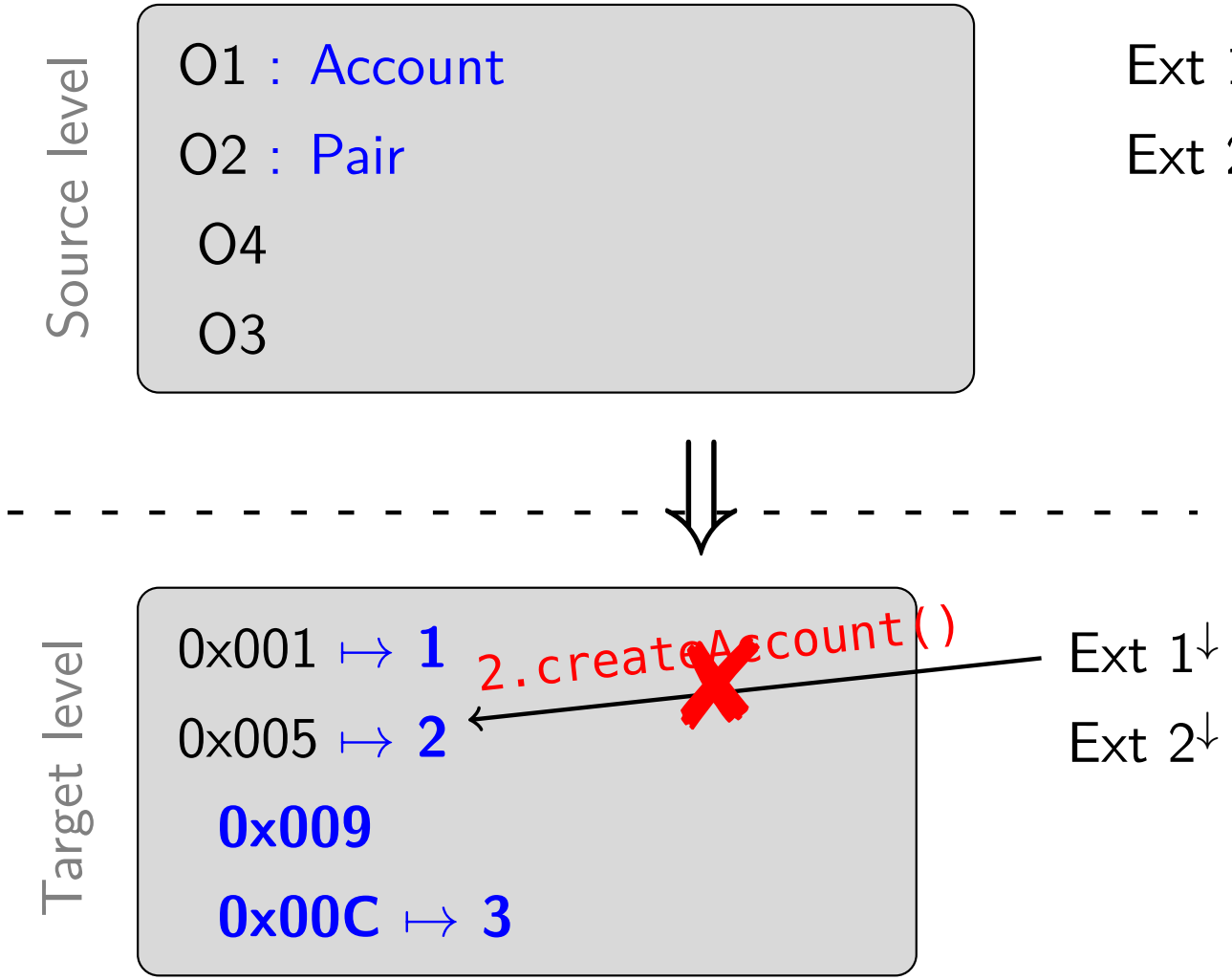
Dynamic Memory Allocation



- Object id guessing
- map Oid to natural numbers
- add Oid to map
- lookup ($\mathbf{O}(1)$) when number is received
- dynamic typecheck for: current object arguments

Why is this secure?

Source level

```
class ...
 secret = 1
```

Target level

Why is this secure?

Source level

```
class ...
 secret = 1
```

- -

Target level

```
class ...
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```

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```

Target level

```
class ...
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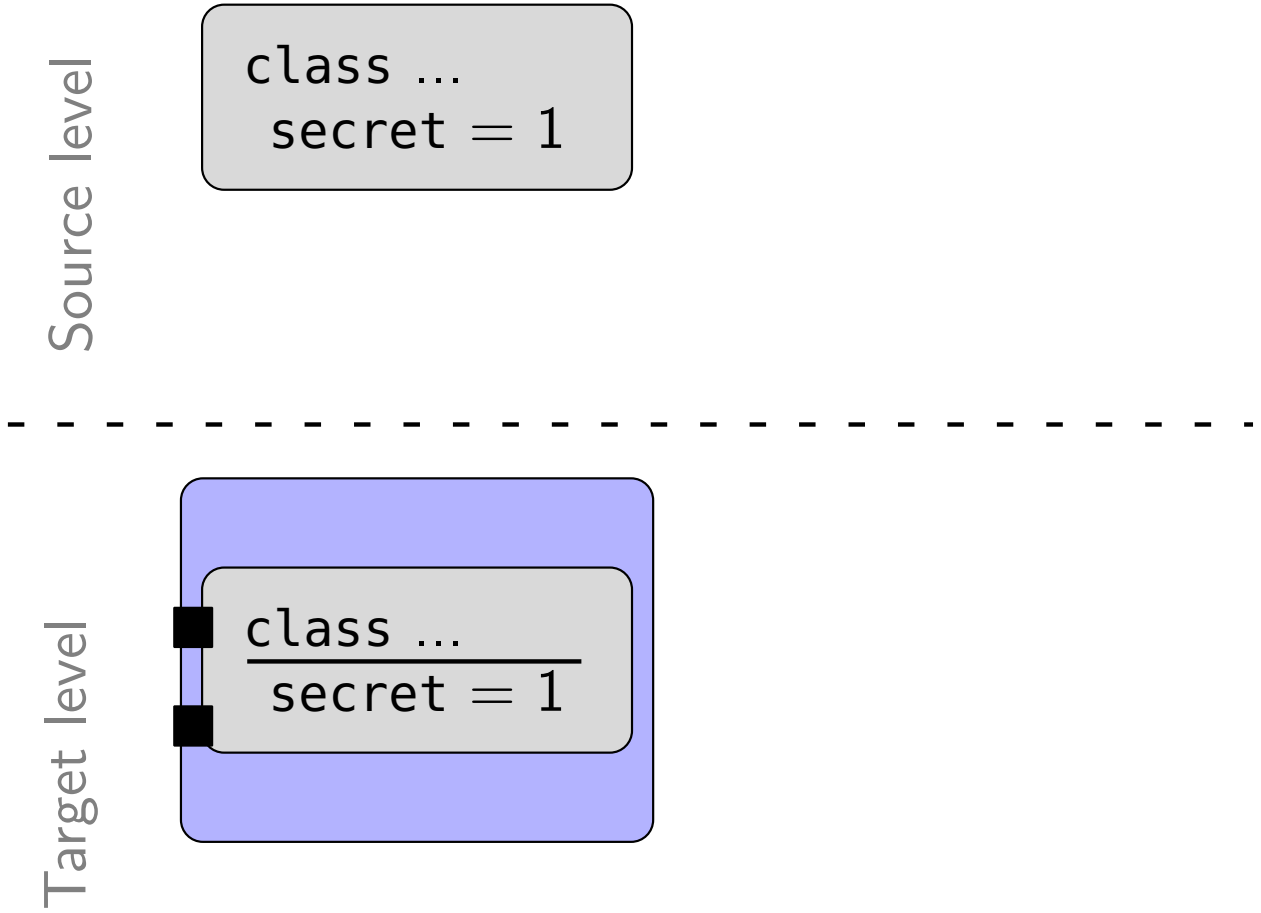
```

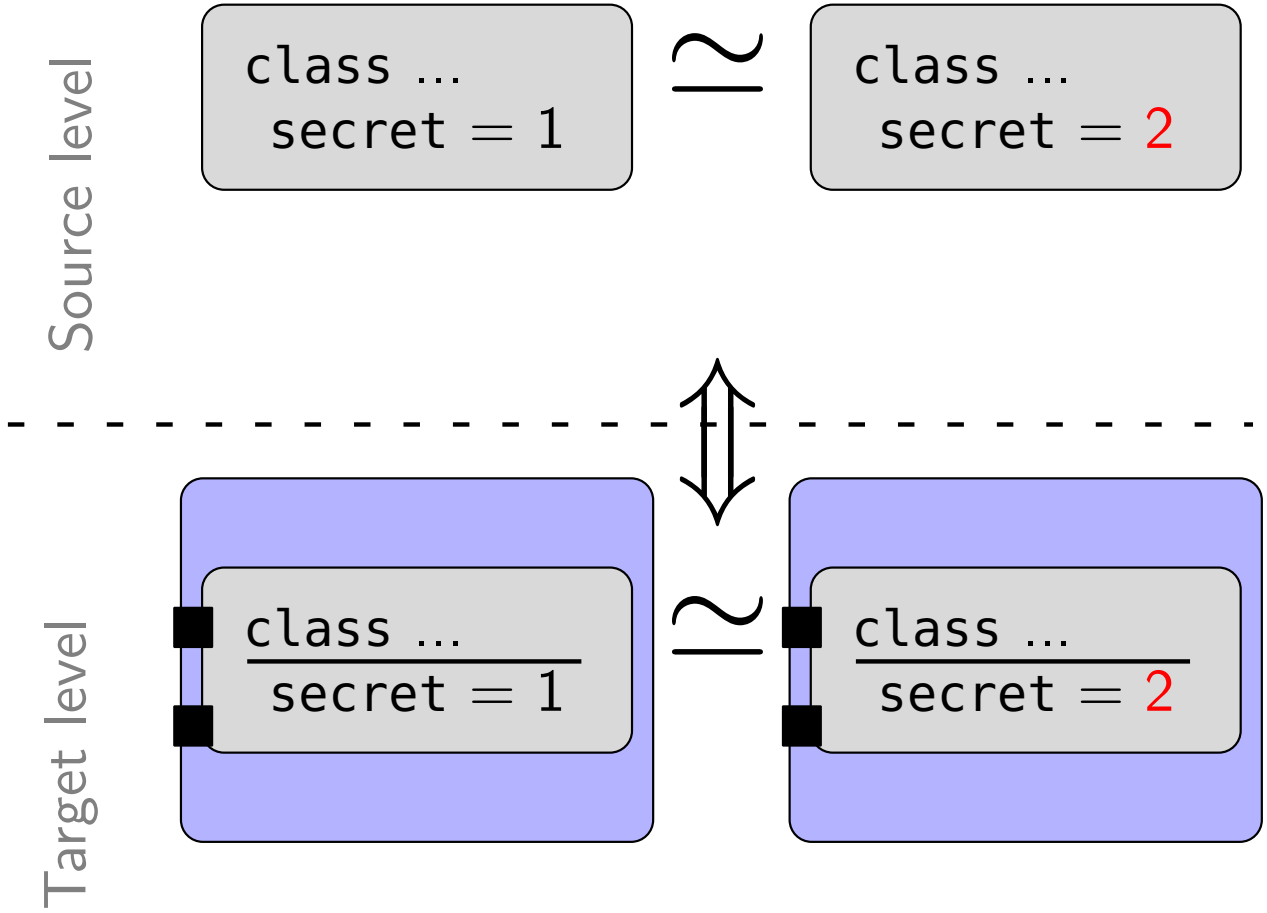
- we only add checks

Why is this secure?



- we only add checks

Why is this secure?



- we only add checks
- we need to prove full abstraction

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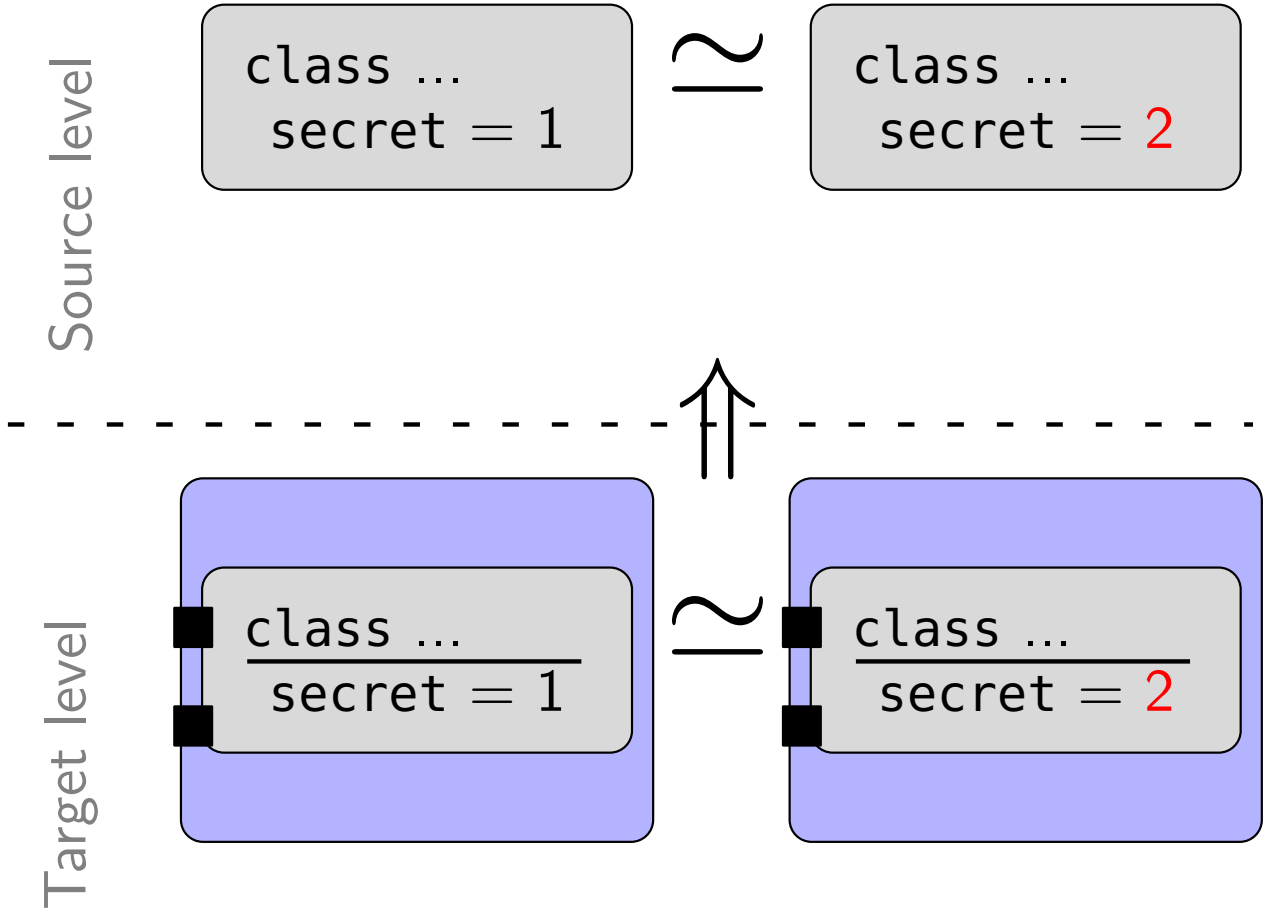

- we only add checks
- we need to prove full abstraction
- this is trivial

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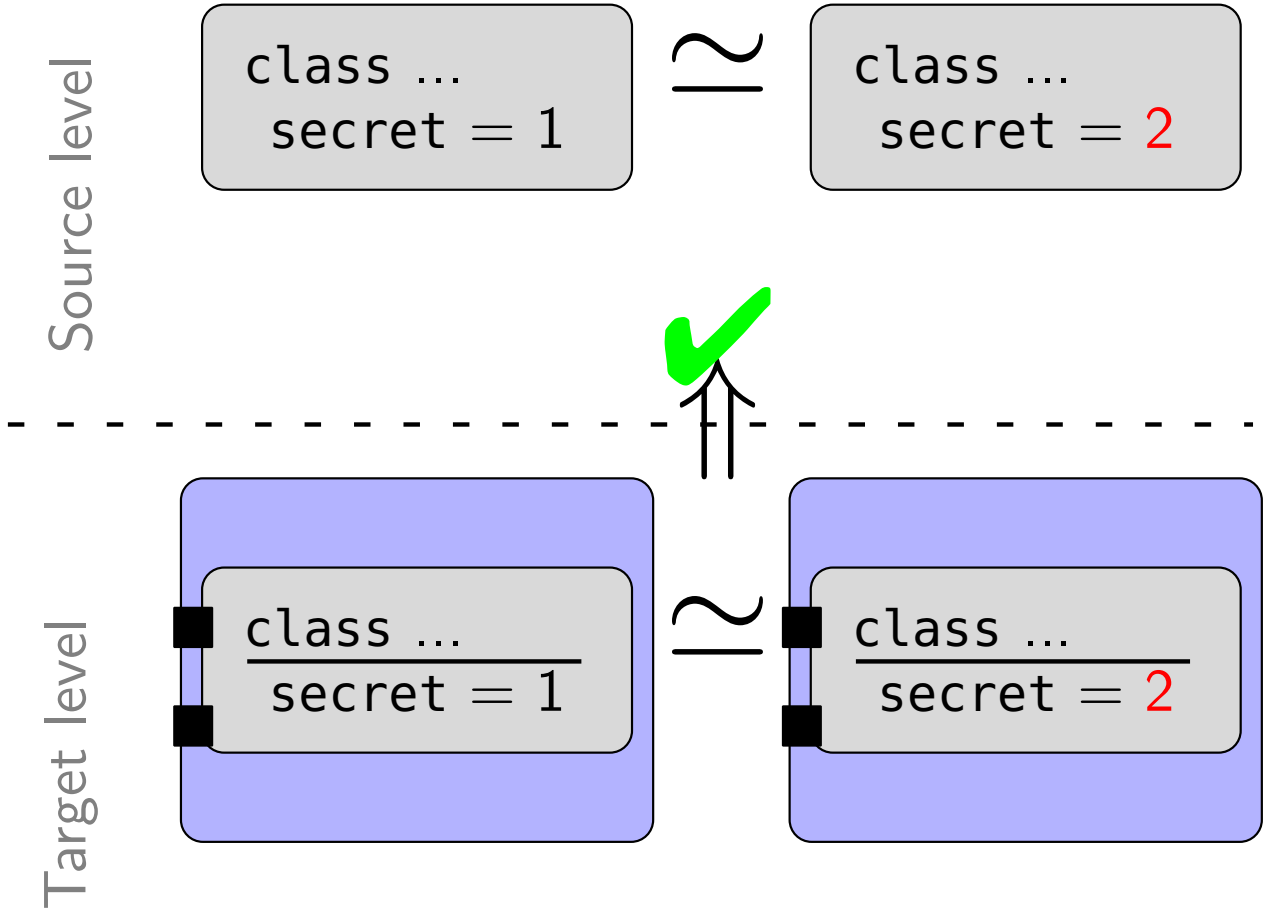

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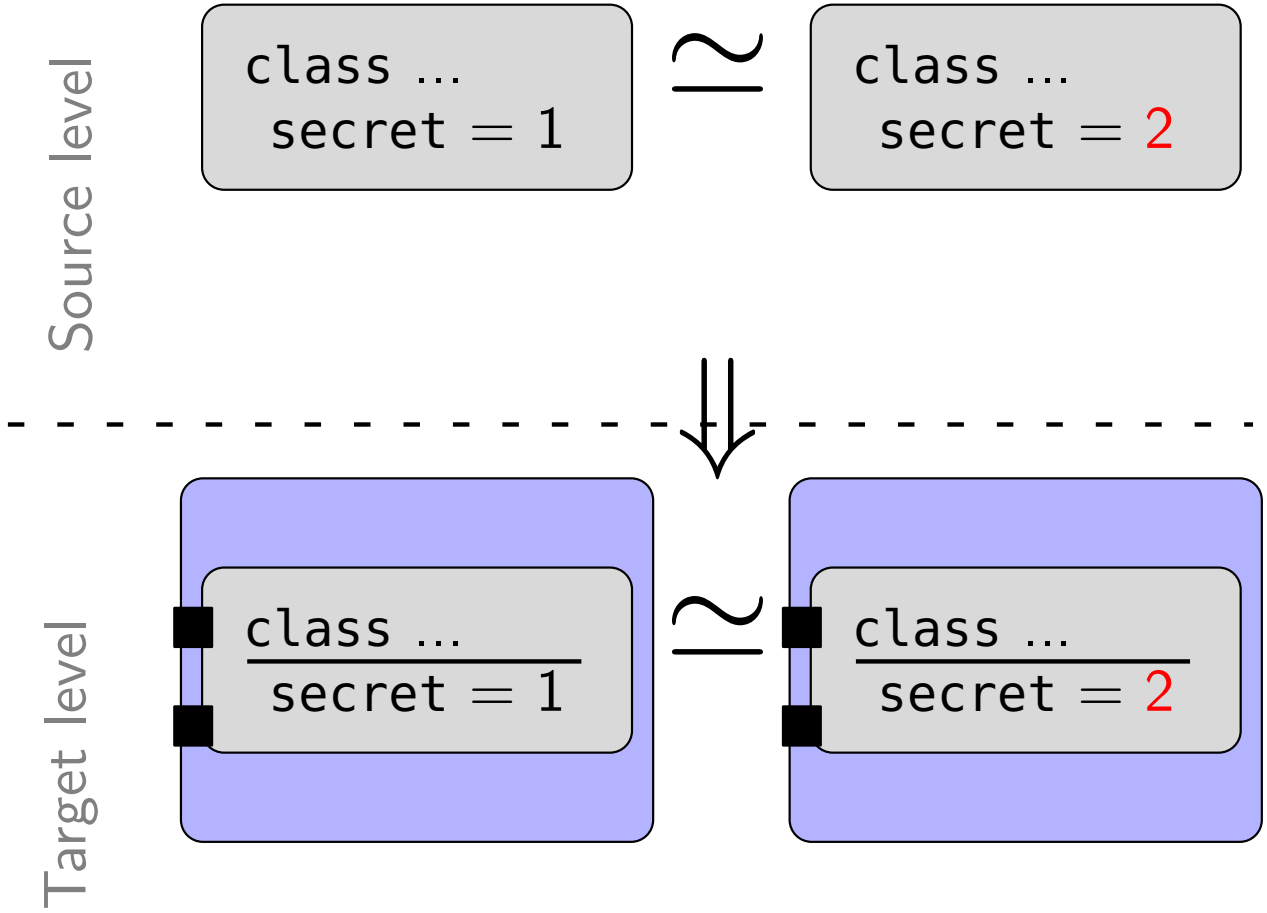

- we only add checks
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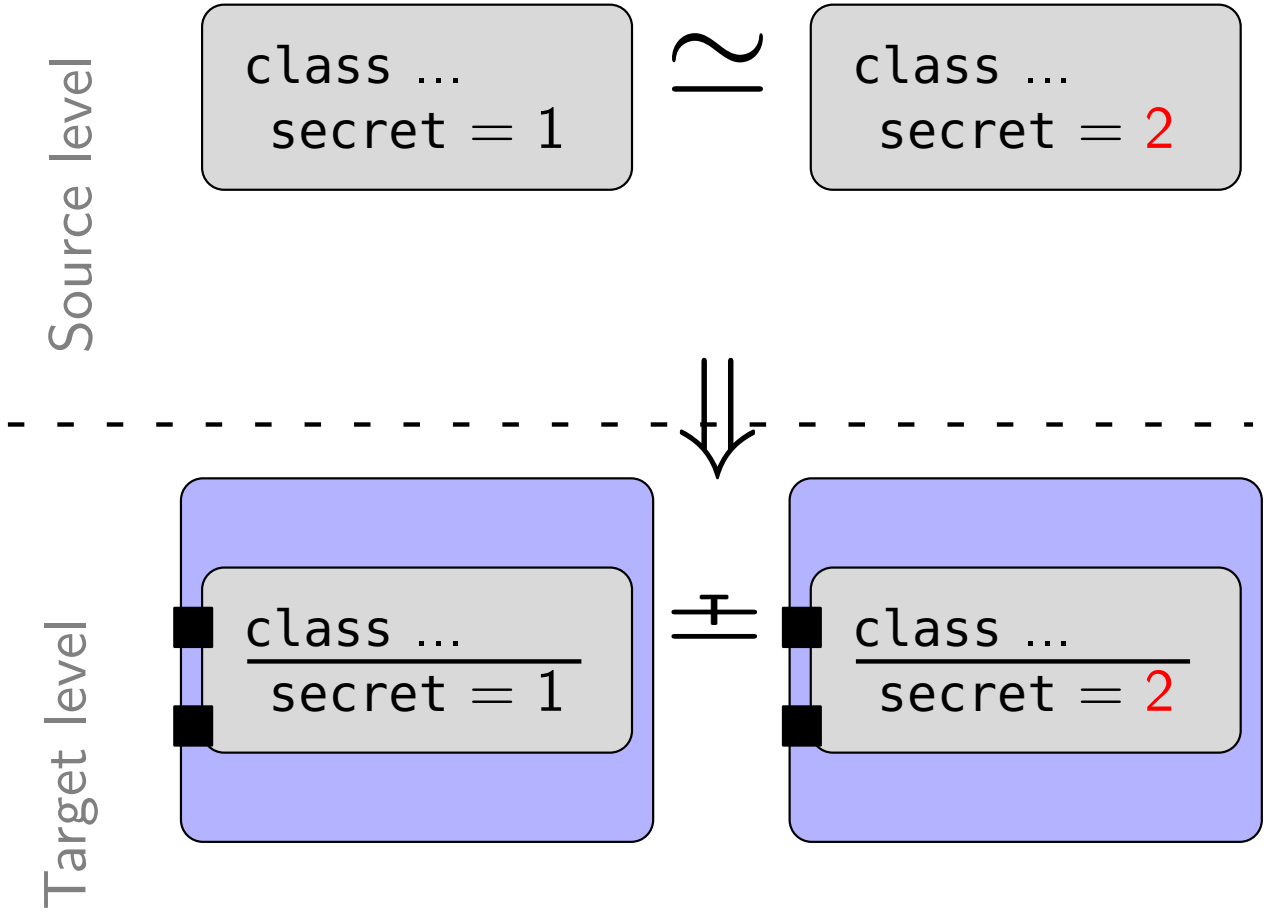
- this is **NOT**

Why is this secure?



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- but we use trace semantics

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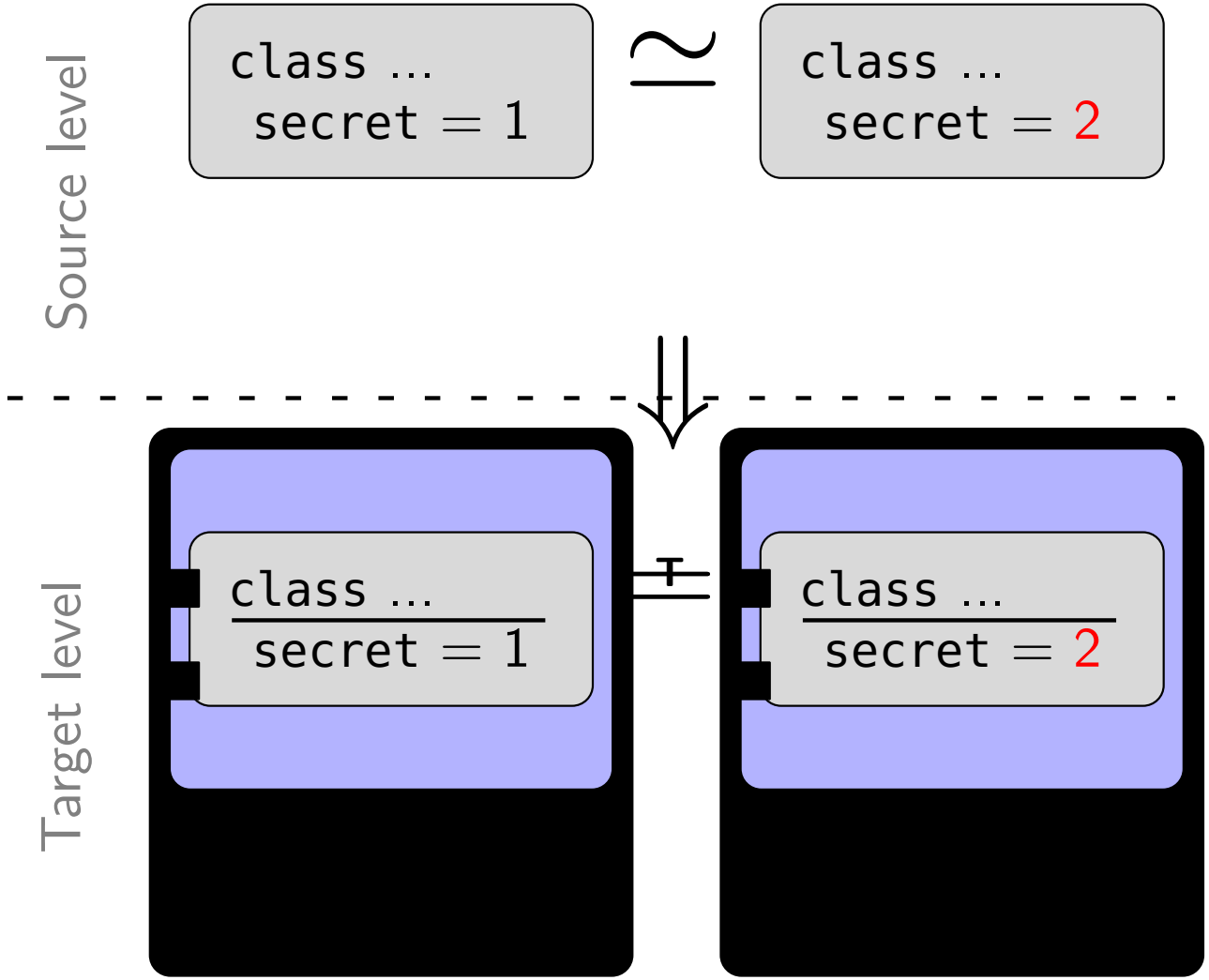

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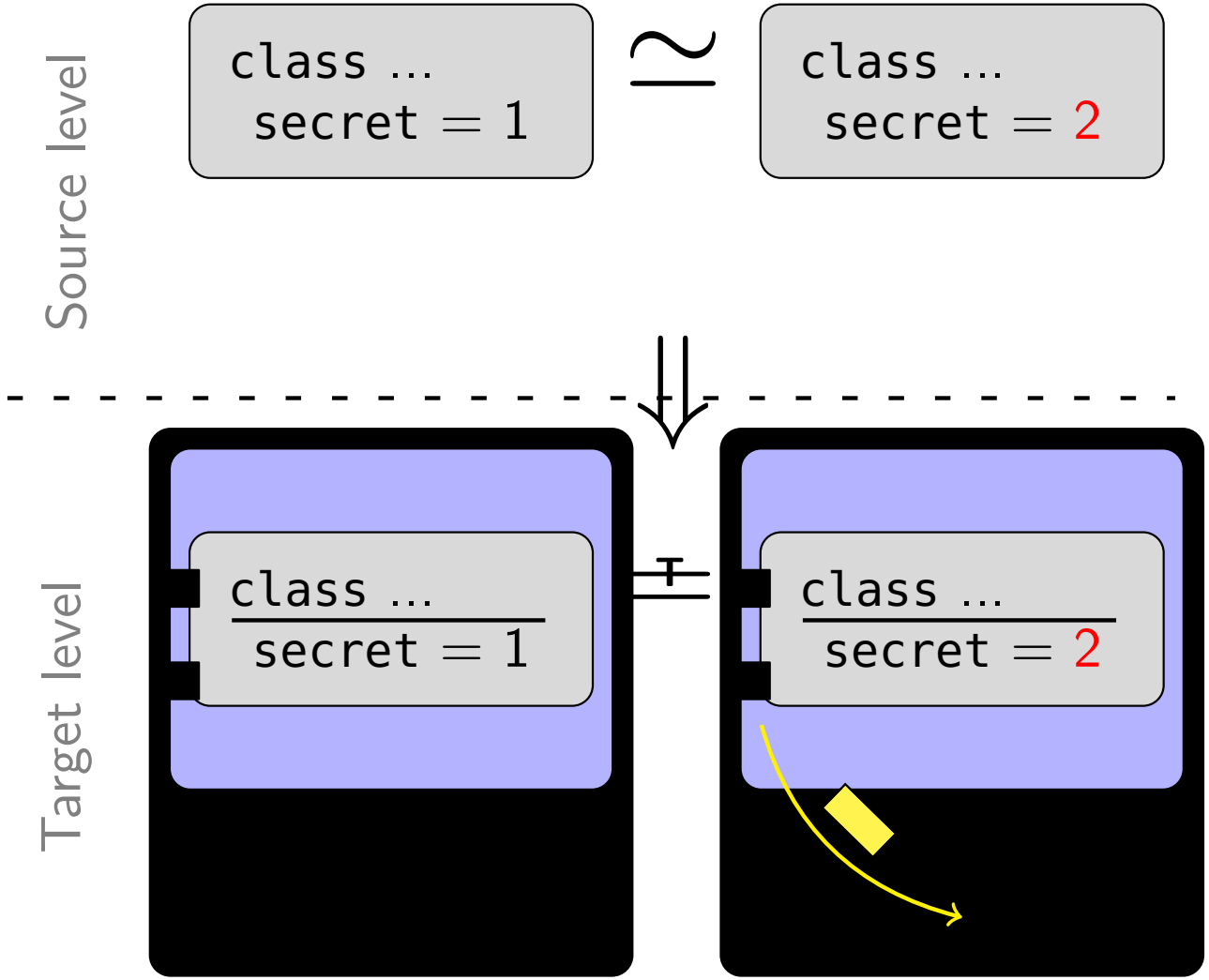

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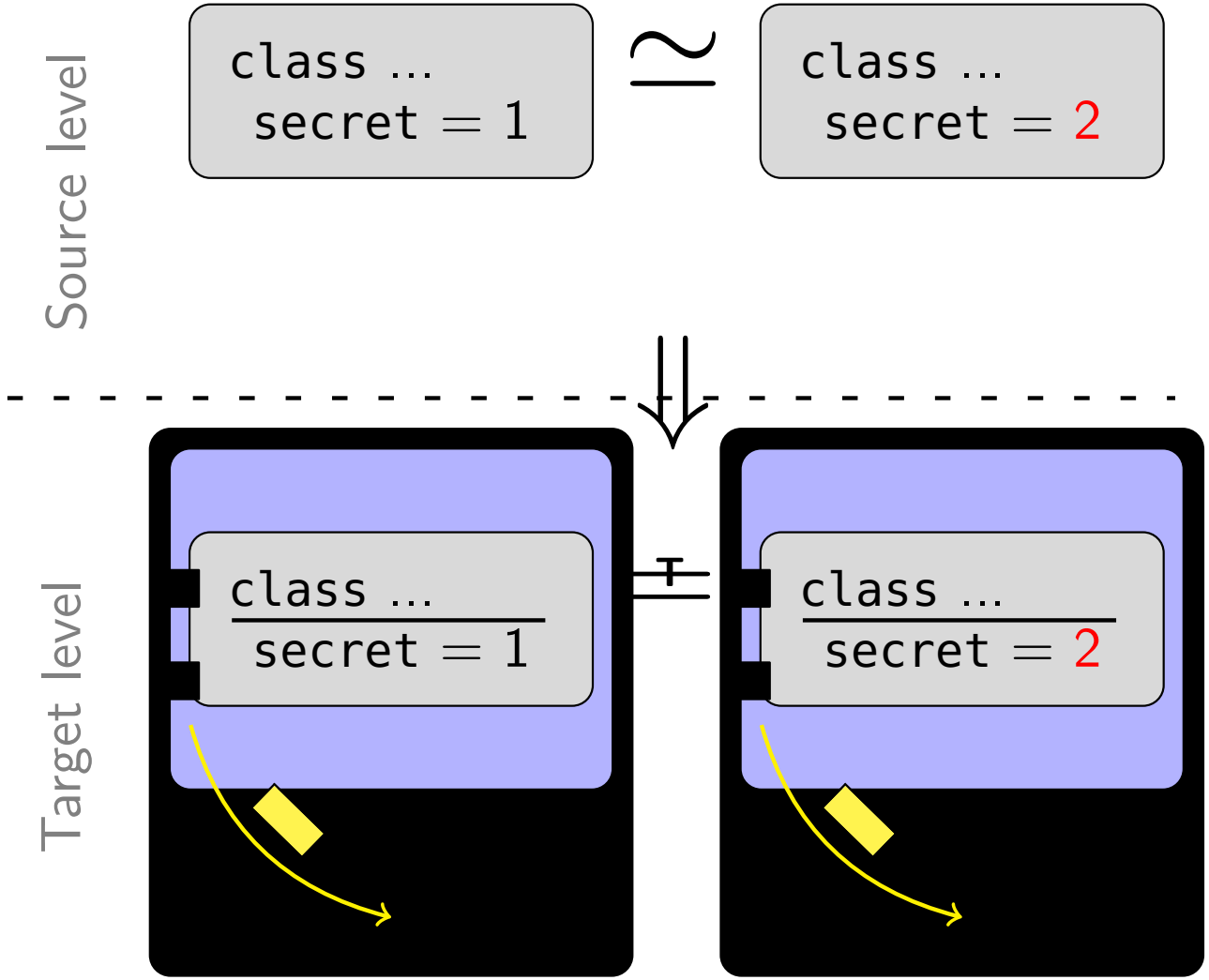

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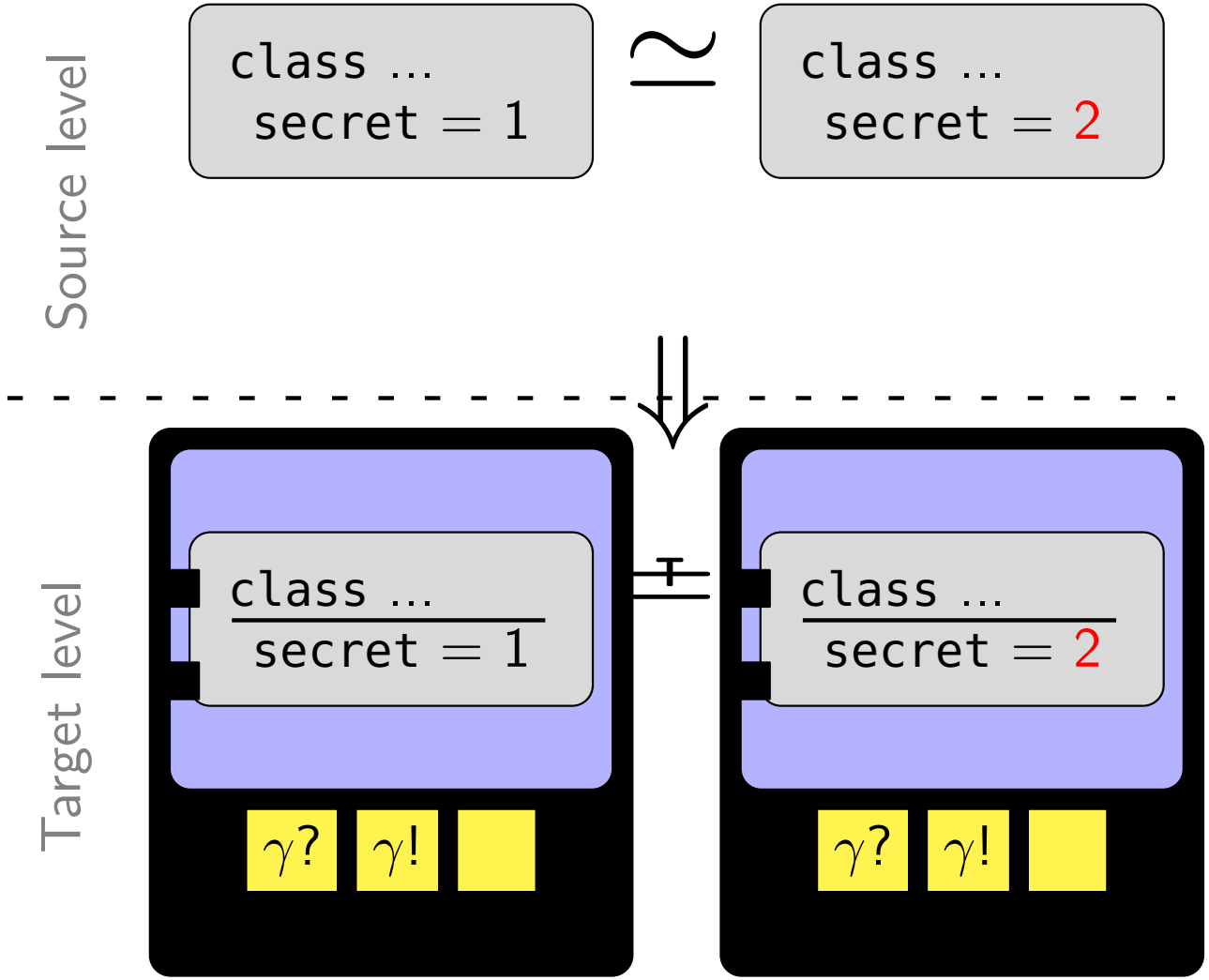

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- and prove the contrapositive

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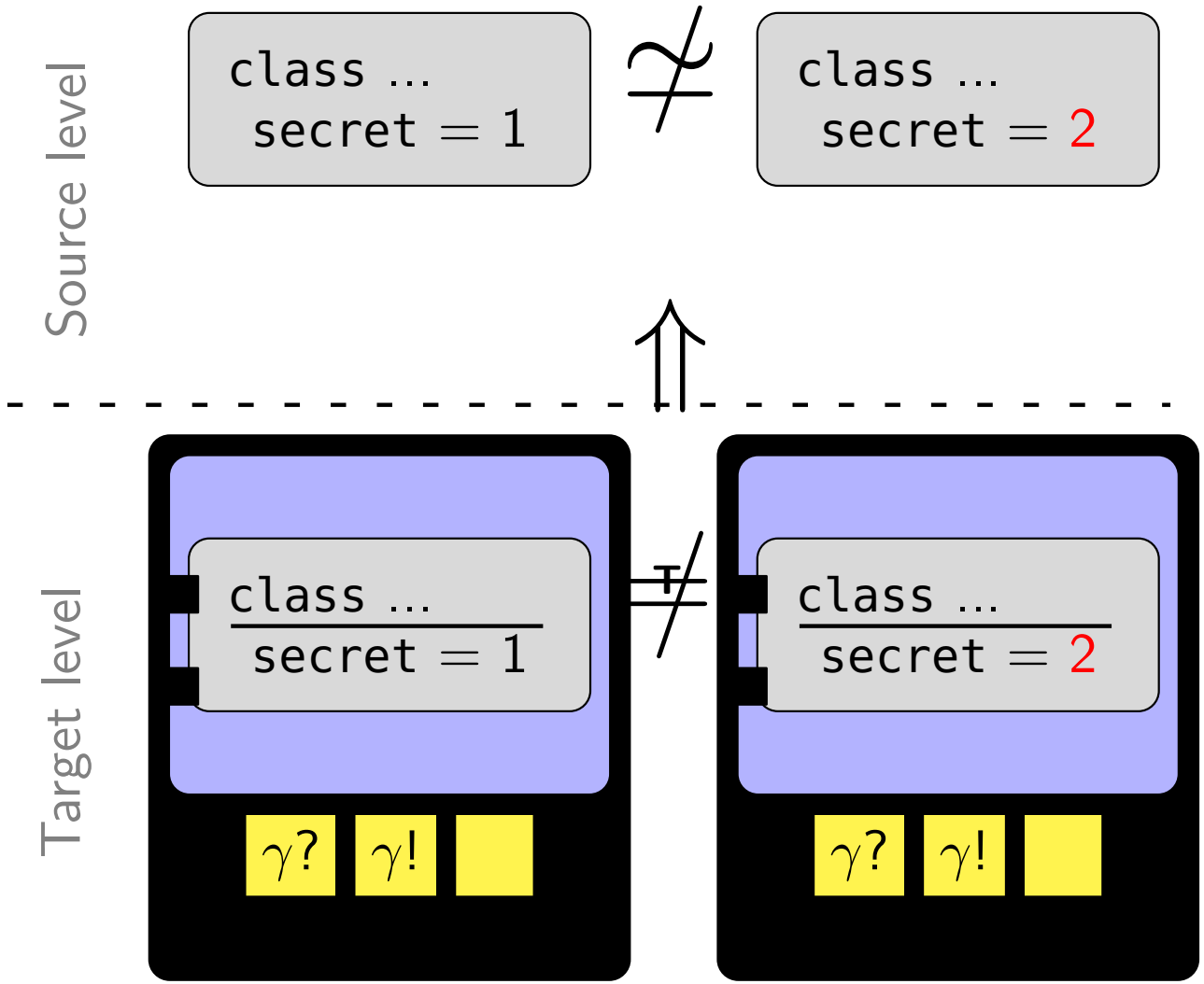

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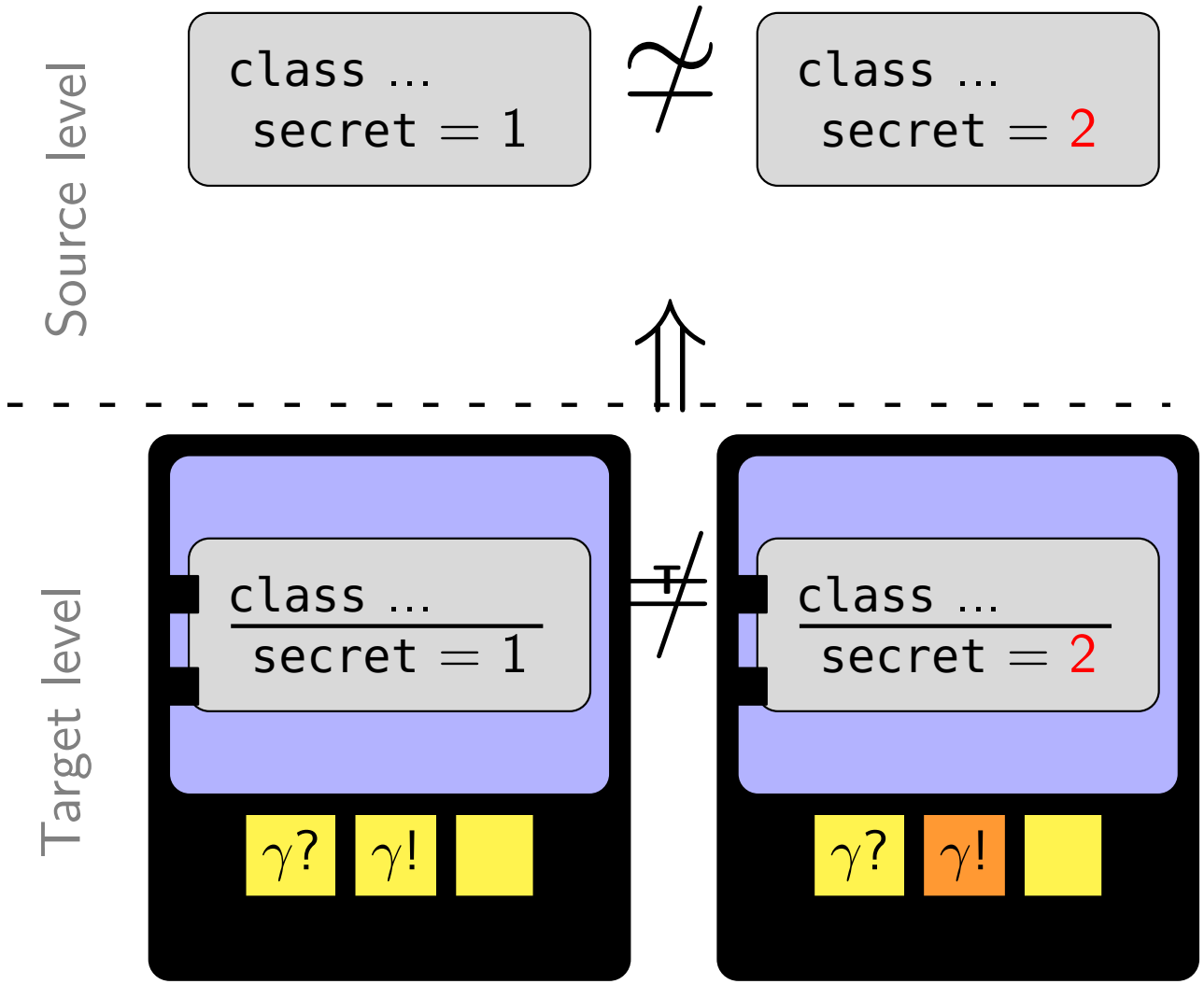

- we only add checks
- we need to prove full abstraction
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- this is **NOT**
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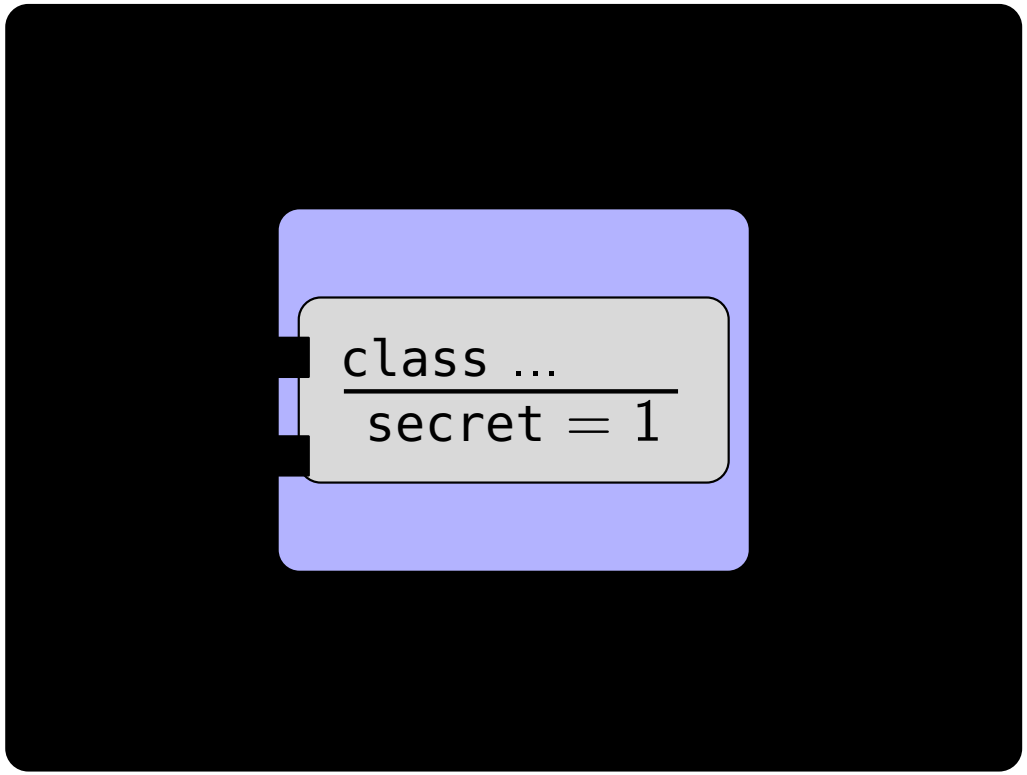
- and prove the contrapositive

Why can we do this?

Source

Target level



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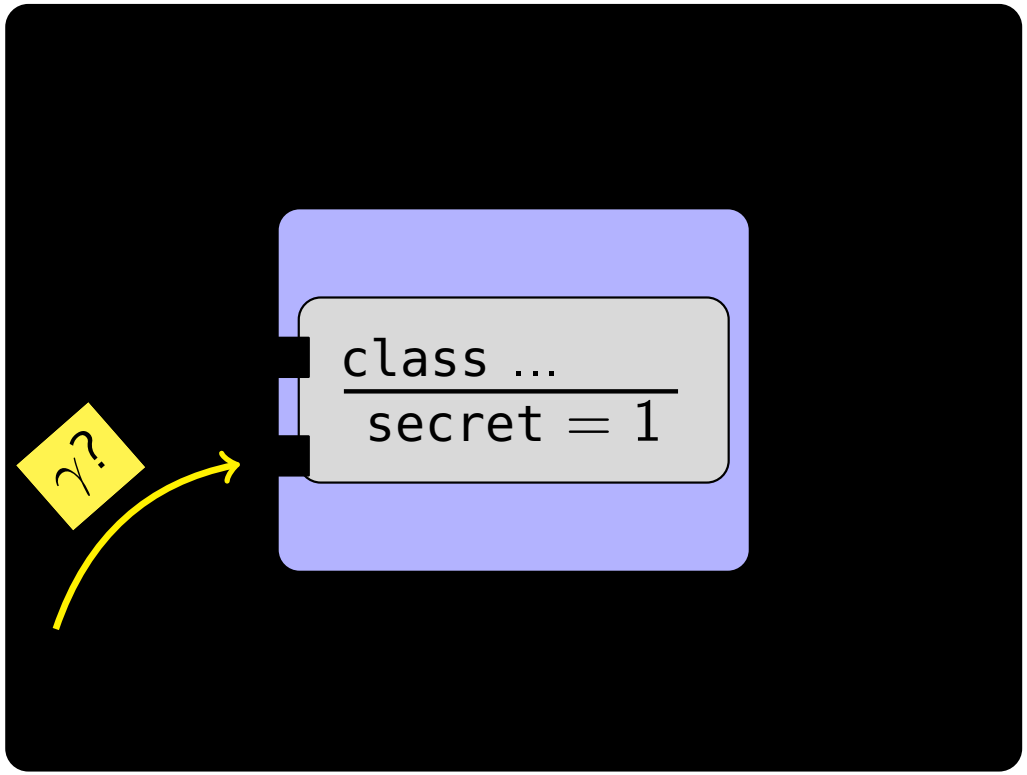
Target level



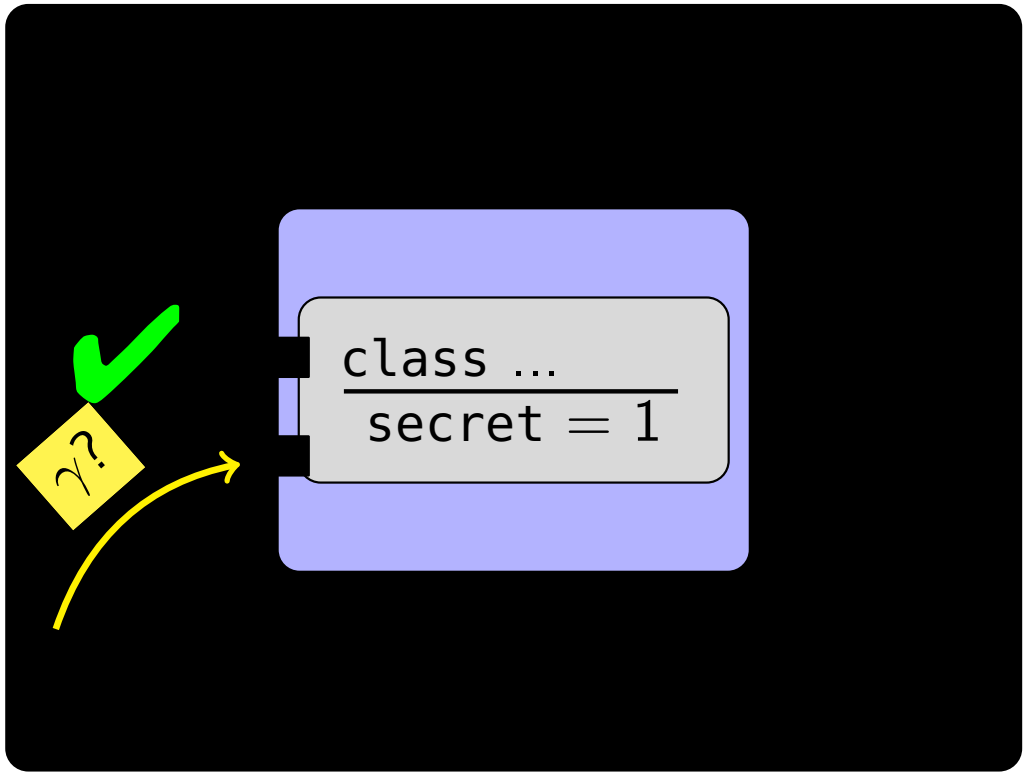
- analyse incoming traces

Why can we do this?

Source

Program $P \approx \gamma$?

Target level

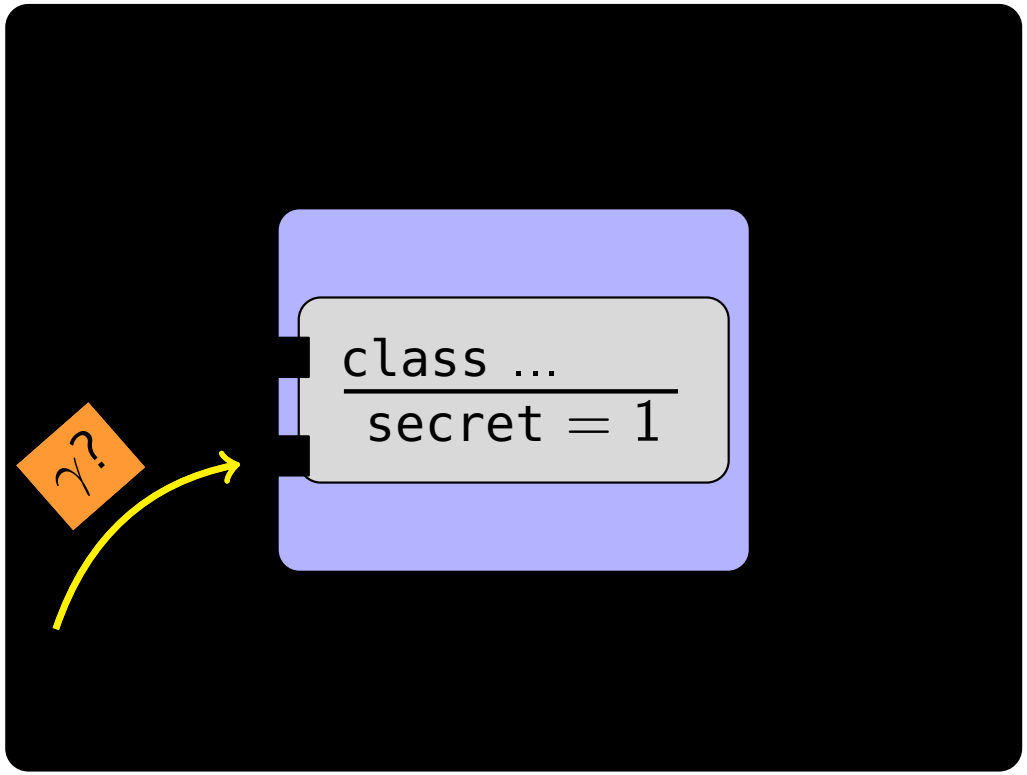


- analyse incoming traces
- let the *good* ones is

Why can we do this?

Source

Target level



- analyse incoming traces
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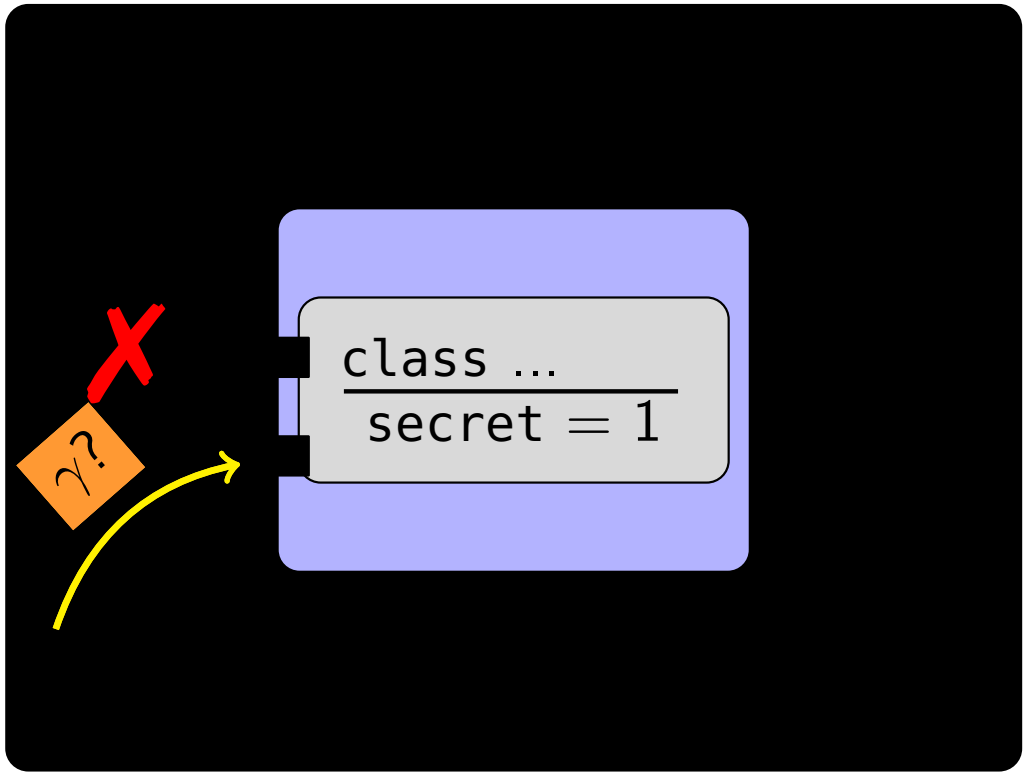
Source

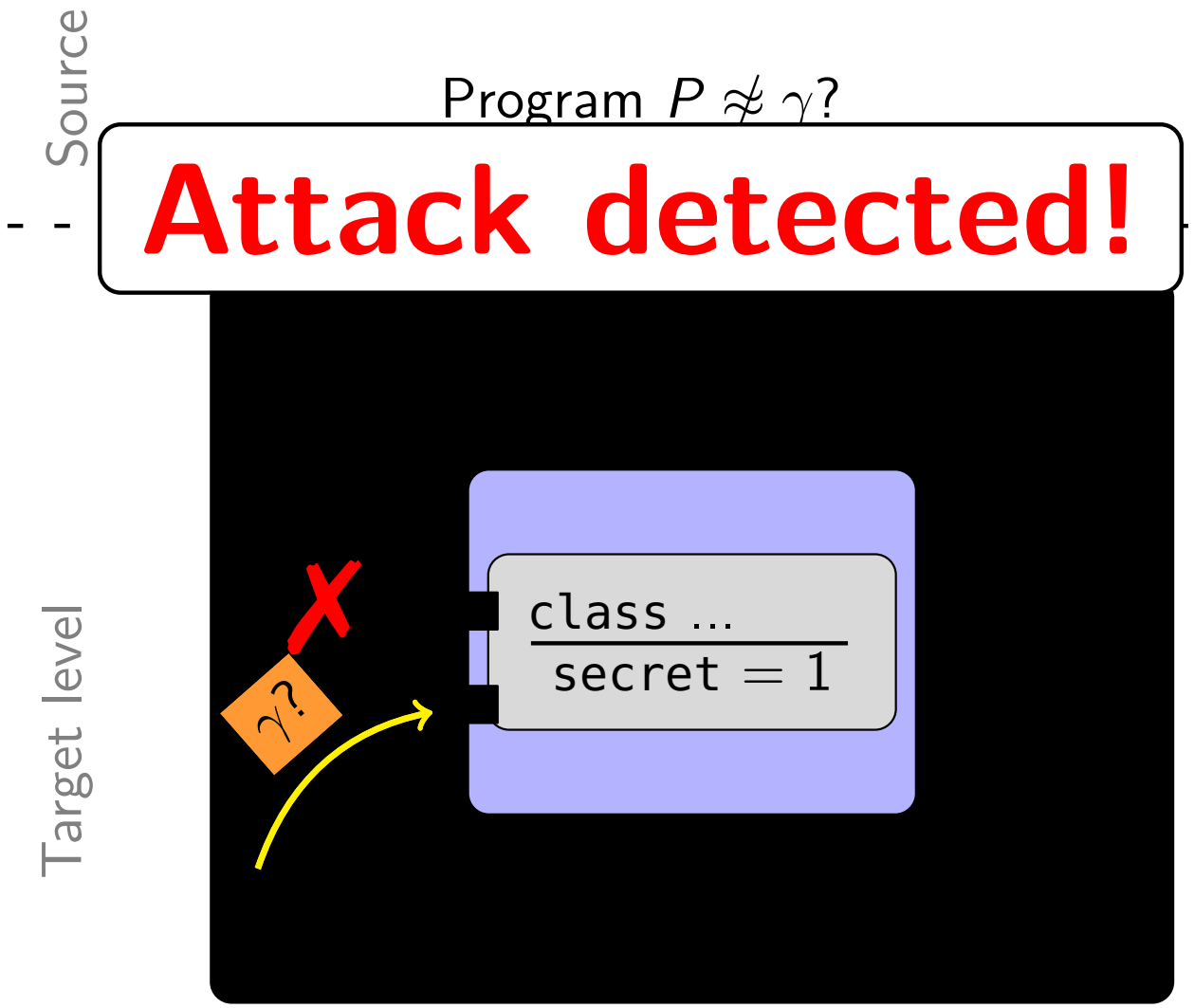
Program $P \not\approx \gamma$?

Target level



- analyse incoming traces
- let the *good* ones is
- block the *bad* ones

Why can we do this?



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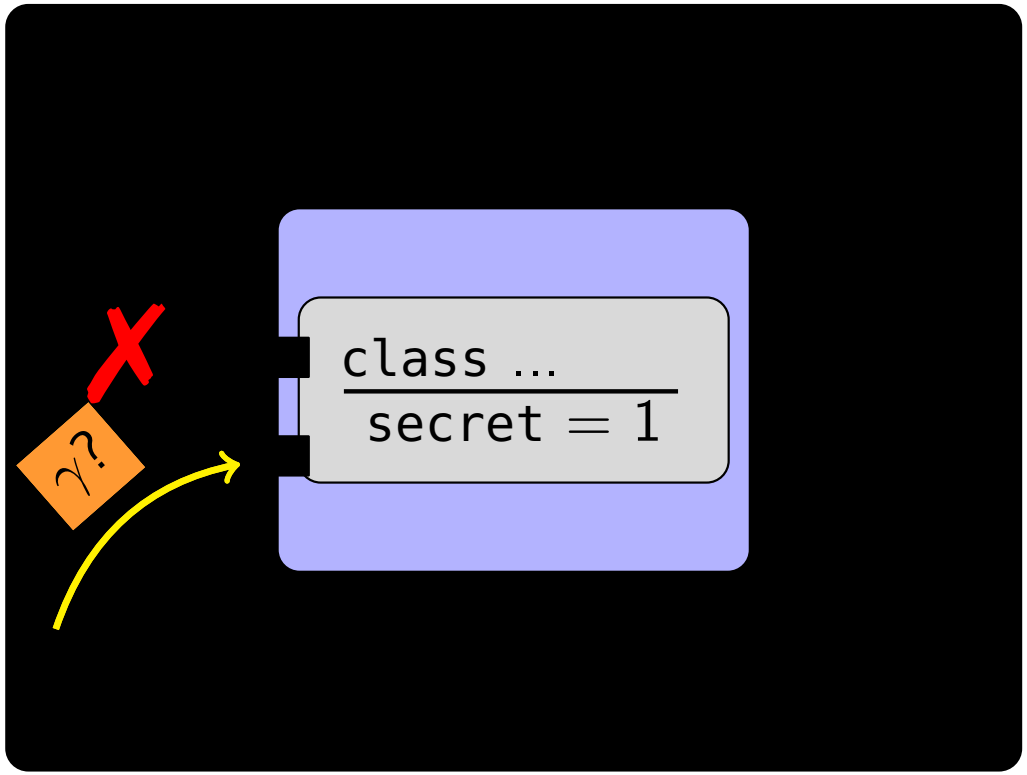

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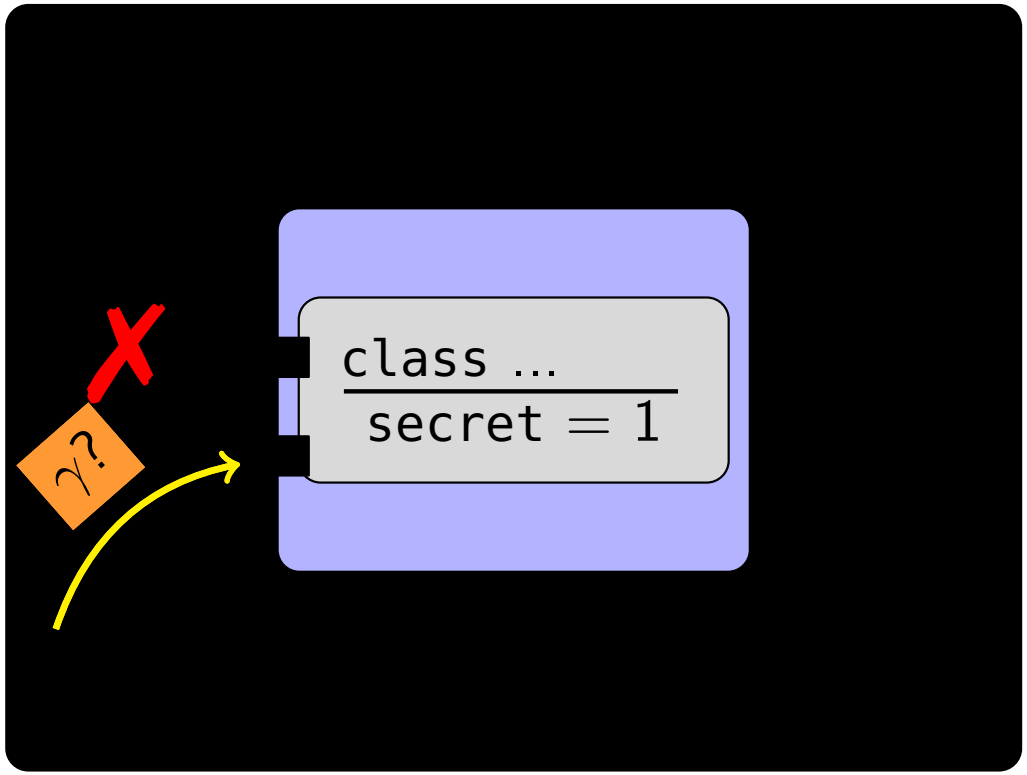

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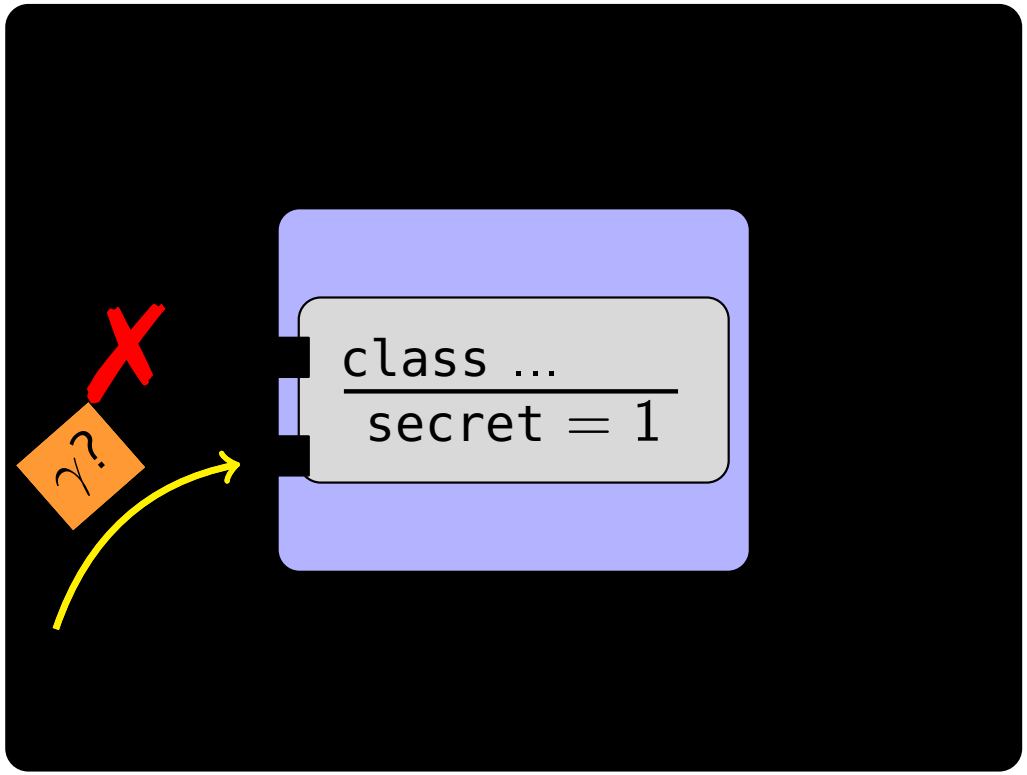

- analyse incoming traces
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Secure Compilation with Equivalence classes

Equivalence classes!!

Conclusion

- PMA is an interesting security architecture

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- you can reason about it with simple traces

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Conclusion

Thank you!

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Conclusion

Thank you!

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Qs ?

Compiler compositionality

Labels of $\text{Traces}^{\mathsf{L}}_{\mathsf{A+I}}$

Labels	$\mathfrak{l} ::= \tau \mid \mathfrak{a}$
Observable actions	$\mathfrak{a} ::= \mathfrak{g}? \mid \mathfrak{d}! \mid \surd$
Actions	$\mathfrak{g} ::= \texttt{call}\ p(r; f) \mid \texttt{ret}\ p(r; f)$
Prefixable actions	$\mathfrak{d} ::= \mathfrak{g} \mid \mathfrak{o}(a, v).\mathfrak{d}$
Prefixes	$\mathfrak{o} ::= \texttt{read} \mid \texttt{write}$

Labels of Traces^{S}_{A+I}

Labels	$\lambda ::= \tau \mid \alpha$
Observable actions	$\alpha ::= \gamma? \mid \gamma! \mid \surd$
Actions	$\gamma ::= \texttt{call}\ \overline{v} \mid \texttt{ret}\ p\ v$

StripNI(·,)

$$
\begin{aligned}
\mathsf{StripNI}(\Theta, \mathfrak{g}) &= \mathfrak{g} \\
\mathsf{StripNI}(\Theta, \mathtt{write}(a, v)\mathfrak{d}) &= \mathtt{write}(a, v)\mathfrak{d}' \\
&\quad \text{if } \mathsf{StripNI}(\Theta, \mathfrak{d}) = \mathfrak{d}' \\
\mathsf{StripNI}(\Theta, \mathsf{read}(a, v)\mathfrak{d}) &= \mathfrak{d}' \\
&\quad \text{if } \mathsf{StripNI}(\Theta, \mathfrak{d}) = \mathfrak{d}' \text{ and } \mathsf{NI}(\Theta, a) \\
\mathsf{StripNI}(\Theta, \mathsf{read}(a, v)\mathfrak{d}) &= \mathsf{read}(a, v)\mathfrak{d}' \\
&\quad \text{if } \mathsf{StripNI}(\Theta, \mathfrak{d}) = \mathfrak{d}' \text{ and } \neg\mathsf{NI}(\Theta, a)
\end{aligned}
$$

NI(·)

$$\begin{aligned}\mathsf{NI}(\Theta, a) \triangleq \forall v, w. \quad & \Theta \overset{\mathfrak{a}_1}{\Longrightarrow} \Theta' \text{ and } \Theta \overset{\mathfrak{a}_2}{\Longrightarrow} \Theta'' \\ & \text{and } \mathfrak{a}_1 = \overline{\mathfrak{o}(a', v')}\mathsf{read}(a, v)\mathfrak{d}! \\ & \text{and } \mathfrak{a}_2 = \overline{\mathfrak{o}(a', v')}\mathsf{read}(a, w)\mathfrak{d}! \\ & \text{and } \mathsf{Tr\text{-}state}(\Theta') = \mathsf{Tr\text{-}state}(\Theta'')\end{aligned}$$

Definitions

Definition (Contextual equivalence for A+I)

Definition (Fully abstract trace semantics for A+I)

Given that $\mathsf{Traces}^{\mathsf{L}}_{\mathsf{A+I}}(P) = \mathsf{Tr\text{-}state}(\Theta_0(P))$,
$P_1 \simeq^{\mathsf{A+I}} P_2 \iff P_1 \stackrel{\mathsf{T}}{=}^{\mathsf{A+I}} P_2$

Definition (Fully abstract compilation)

For any two source-level components C_1 and C_2, we have:
$C_1 \simeq^{\mathsf{J+E}} C_2 \iff [\![C_1]\!]^{\mathsf{J+E}}_{\mathsf{A+I}} \simeq^{\mathsf{A+I}} [\![C_2]\!]^{\mathsf{J+E}}_{\mathsf{A+I}}$.

Randomisation and Program Equivalence for AIM

Definition (Contextual preorder for AIM)

$$P_1 \sqsubseteq^{\mathsf{AIM}}_{\sim\sigma} P_2 \triangleq \mathtt{Pr}(\forall \mathbb{P},\ O_1.\ \exists O_2.\ \ \mathbb{P}[P_1, O_1]\Uparrow \iff \mathbb{P}[P_2, O_2]\Uparrow) > \sigma.$$

Definition (Contextual equivalence for AIM)

$$P_1 \simeq^{\mathsf{AIM}}_{\sigma} P_2 \triangleq P_1 \sqsubseteq^{\mathsf{AIM}}_{\sim\sigma} P_2 \text{ and } P_2 \sqsubseteq^{\mathsf{AIM}}_{\sim\sigma} P_1.$$

Definition (Trace equivalence for AIM)

$$P_1 \overset{\mathsf{T}}{=}^{\mathsf{AIM}}_{\sigma} P_2 \triangleq \mathtt{Pr}(\mathsf{Traces}_{\mathsf{AIM}}(P_1, O_1) = \mathsf{Traces}_{\mathsf{AIM}}(P_2, O_2)) > \sigma.$$