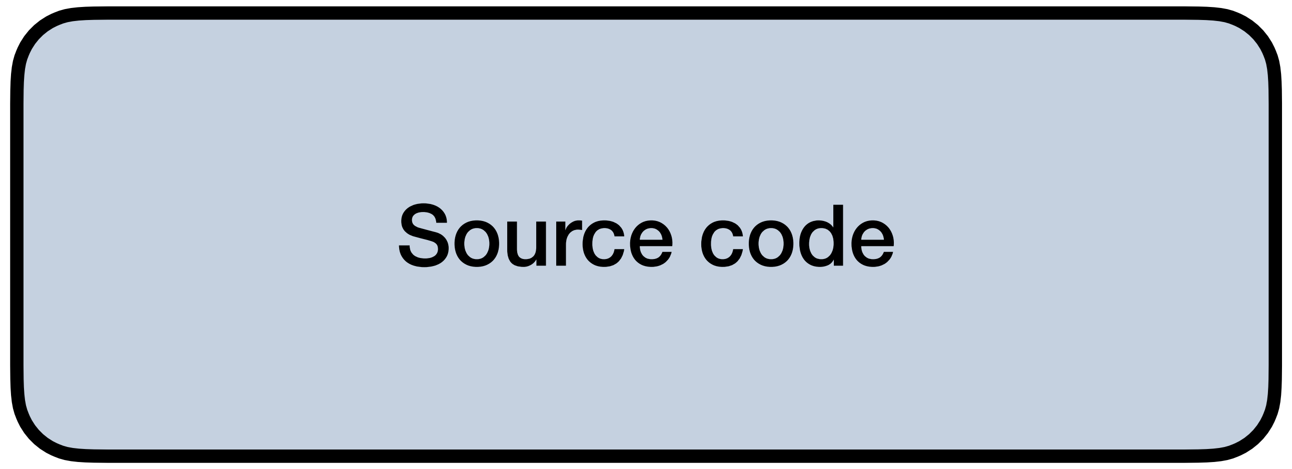
Nanopass Back-Translation of Call-Return Trees for Mechanized Secure Compilation Proofs

Jérémy Thibault, Joseph Lenormand, Catalin Hritcu

MAX PLANCK INSTITUTE
FOR SECURITY AND PRIVACY

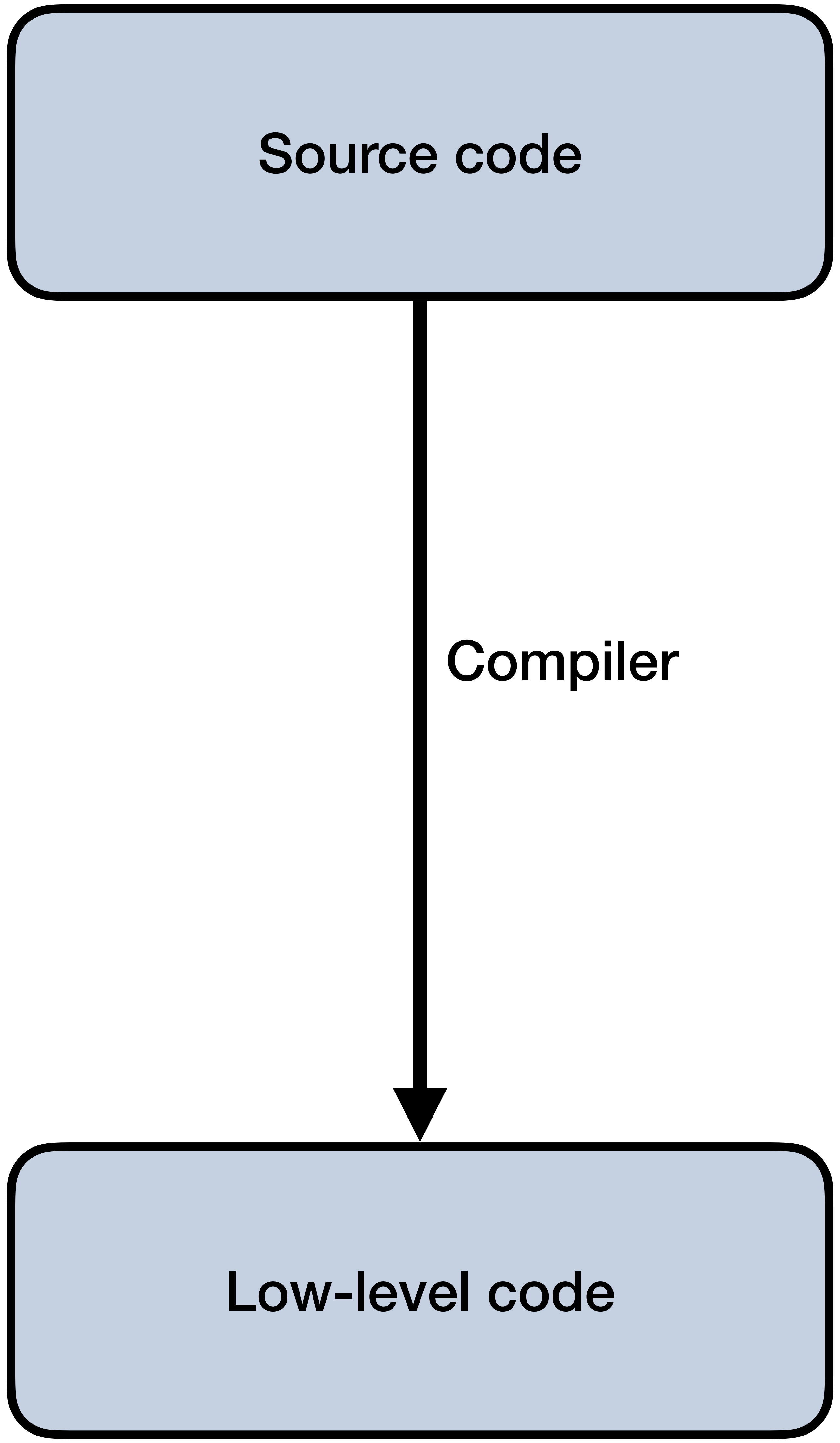
Source code



Source code

High-level abstractions:

- Types
- Structured control-flow
- Verification, static analysis, etc.



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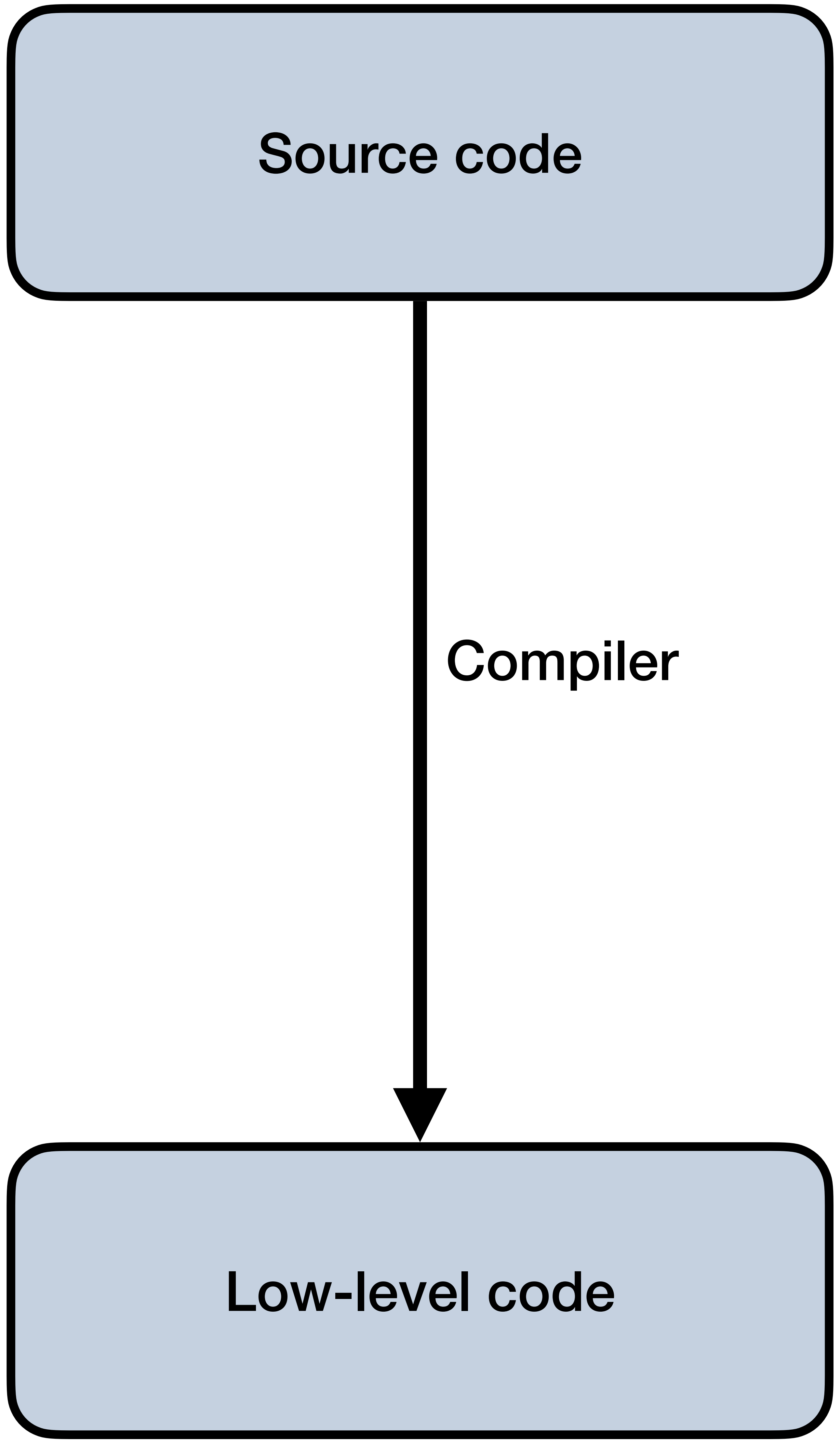

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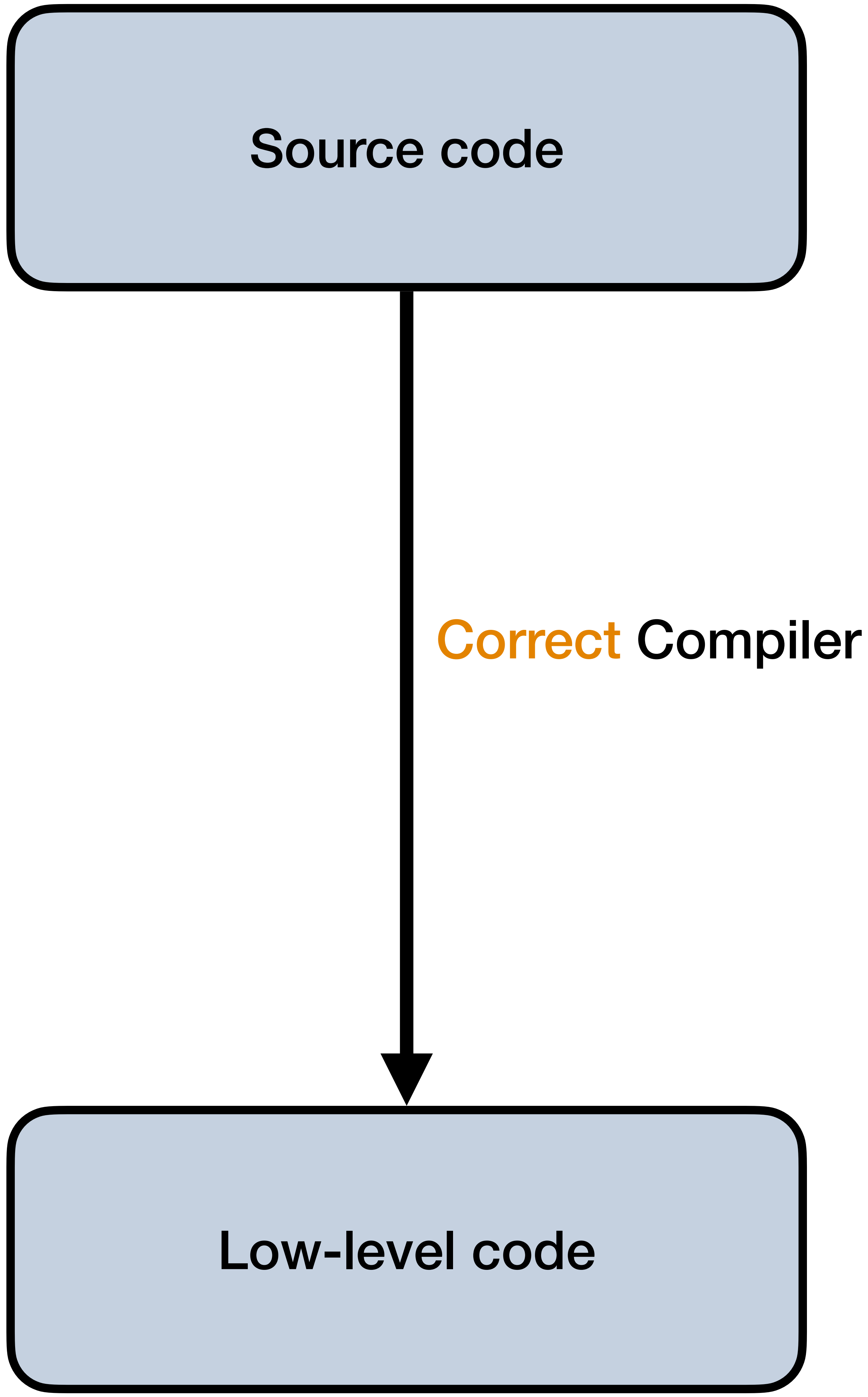
No high-level abstraction anymore



Source code

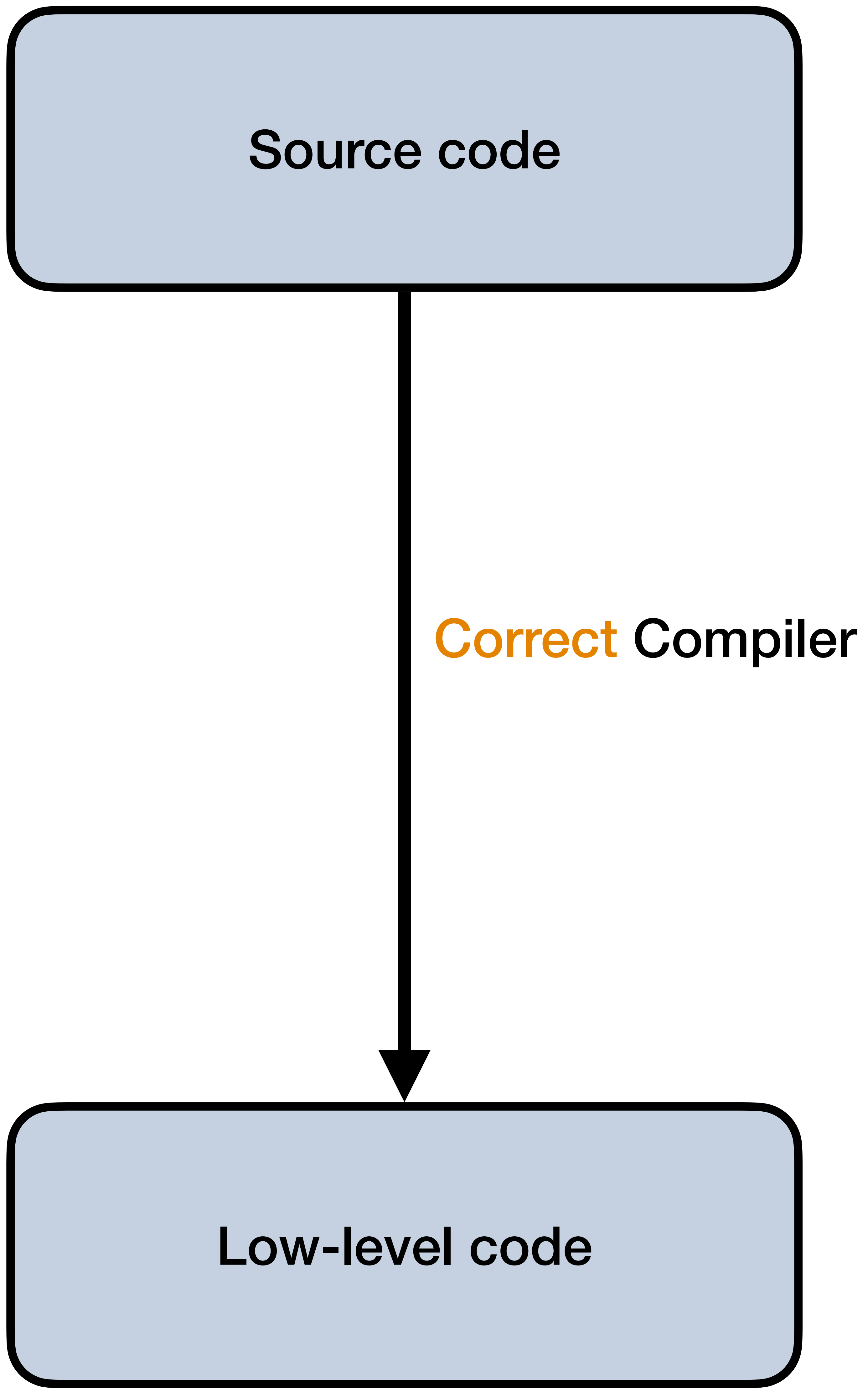
Correct Compiler

Low-level code

High-level abstractions:

- Types
- Structured control-flow
- Verification, static analysis, etc.

No high-level abstraction anymore



Source code

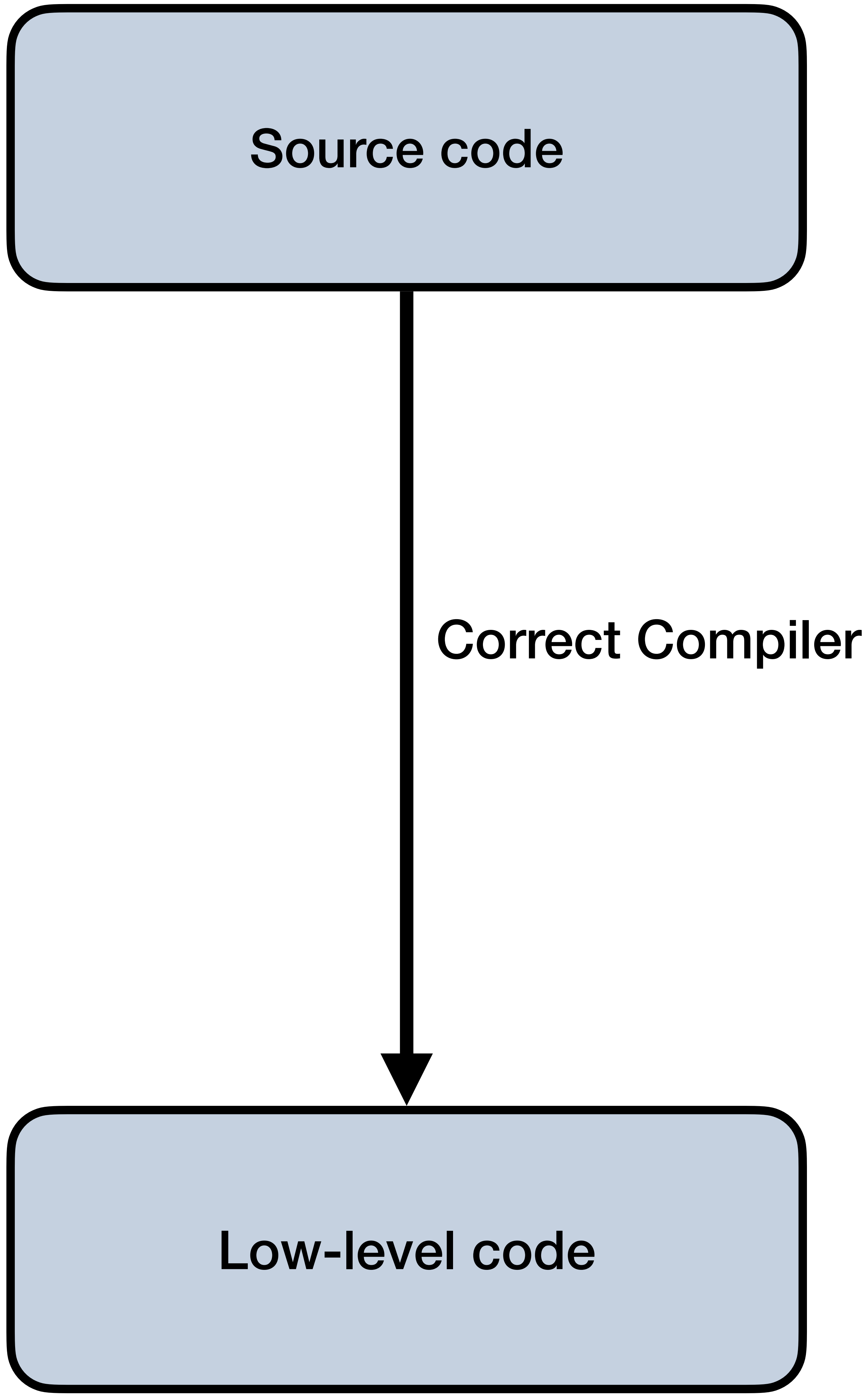
Correct Compiler

Low-level code

High-level abstractions:

- Types
- Structured control-flow
- Verification, static analysis, etc.

High-level abstractions preserved?



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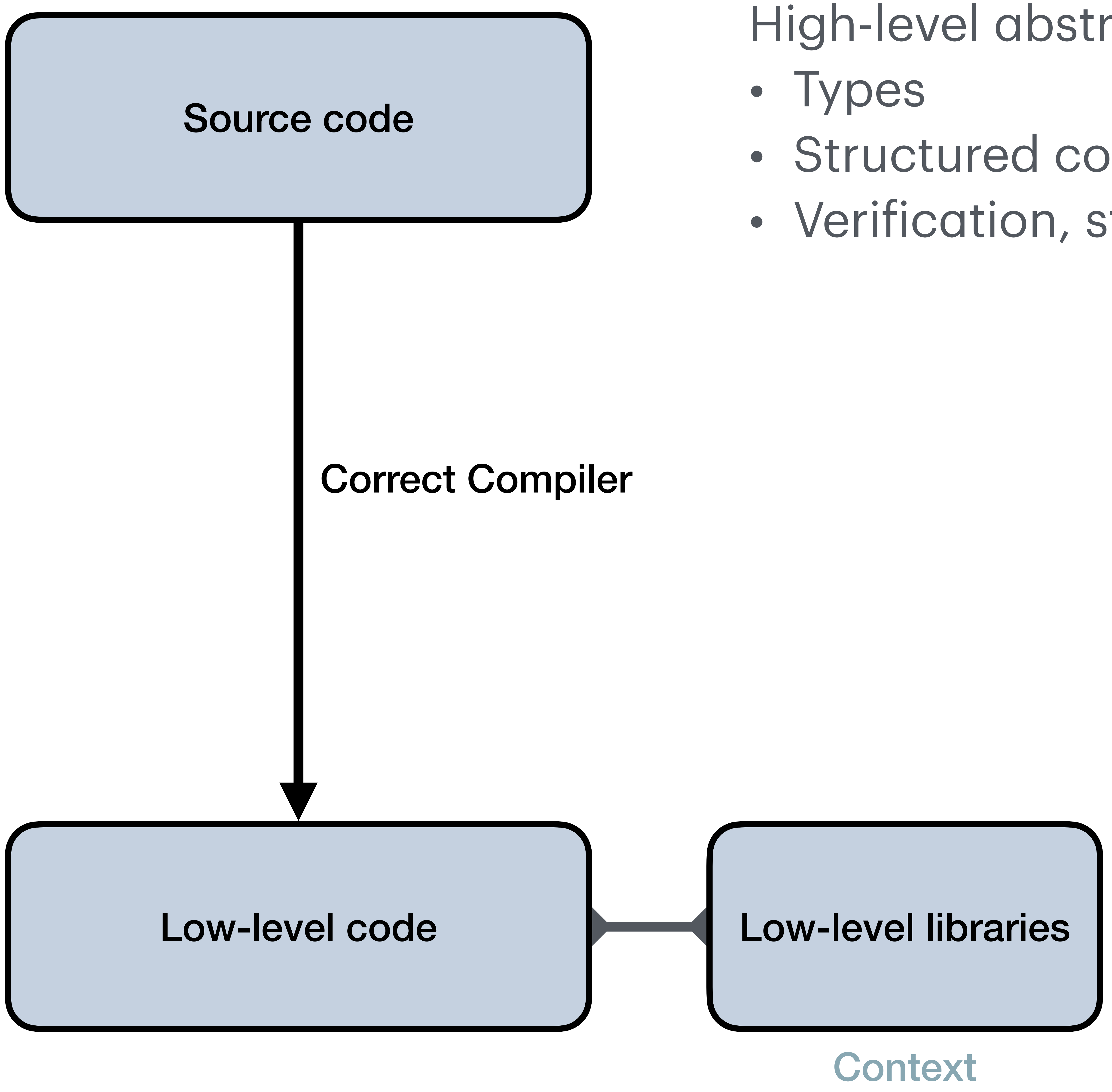

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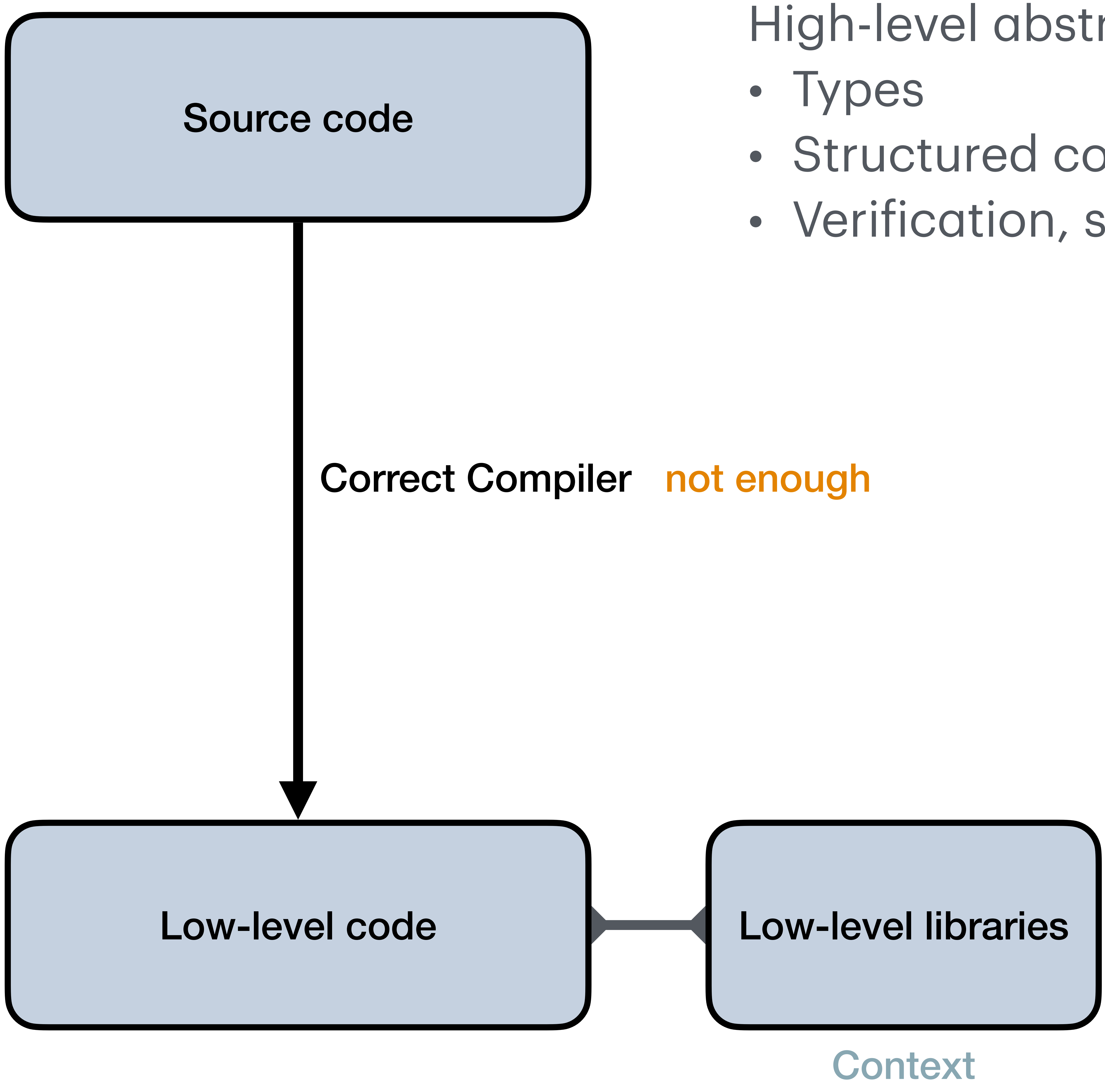


Source code

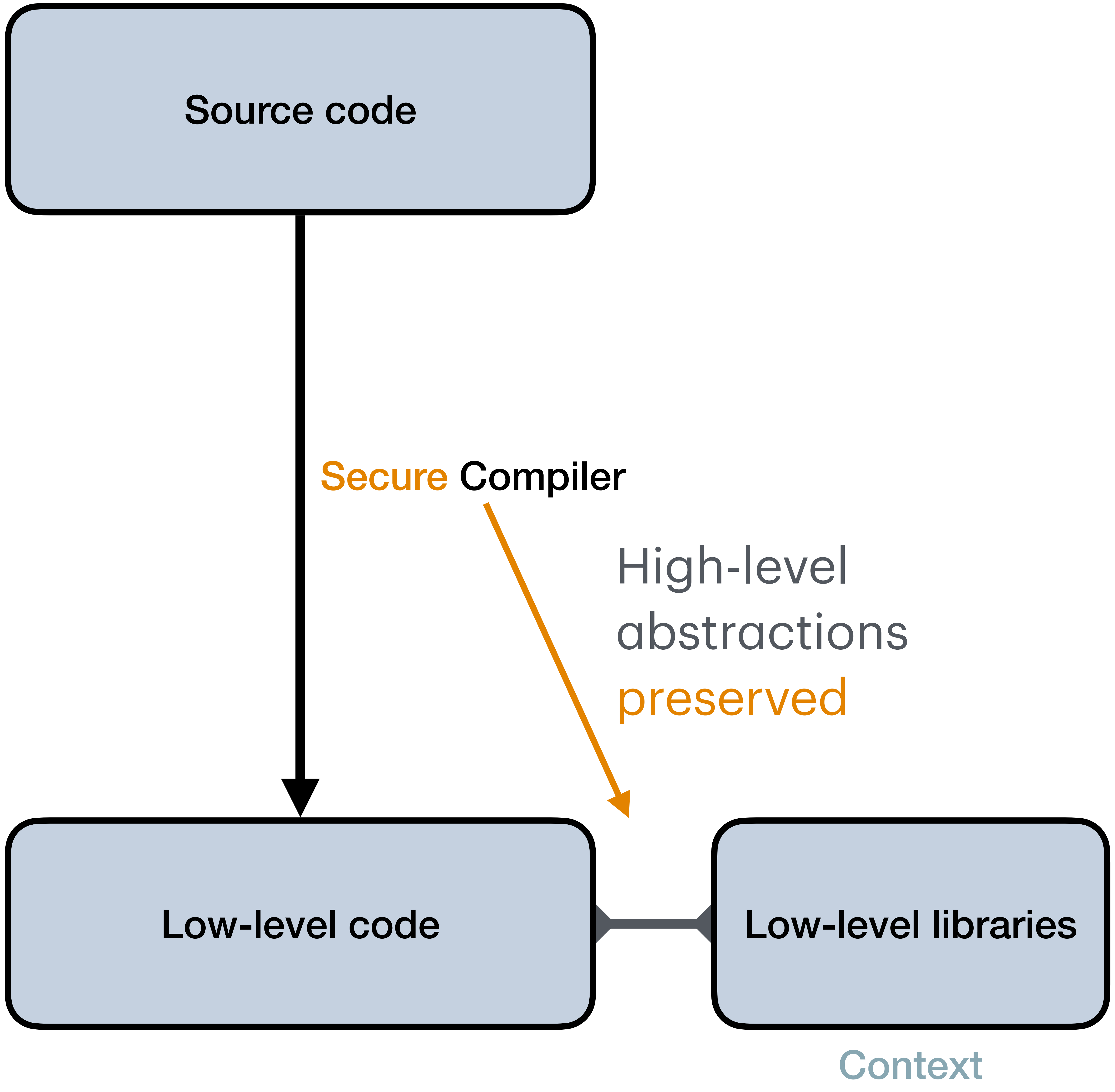
Correct Compiler not enough

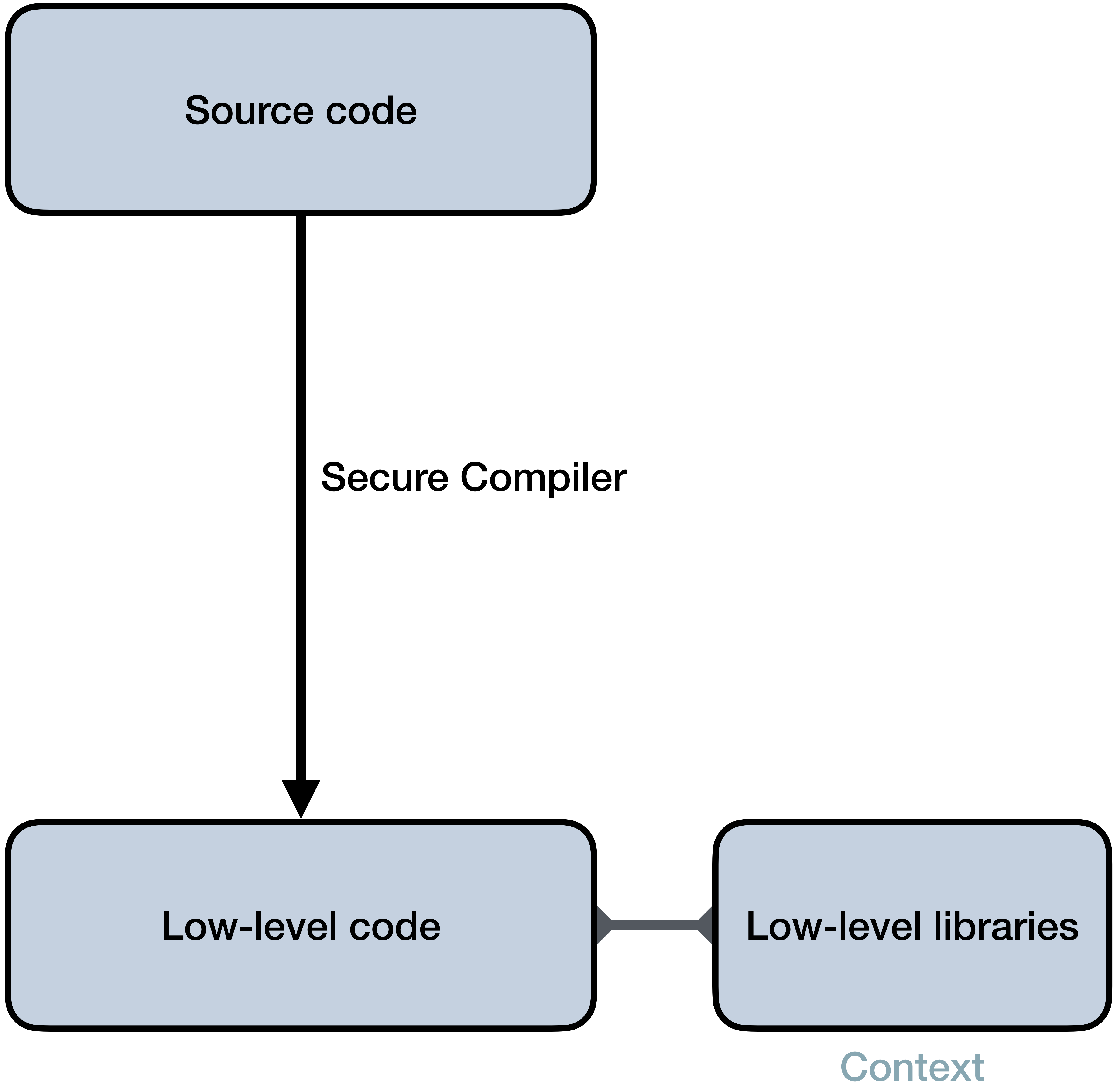
Low-level code

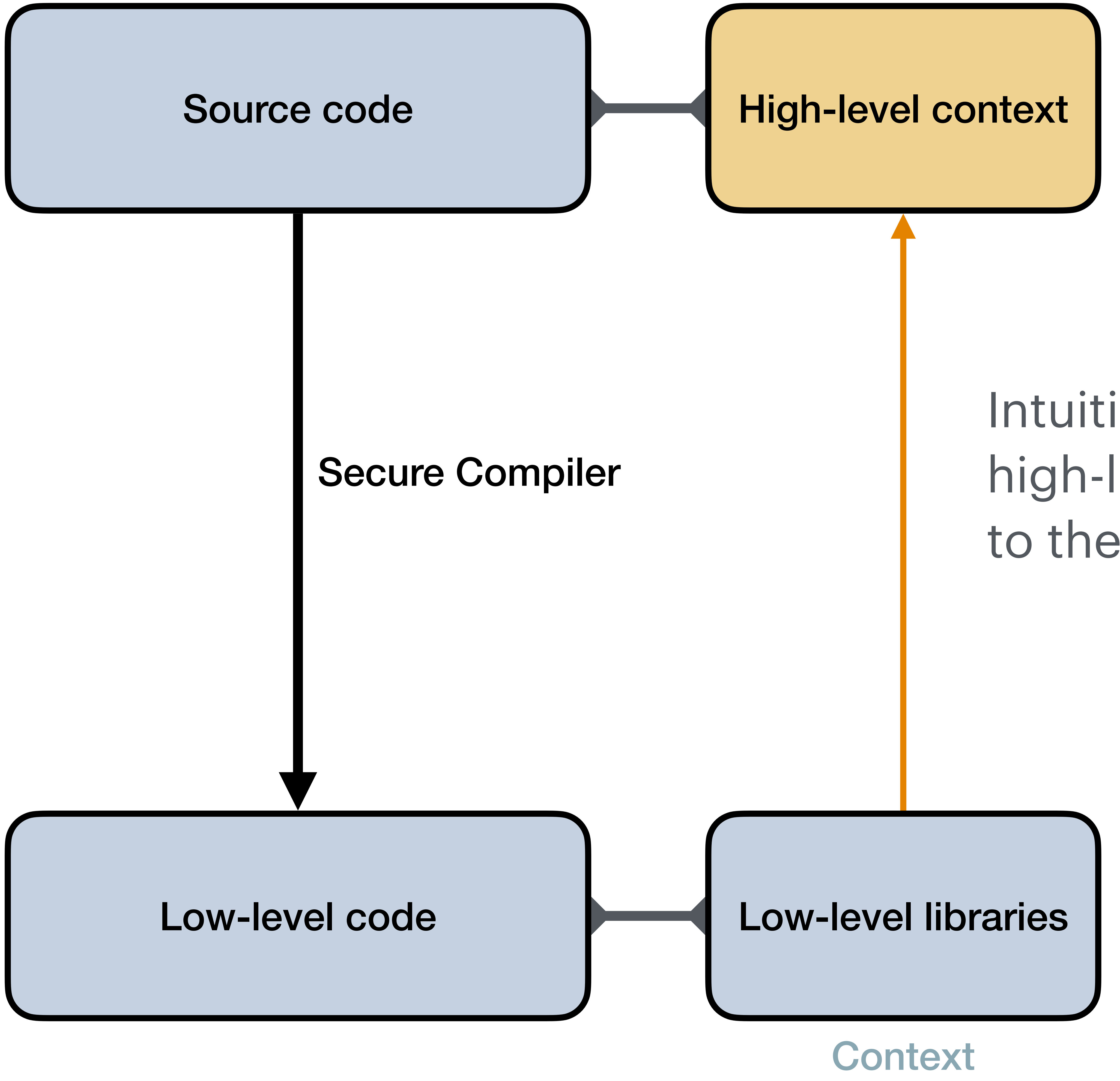
Low-level libraries

Context

Unverified, untrusted,
possibly full of bugs or
even attacker-controlled


Source code
Secure Compiler
High-level
abstractions
preserved
Low-level code
Low-level libraries
Context


Source code
Secure Compiler
Low-level code
Low-level libraries
Context



Intuition: existence of a high-level context “similar” to the low-level one

Example: Robust Safety Preservation (RSP)

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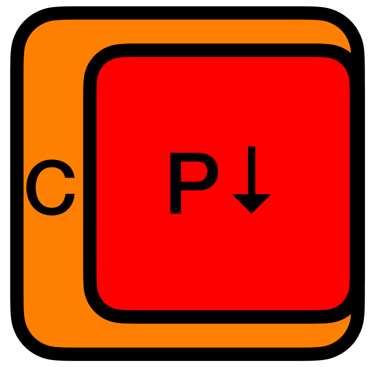
If



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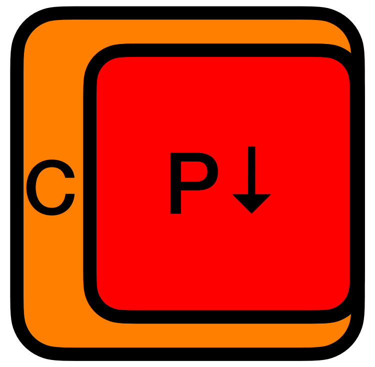
If 

produces finite trace **m**

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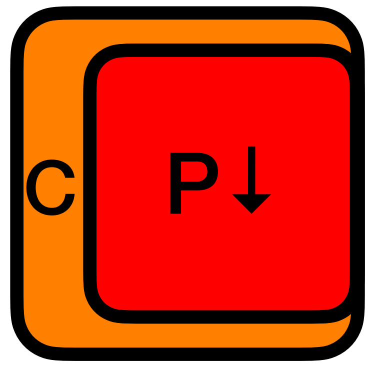
If  produces finite trace **m** (witness of a violation of a certain safety property)

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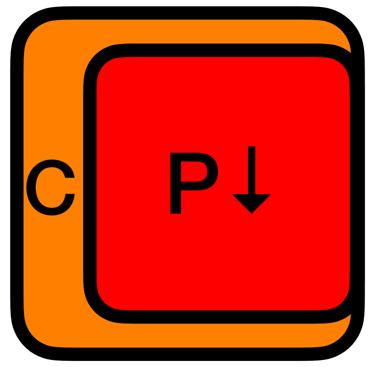
If 

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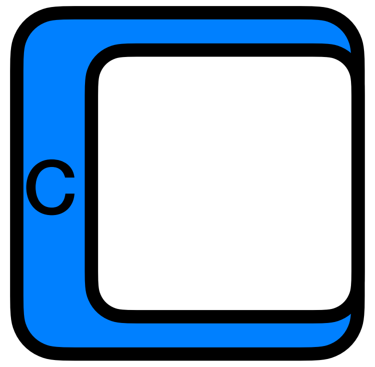
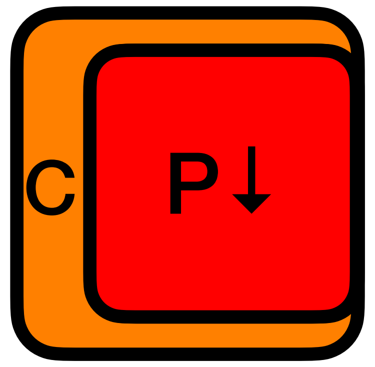
then there exists 

Example: Robust Safety Preservation (RSP)

If 

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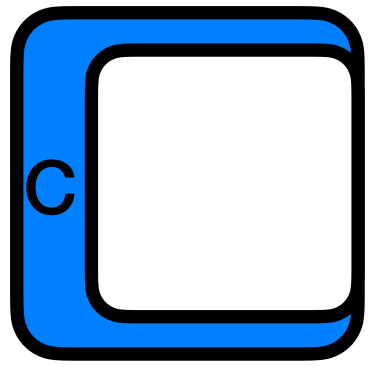
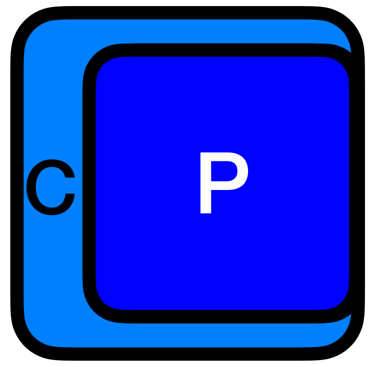
then there exists 

such that 

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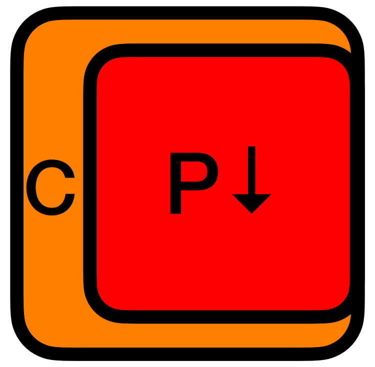
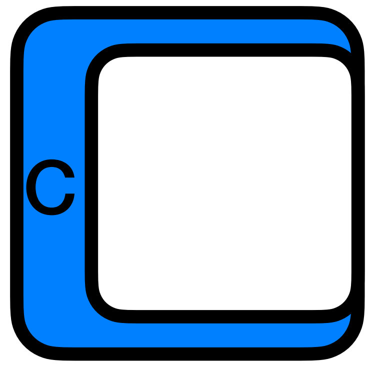
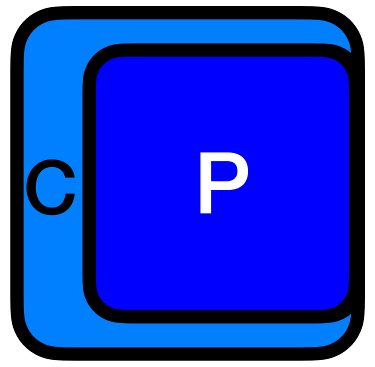
If  produces finite trace **m** (witness of a violation of a certain safety property)

then there exists  such that  produces **m**

⇒ preservation of safety properties

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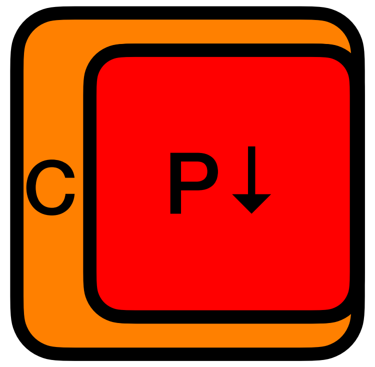
If 

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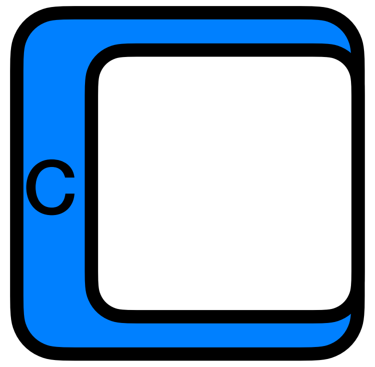
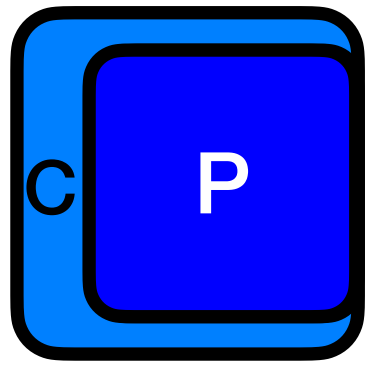
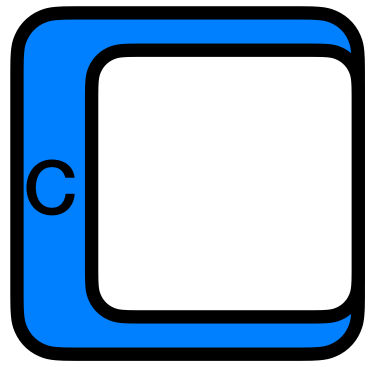
then there exists 

such that 

produces **m**

⇒ preservation of safety properties

Trace-based back-translation:

given **m**, build a context 

A Proof Technique for RSP

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Prior work: proof technique for RSP designed to be mechanized

(Abate et al. (2018), When Good Components Go Bad: Formally Secure Compilation Despite Dynamic Compromise)

A Proof Technique for RSP

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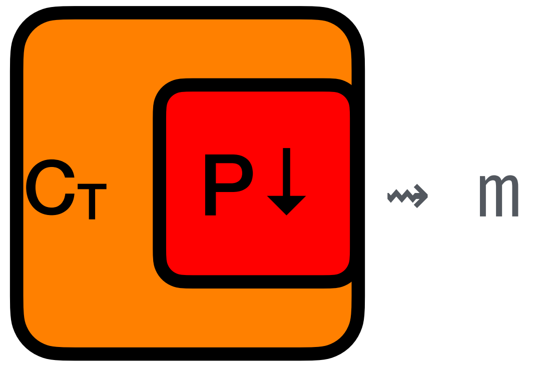
Source

Target



C_T $P\downarrow$ $\rightsquigarrow$ m

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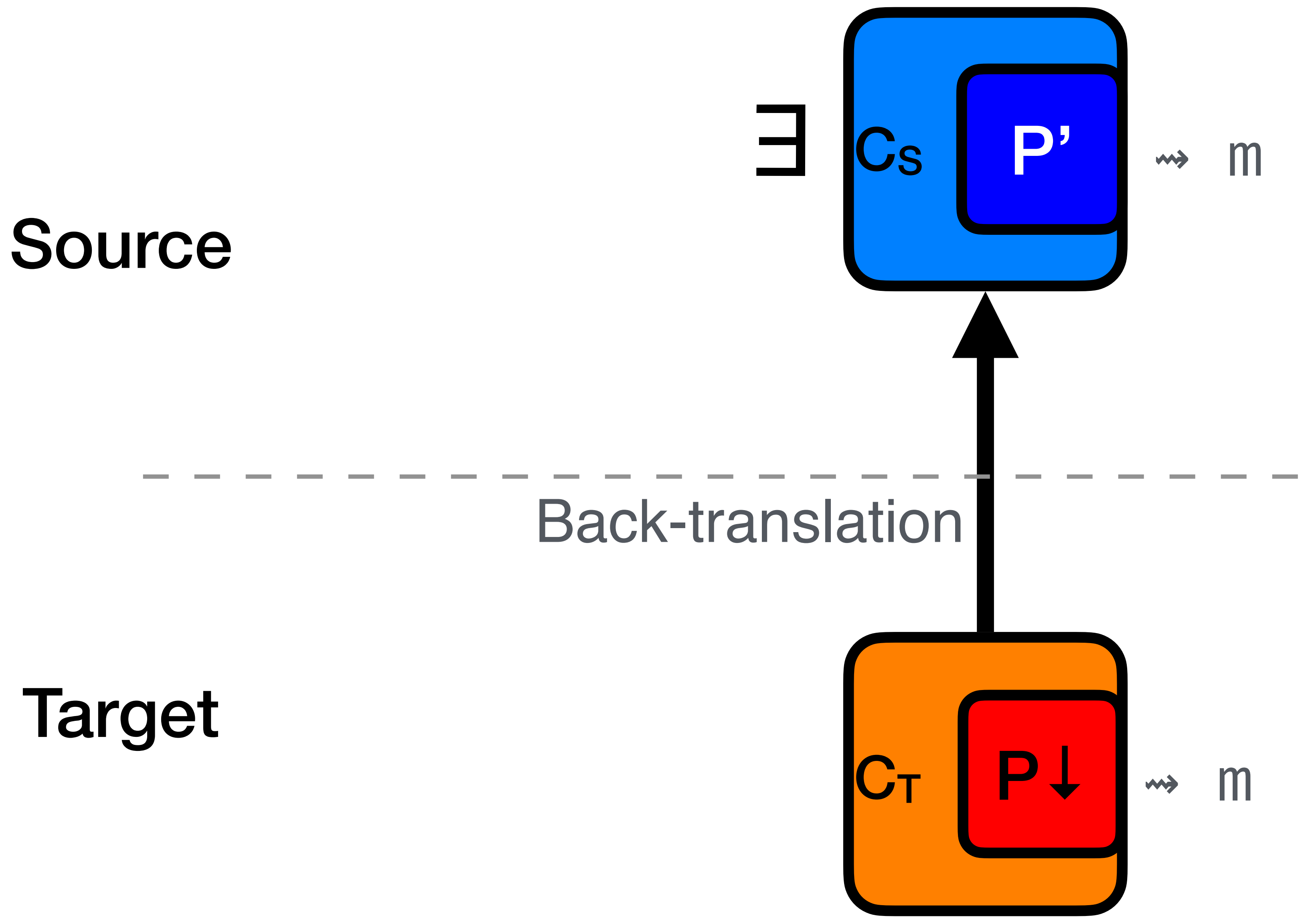

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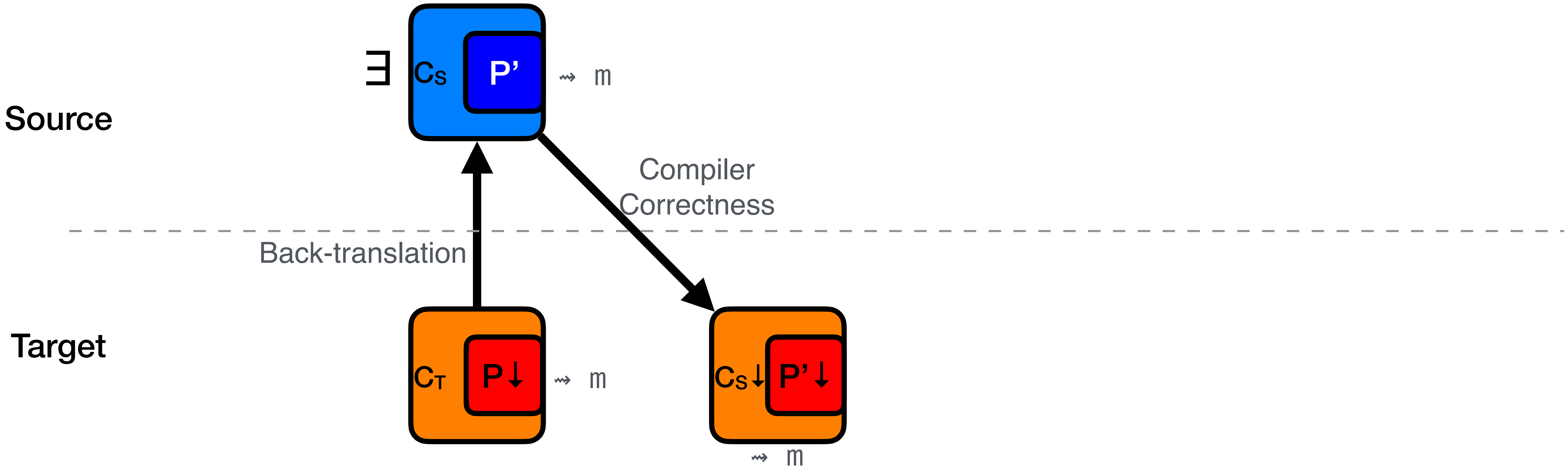

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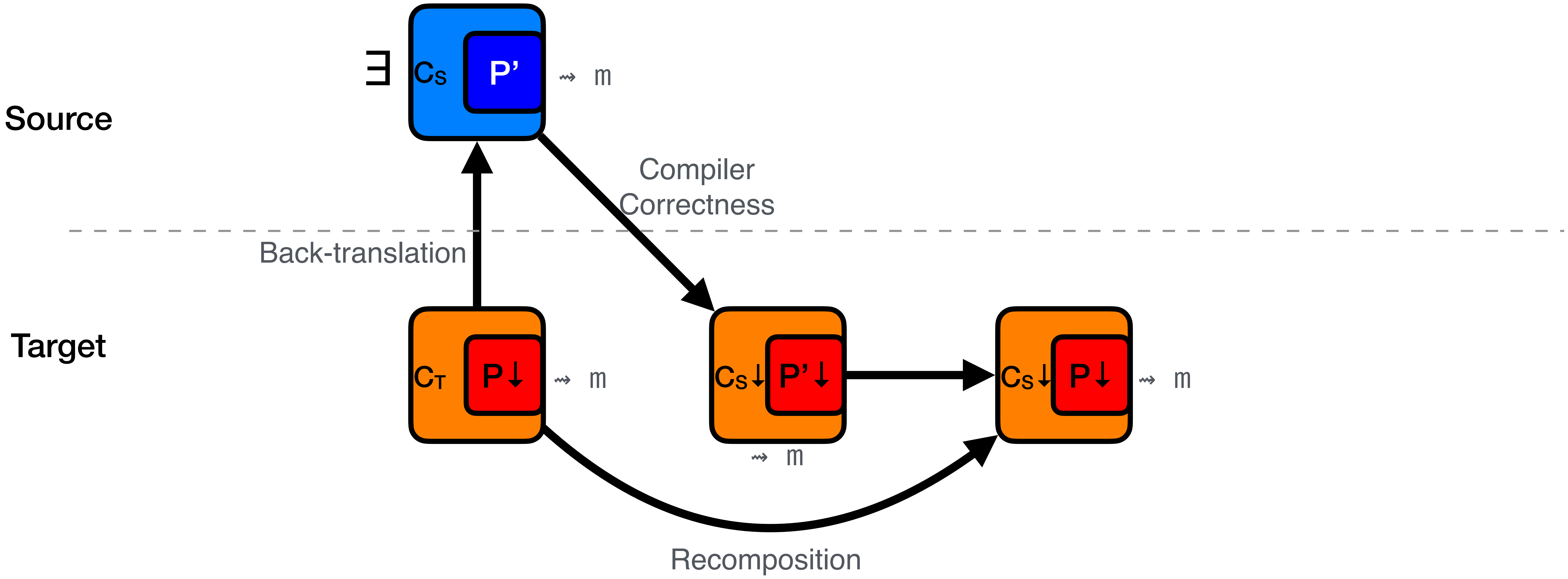

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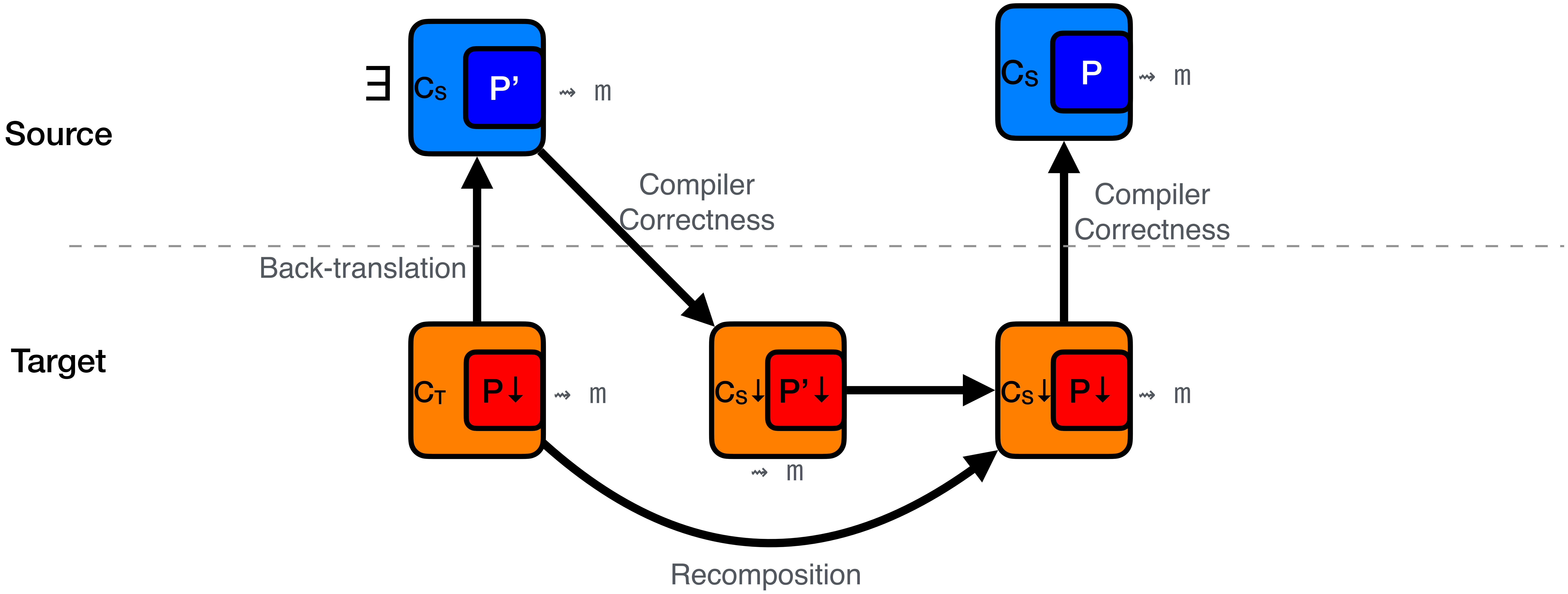

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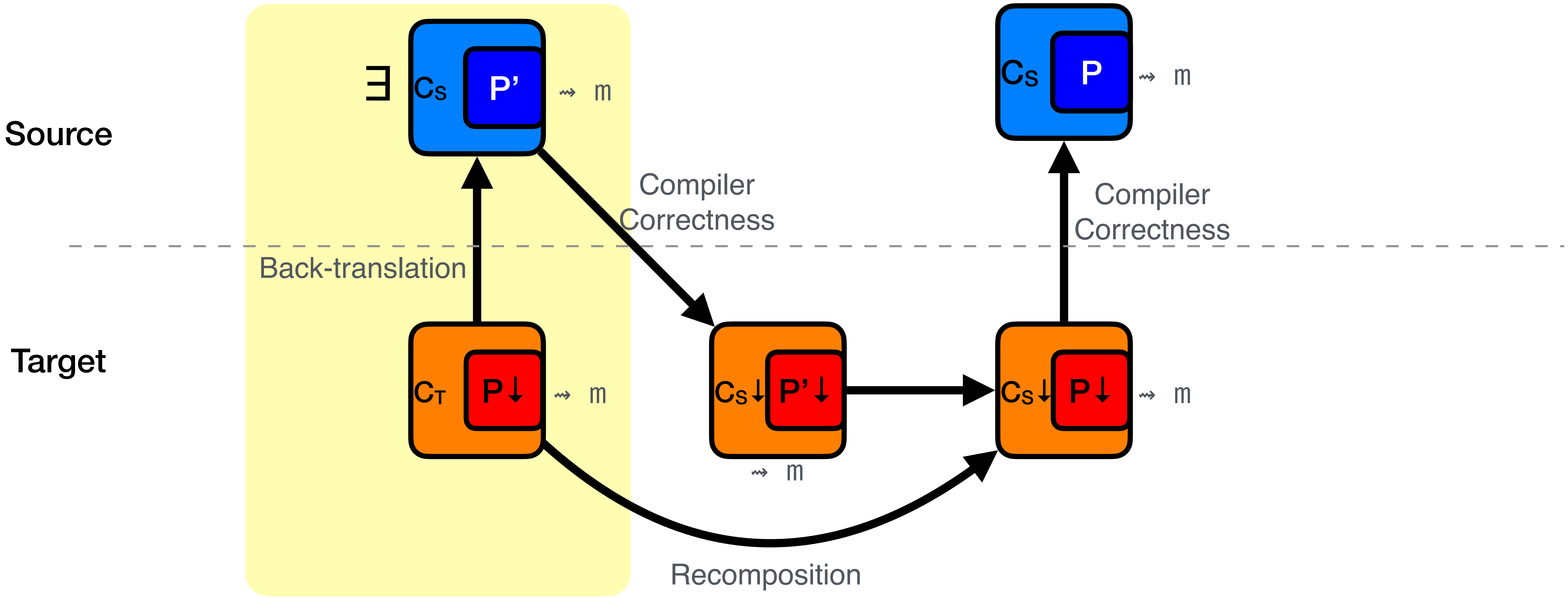

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A Simple Back-Translation for RSP

```
Call C P 1;
Call P C 2;
Ret  C P 3;
Ret  P C 4;
```

A Simple Back-Translation for RSP

```
Call C P 1;
Call P C 2;
Ret  C P 3;
Ret  P C 4;
```

ctr ↦ 0

C

ctr ↦ 0

P

A Simple Back-Translation for RSP

```
c():
```

```
Call C P 1;
Call P C 2;
Ret  C P 3;
Ret  P C 4;
```

ctr ⟼ 0

C

ctr ⟼ 0

P

A Simple Back-Translation for RSP

```
Call C P 1;

Call P C 2;

Ret  C P 3;

Ret  P C 4;
```

```
C():
if (ctr = 0) {
```

ctr ⟼ 0

C

ctr ⟼ 0

P

A Simple Back-Translation for RSP

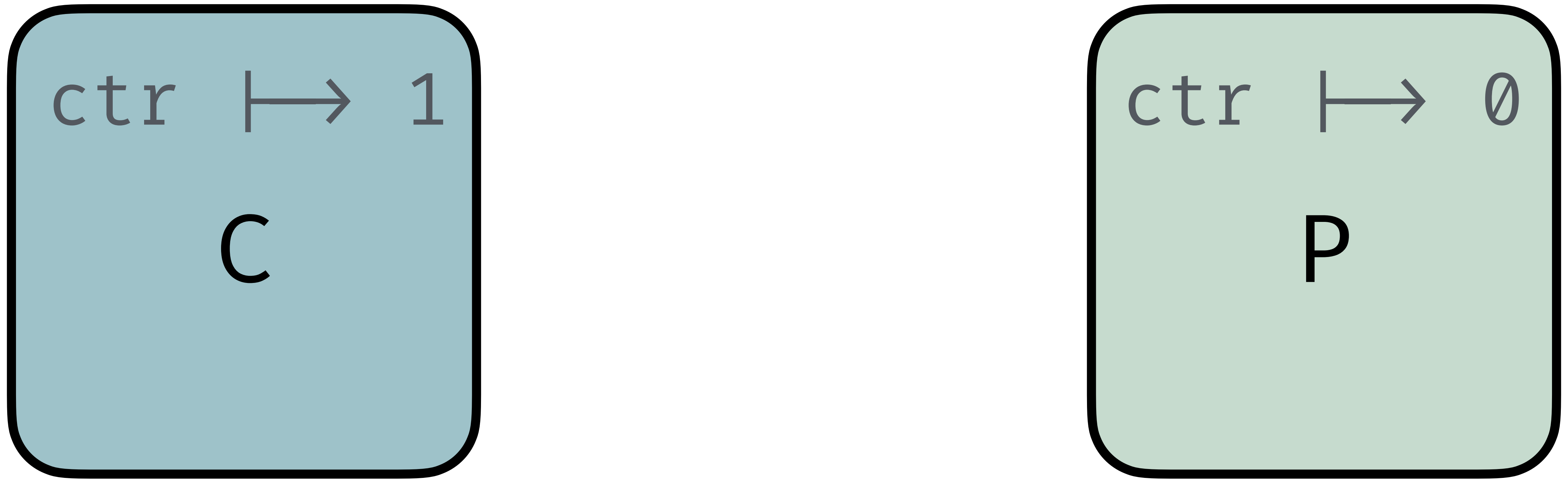
```
Call  C P 1;

Call  P C 2;

Ret   C P 3;

Ret   P C 4;
```

```
C():
if (ctr = 0) {
  ctr++;
```



ctr ⟼ 1

C

ctr ⟼ 0

P

A Simple Back-Translation for RSP

```
Call C P 1;

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Ret  P C 4;
```
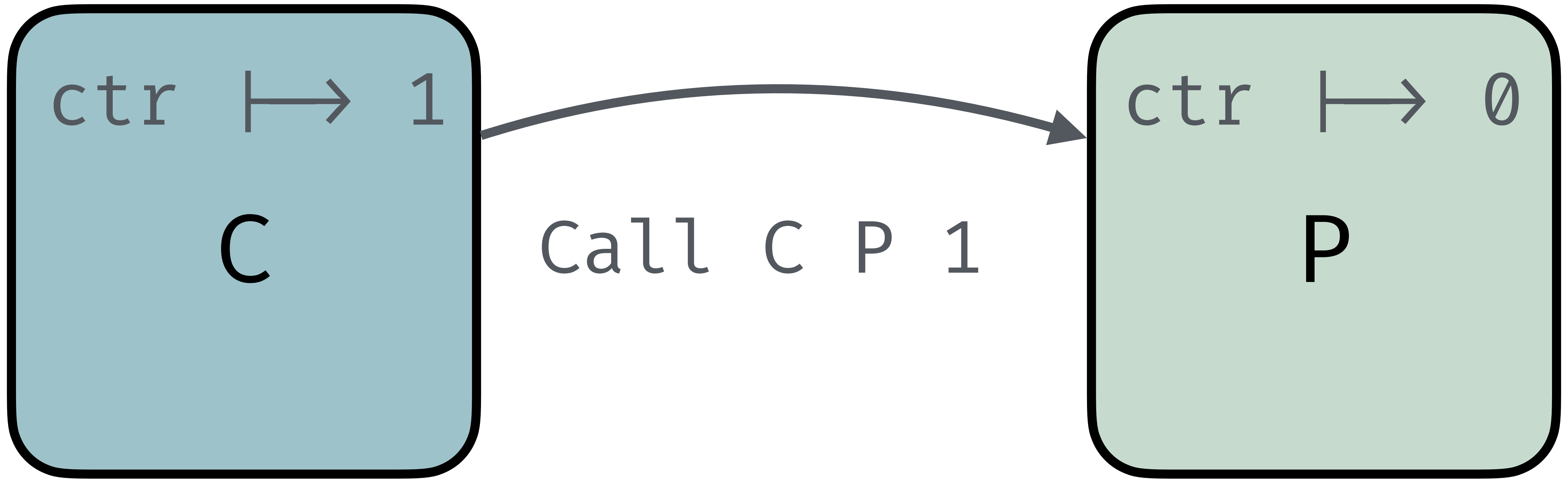

```
C():
if (ctr = 0) {
  ctr++;
  P(1);
```



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P():
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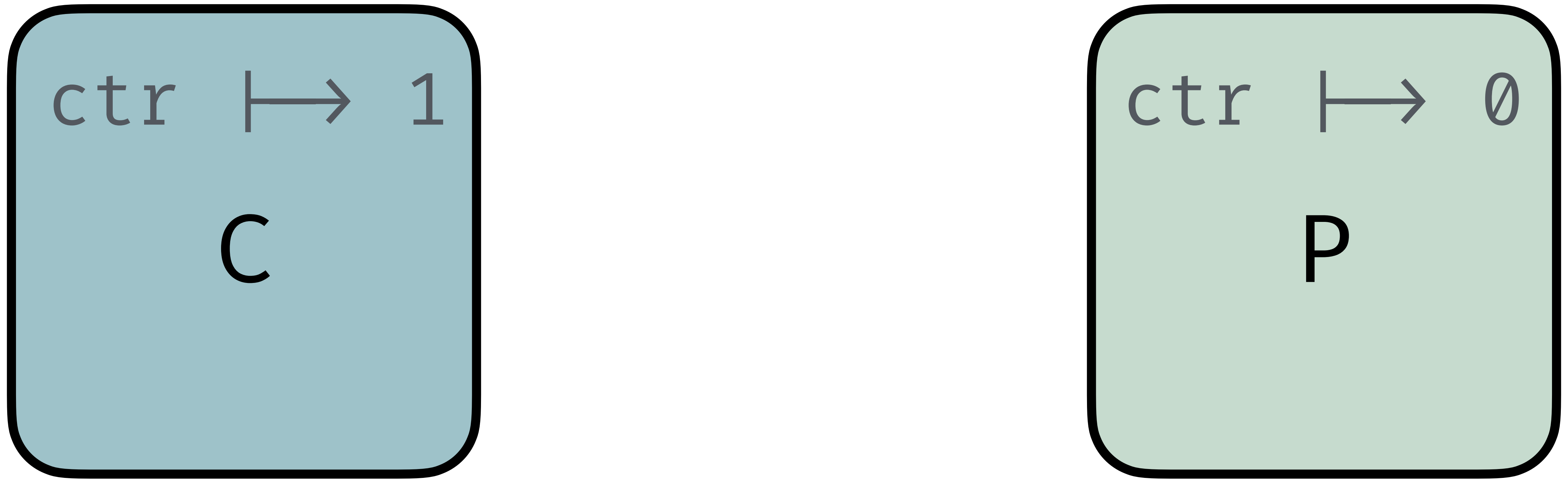

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P():
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ctr ↦ 1

C

ctr ↦ 0

P

A Simple Back-Translation for RSP

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A Simple Back-Translation for RSP

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Call C P 1;
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```
C():
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P():
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  C(2);
```

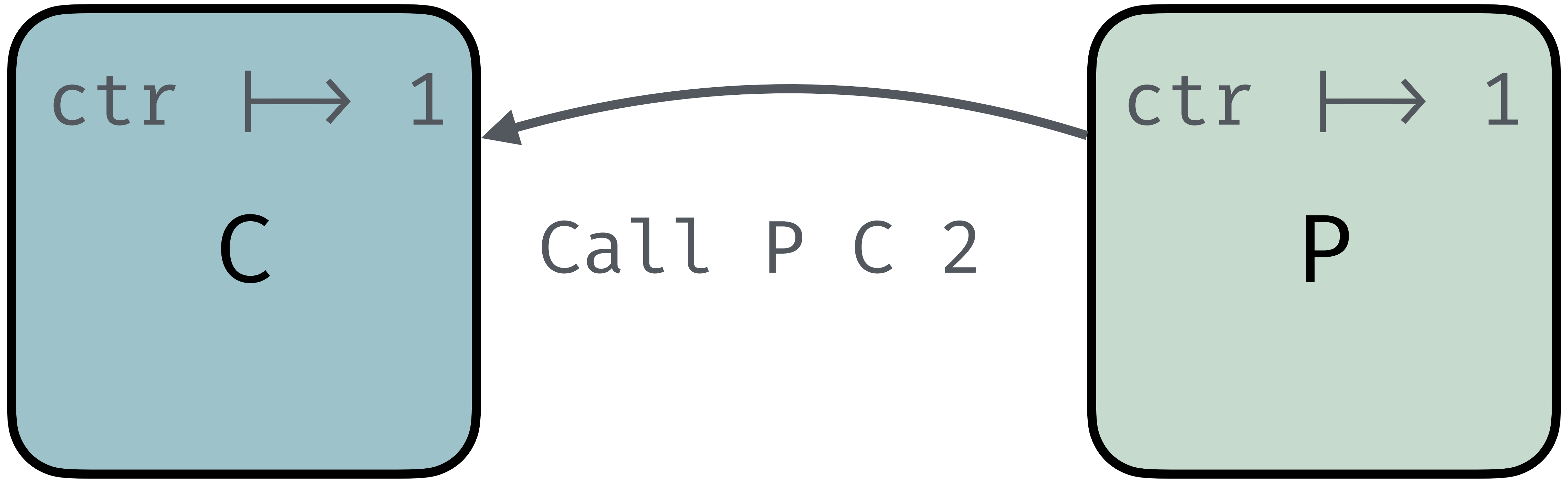

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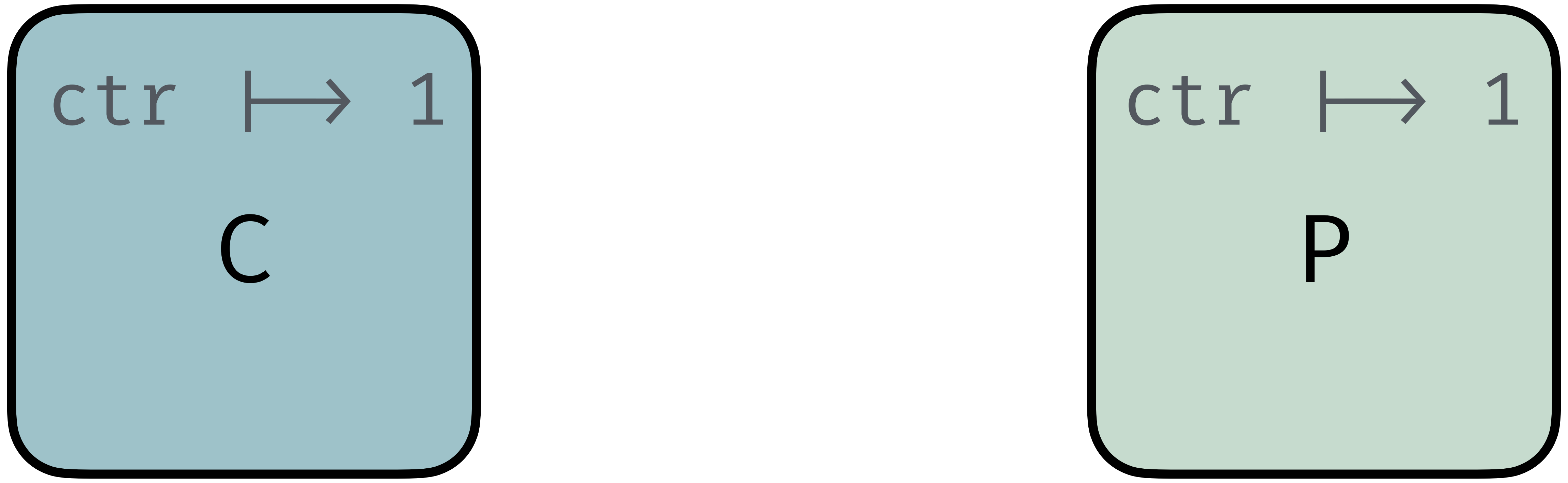

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C():
if (ctr = 0) {
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  C();
```

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P():
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ctr ⟼ 1

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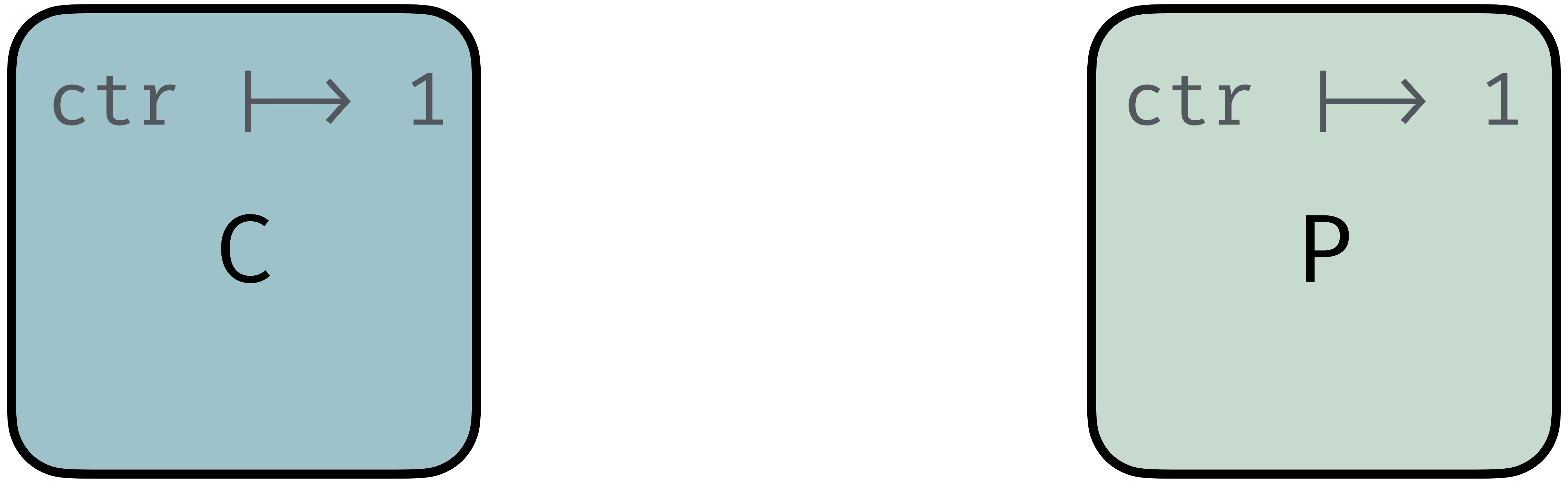

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```

```
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if (ctr = 0) {
  ctr++;
  P(1);
  C();
} else if (ctr = 1) {
  ctr++;
```

```
P():
if (ctr = 0) {
  ctr++;
  C(2);
```

ctr ⟼ 2

C

ctr ⟼ 1

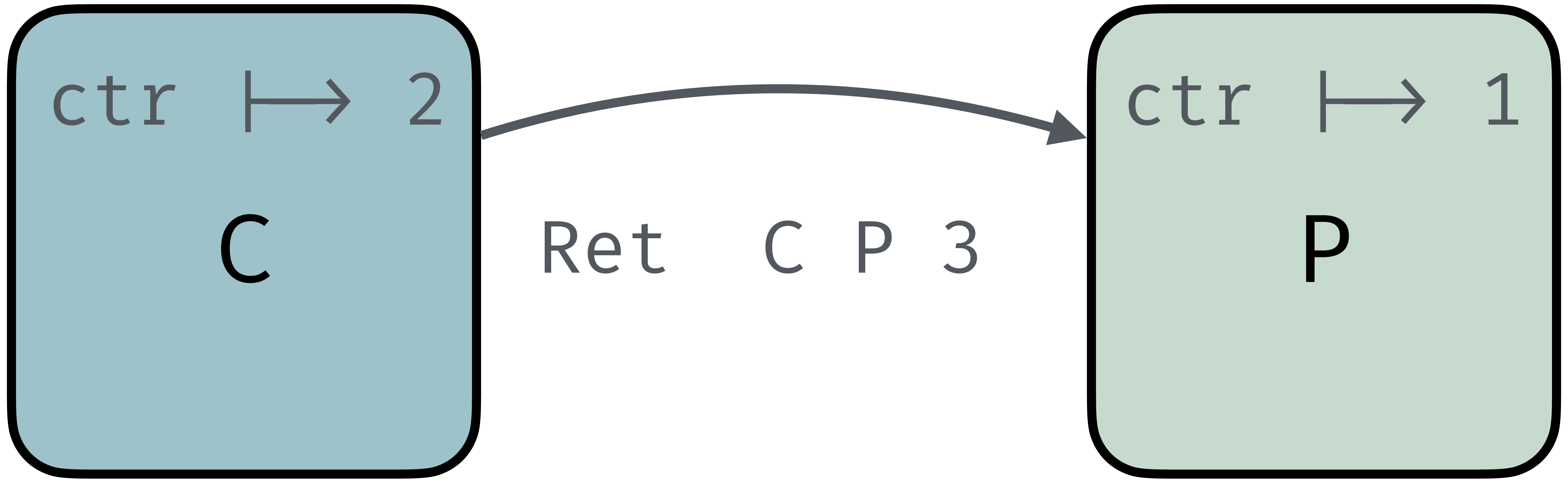
P

A Simple Back-Translation for RSP

```
Call C P 1;

Call P C 2;

Ret  C P 3;

Ret  P C 4;
```

```
C():
if (ctr = 0) {
  ctr++;
  P(1);
  C();
} else if (ctr = 1) {
  ctr++;
  return 3
}
```

```
P():
if (ctr = 0) {
  ctr++;
  C(2);
```



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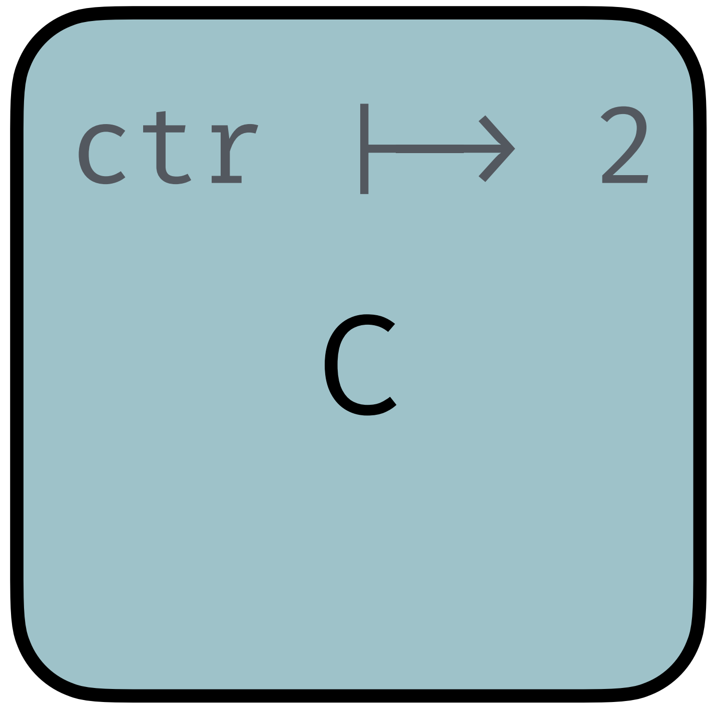

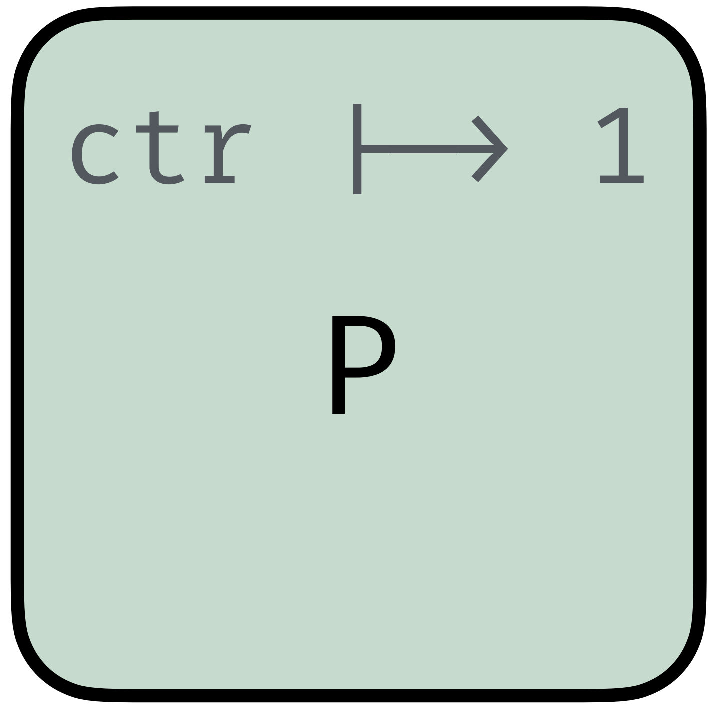

A Simple Back-Translation for RSP

```
Call  C P 1;

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C():
if (ctr = 0) {
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  C();
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  return 3
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  C(2);
  P();
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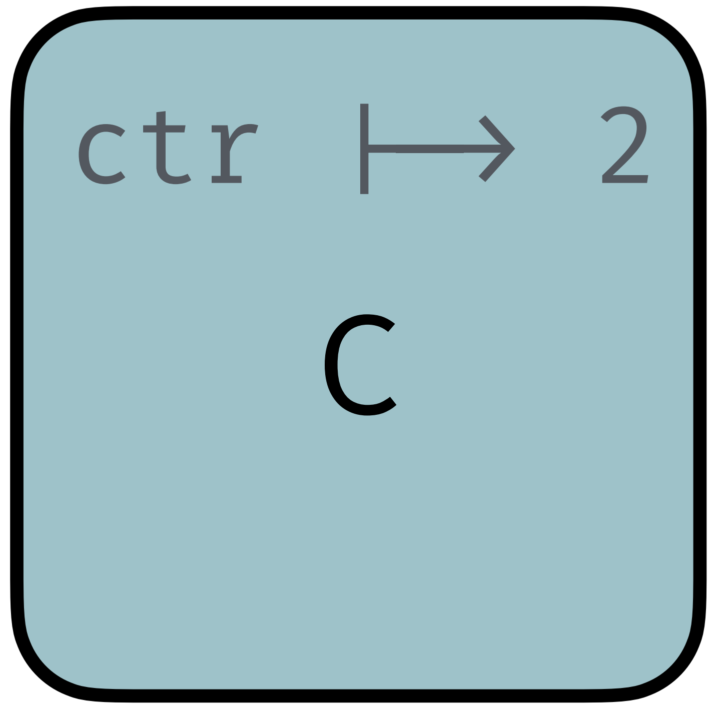
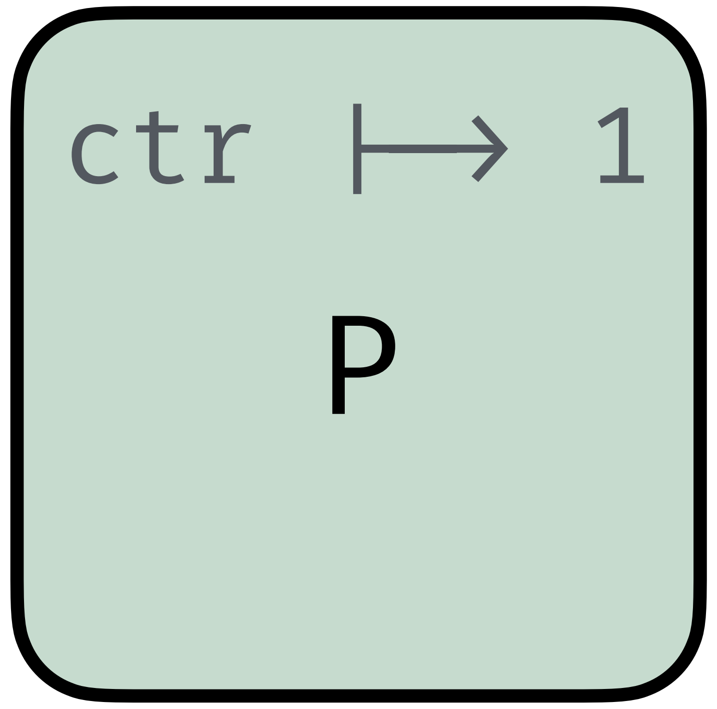


ctr ↦ 2

C



ctr ↦ 1

P

A Simple Back-Translation for RSP

```
Call C P 1;
Call P C 2;
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```

```
C():
if (ctr = 0) {
  ctr++;
  P(1);
  C();
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  return 3
}
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P():
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  C(2);
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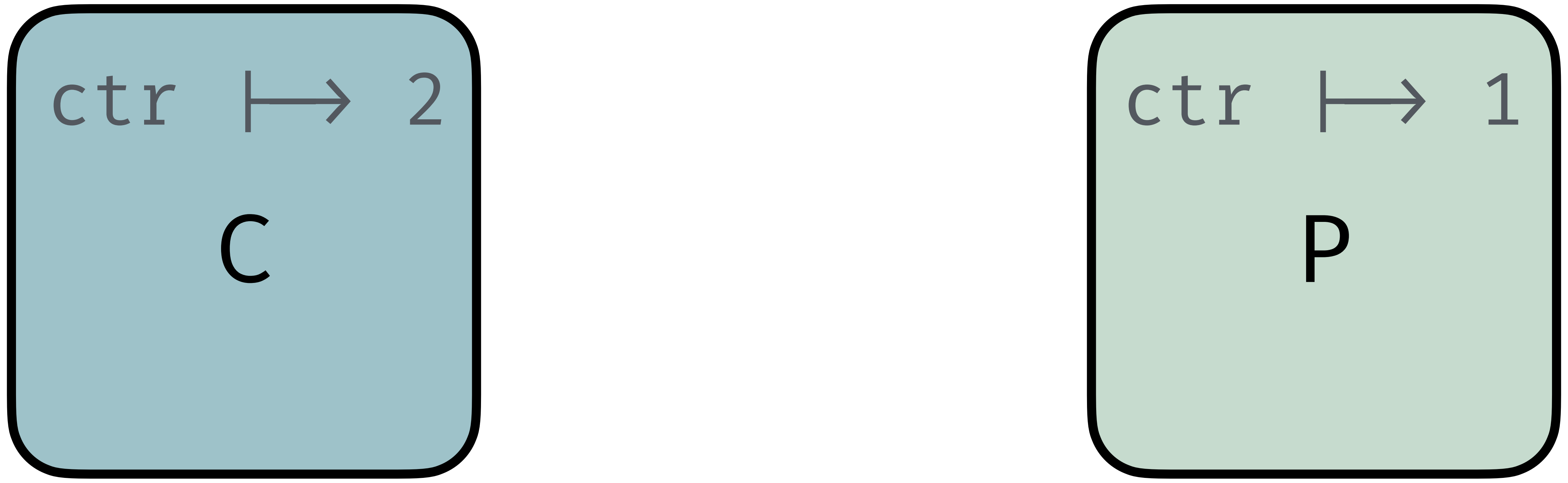

ctr ⟼ 2

C

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```
Call C P 1;
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P():
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```

ctr ⟼ 2

C

ctr ⟼ 2

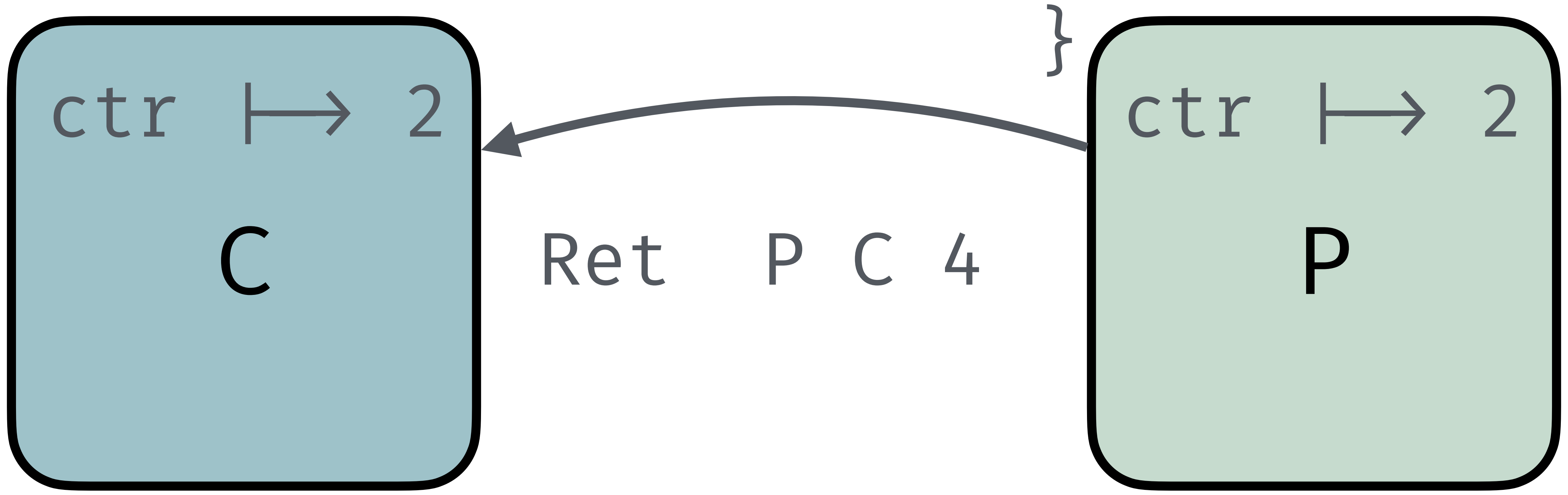
P

A Simple Back-Translation for RSP

```
Call C P 1;
Call P C 2;
Ret  C P 3;
Ret  P C 4;
```

```
C():
if (ctr = 0) {
  ctr++;
  P(1);
  C();
} else if (ctr = 1) {
  ctr++;
  return 3
}
```

```
P():
if (ctr = 0) {
  ctr++;
  C(2);
  P();
} else if (ctr = 1) {
  ctr++;
  return 4
}
```



Implementing and verifying this back-translation

(Abate et al. (2018), When Good Components Go Bad: Formally Secure Compilation Despite Dynamic Compromise)

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- Simple logic: just emit the events one by one
- Proof by induction on the trace

(Abate et al. (2018), When Good Components Go Bad: Formally Secure Compilation Despite Dynamic Compromise)

Implementing and verifying this back-translation

Decently easy:

- Manipulates one finite object (a trace)
- Simple logic: just emit the events one by one
- Proof by induction on the trace
- Less than 600 LoC (including comments)

(Abate et al. (2018), When Good Components Go Bad: Formally Secure Compilation Despite Dynamic Compromise)

Can we get a stronger result?

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- So far: safety properties only
- Some security properties are more than safety: hypersafety (noninterference), relational hypersafety (observational equivalence)
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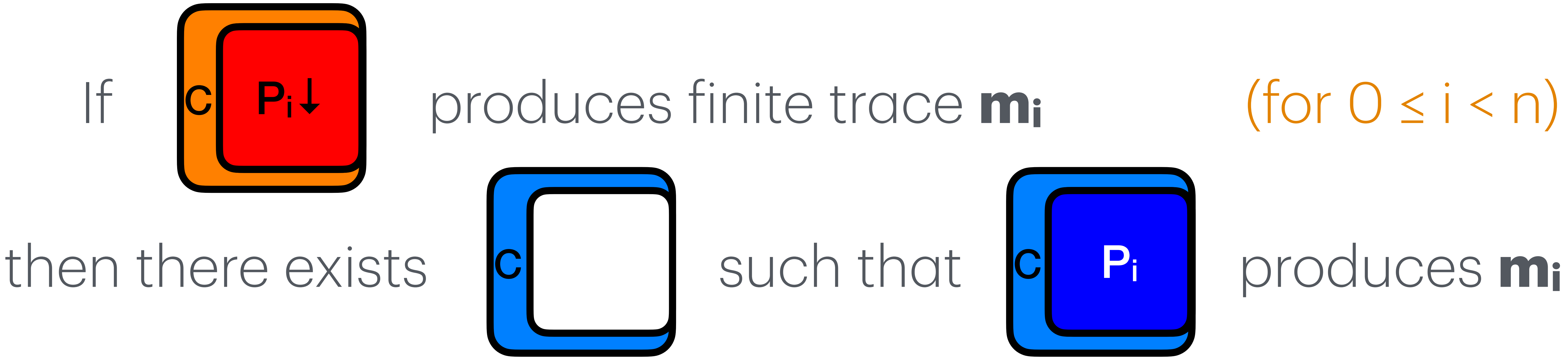
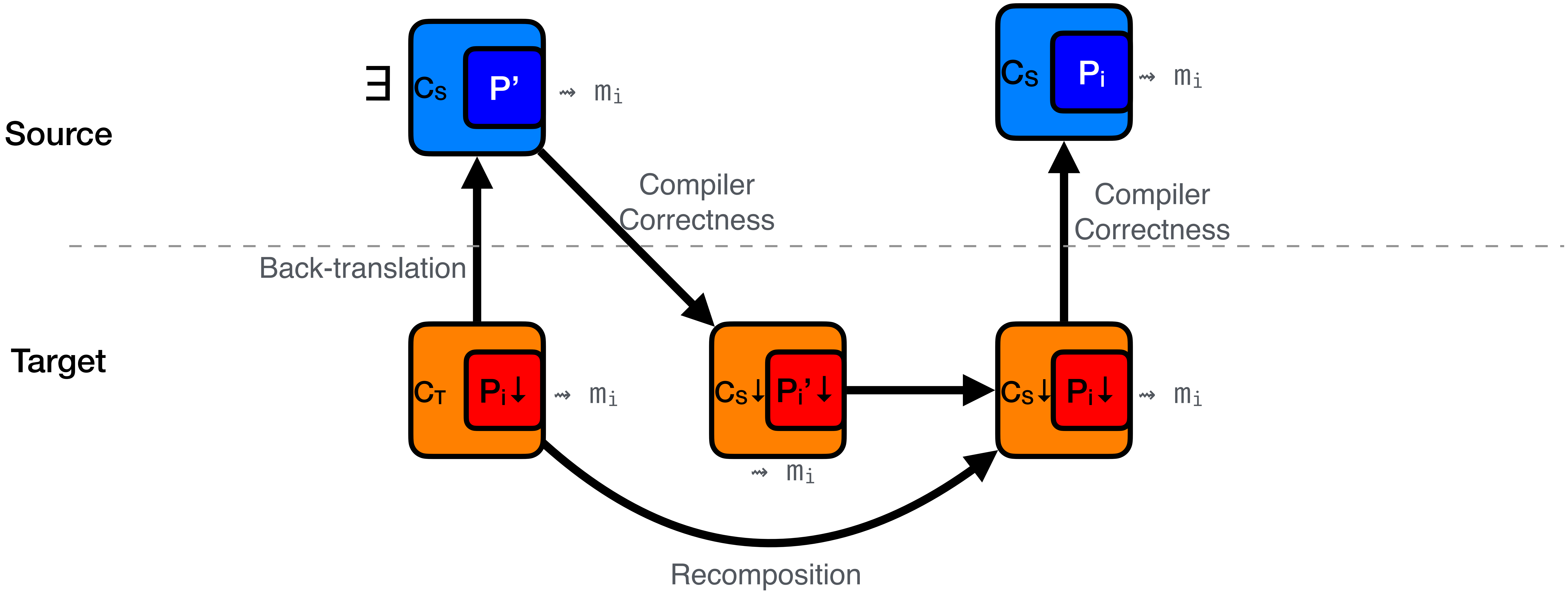


If produces finite trace $\mathbf{m_i}$ (for $0 \leq i < n$)

then there exists such that produces $\mathbf{m_i}$

Adapting the proof for multiple programs



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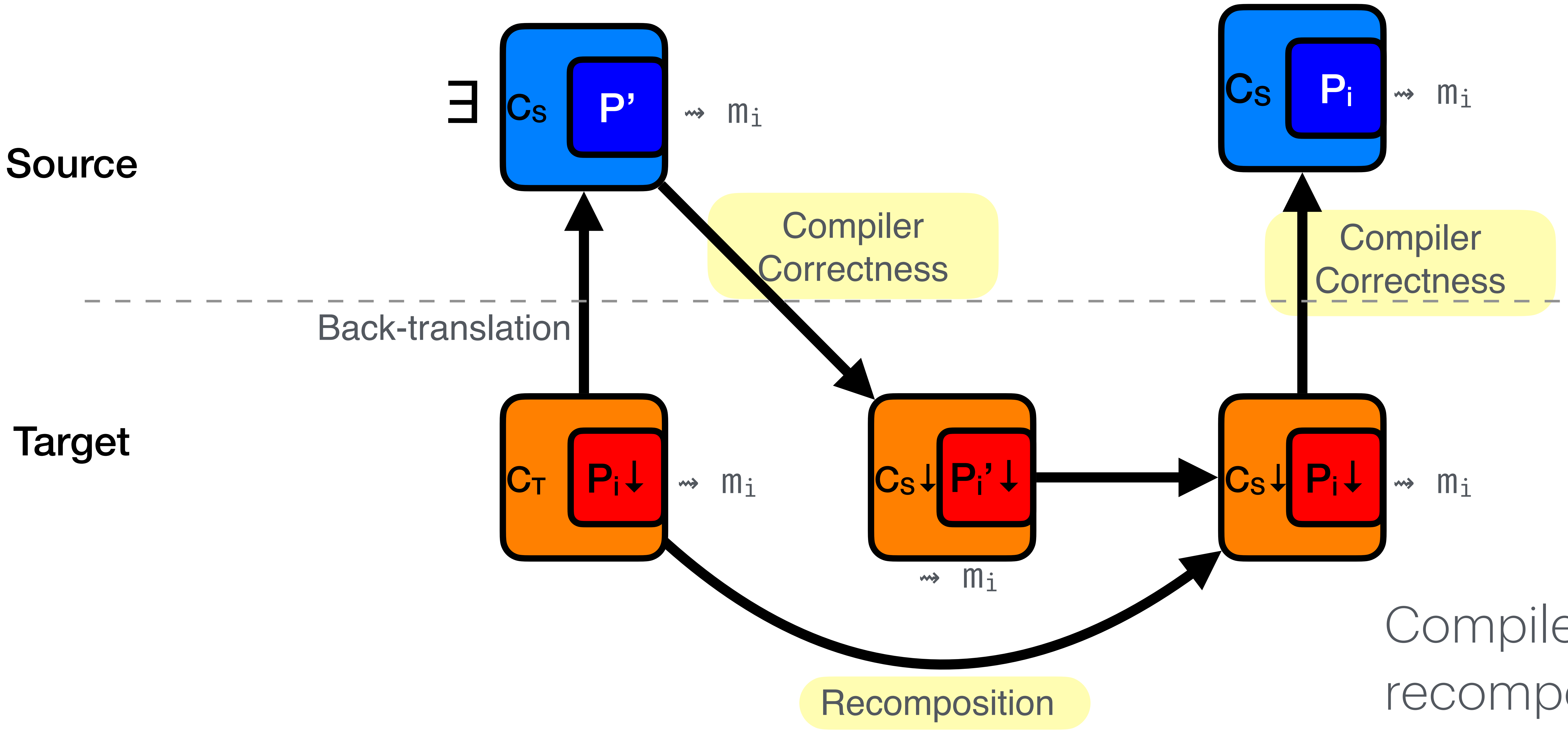
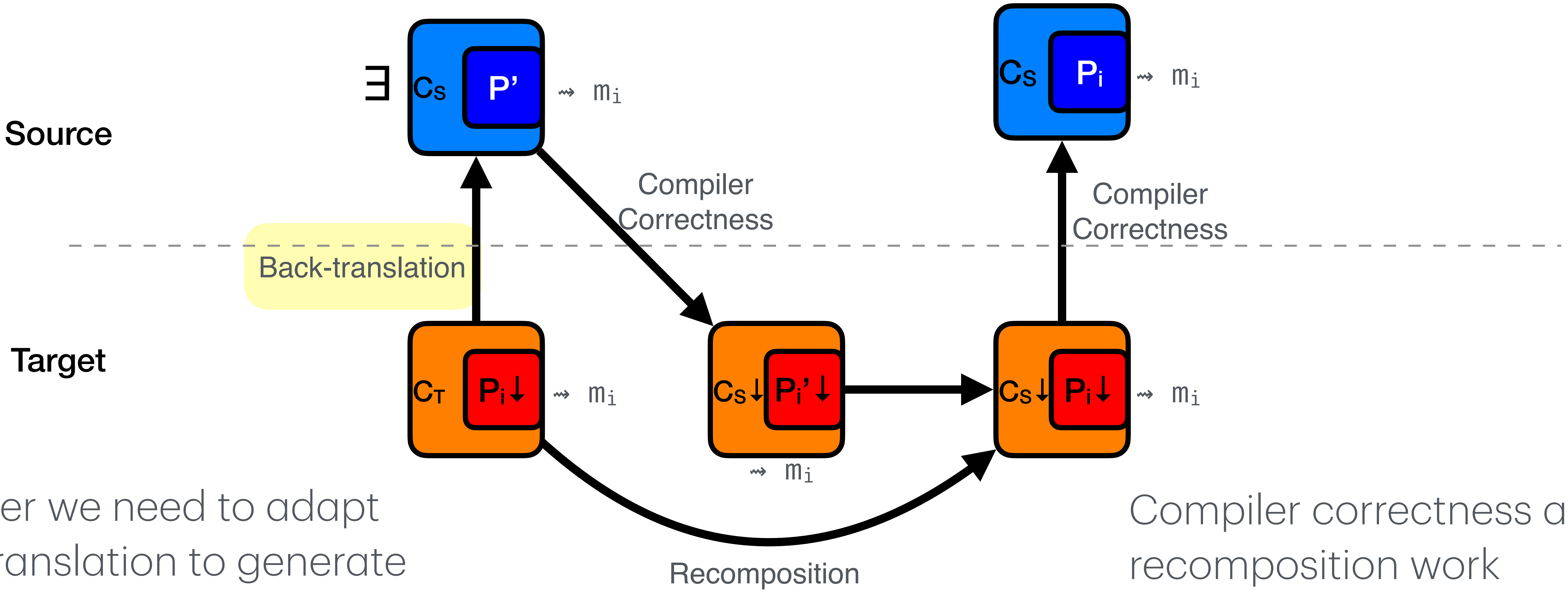


Compiler correctness and recomposition work pointwise, so we don't need to modify them

Adapting the proof for multiple programs



However we need to adapt back-translation to generate one context and several programs

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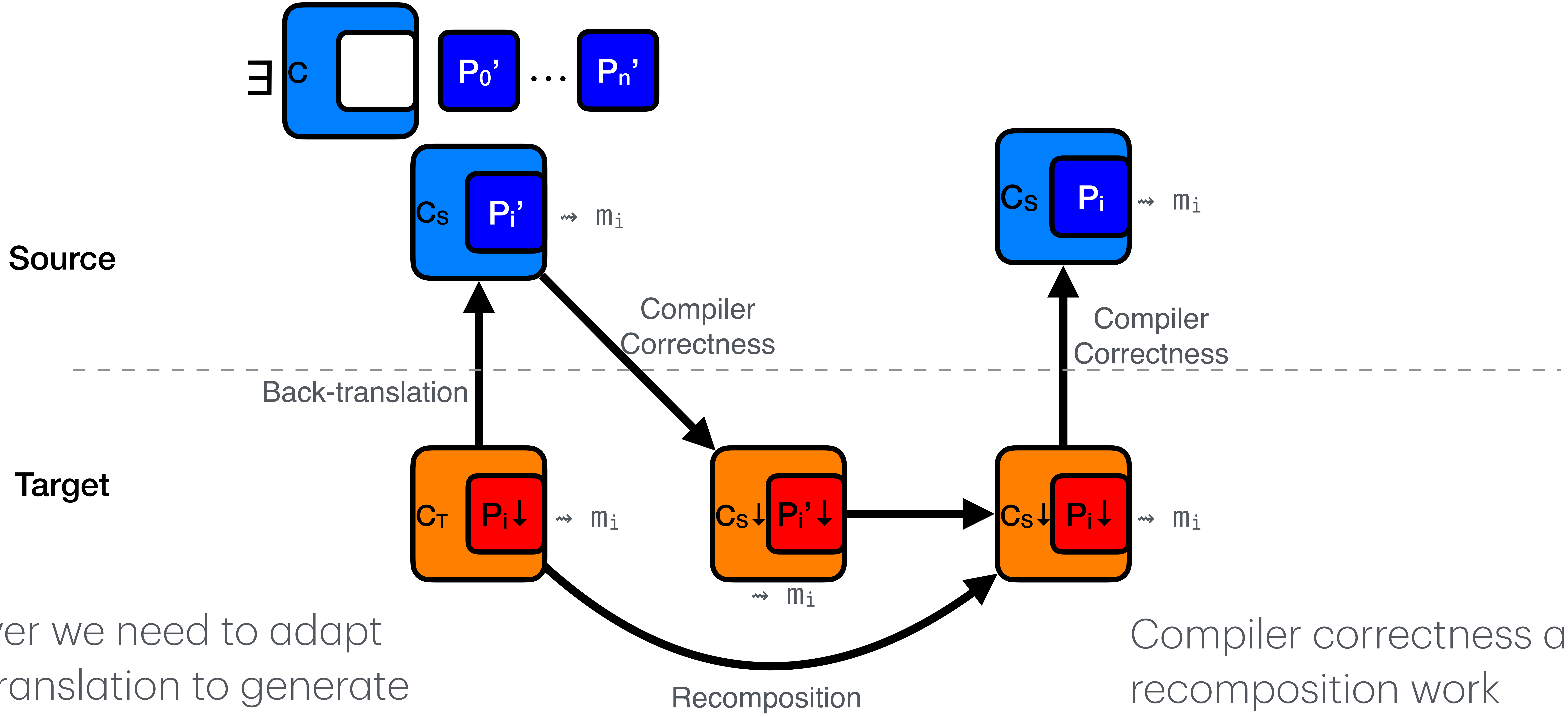

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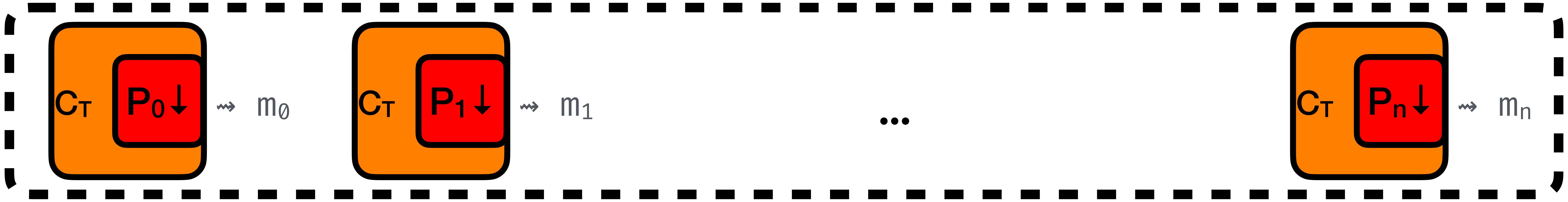
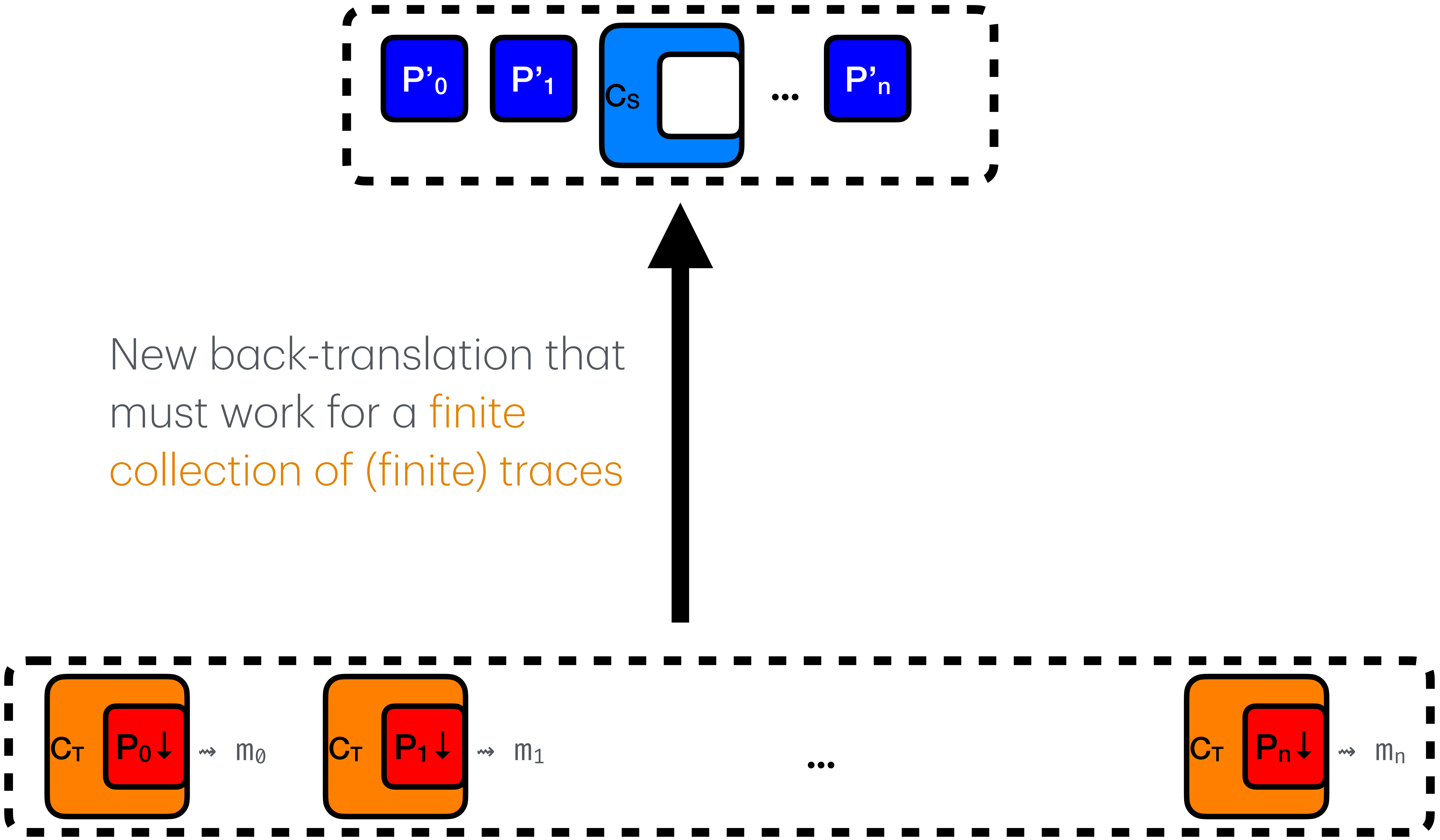
Back-translation for several traces

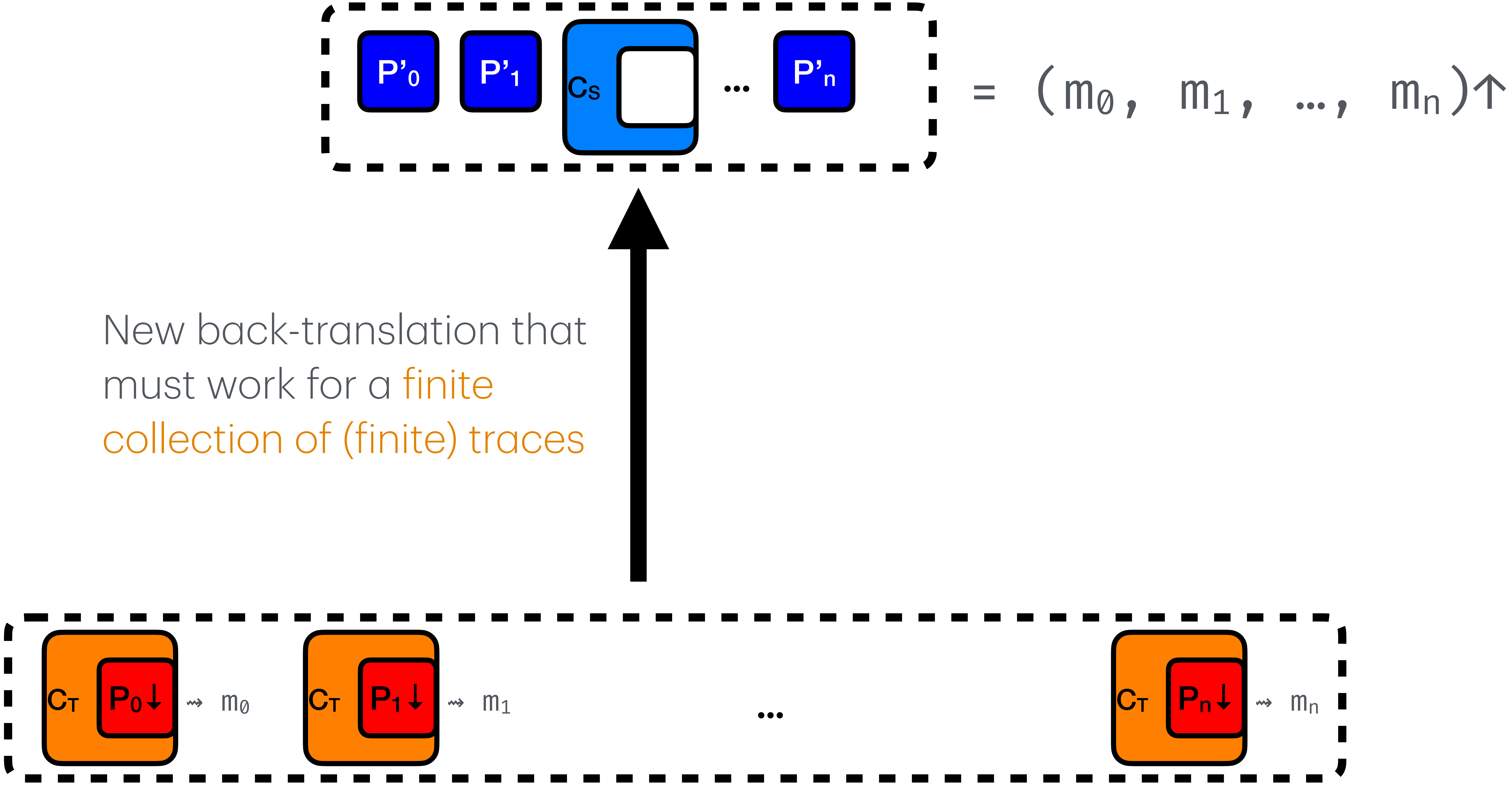


Back-translation for several traces



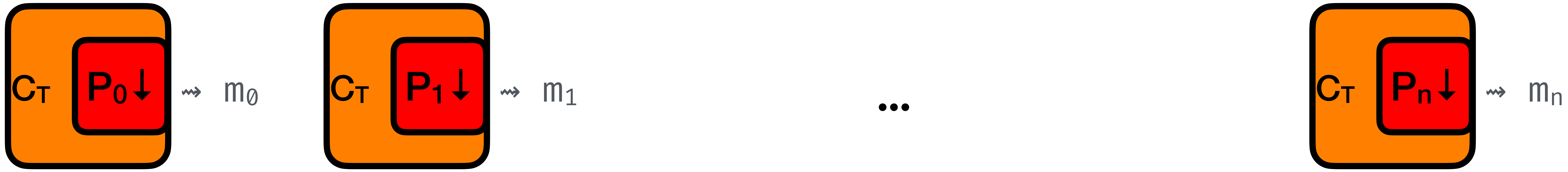
New back-translation that must work for a finite collection of (finite) traces

Back-translation for several traces



New back-translation that must work for a finite collection of (finite) traces

Structure of the traces



C_T $P_0\downarrow$ ⇝ m_0

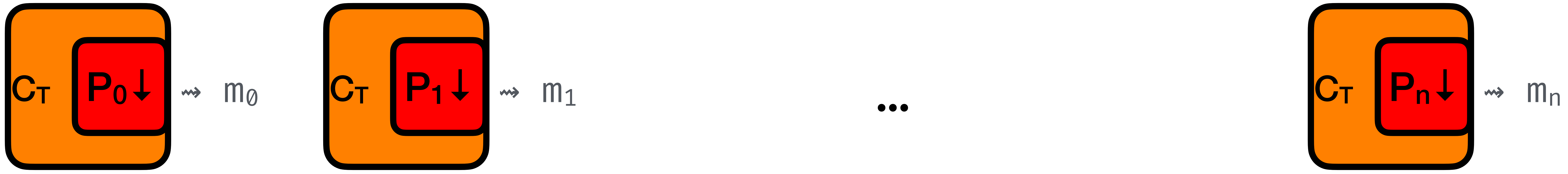
C_T $P_1\downarrow$ ⇝ m_1

...

C_T $P_n\downarrow$ ⇝ m_n

Structure of the traces

Traces are produced by the same context but different programs

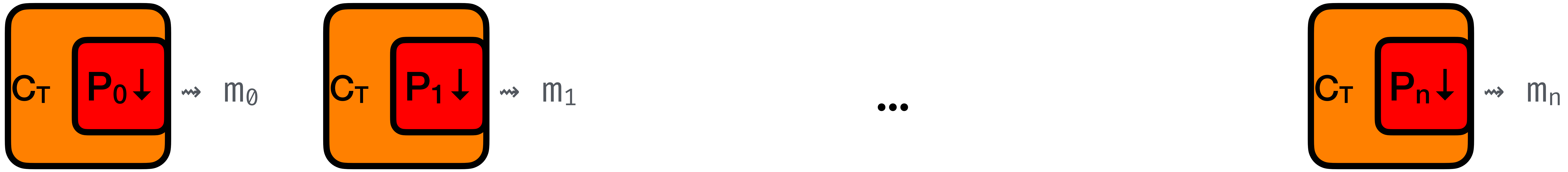


$C_T\ P_0{\downarrow} \rightsquigarrow m_0$ $C_T\ P_1{\downarrow} \rightsquigarrow m_1$ ... $C_T\ P_n{\downarrow} \rightsquigarrow m_n$

Structure of the traces

Traces are produced by the same context but different programs

Determinacy property: traces can only differ because the programs did something different

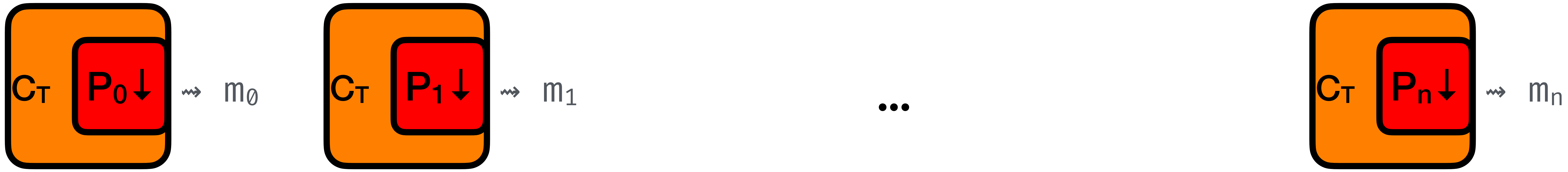


Structure of the traces

Traces are produced by the same context but different programs

Traces $m_0, m_1, \ldots, m_n$ can be represented by a tree T that branches on events from P

Determinacy property: traces can only differ because the programs did something different


C_T $P_0\downarrow$ $\rightsquigarrow m_0$
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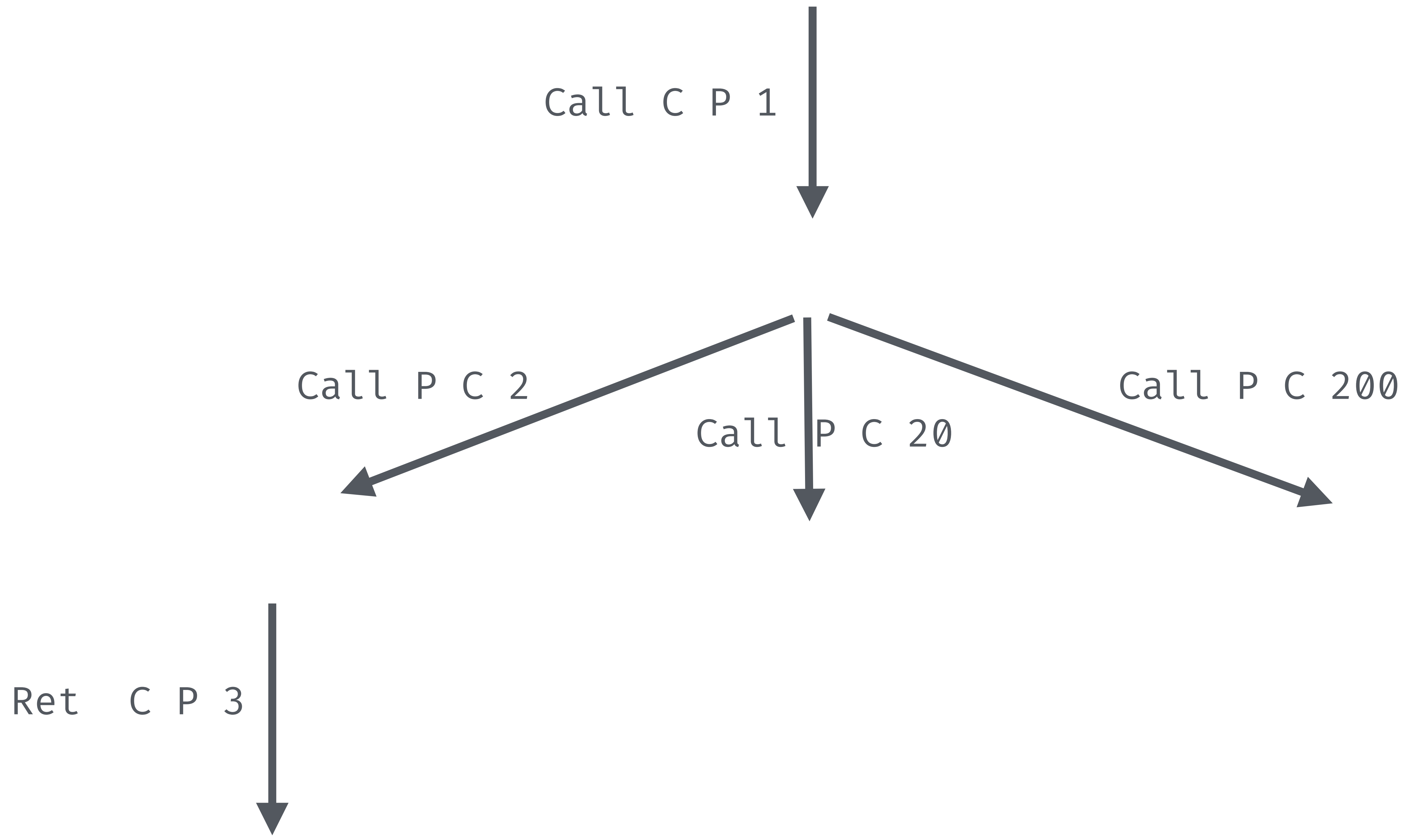
Back-translating trees is harder



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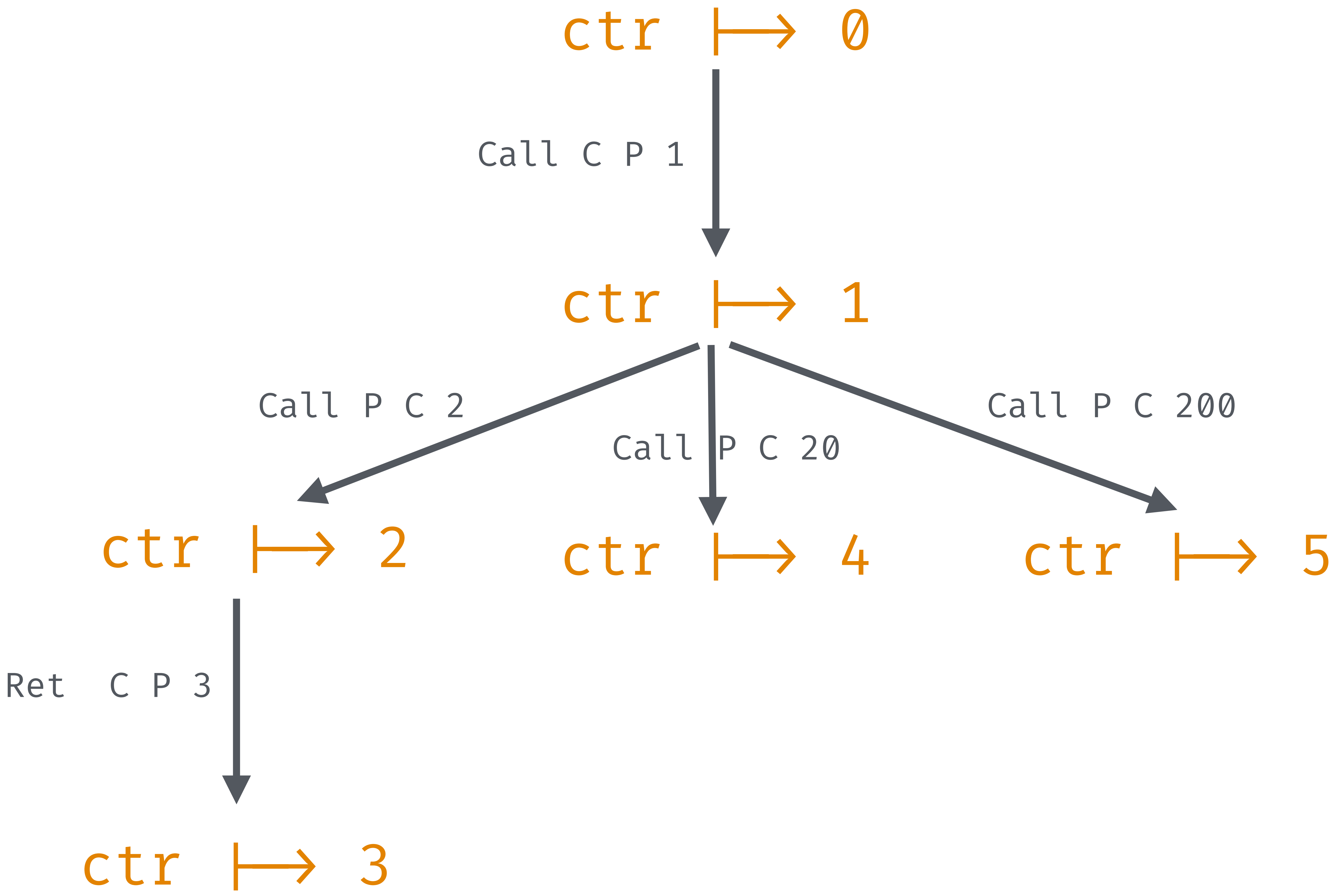

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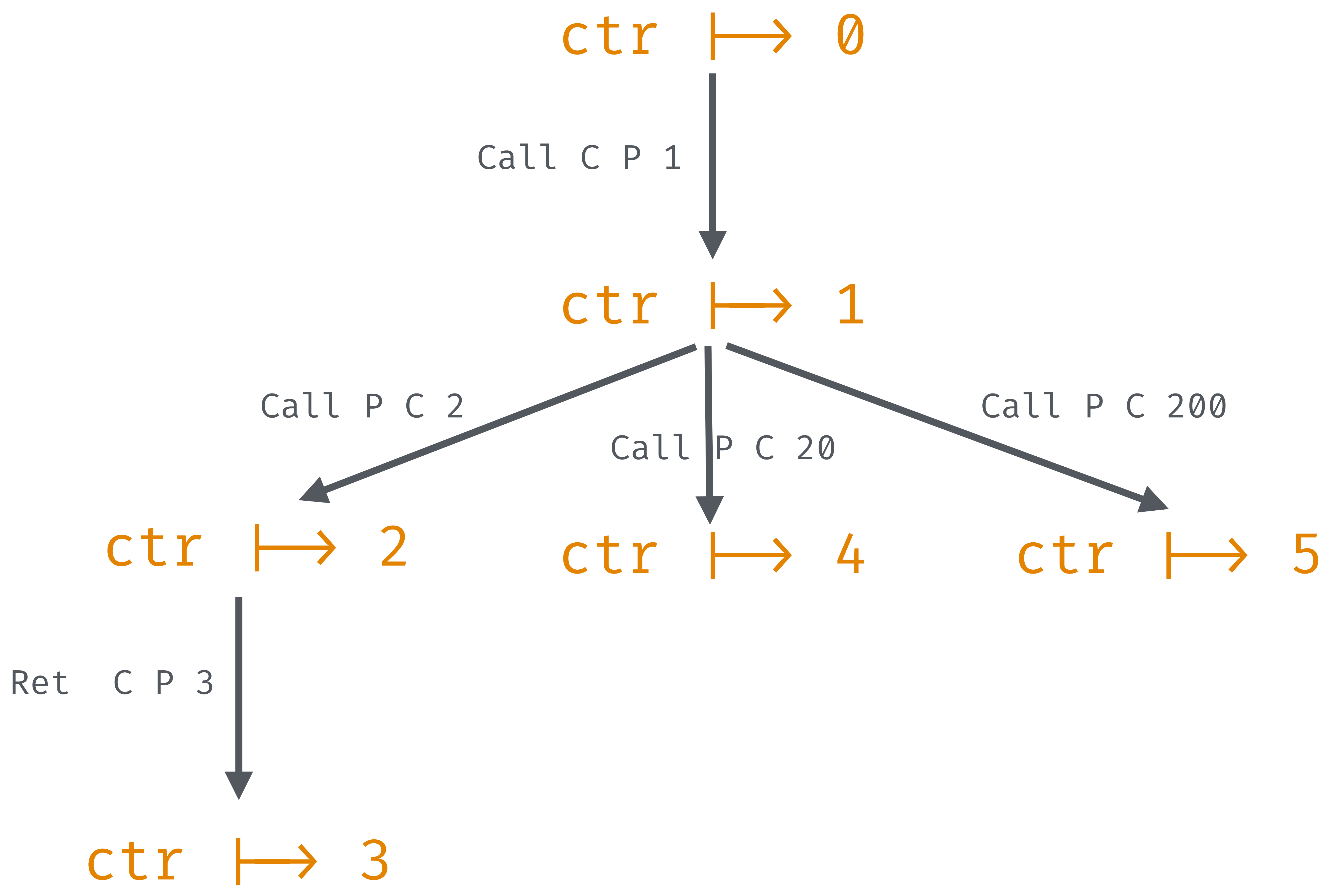
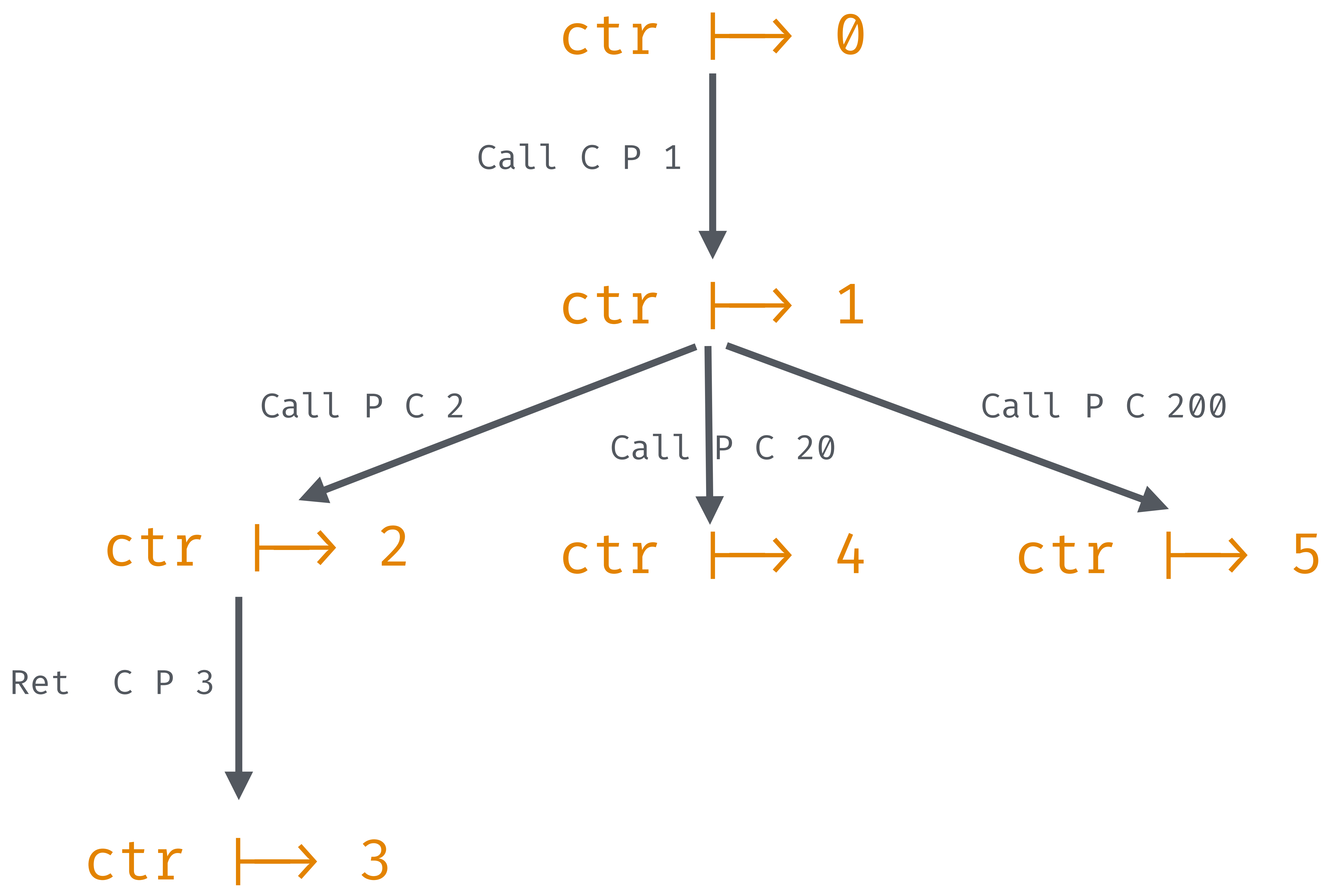


To back-translate:

- Generalize the counter to record position in the tree
- Context needs to look at argument and return value before updating its local counter
- Also need to look at current local counter

Back-translating trees is harder



```
if (ctr = K && call_arg = V) {
  ctr := NEXT_CTR(K, V);
  DO_EVENT(K, V);
  C();
}
…
```

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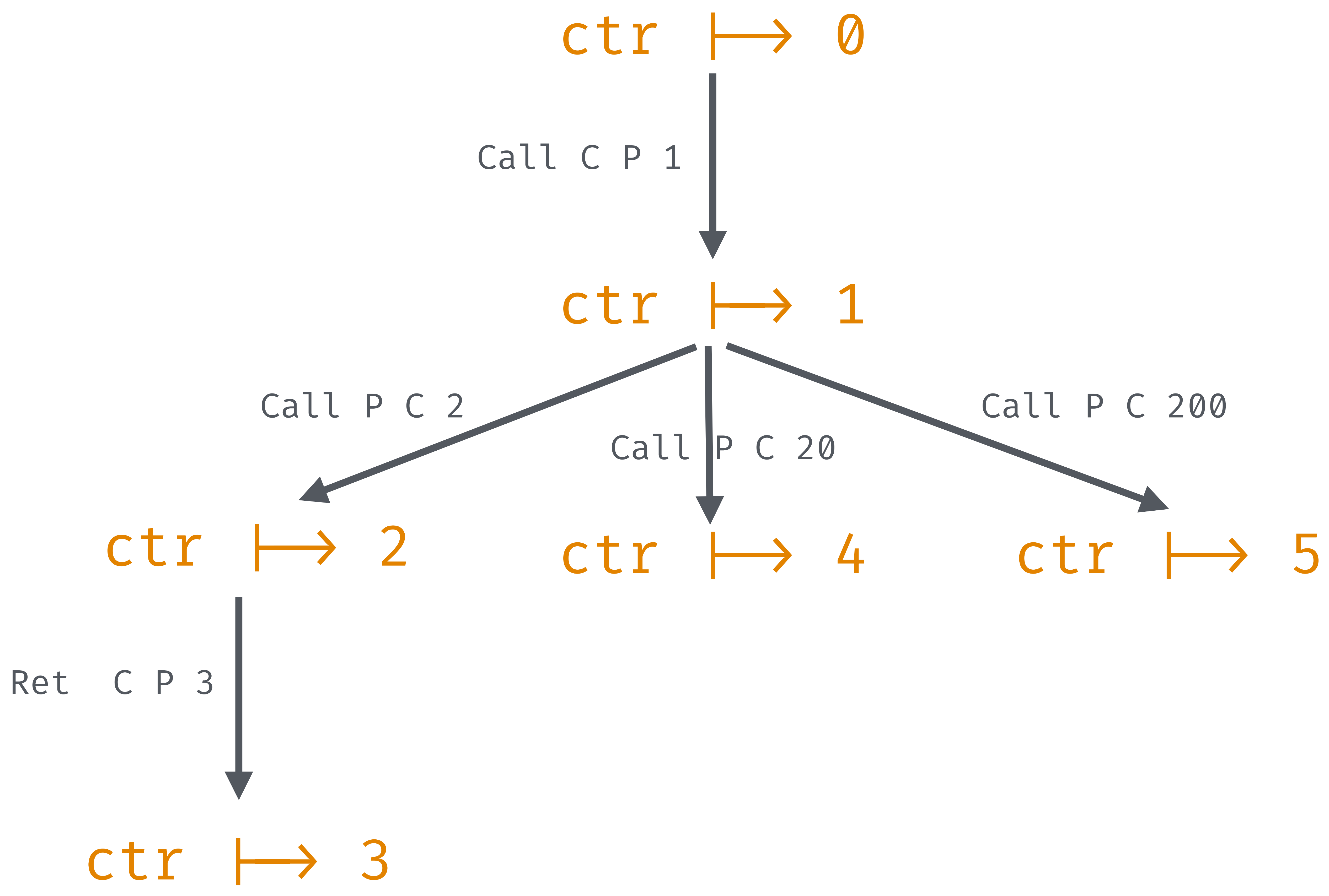

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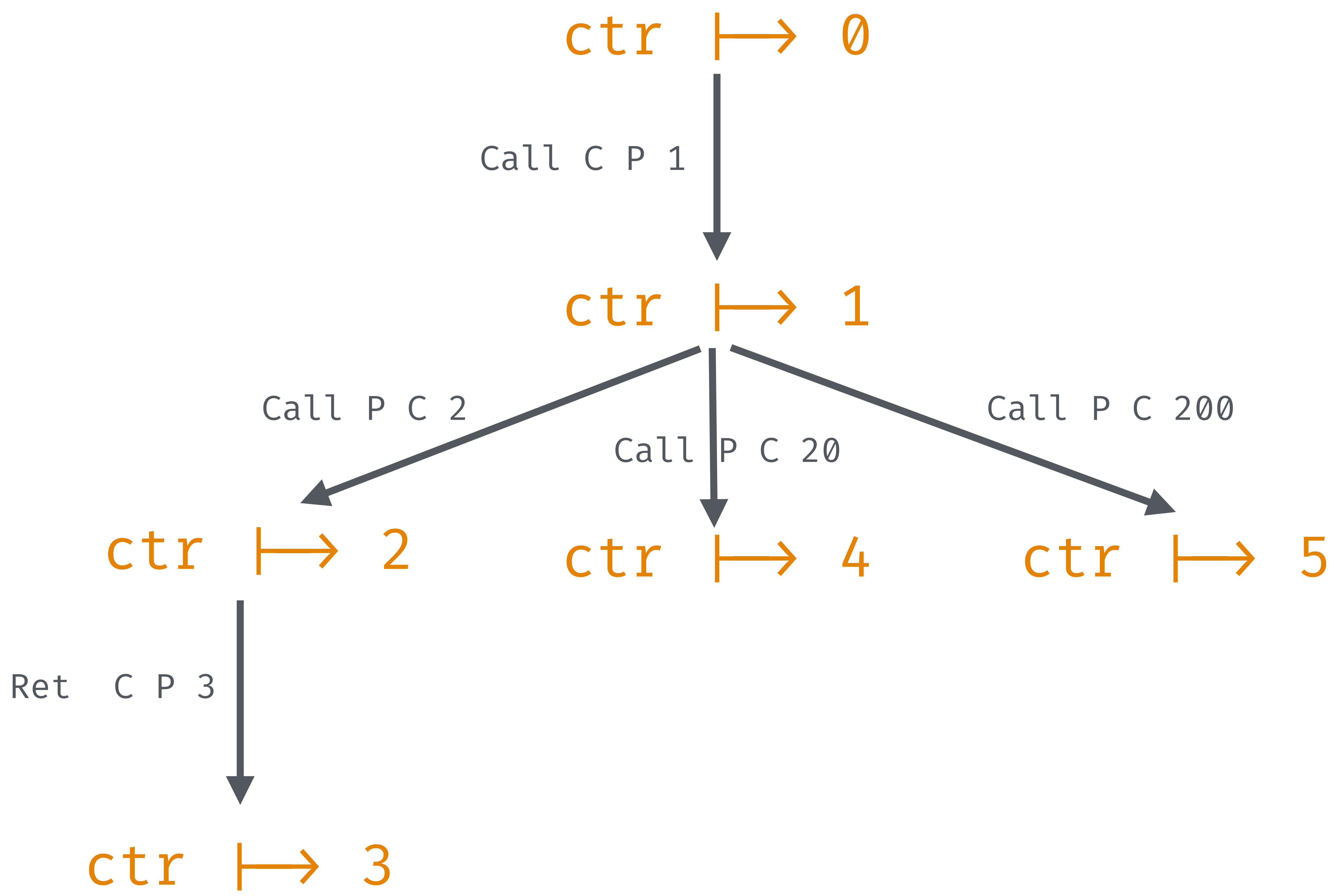
Back-translation function is not trivial!

Proving the back-translation is also harder



ctr ⟼ 0

Call C P 1

ctr ⟼ 1

Call P C 2

Call P C 20

Call P C 200

ctr ⟼ 2

ctr ⟼ 4

ctr ⟼ 5

Ret C P 3

ctr ⟼ 3

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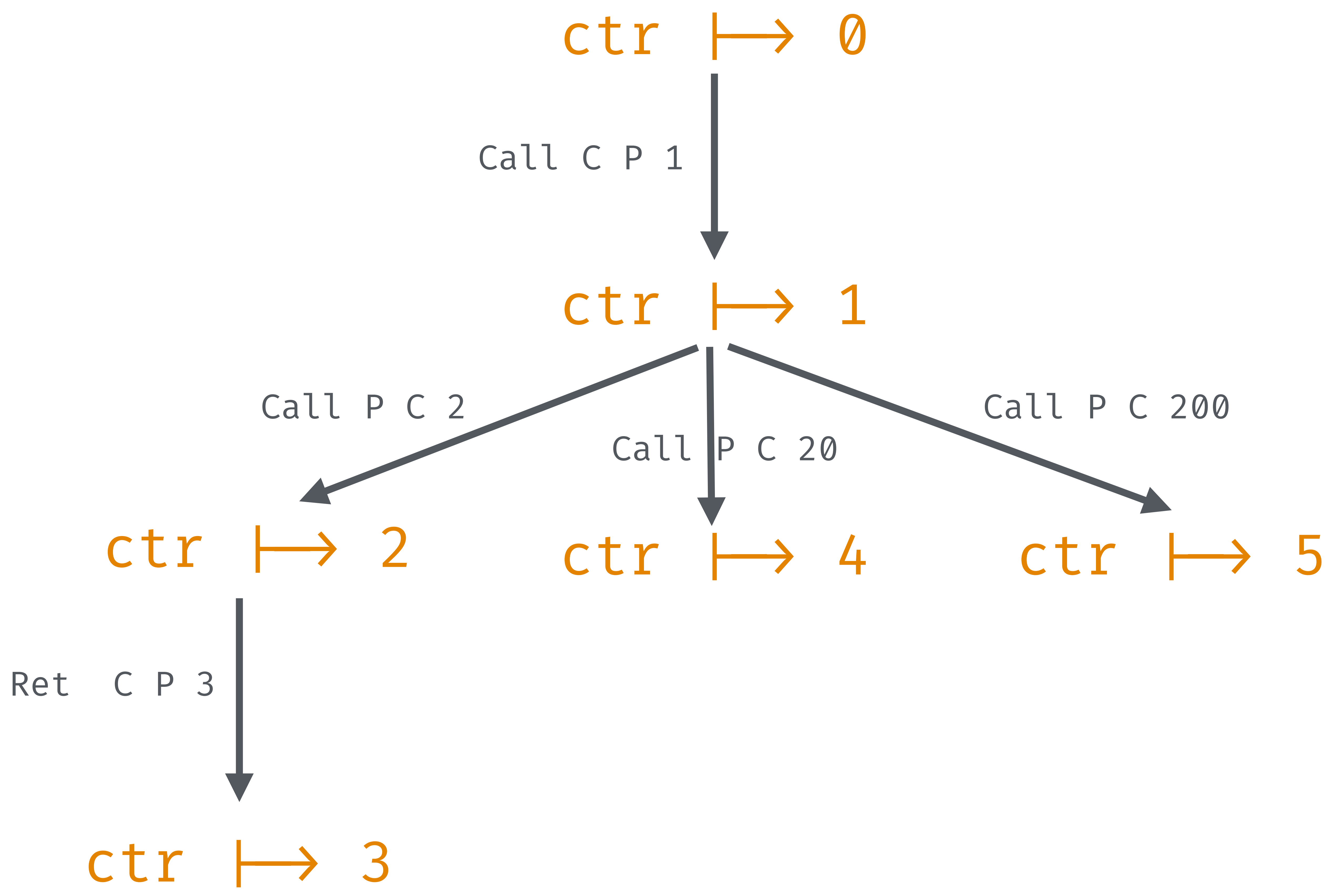

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Non-trivial invariants!

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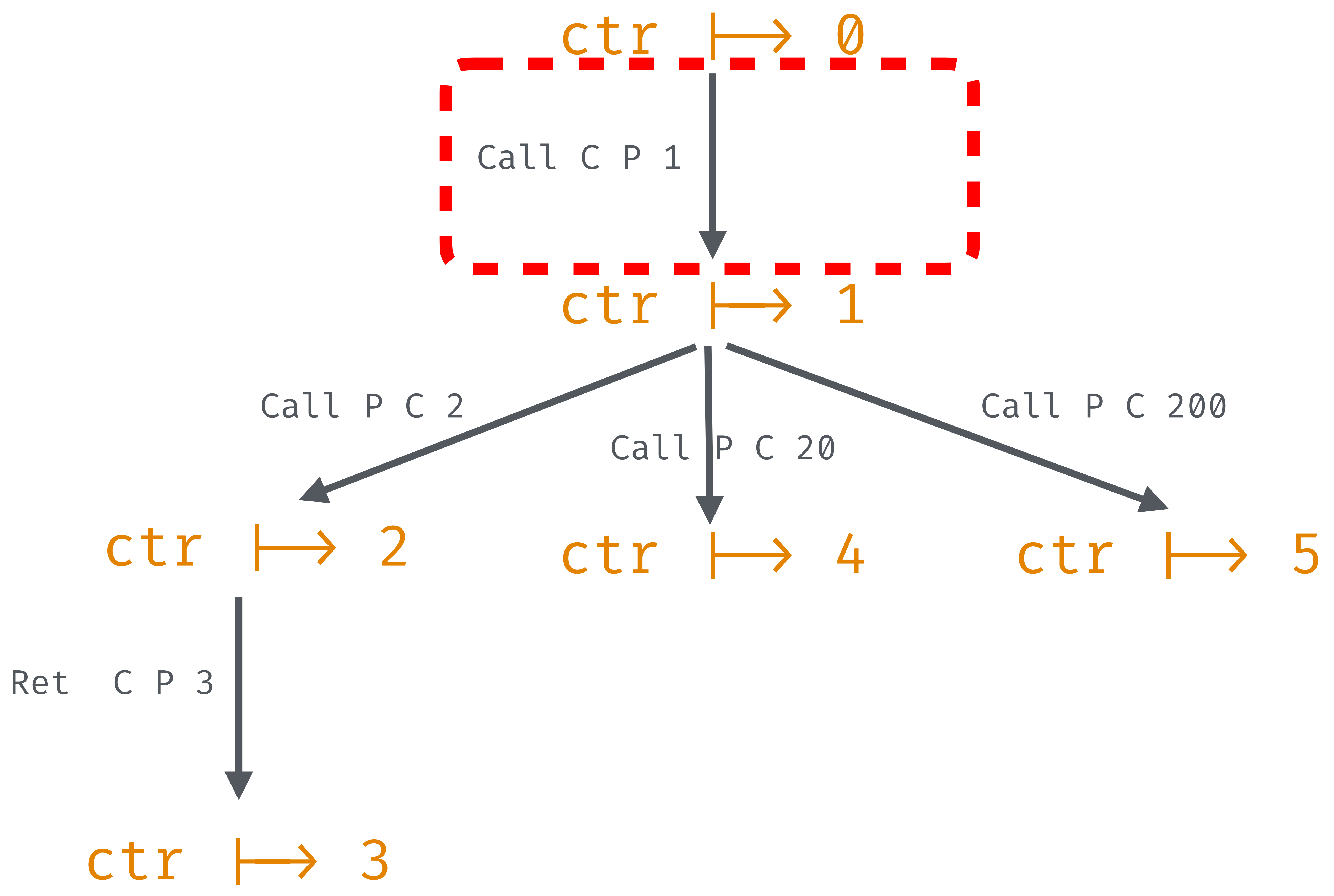

Non-trivial invariants!

- Context can only do one event

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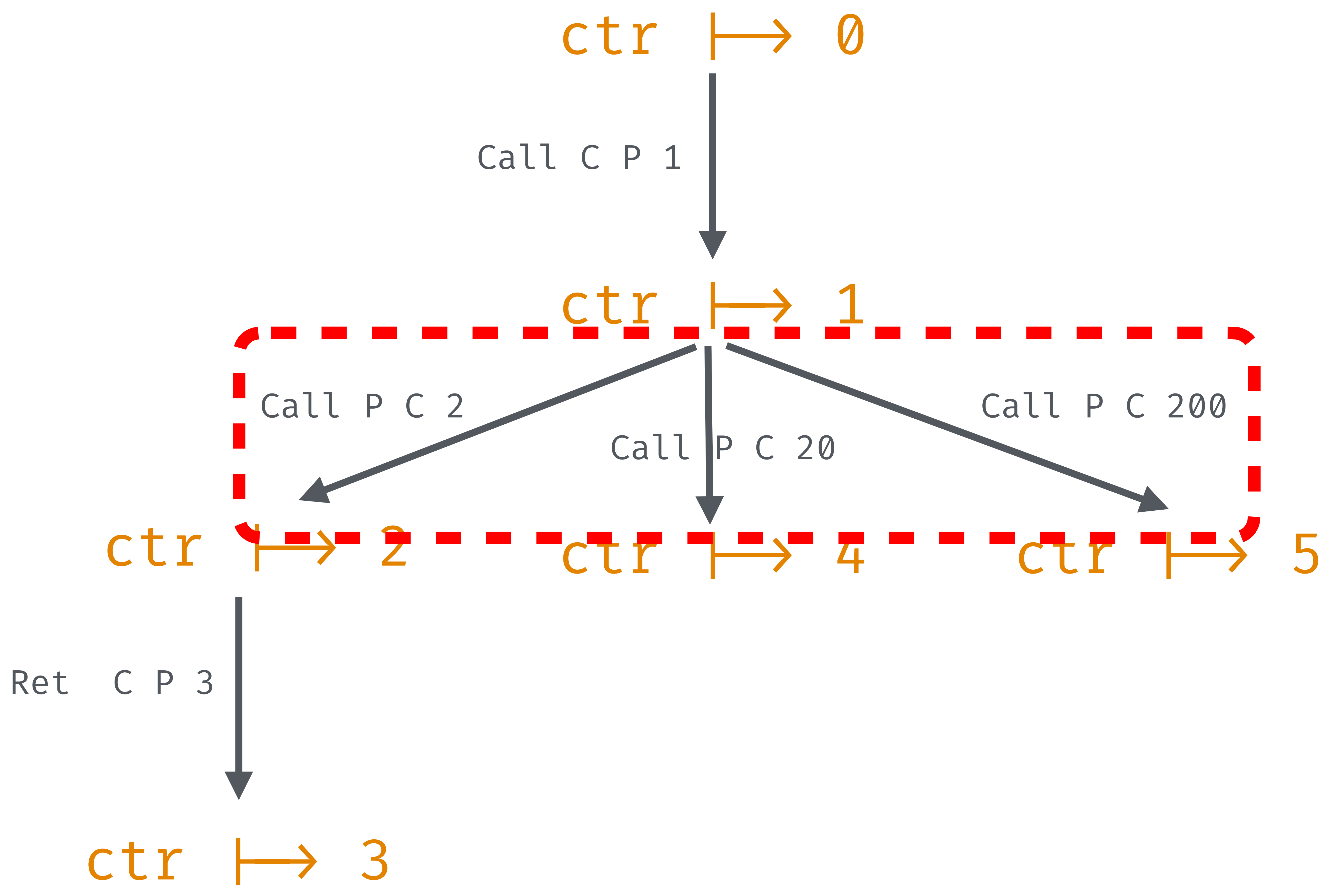

Non-trivial invariants!

- Context can only do one event
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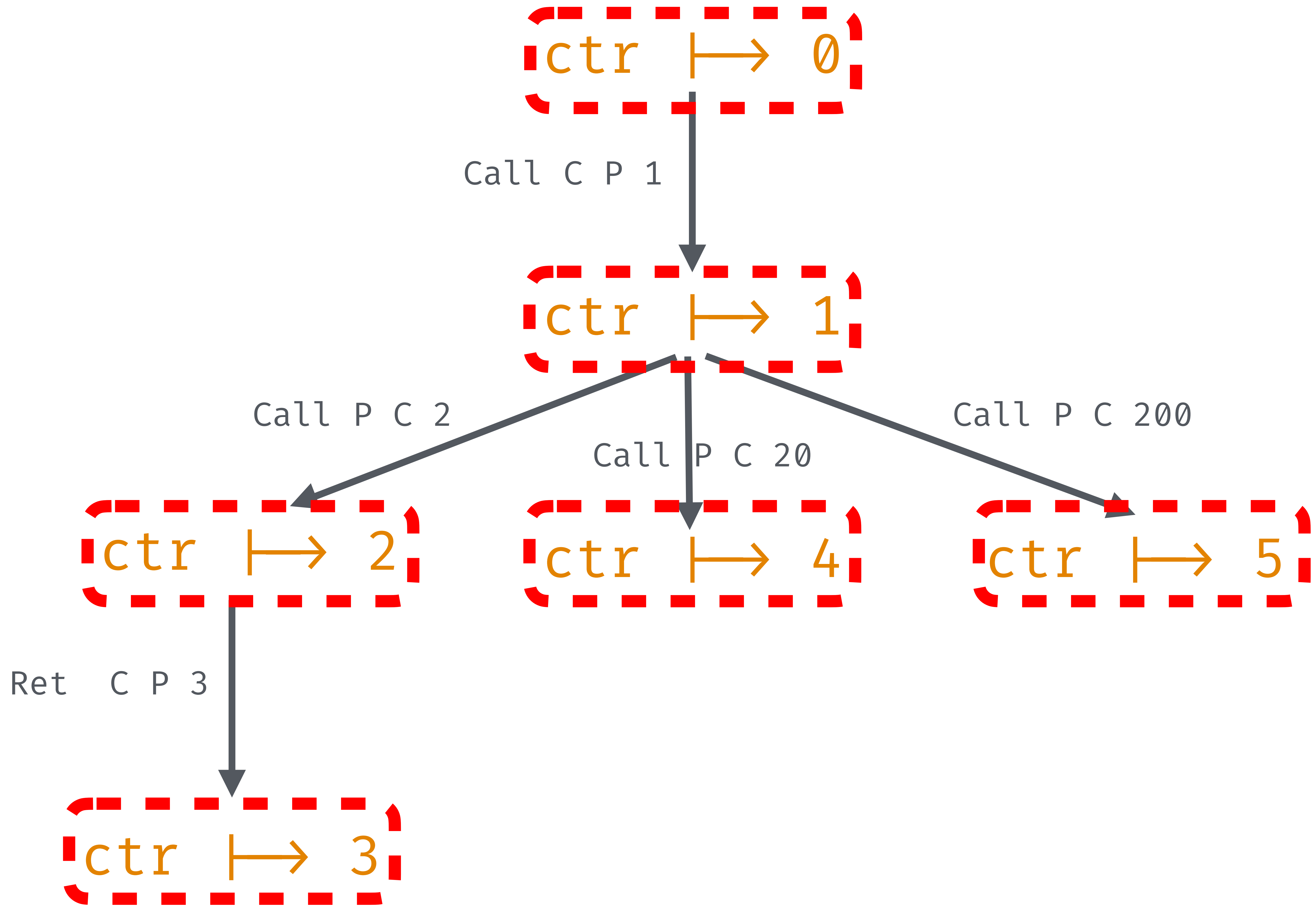

Non-trivial invariants!

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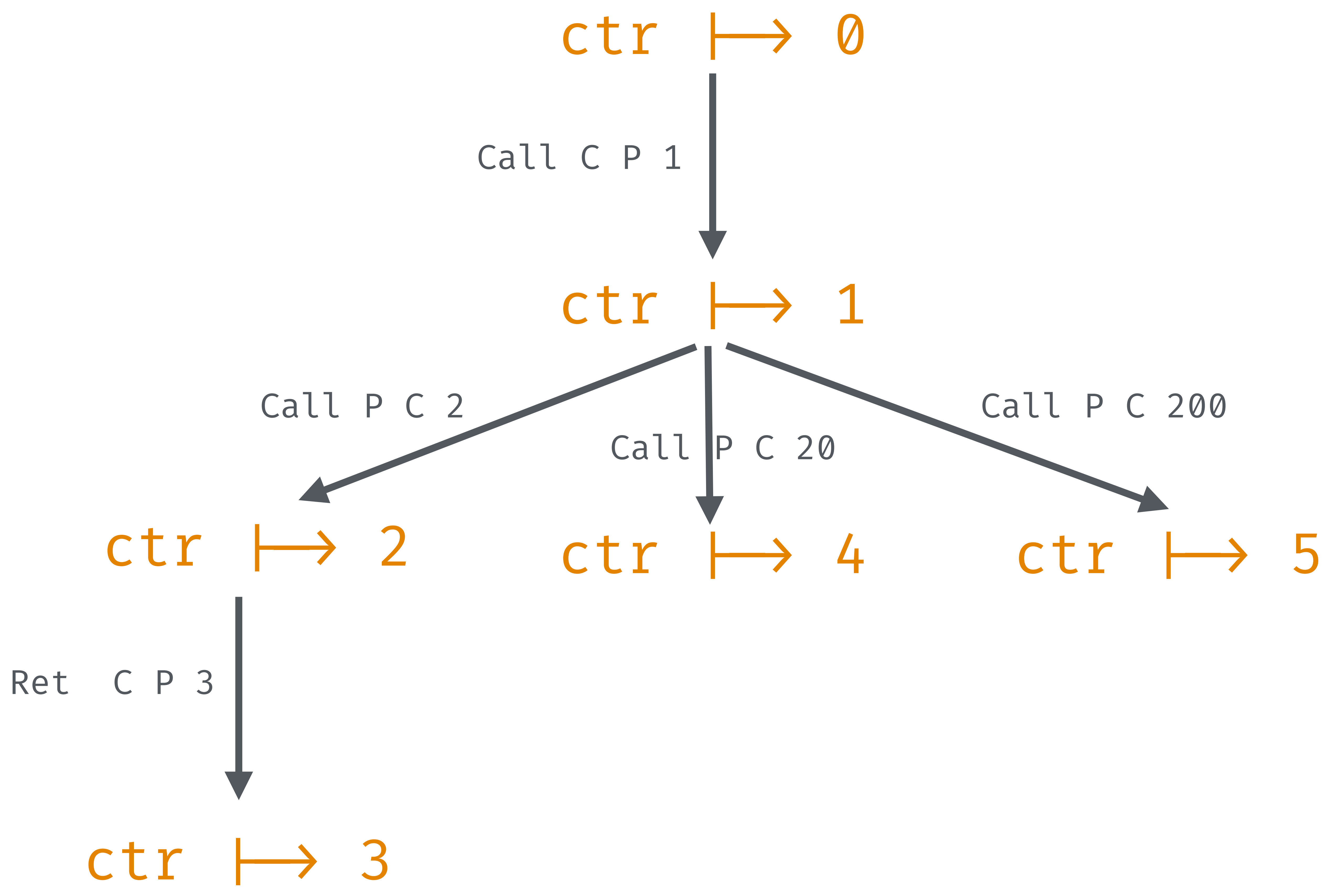

Non-trivial invariants!

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- No duplicate events
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- To handle returns: well-bracketedness

Back-translation in several steps

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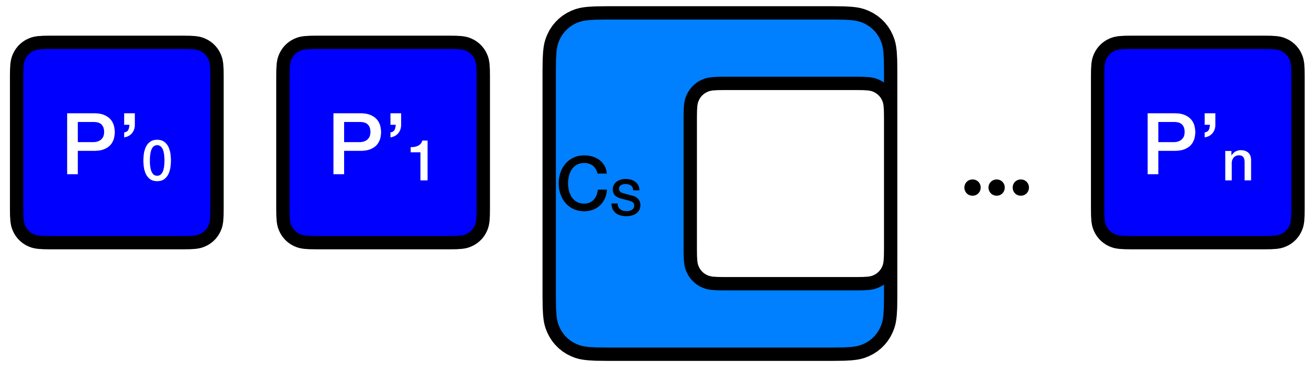

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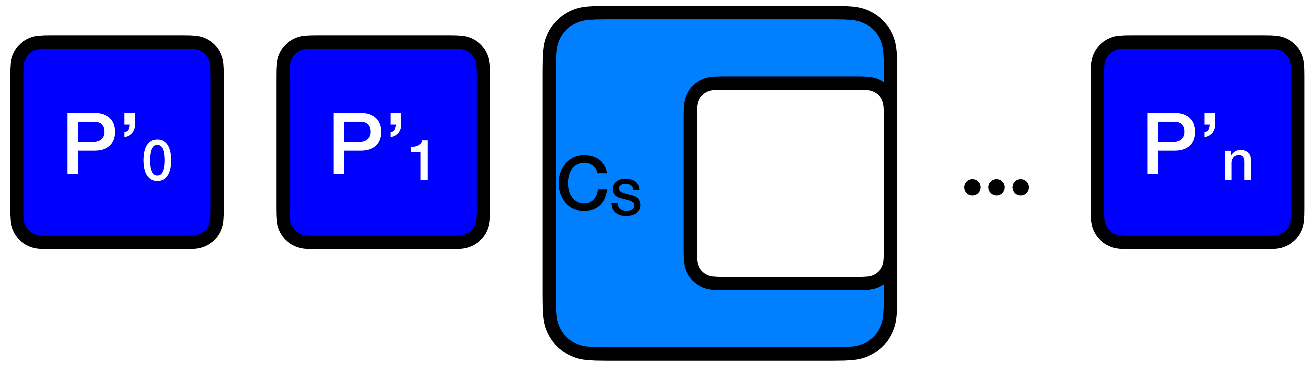
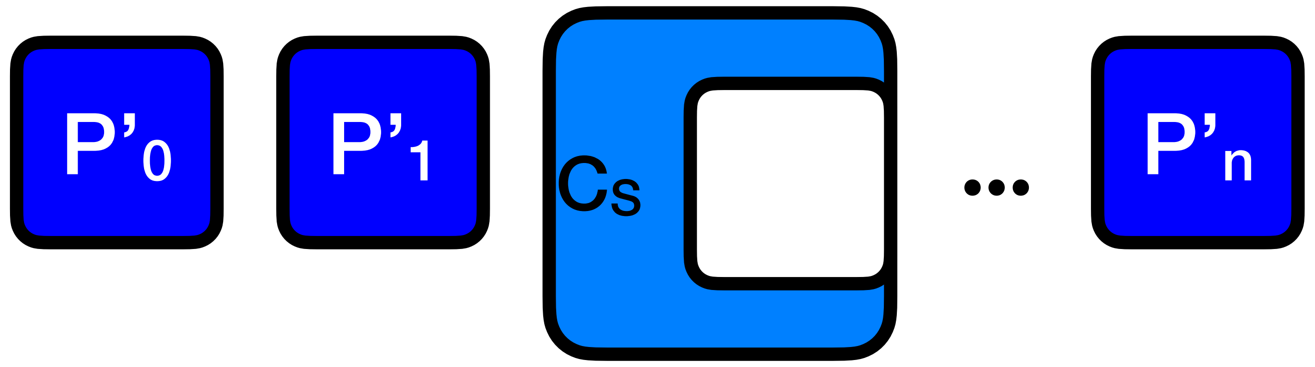


Tree T

Back-translation in several steps

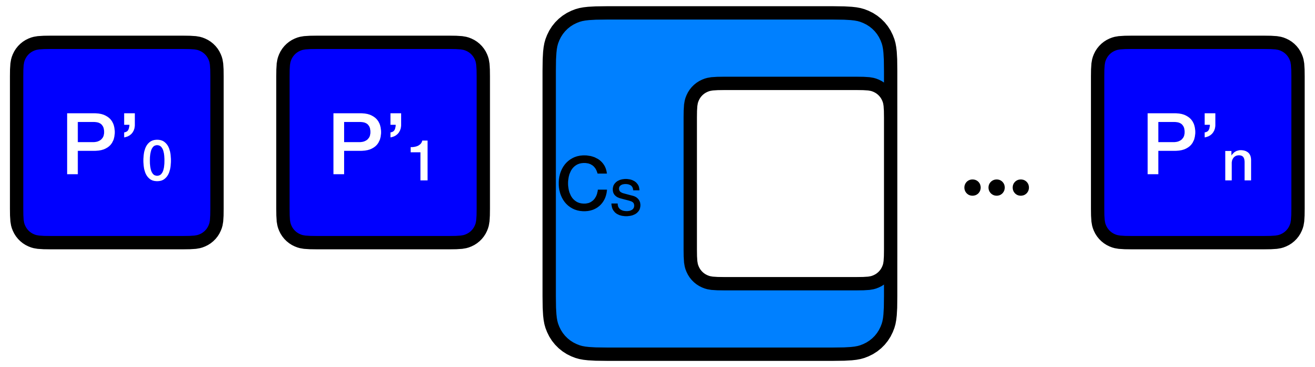


Tree T’ with ctr

↑

Tree T

Back-translation in several steps



Tree T' with stack record

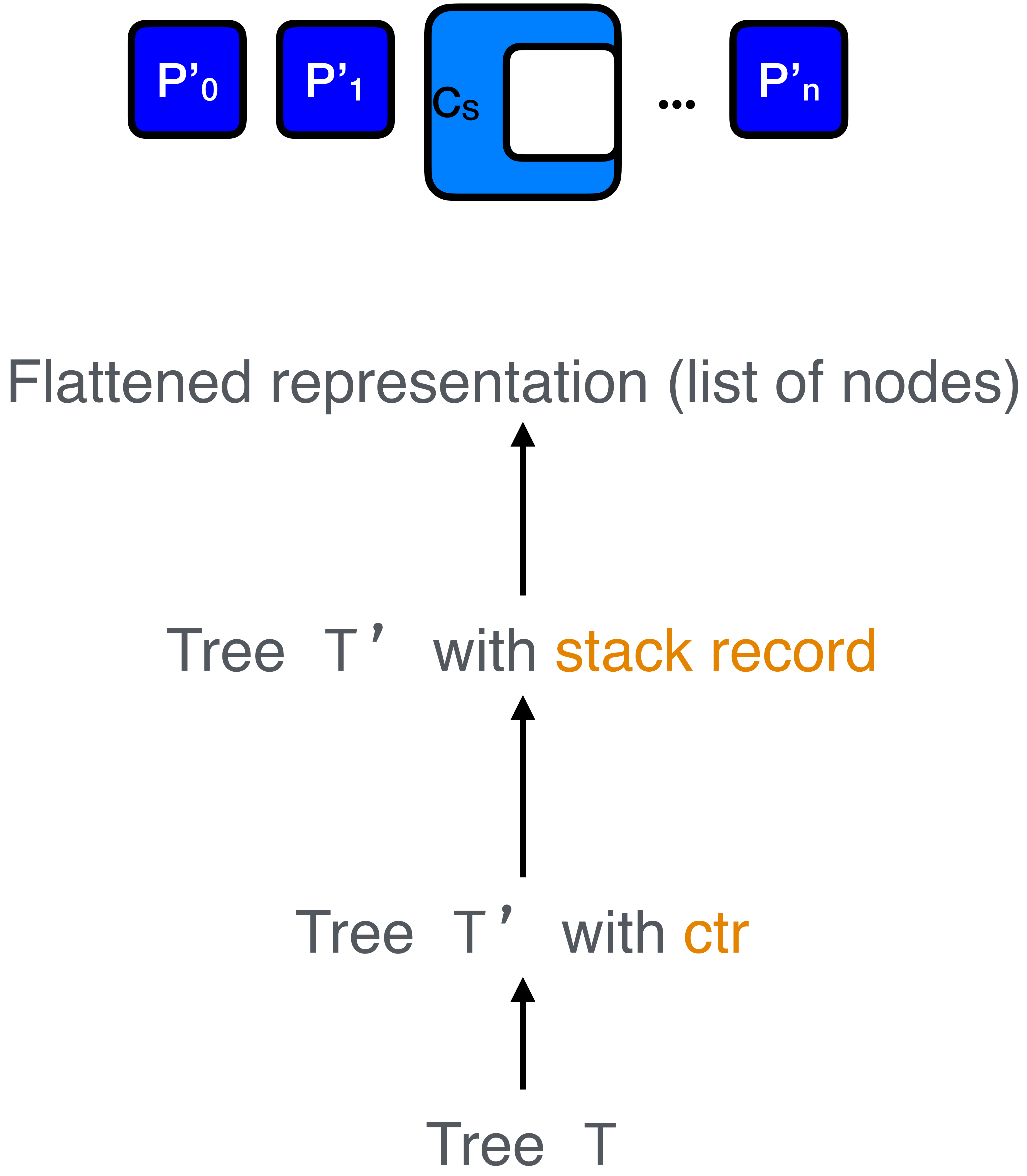
↑

Tree T' with ctr

↑

Tree T

Back-translation in several steps



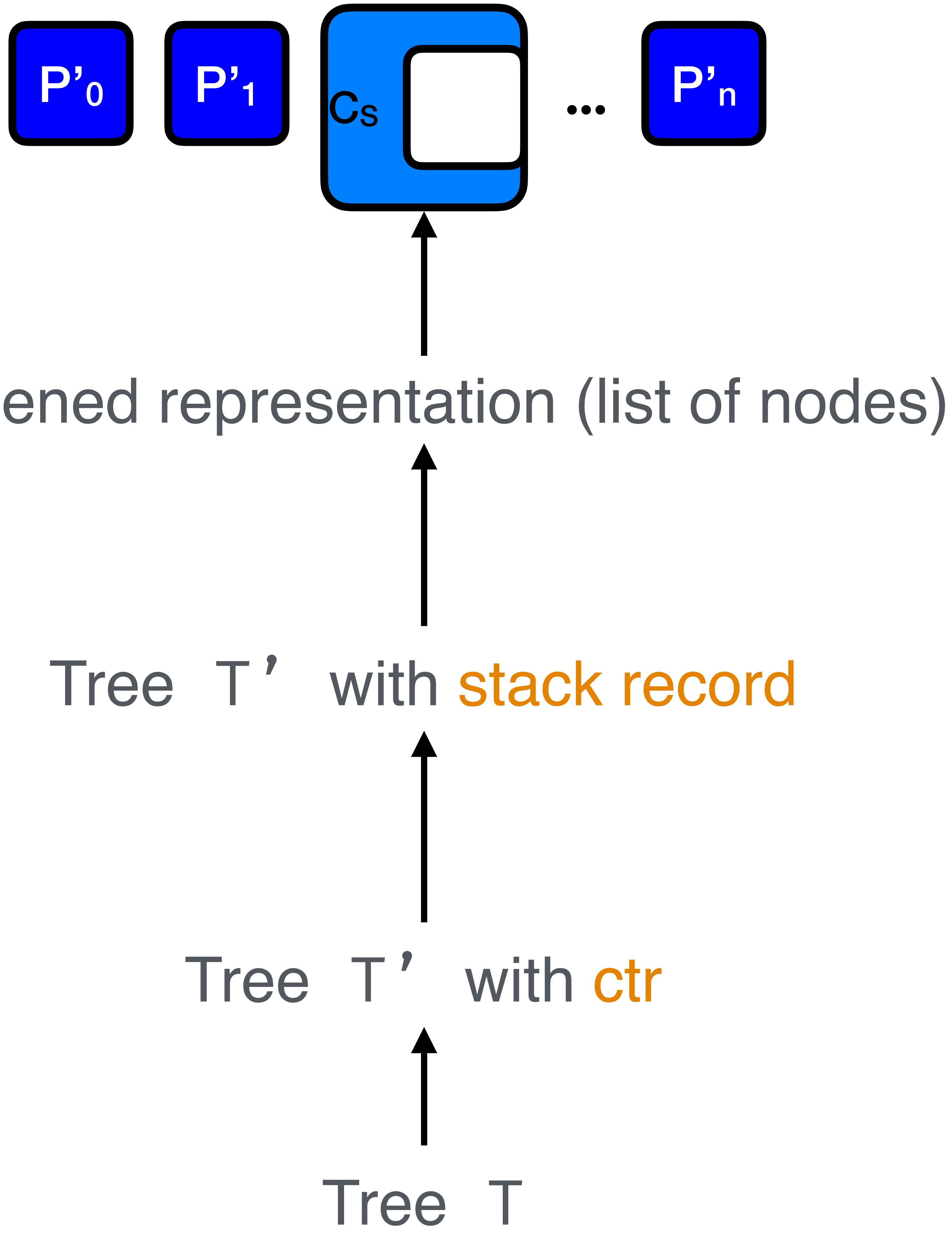
Flattened representation (list of nodes)

Tree T' with stack record

Tree T' with ctr

Tree T

Back-translation in several steps



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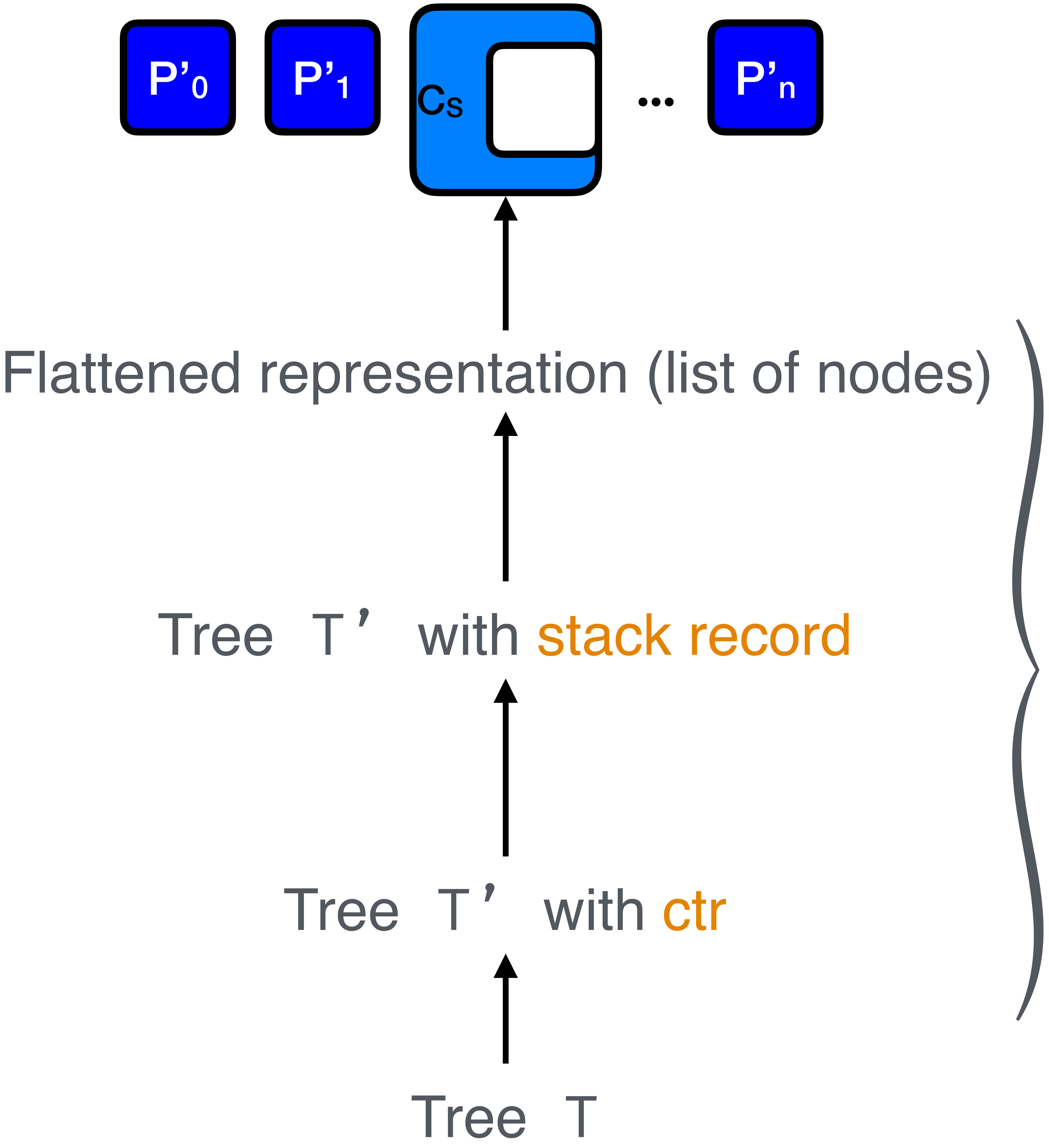

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Passes as small as possible to simplify implementation and reasoning

Proving back-translation (2)

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$s, stack \rightarrow_e s', stack'$

Proving back-translation (2)

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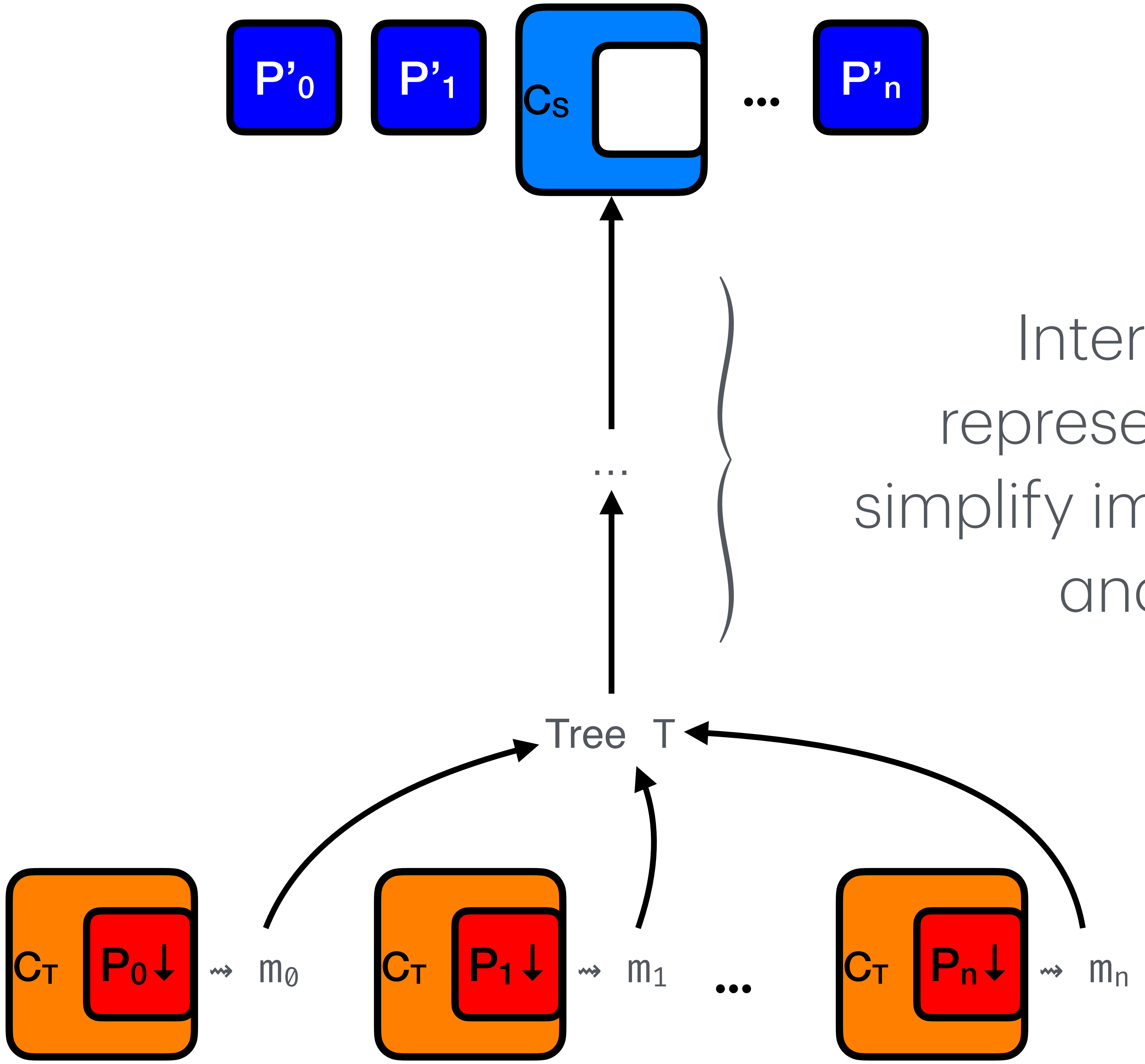
$$\frac{\texttt{stack = (C,P) :: stack'} \qquad \texttt{e = Ret P C z} \qquad \dots}{\texttt{s, stack} \rightarrow_{\texttt{e}} \texttt{s', stack'}}$$

Proving back-translation (3)

- Each pass: CompCert-style forward simulation
  - Small passes means individual proofs are not so complicated
- What is difficult: “flattening”
  - Pass that goes from trees to list of nodes (closer to final code)
  - Unicity and determinacy conditions
- In the actual implementation: multiples compartments, not just two

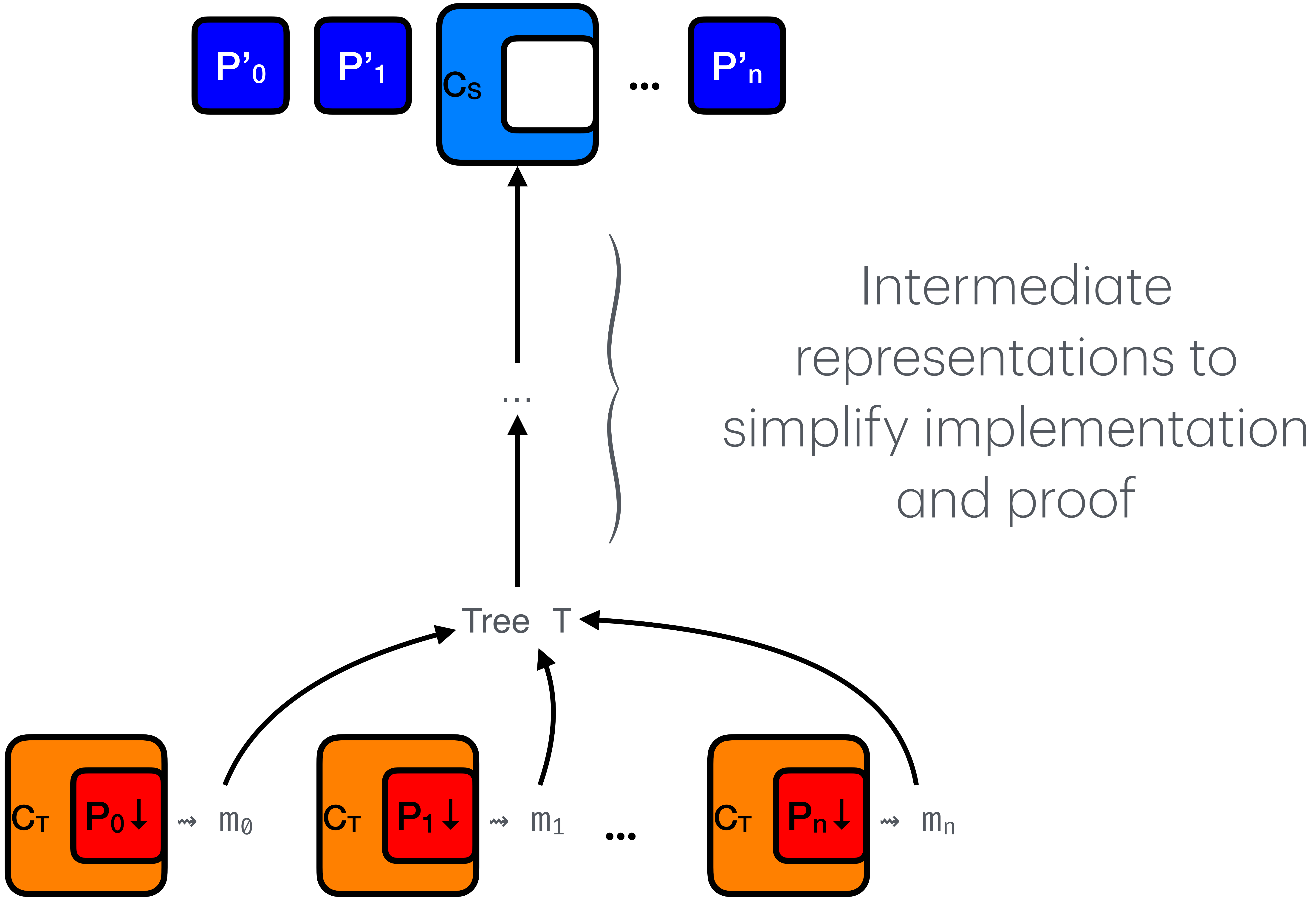
Conclusion



Intermediate representations to simplify implementation and proof

Conclusion

- Adapted a proof to obtain a much strong criterion



P'₀
P'₁
Cs
...
P'ₙ
Intermediate representations to simplify implementation and proof
...
Tree T
CT
P₀↓
⇝ m₀
CT
P₁↓
⇝ m₁
...
CT
Pₙ↓
⇝ mₙ

Conclusion

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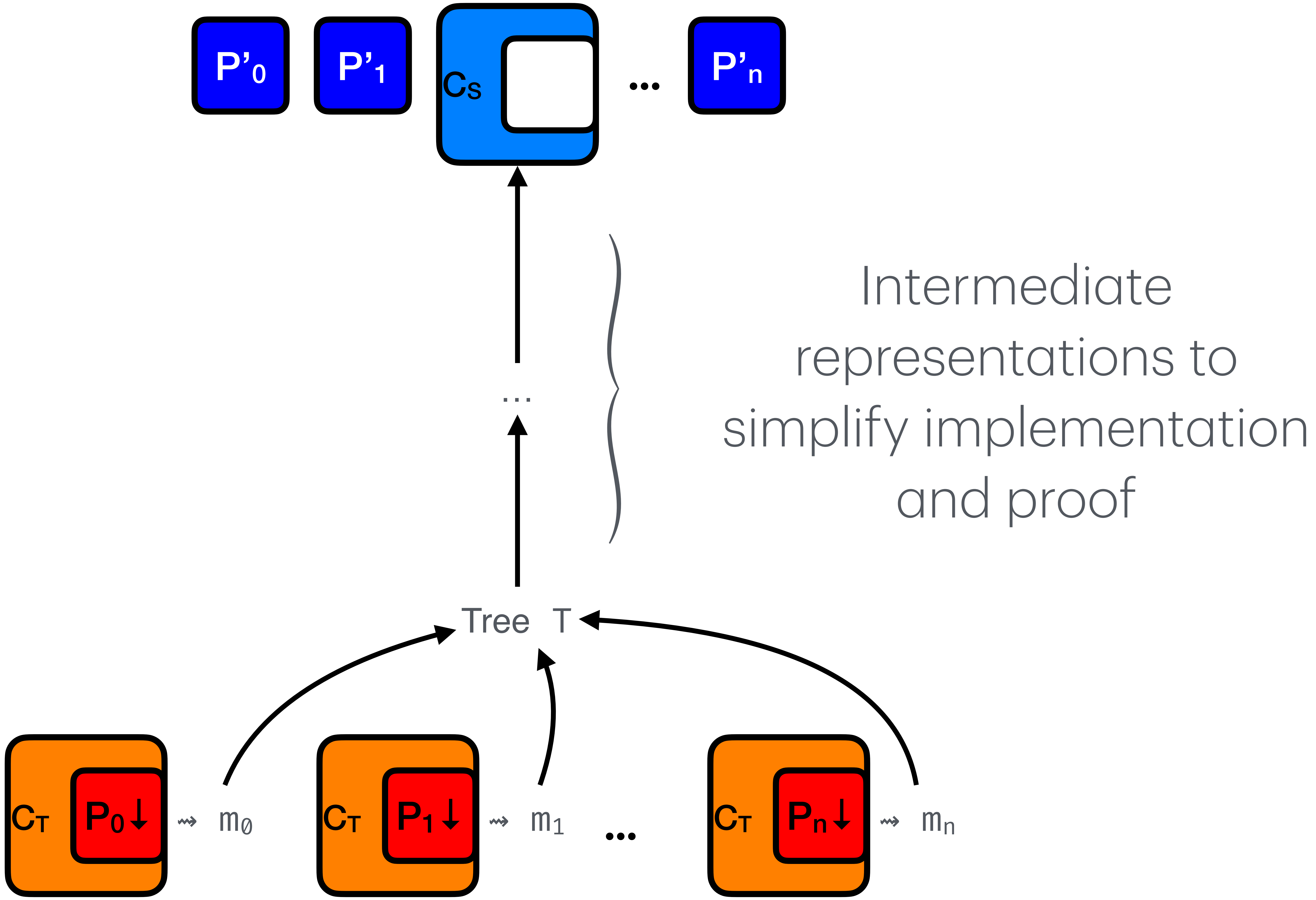
- Simplified implementation and proof by slicing the back-translation into multiple steps



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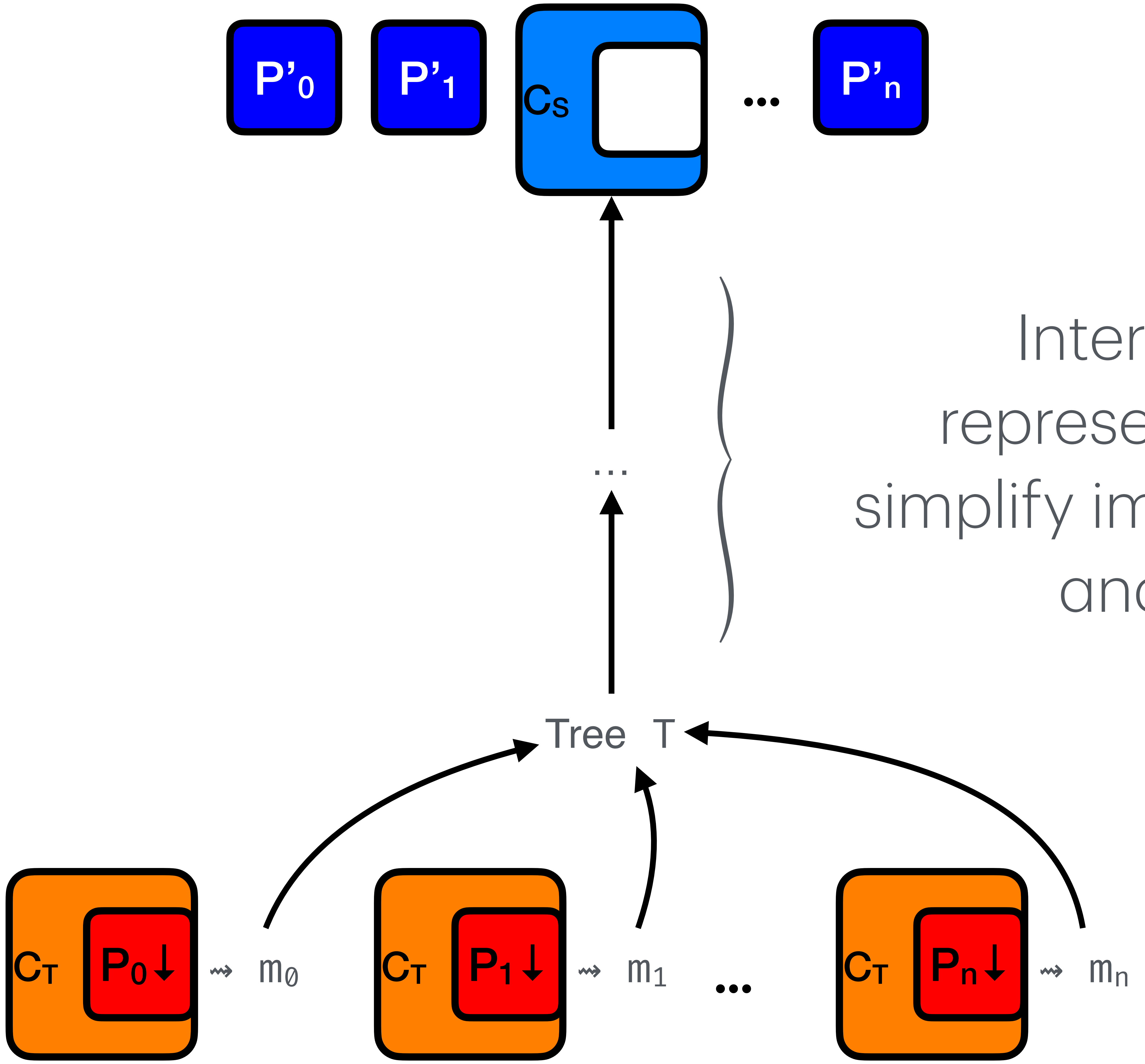
Conclusion

- Adapted a proof to obtain a much strong criterion
- Simplified implementation and proof by slicing the back-translation into multiple steps
- Also helps with parallelizing the proof process



Intermediate representations to simplify implementation and proof