Towards More Efficient and Trustworthy Formally Secure Compilation Against Speculative Side-Channel Attacks

Jonathan Baumann

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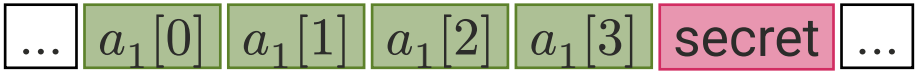
Formally Verified Security group, MPI-SP, Germany

Spectre (v1)

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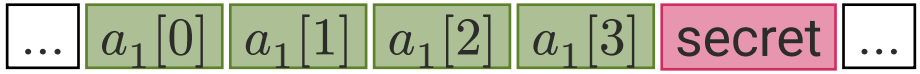
    x ← a2[j]

else
    ...
```

Spectre (v1)

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👀 $\mathtt{i} < size(\mathtt{a}_1)$

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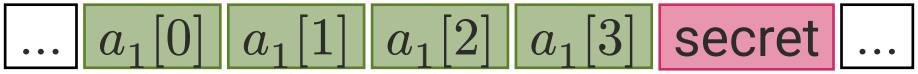


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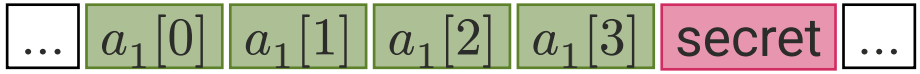


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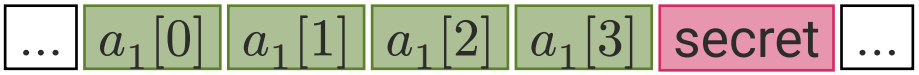
👀 $\mathtt{a}_1[\mathtt{i}]$

Spectre (v1)

let $\mathtt{i} = 4$

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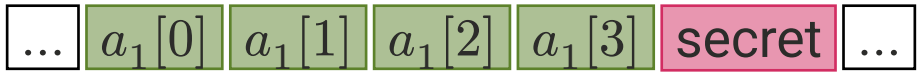

speculates by predicting branch

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    j ← a1[i];
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else
    ...
```
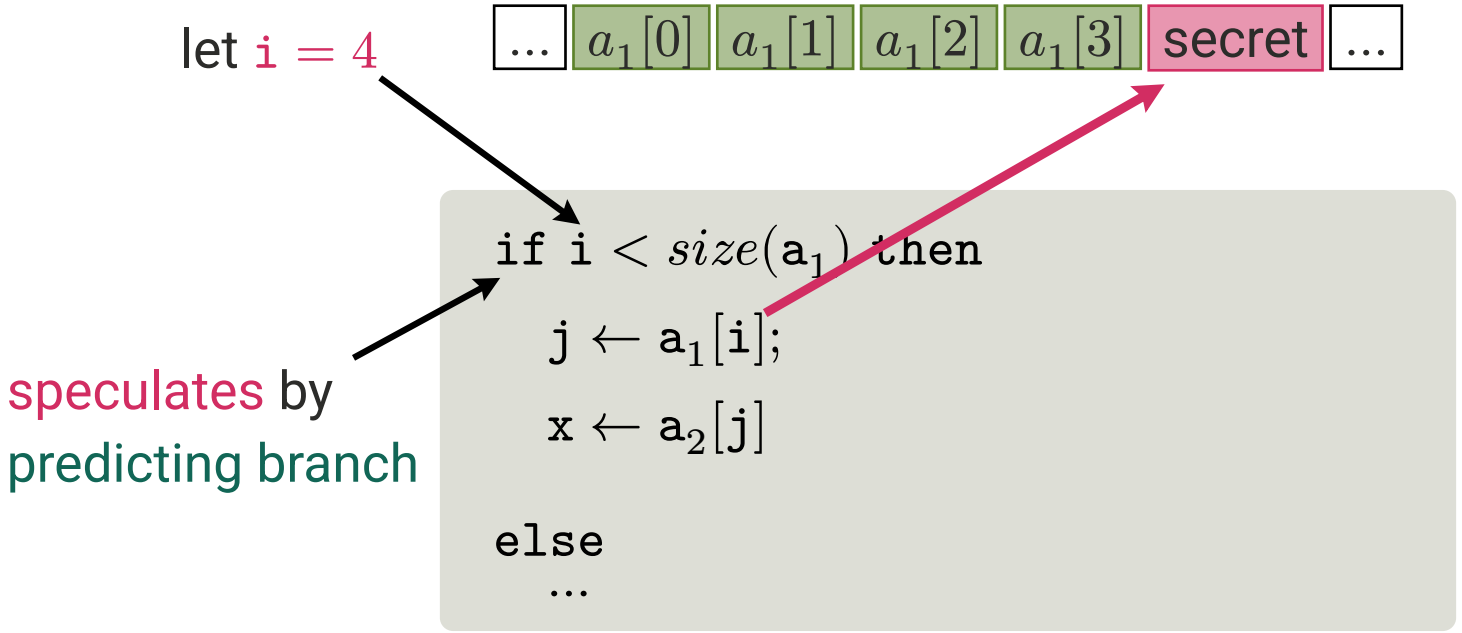
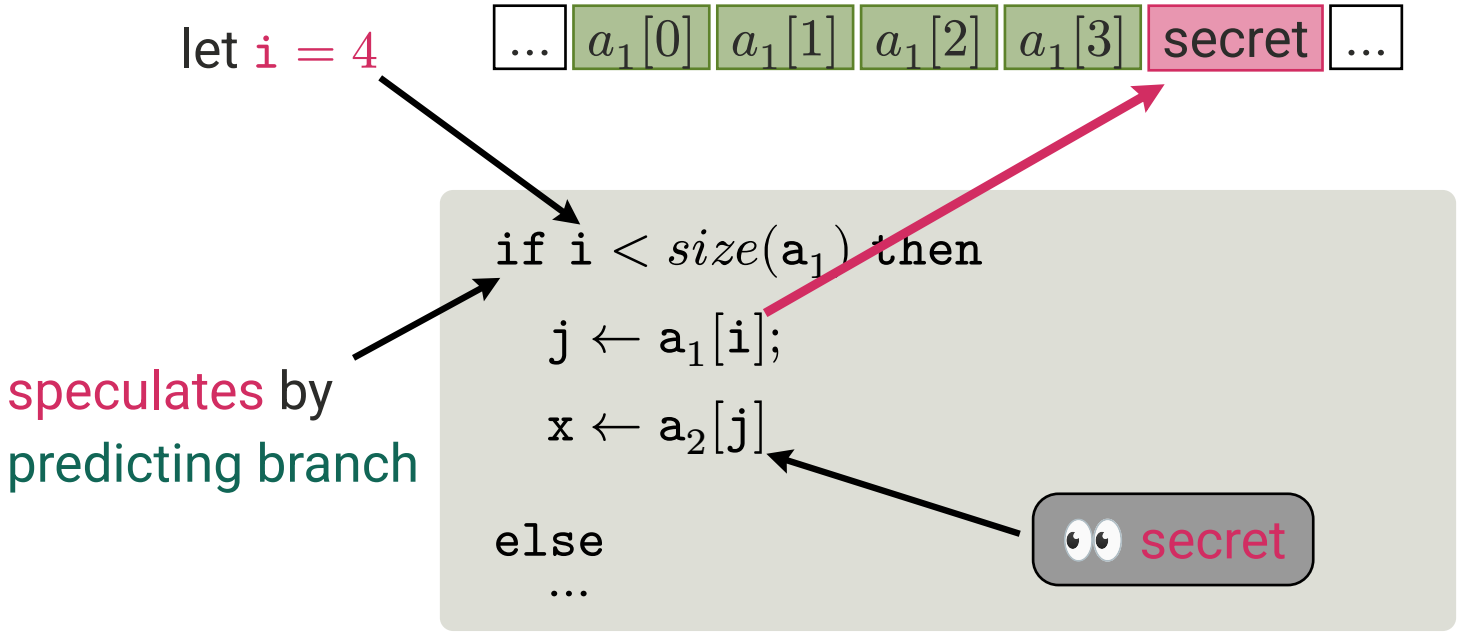

Spectre (v1)


let i = 4
... $a_1[0]$ $a_1[1]$ $a_1[2]$ $a_1[3]$ secret ...
if i < $size(a_1)$ then
j ← a_1[i];
x ← a_2[j]
else
...
speculates by
predicting branch

Spectre (v1)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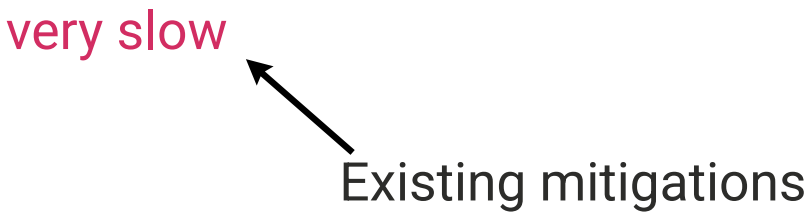
secret

Previous Spectre Mitigations

Existing mitigations

Previous Spectre Mitigations



Previous Spectre Mitigations

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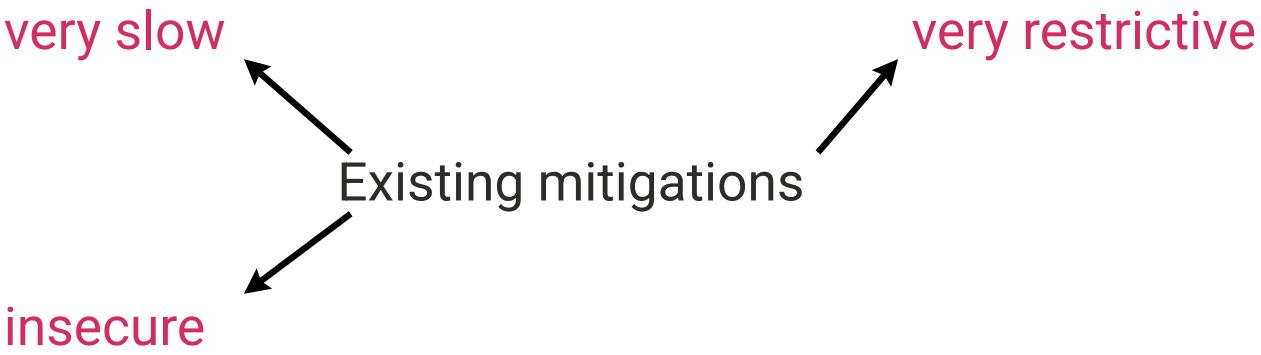
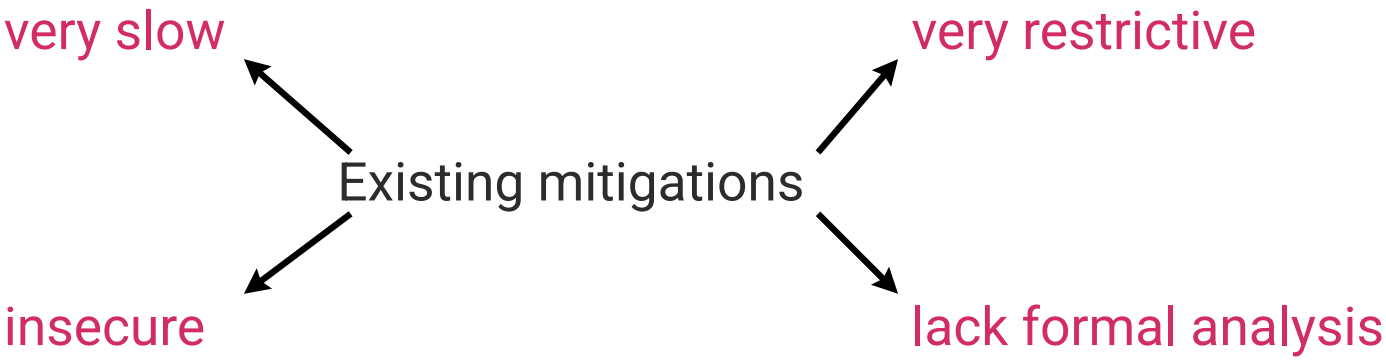


Previous Spectre Mitigations



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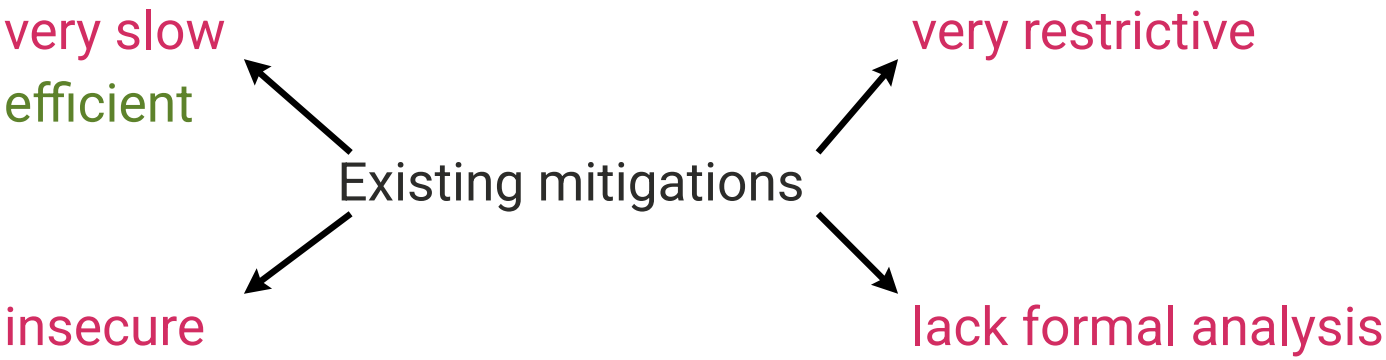
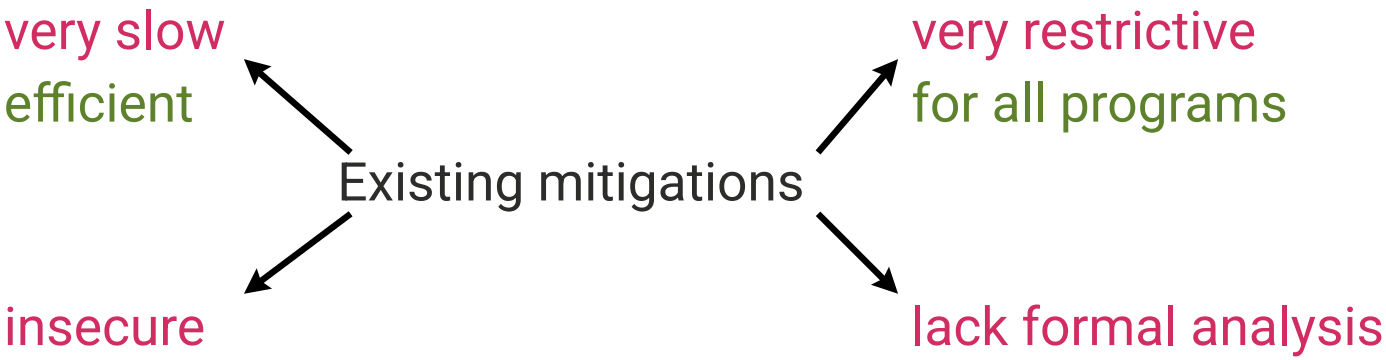
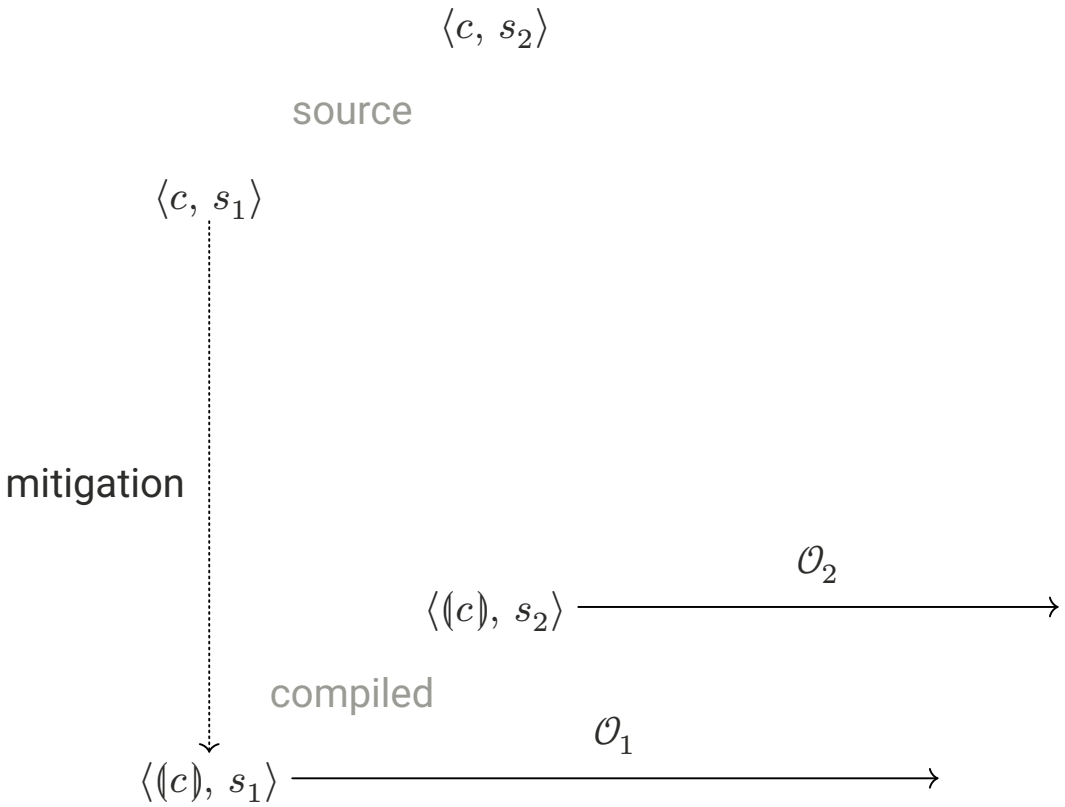


Previous Spectre Mitigations

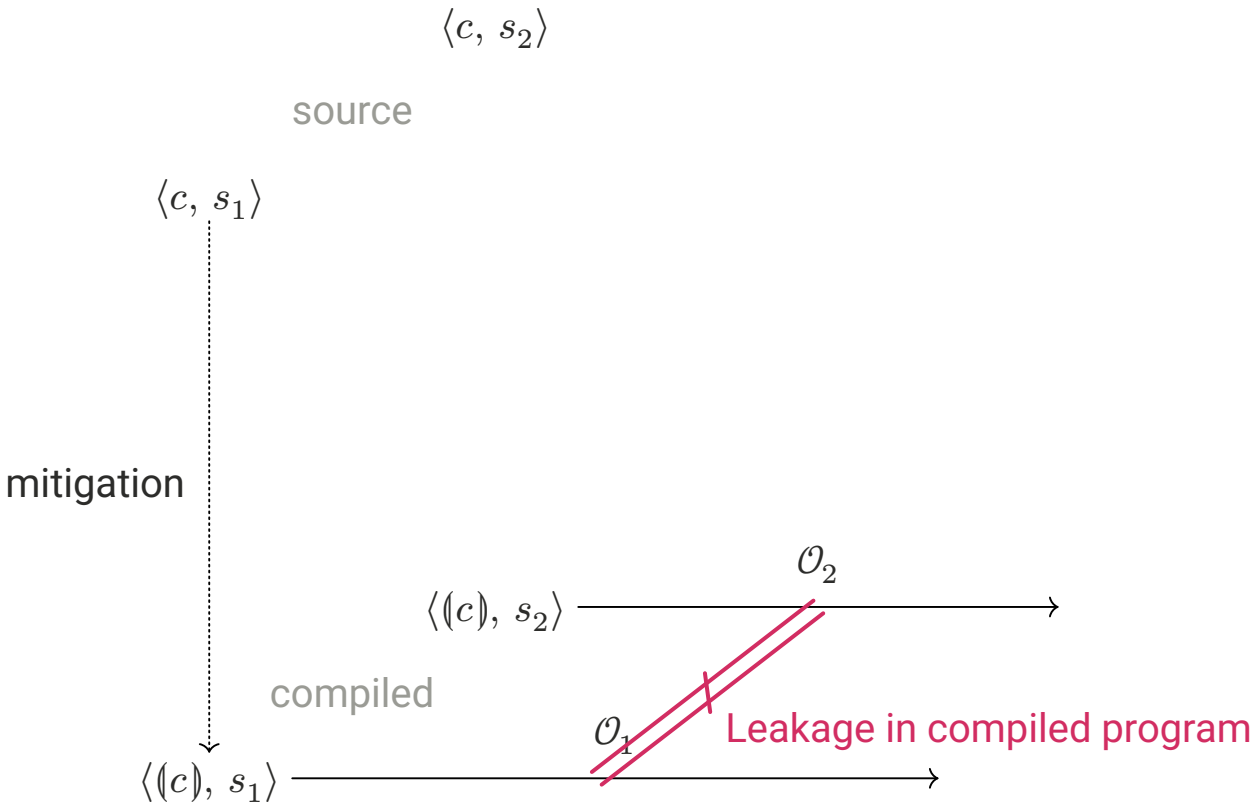


Previous Spectre Mitigations

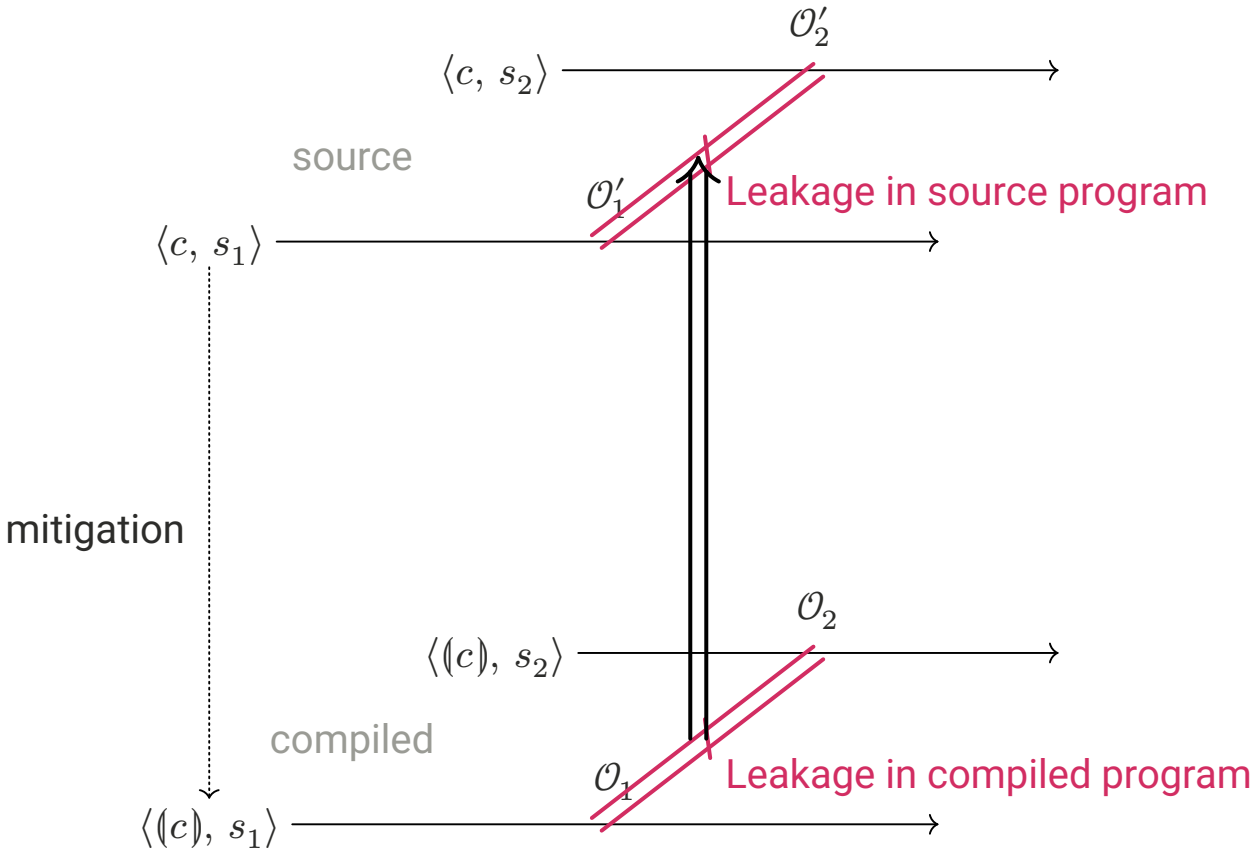
Security for Arbitrary Programs



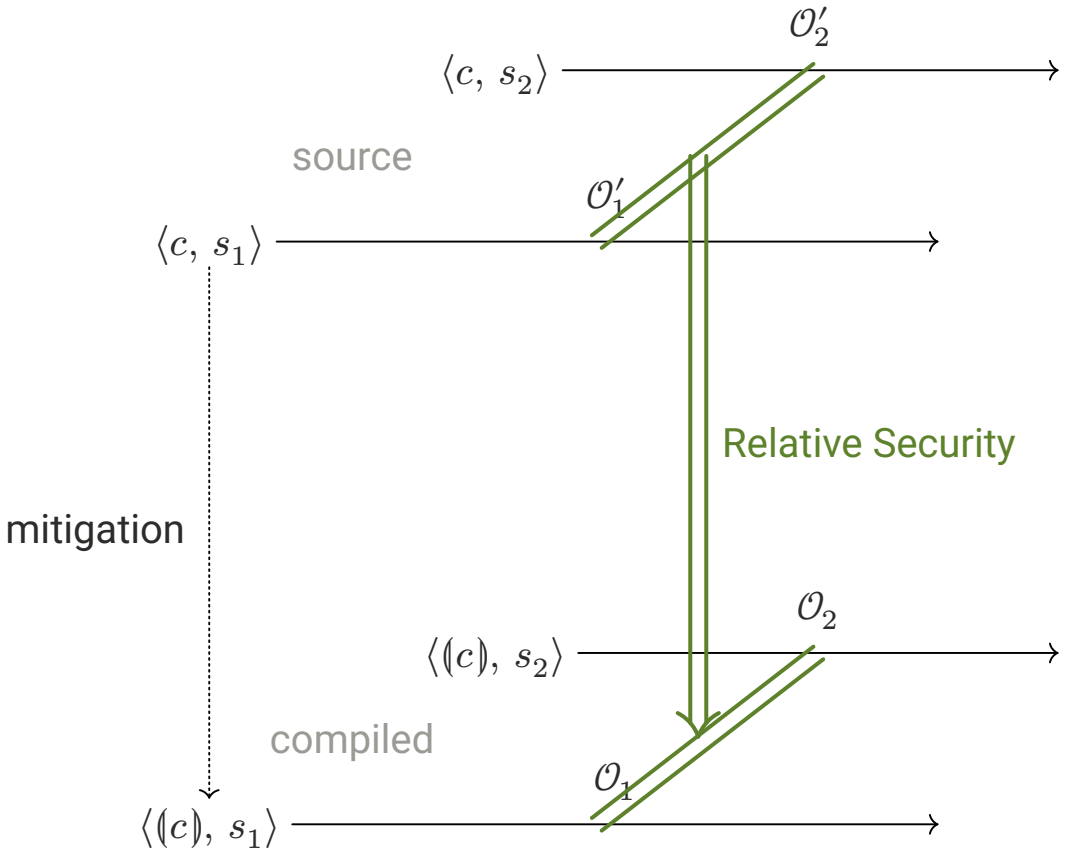
Security for Arbitrary Programs

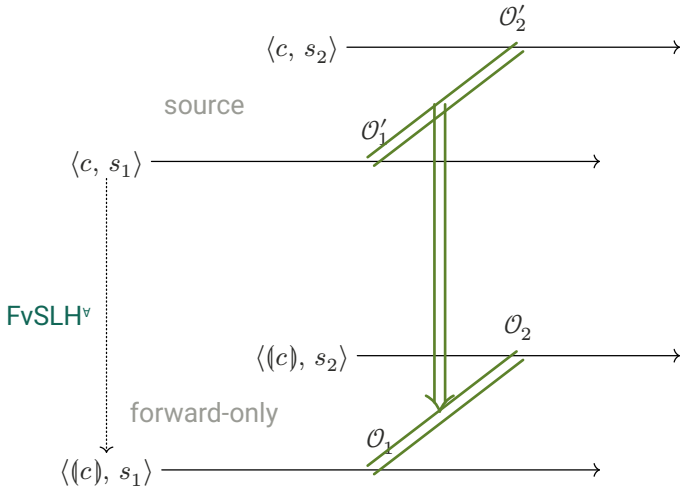


Security for Arbitrary Programs



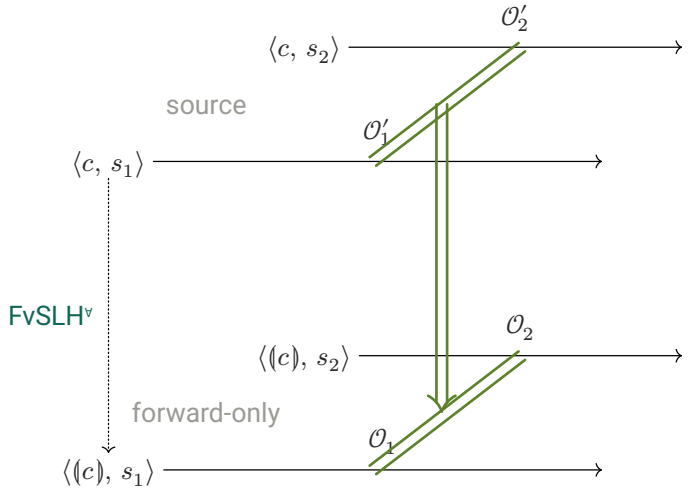
Security for Arbitrary Programs




$\mathcal{O}_2'$
$\langle c,\ s_2 \rangle$
source
$\mathcal{O}_1'$
$\langle c,\ s_1 \rangle$
FvSLH$^\forall$
$\mathcal{O}_2$
$\langle (\!|c|\!),\ s_2 \rangle$
forward-only
$\mathcal{O}_1$
$\langle (\!|c|\!),\ s_1 \rangle$

More Efficient and Trustworthy Formally Secure Compilation

more efficient than previous general mitigations



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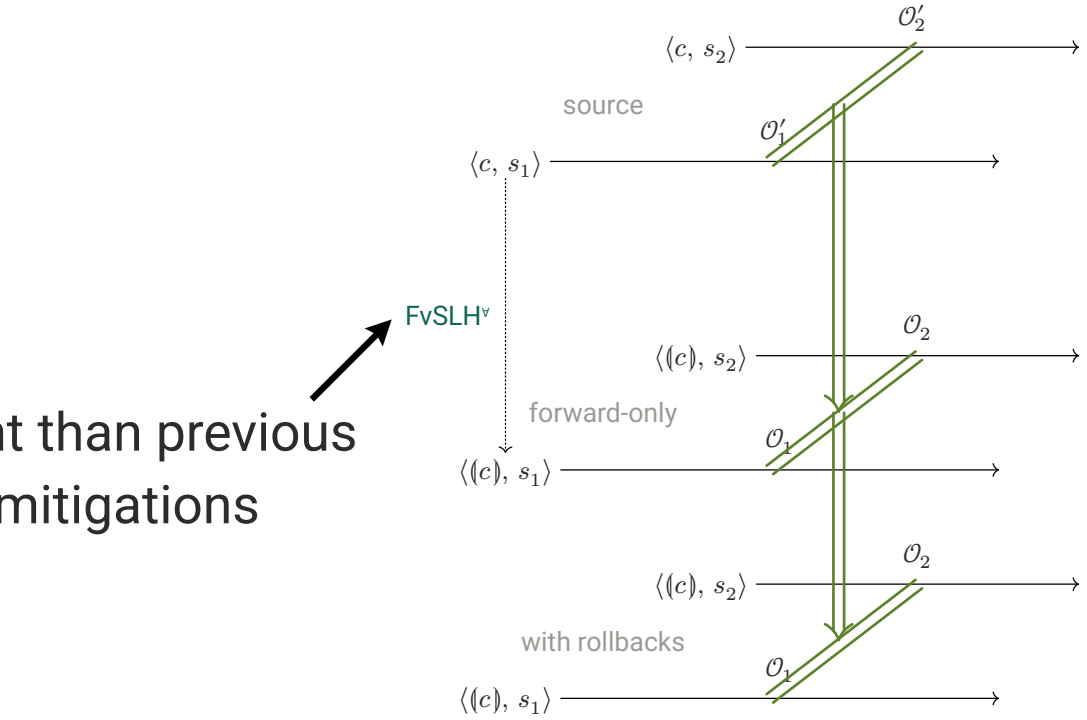

More Efficient and Trustworthy Formally Secure Compilation

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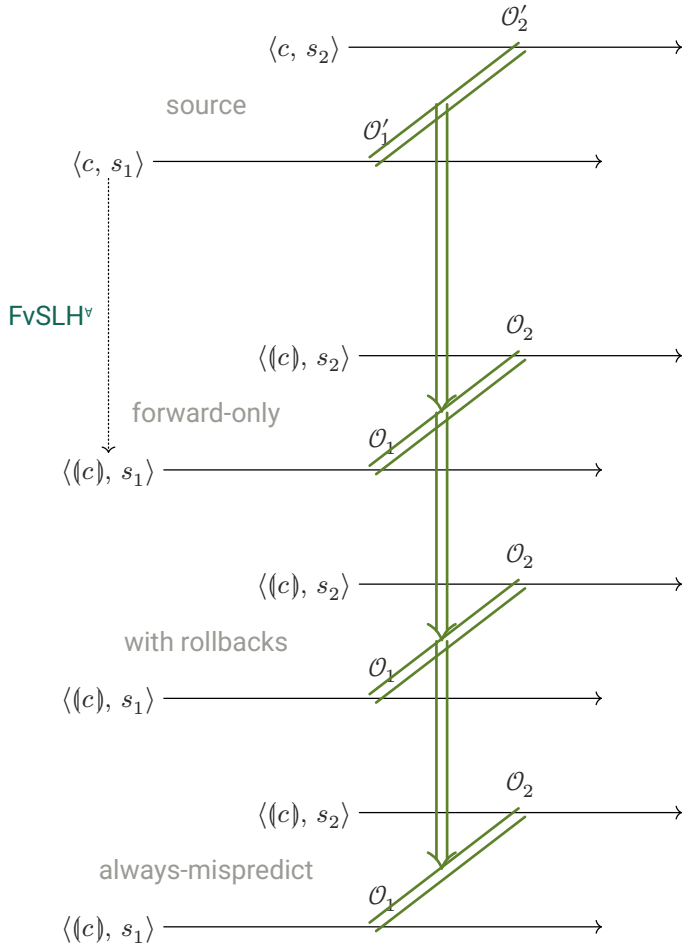
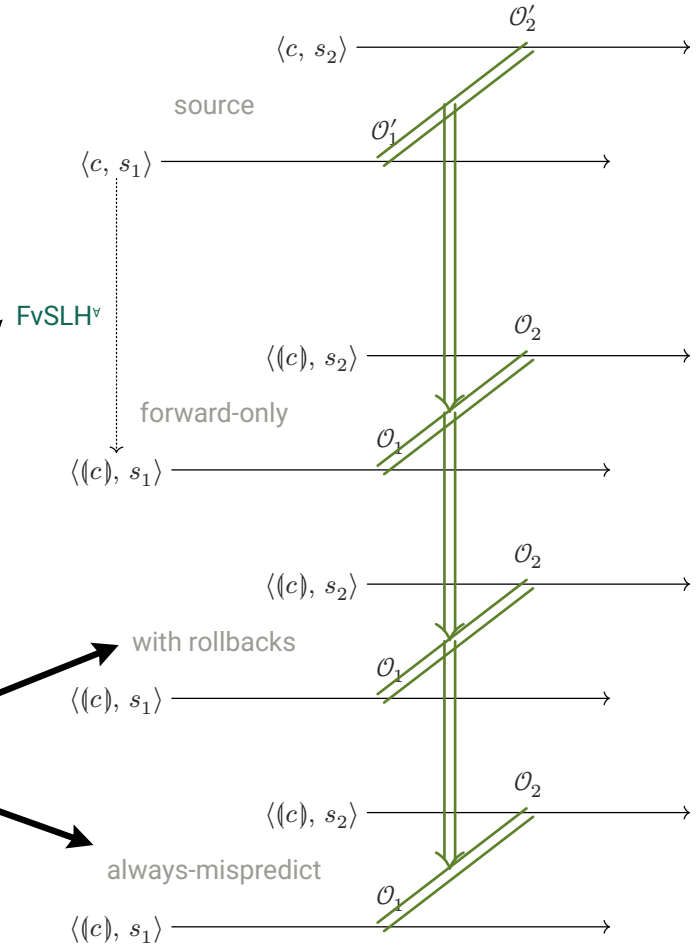


More Efficient and Trustworthy Formally Secure Compilation

more efficient than previous general mitigations

more precise models



More Efficient and Trustworthy Formally Secure Compilation

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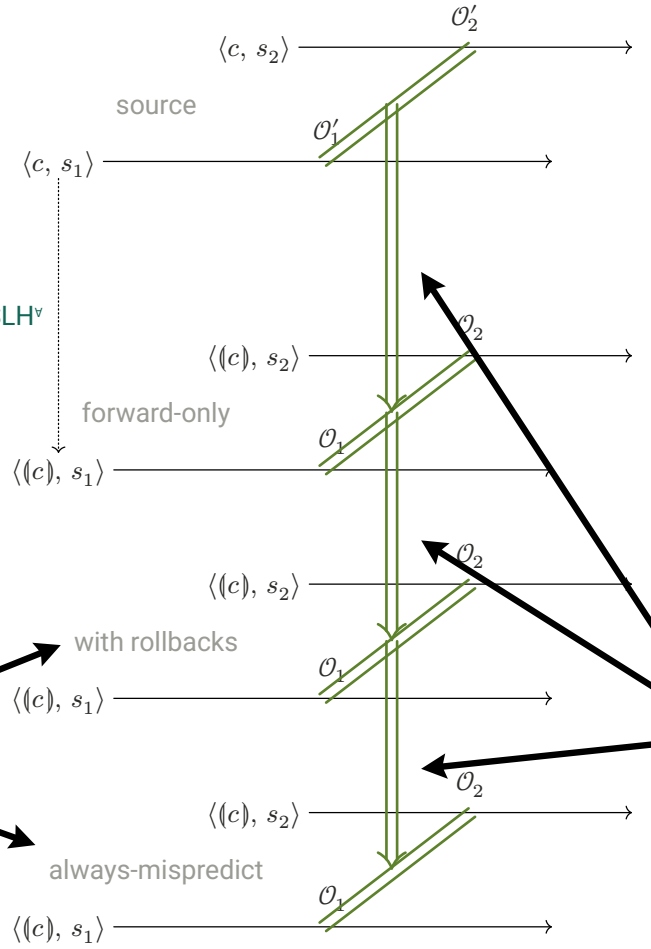
more precise models



all steps fully mechanized in Rocq

More Efficient and Trustworthy Formally Secure Compilation

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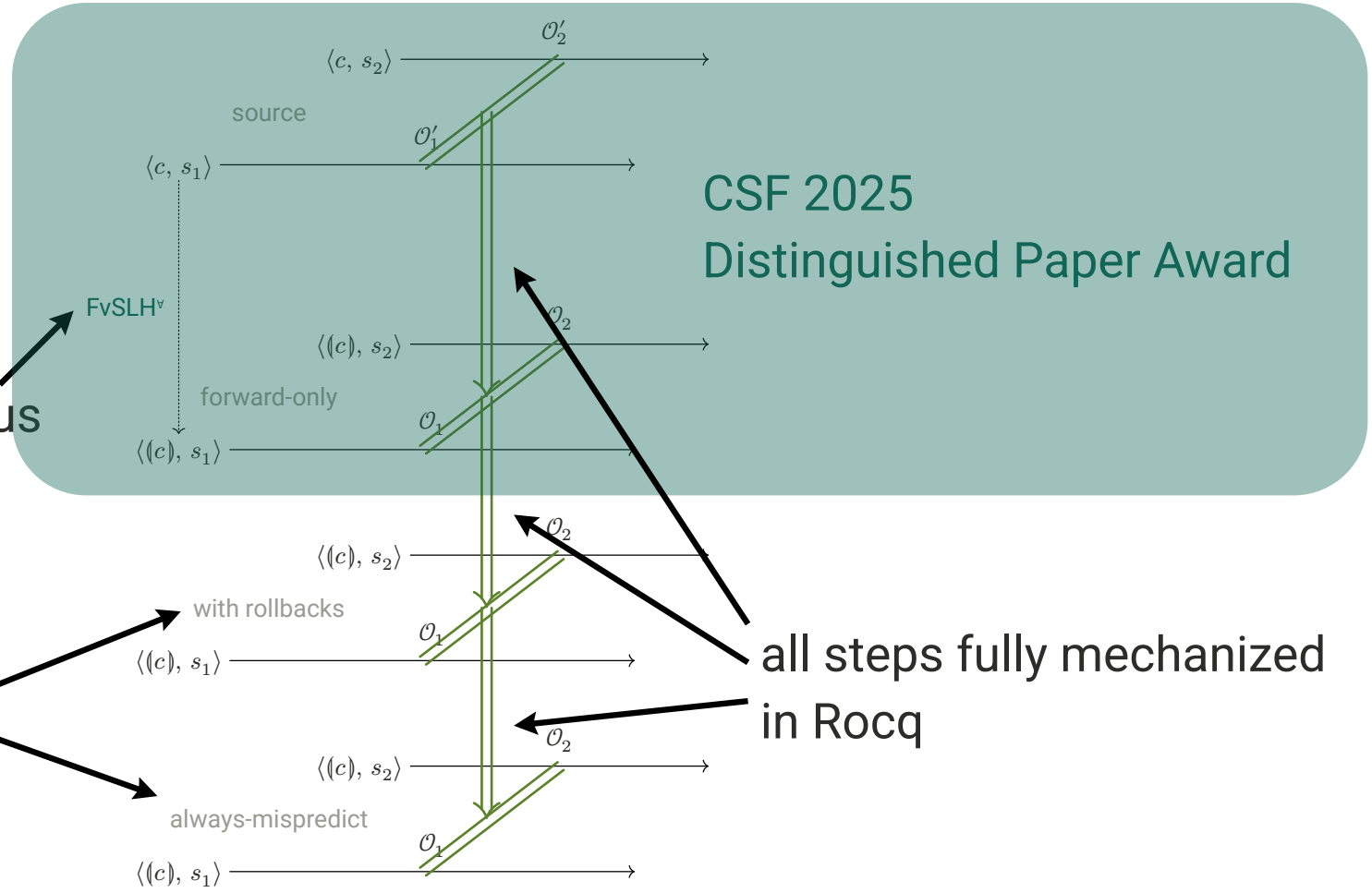

more efficient than previous general mitigations

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Flexible SLH:
Providing Efficient Protections To All Programs

Previous Work: Selective SLH (Shivakumar et al. 2023)

$$\texttt{if i} \;< size(\texttt{a}_1)\; \texttt{then}$$

$$\texttt{j} \leftarrow \texttt{a}_1\,[\texttt{i}\,];$$
$$\texttt{x} \leftarrow \texttt{a}_2\,[\texttt{j}\,]$$

$$\texttt{else}$$

Previous Work: Selective SLH (Shivakumar et al. 2023)

$$\texttt{if } \mathtt{i}_{\mathbb{T}} < size(\mathtt{a}_1)_{\mathbb{T}} \texttt{ then}$$

$$\mathtt{j}_{\mathbb{T}} \leftarrow \mathtt{a}_{1\mathbb{T}}[\mathtt{i}_{\mathbb{T}}];$$

$$\mathtt{x}_{\mathbb{F}} \leftarrow \mathtt{a}_{2\mathbb{F}}[\mathtt{j}_{\mathbb{T}}]$$

$$\texttt{else}$$

- CCT type system:
  - variables and arrays public or secret

Previous Work: Selective SLH (Shivakumar et al. 2023)


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if i_T < size(a1)_T then
    j_T ← a1_T[i_T];
    x_F ← a2_F[j_T];
    y ← a3_T[x_F];
    if y < 10 then ... else ...
else
    b := i_T < size(a1)_T ? 1 : b
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- CCT type system:
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  - updated with constant-time conditionals

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- CCT type system:
  - variables and arrays public or secret
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- maintain a misspeculation flag
  - updated with constant-time conditionals
- mask reads to public variables
  - secret variables can not leak anyway

Flexible SLH: Removing Restrictions


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if i_T < size(a_1)_T then
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- Static Information-Flow Analysis

Flexible SLH: Removing Restrictions


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- Static Information-Flow Analysis
  - annotates expressions with labels

Flexible SLH: Removing Restrictions

$$\texttt{if } \mathtt{i}_{\mathbb{T}} < size(\mathtt{a}_1)_{\mathbb{T}} \texttt{ then}$$

$$\quad \mathtt{b} := \mathtt{i}_{\mathbb{T}} < size(\mathtt{a}_1)_{\mathbb{T}} \,?\, \mathtt{b} : 1;$$

$$\quad \mathtt{j}_{\mathbb{T}} \leftarrow \mathtt{a}_{1\mathbb{T}}[\mathtt{i}_{\mathbb{T}}]; \mathtt{j}_{\mathbb{T}} := \mathtt{b} \,?\, 0 : \mathtt{j}_{\mathbb{T}};$$

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$$\quad \mathtt{y}_{\mathbb{F}} \leftarrow \mathtt{a}_{3\mathbb{T}}[\mathtt{x}_{\mathbb{F}}];$$

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- Static Information-Flow Analysis
  - annotates expressions with labels
  - does not prevent the use of secrets

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\quad \texttt{if } \mathtt{y}_{\mathbb{F}} < 10 \texttt{ then } \ldots \texttt{ else } \ldots \\
\texttt{else} \\
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\end{array}
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- Static Information-Flow Analysis
  - annotates expressions with labels
  - does not prevent the use of secrets
  - accepts all programs

Flexible SLH: Removing Restrictions


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- Static Information-Flow Analysis
  - annotates expressions with labels
  - does not prevent the use of secrets
  - accepts all programs
- More masking required:

Flexible SLH: Removing Restrictions

$$\texttt{if } \mathtt{i}_{\mathbb{T}} < size(\mathtt{a}_1)_{\mathbb{T}} \texttt{ then}$$

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- Static Information-Flow Analysis
  - annotates expressions with labels
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- More masking required:
  - secret indices

Flexible SLH: Removing Restrictions

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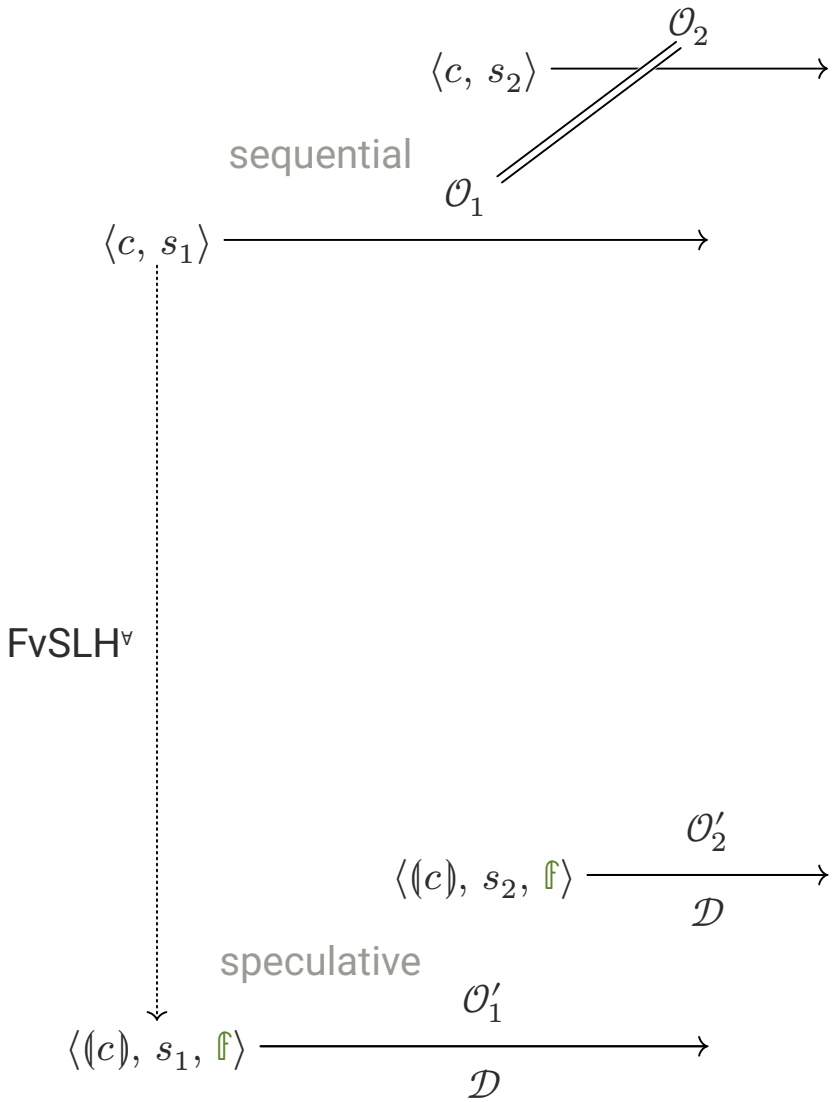
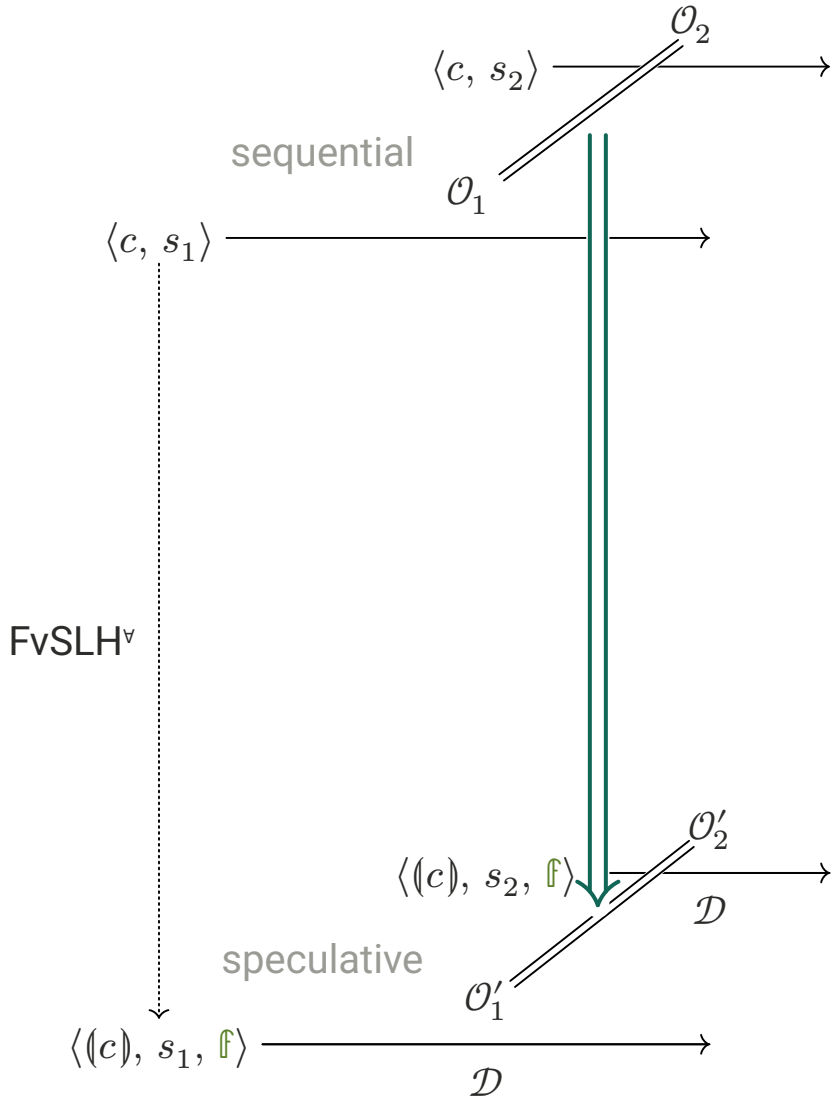
\quad \texttt{if } \mathtt{b} \,\&\&\, \mathtt{y}_{\mathbb{F}} < 10 \texttt{ then } \ldots \texttt{ else } \ldots \\
\texttt{else} \\
\quad \mathtt{b} := \mathtt{i}_{\mathbb{T}} < size(\mathtt{a}_1)_{\mathbb{T}} \,?\, 1 : \mathtt{b}
\end{array}
$$

- Static Information-Flow Analysis
  - annotates expressions with labels
  - does not prevent the use of secrets
  - accepts all programs
- More masking required:
  - secret indices
  - secret branch conditions

Proving Relative Security



Proving Relative Security



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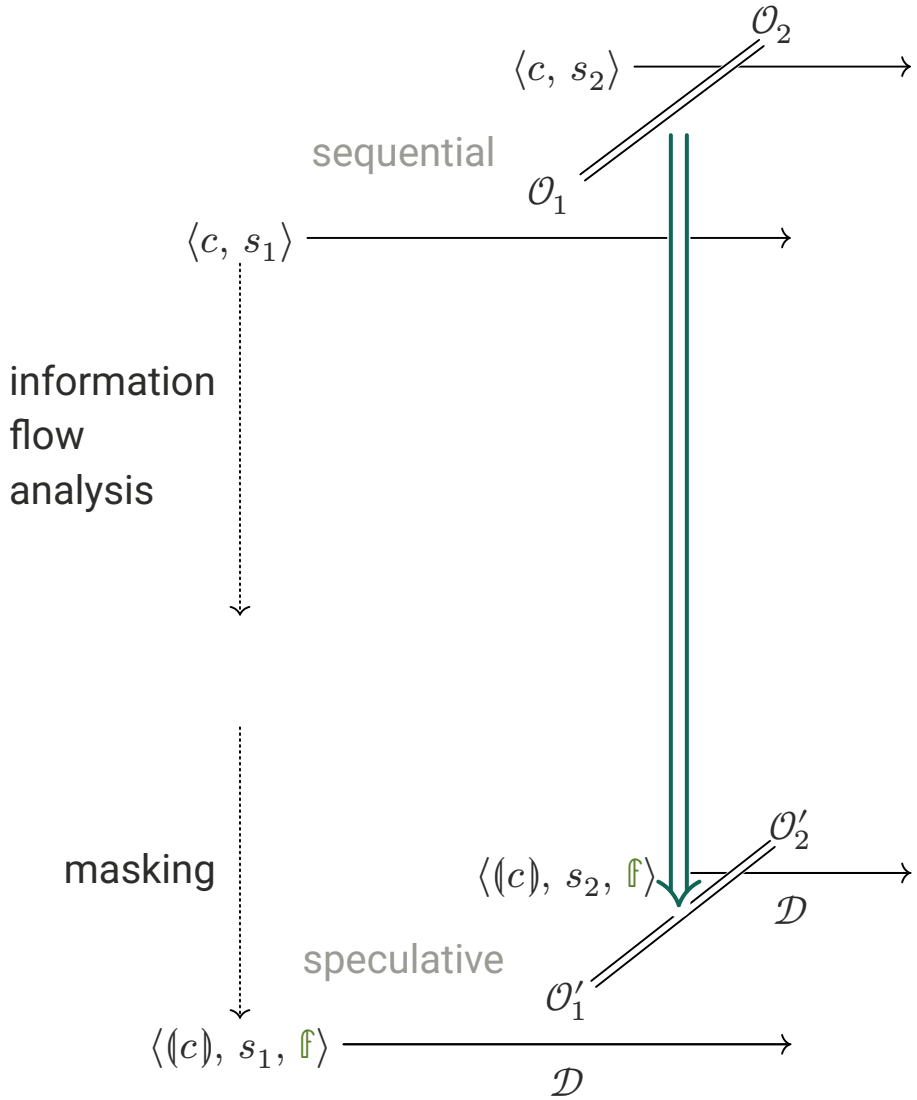
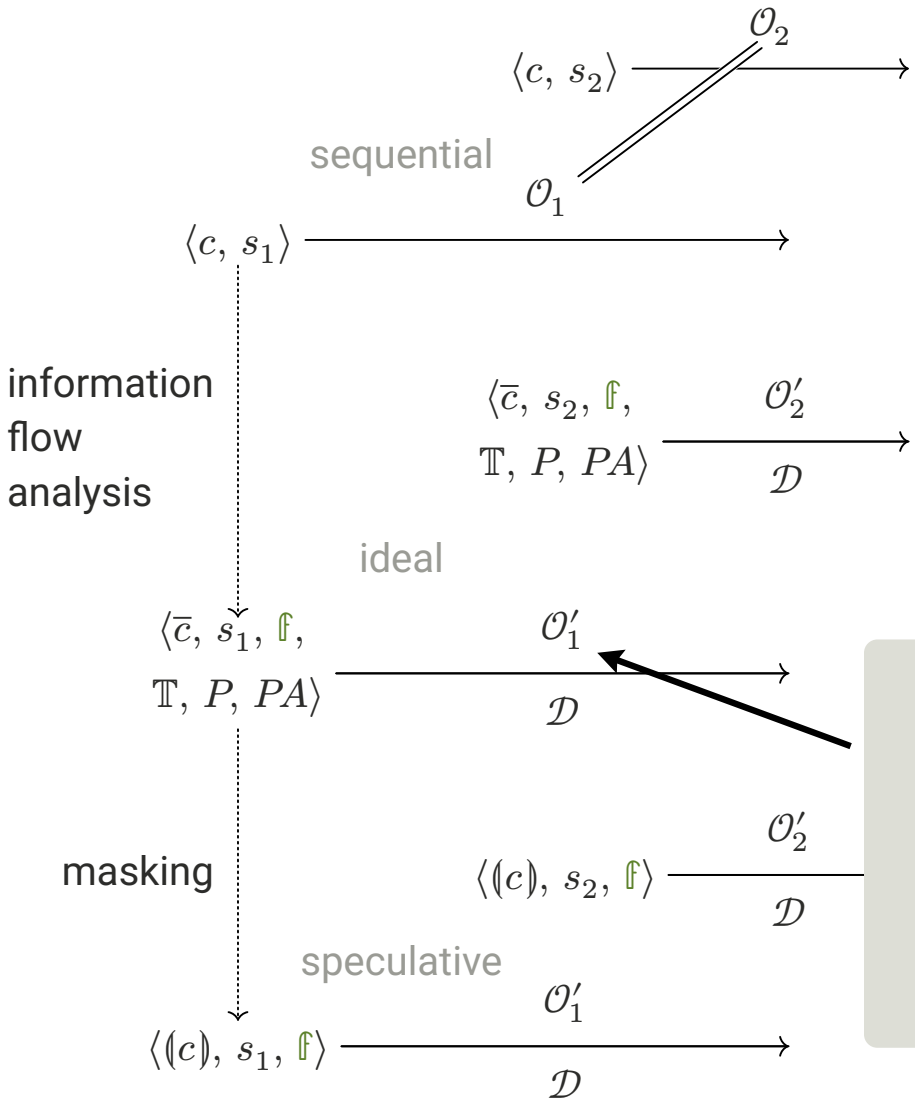
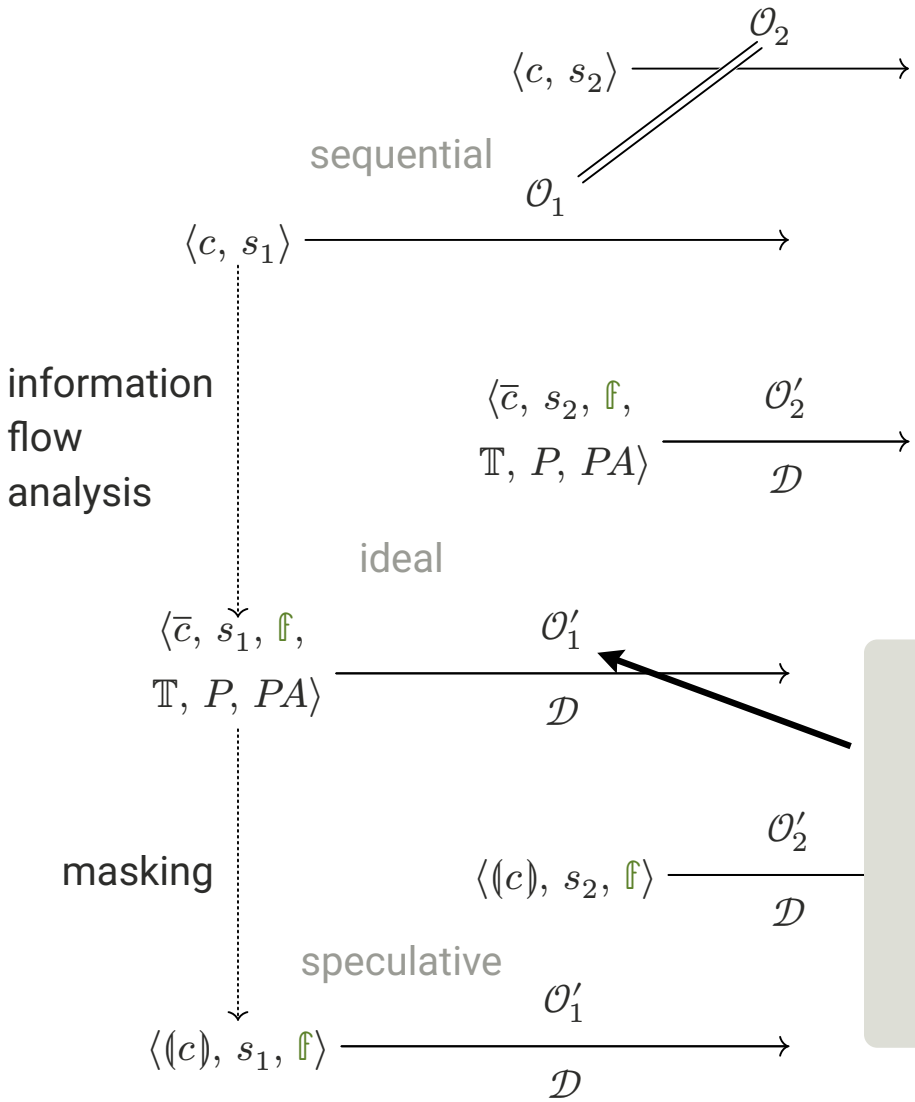


Proving Relative Security



Ideal semantics:

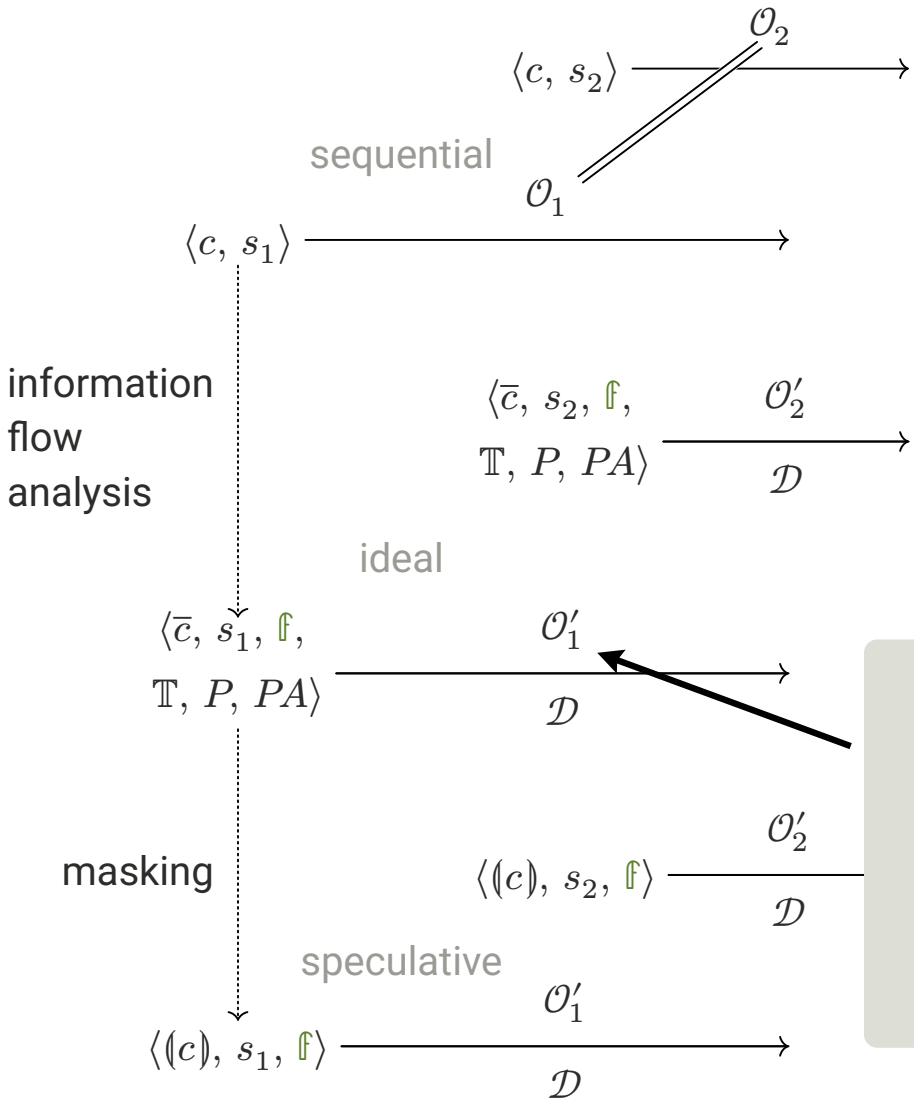
Proving Relative Security



Ideal semantics:

- speculative execution

Proving Relative Security



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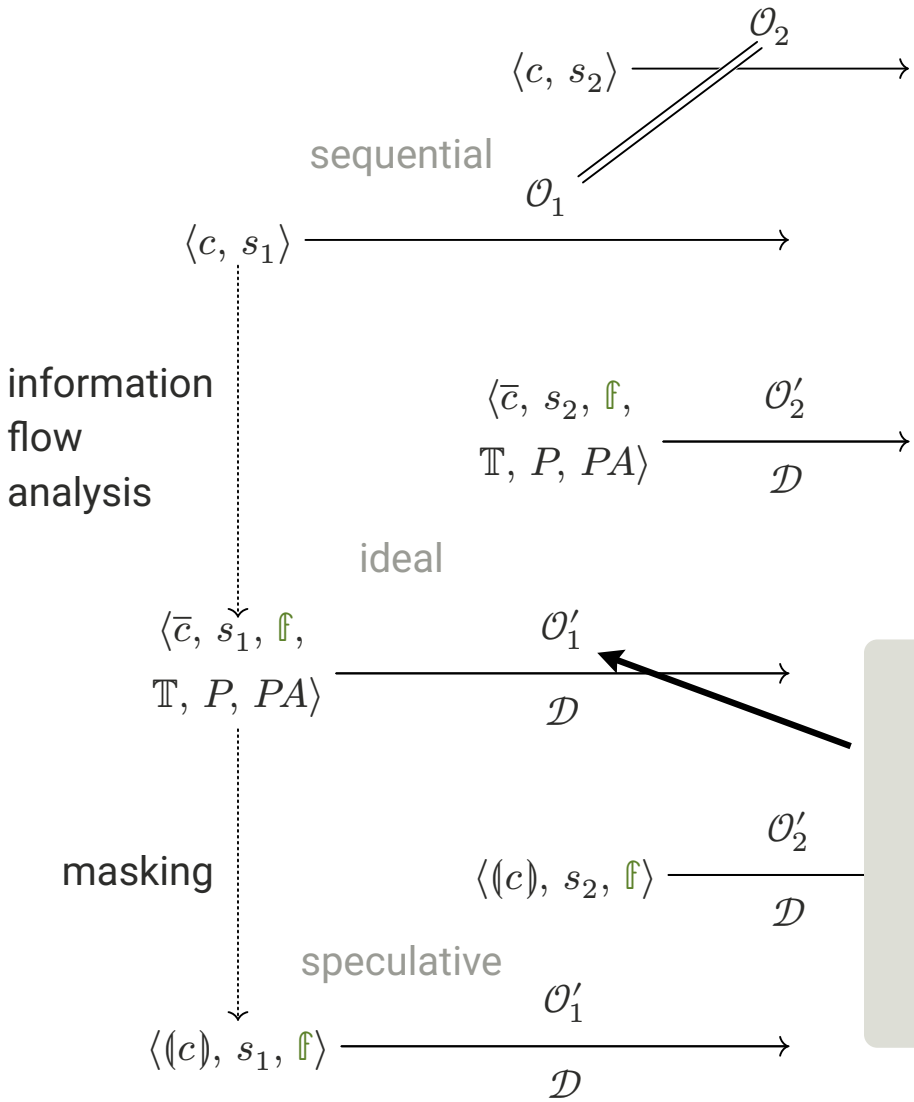

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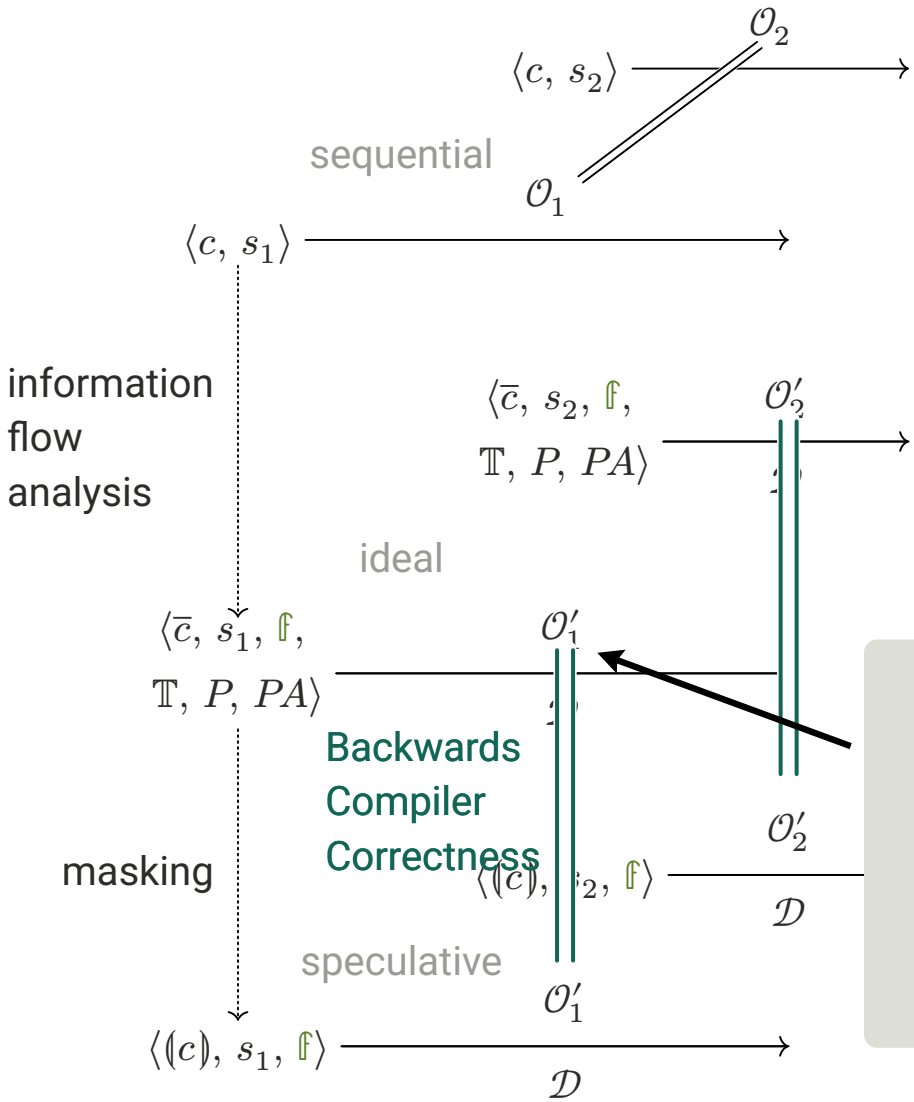

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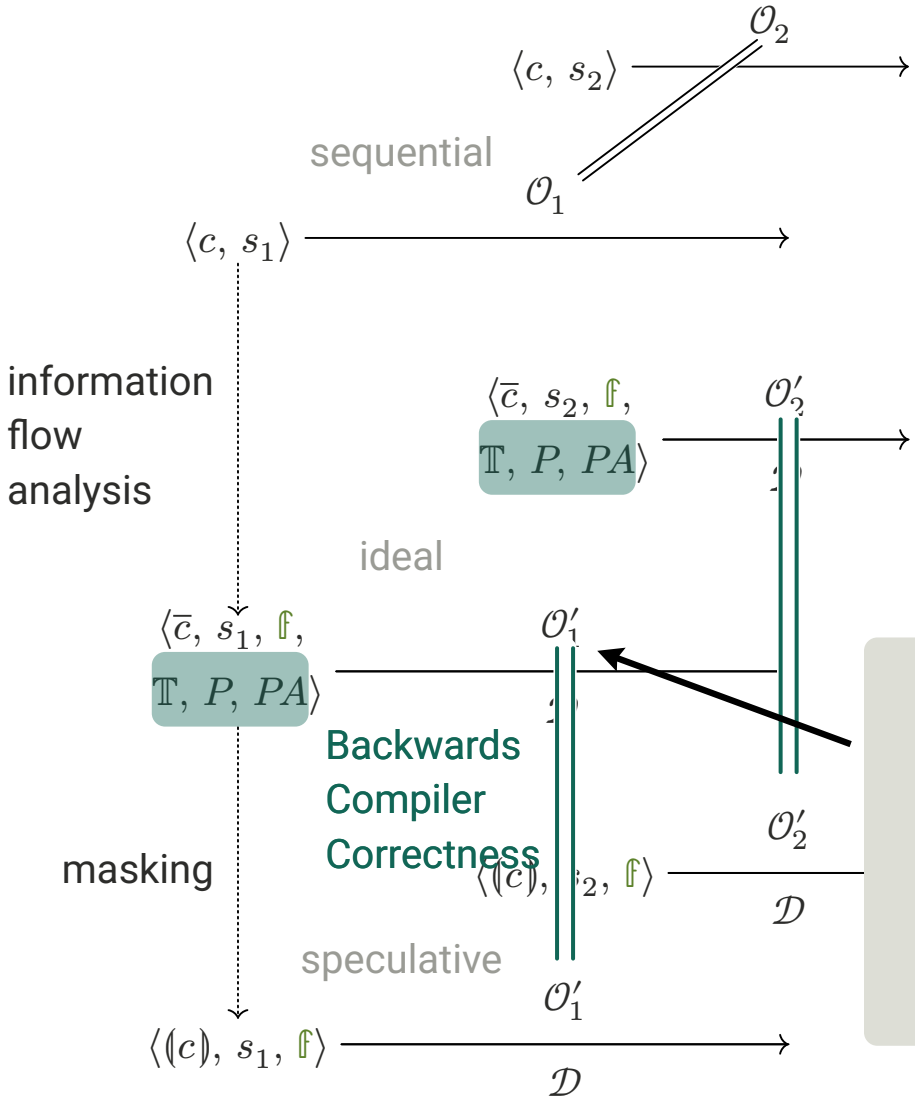

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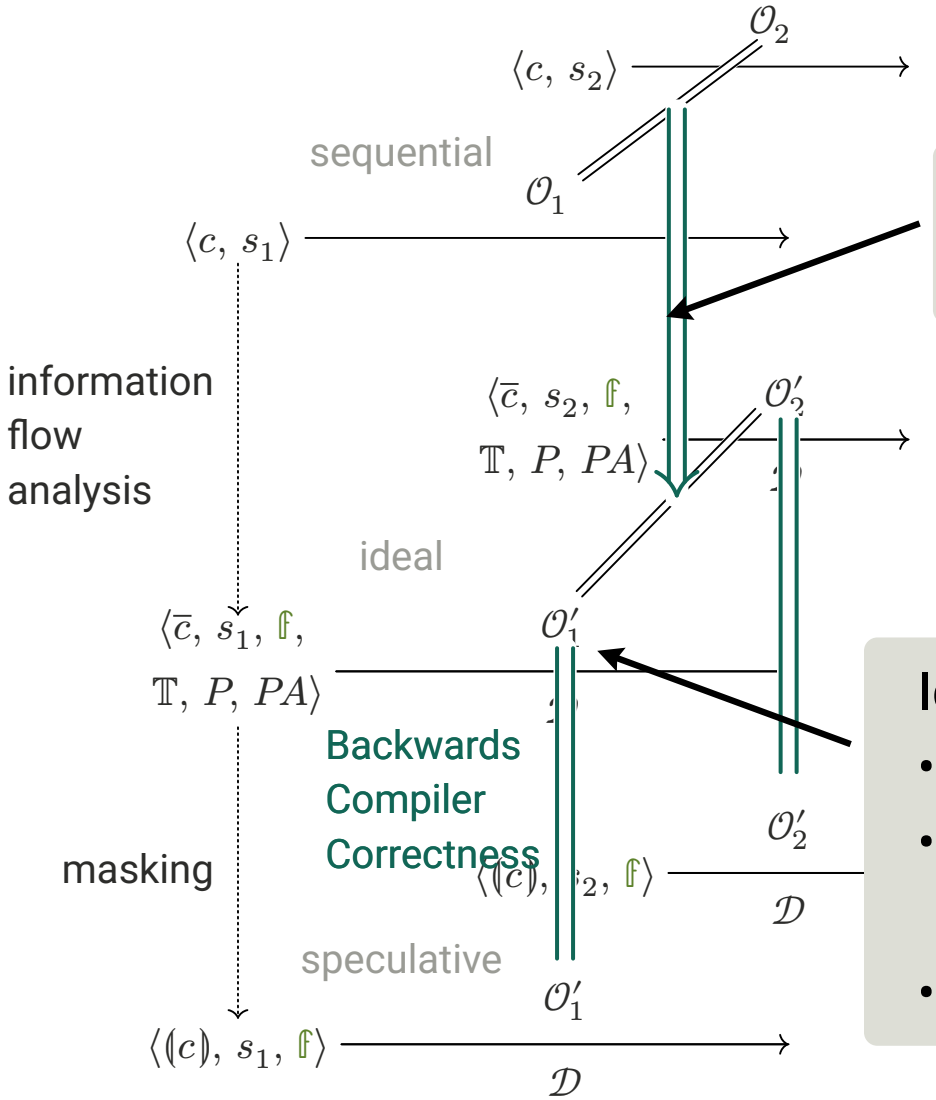

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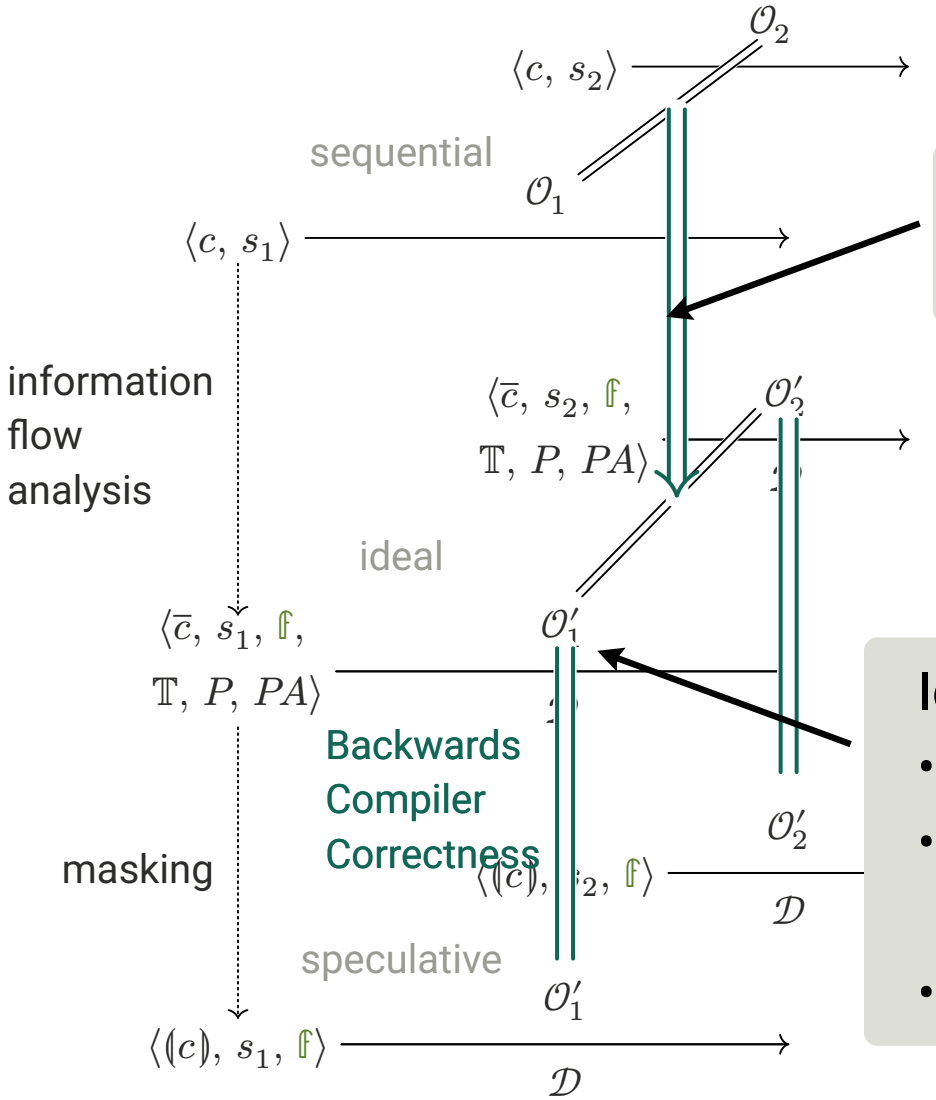

Relative Security of ideal semantics:

⚠️ depends on correctness of annotations

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The information-flow analysis produces well-labeled programs.

$$\langle\!\langle c \rangle\!\rangle_{pc}^{P,PA} = (\overline{c}, P', PA') \Rightarrow P, PA \rightsquigarrow P', PA' \vdash_{pc} \overline{c}$$

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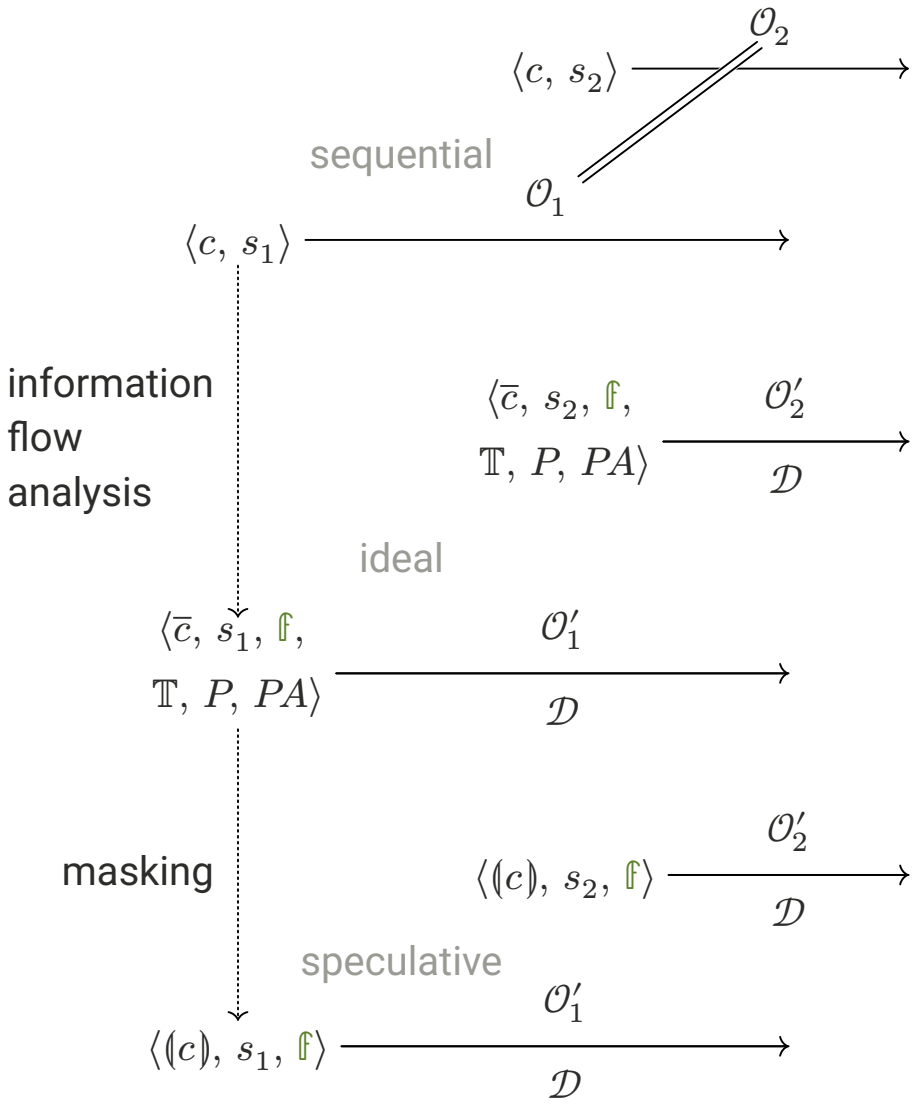

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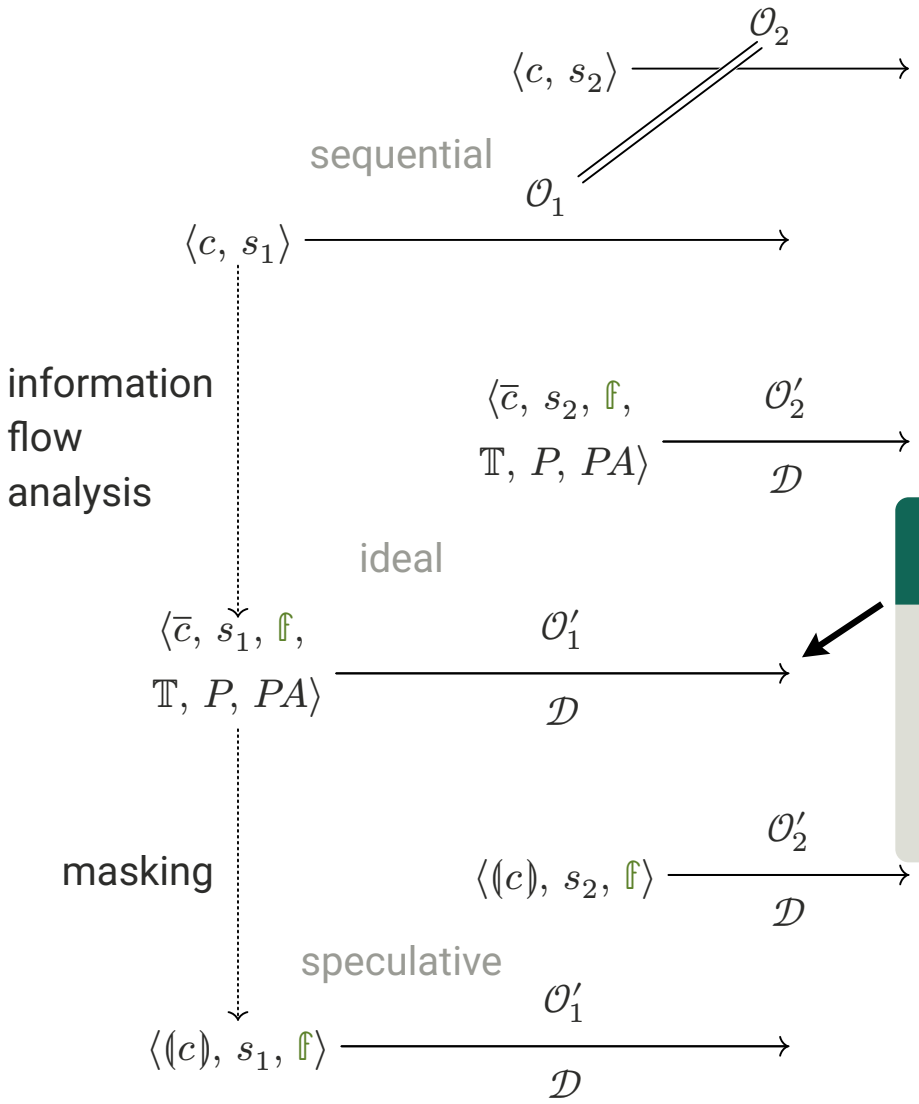
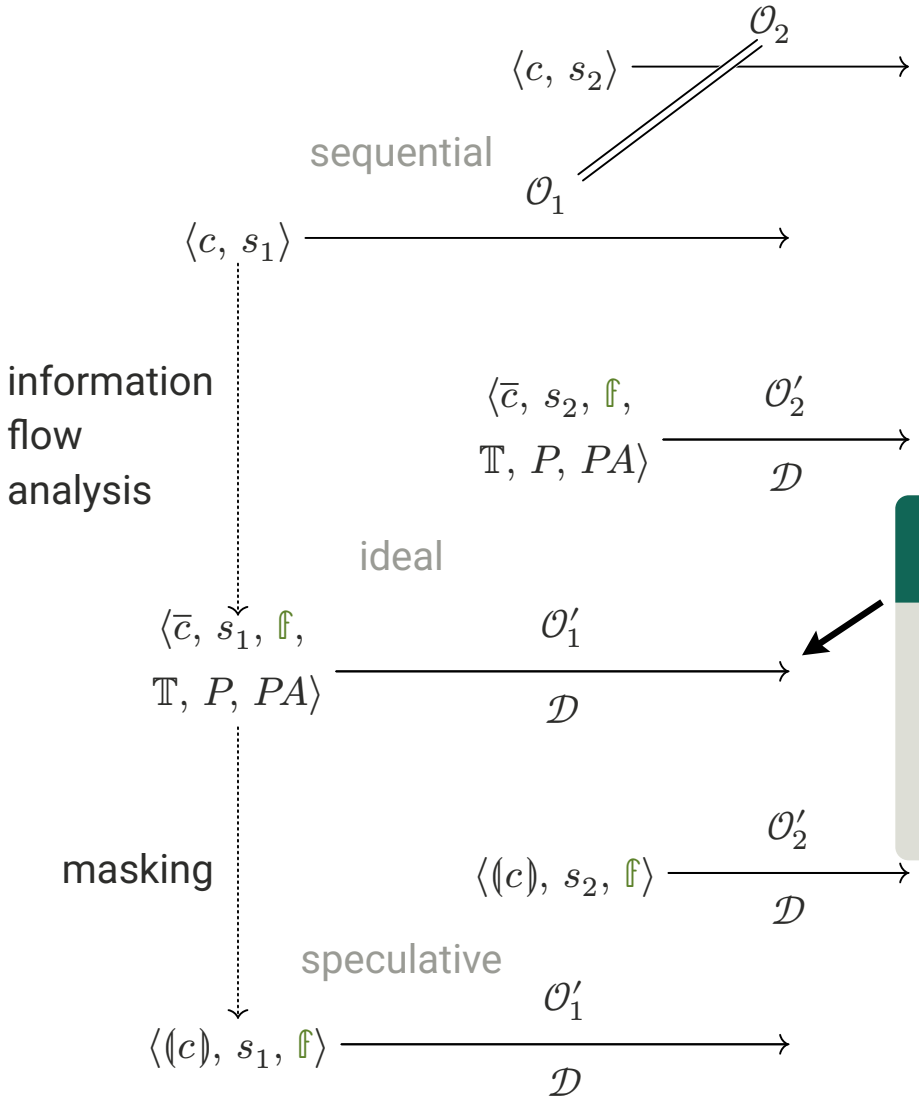


Unwinding

During misspeculation:

Proving Relative Security



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During misspeculation:

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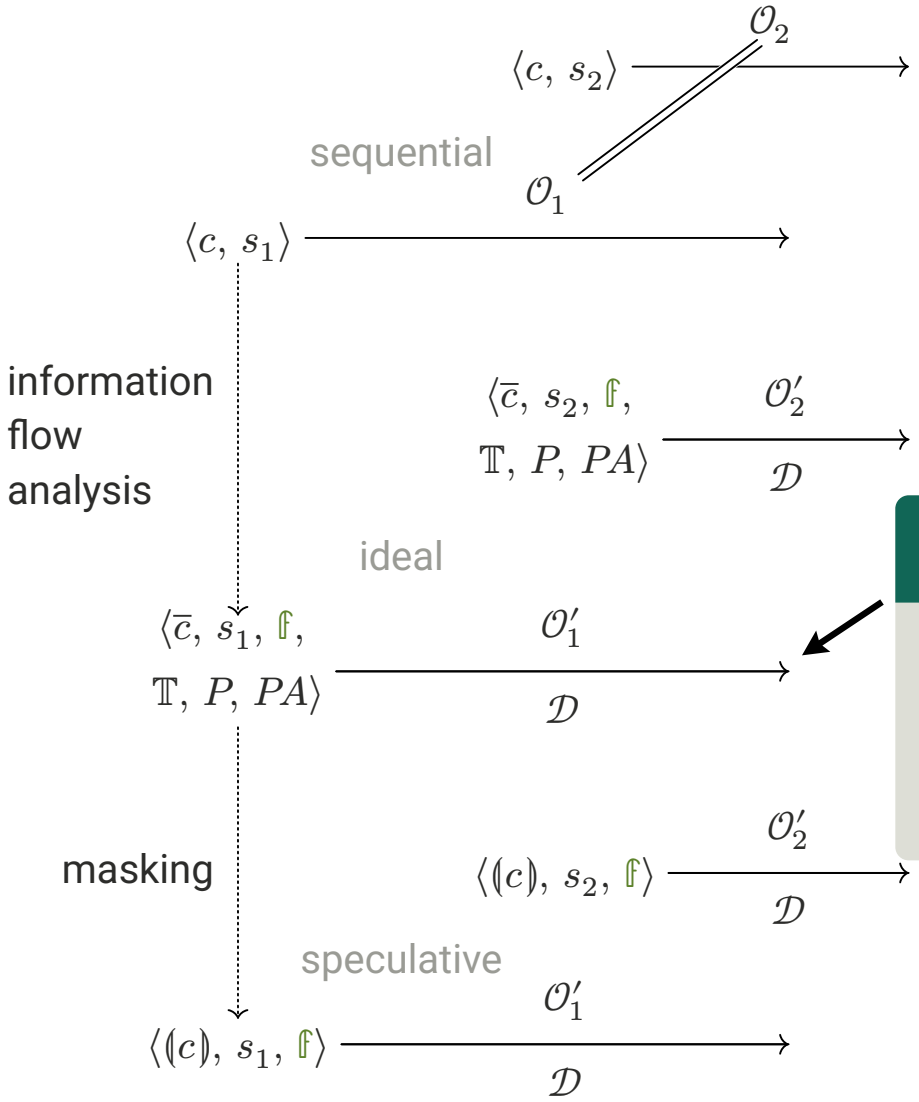

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During misspeculation:

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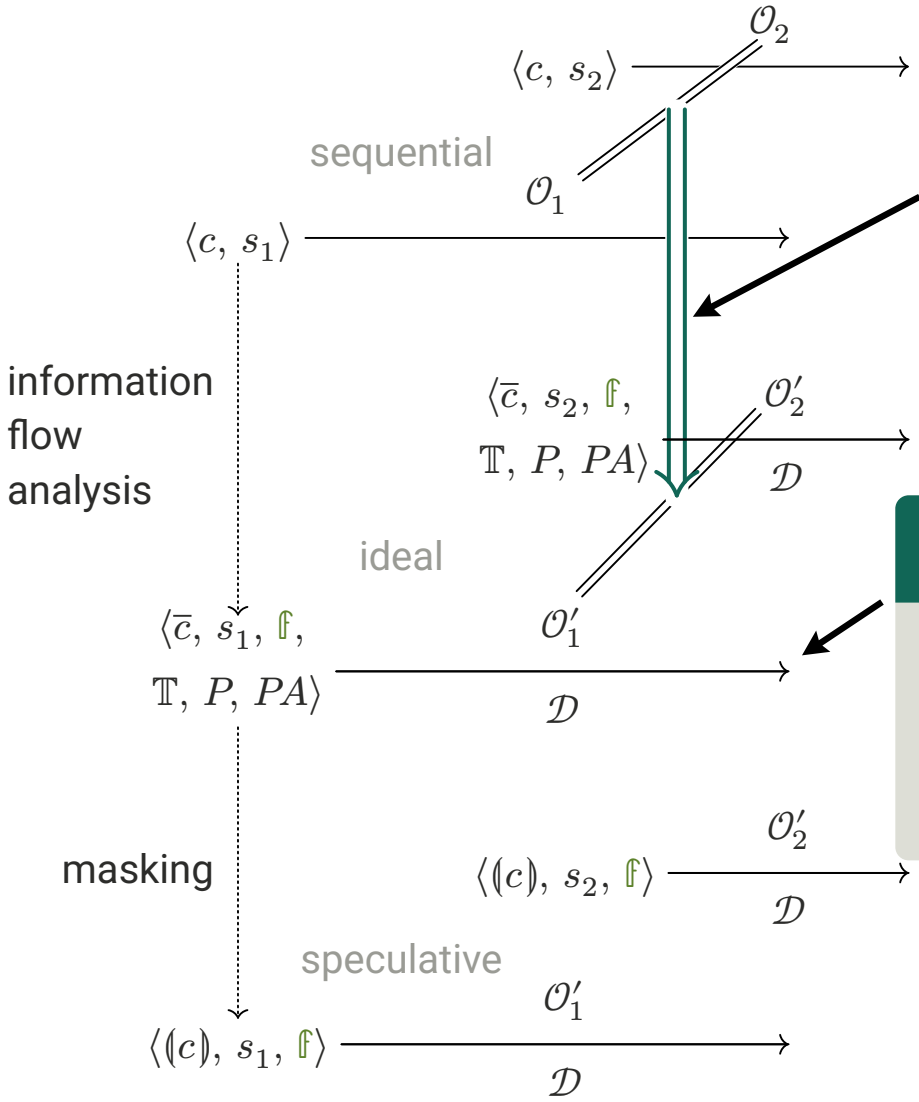

Same behaviour before misspeculation

Unwinding

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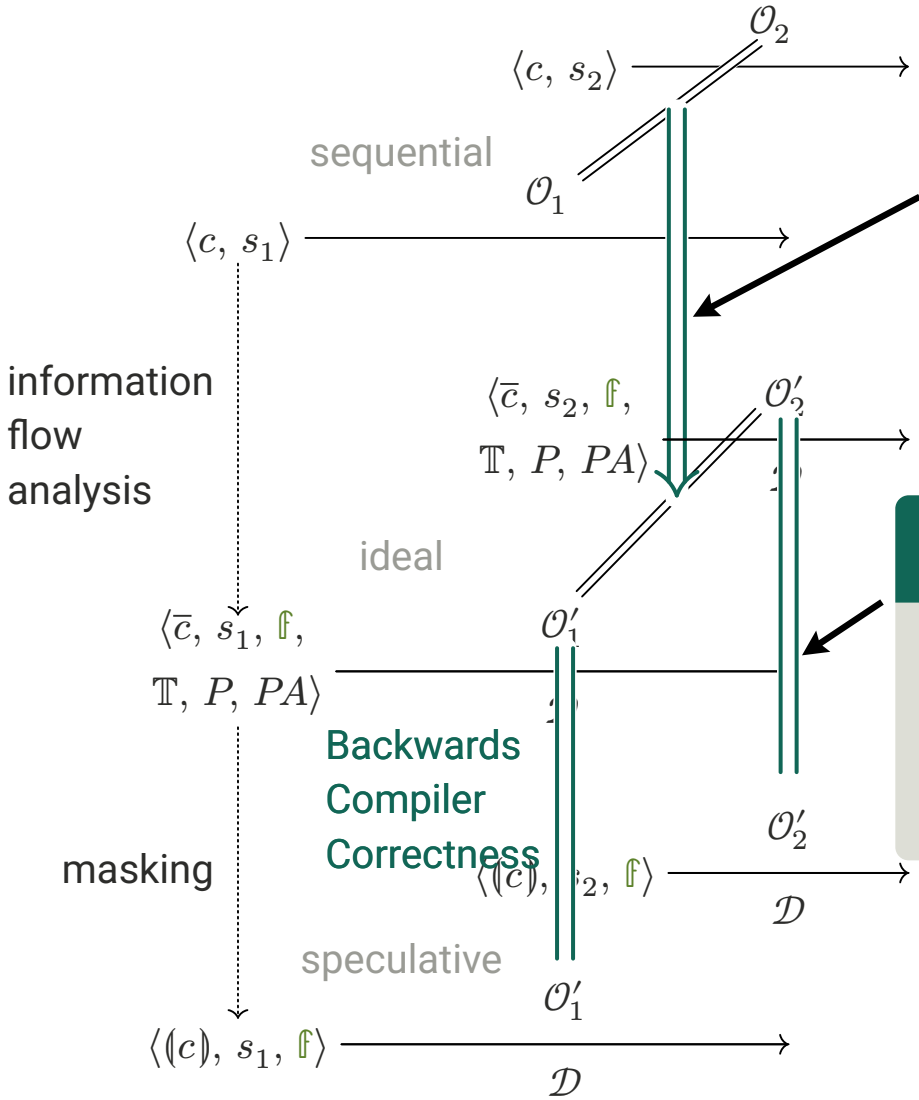

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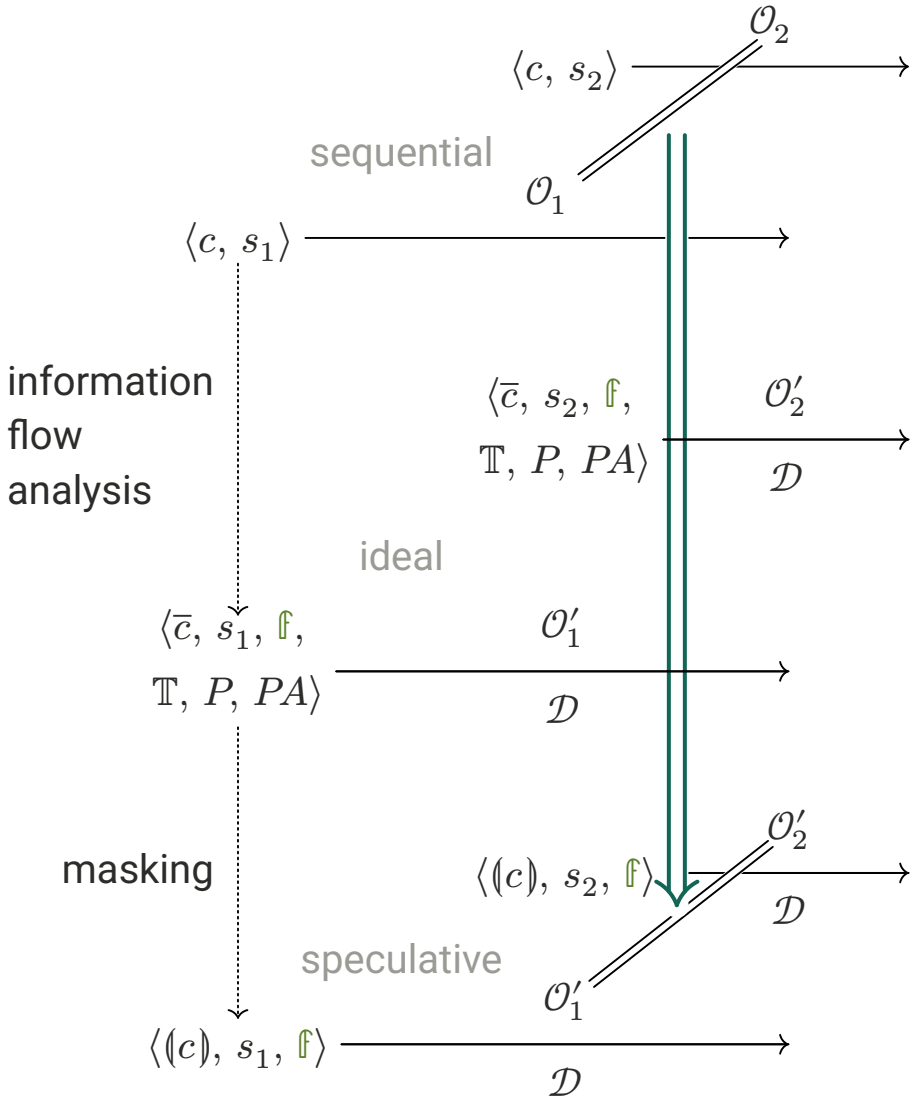

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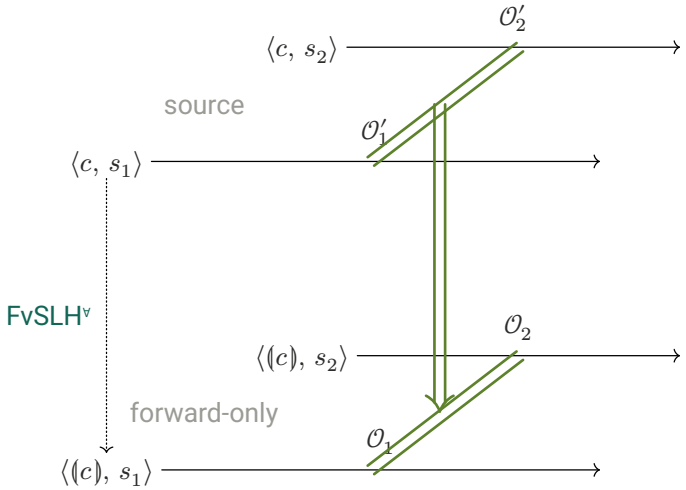
- general: accepts all programs
- efficient: only inserts protections where needed
- no real-world implementation yet

More Realistic Models of Speculation

Translation to More Realistic Models



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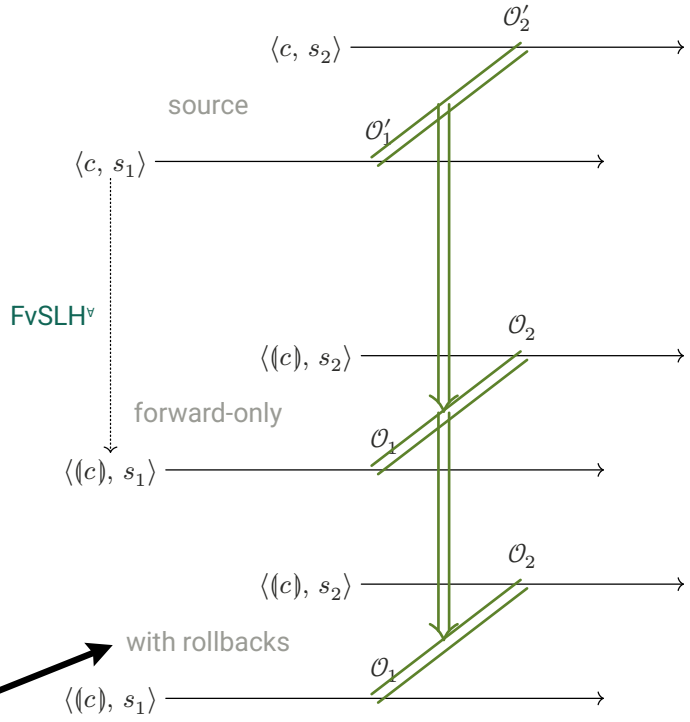
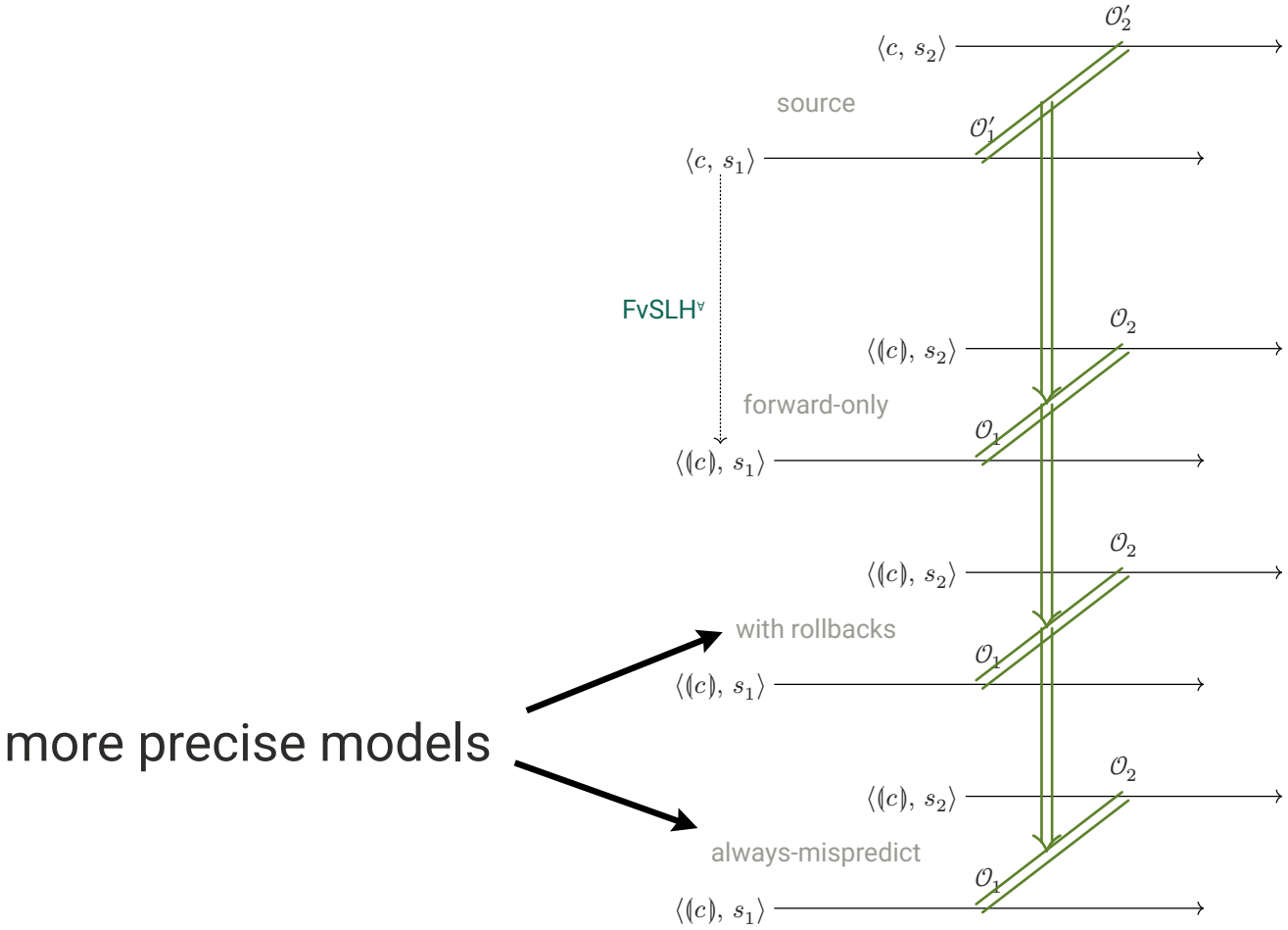


more precise models

Translation to More Realistic Models



Forward-Only Semantics to Rollbacks

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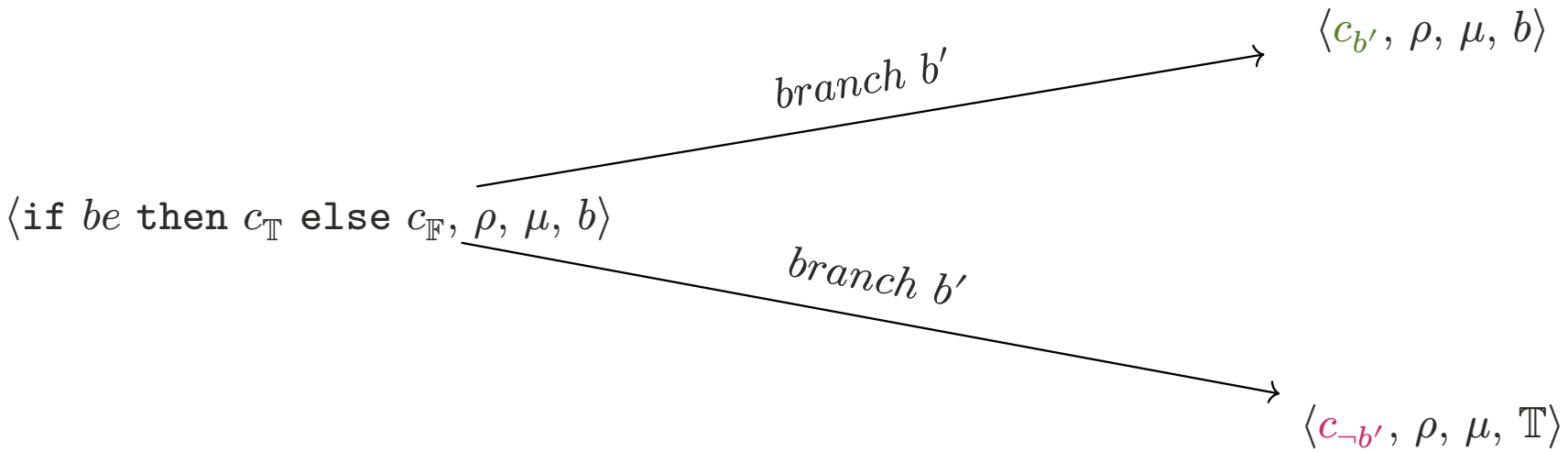

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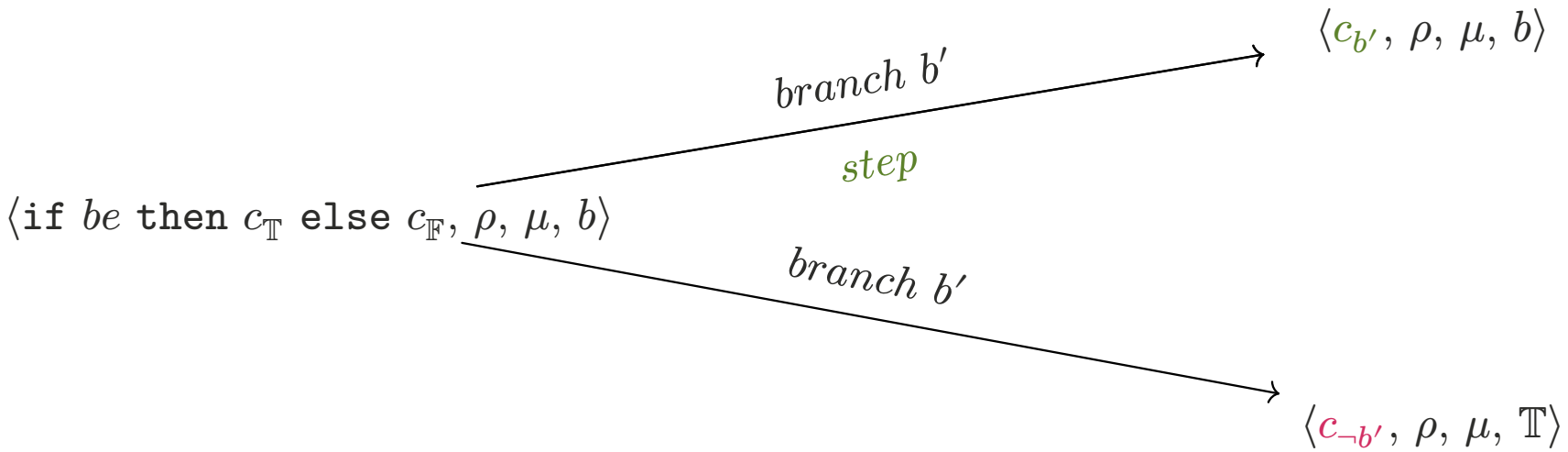

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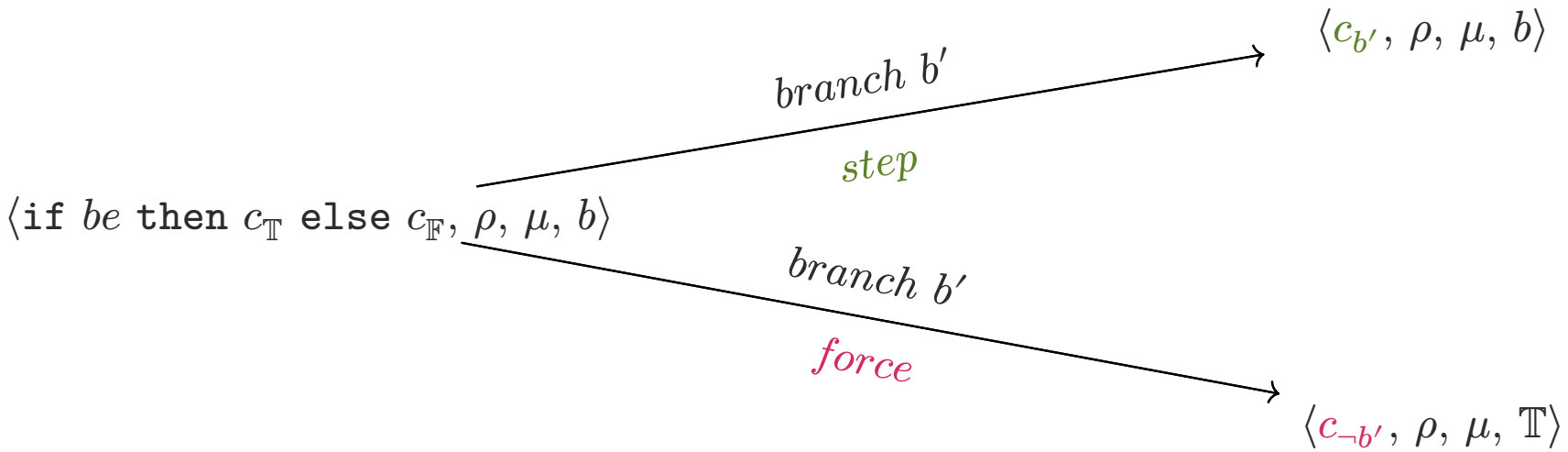

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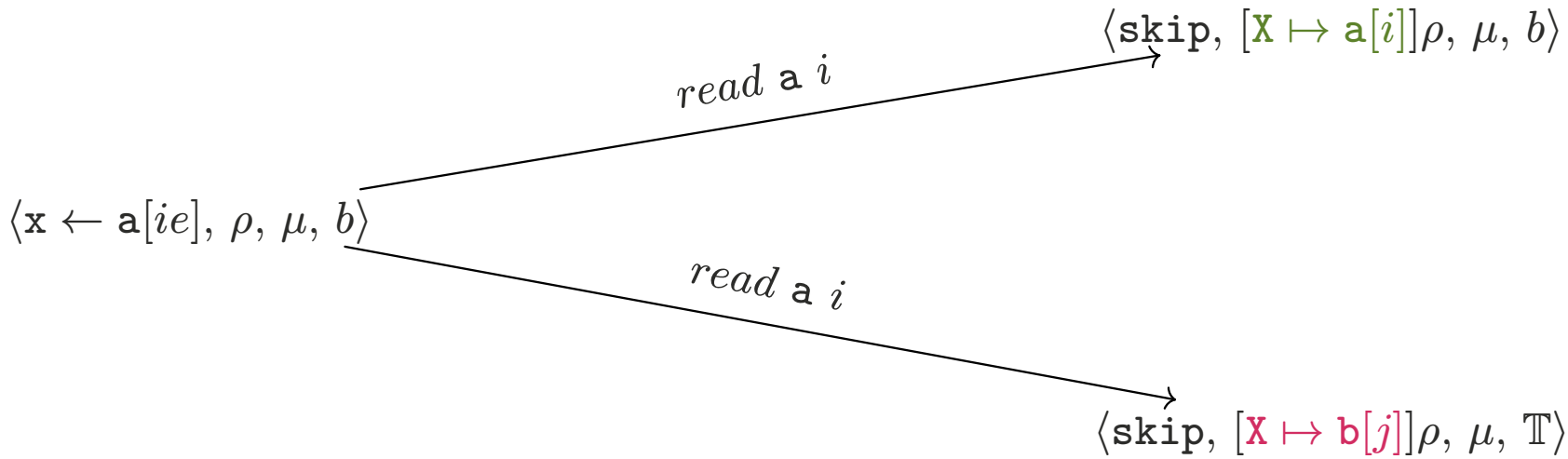

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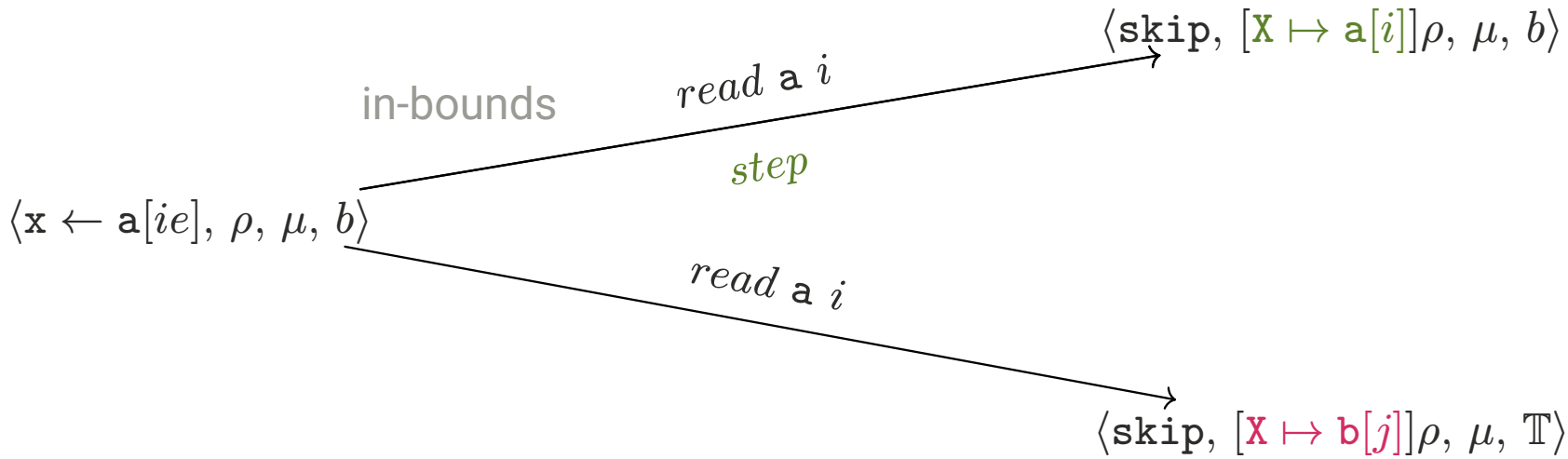

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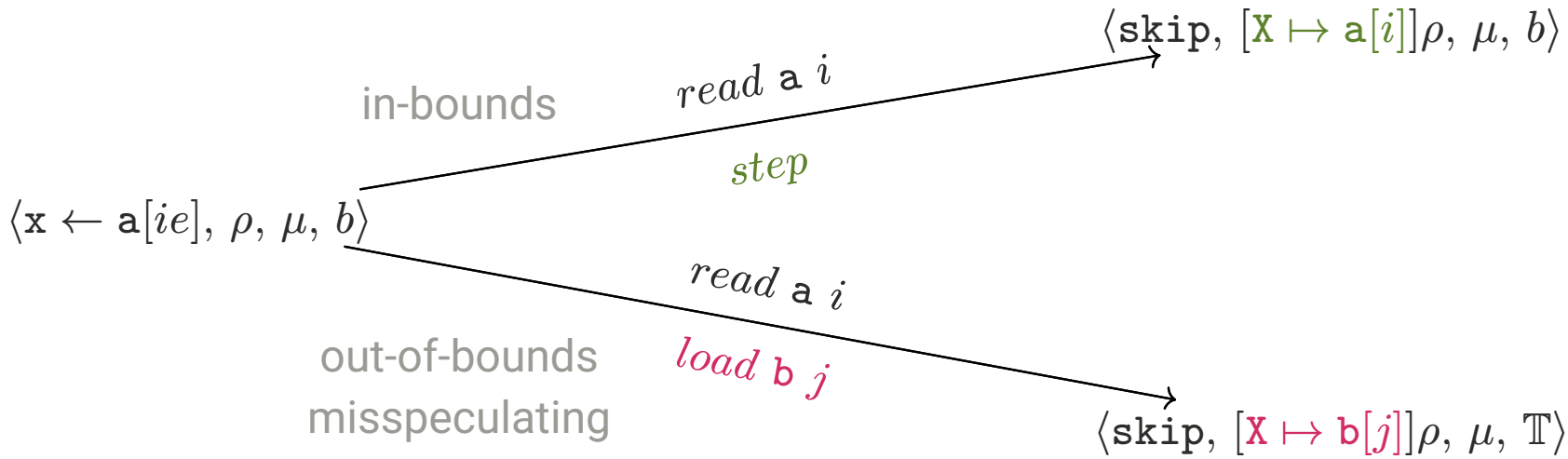

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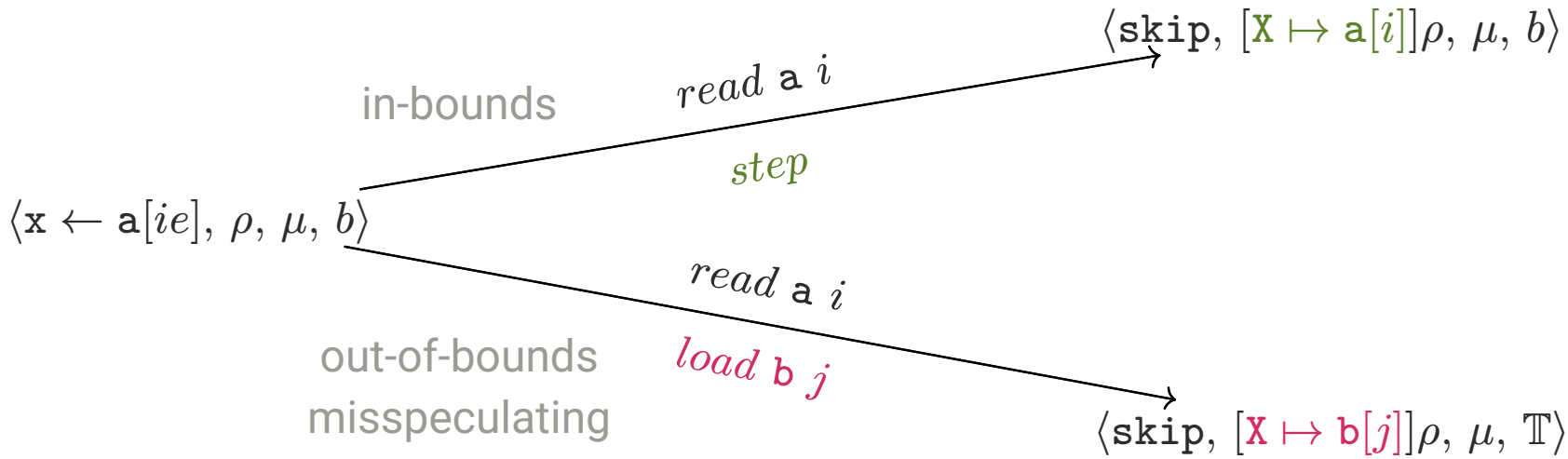
- Forward-only: No rollback mechanism, cannot leave misspeculation



Adding Rollbacks

$$\textsc{Rb\_If\_Force}\ \frac{b' = [\![be]\!]_\rho}{\langle \texttt{if}\ be\ \texttt{then}\ c_{\mathbb{T}}\ \texttt{else}\ c_{\mathbb{F}},\ \rho,\ \mu,\ b\rangle \xrightarrow[force]{branch\ b'}_{\mathrm{rb}} \langle c_{\neg b'},\ \rho,\ \mu,\ \mathbb{T}\rangle}$$

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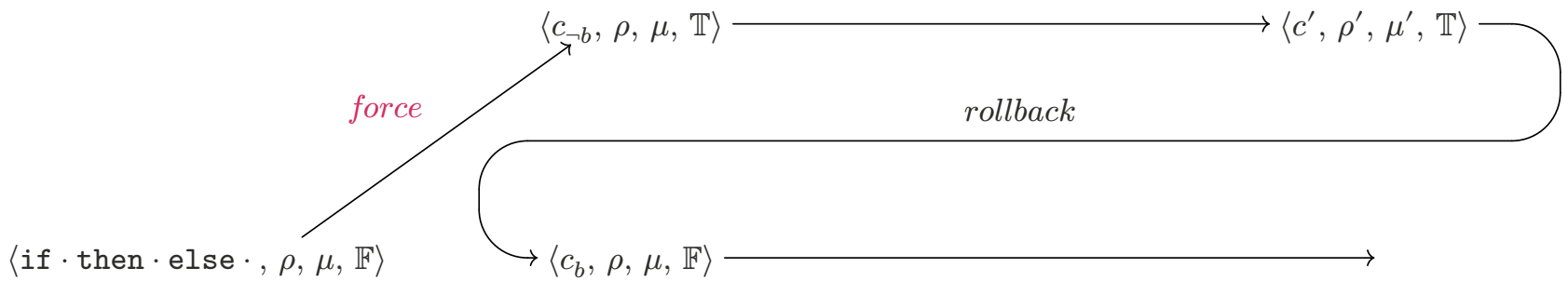

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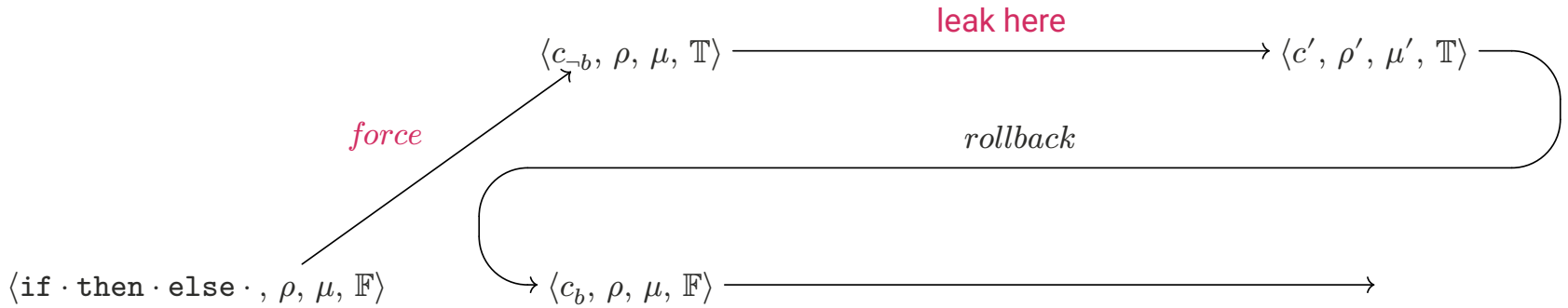

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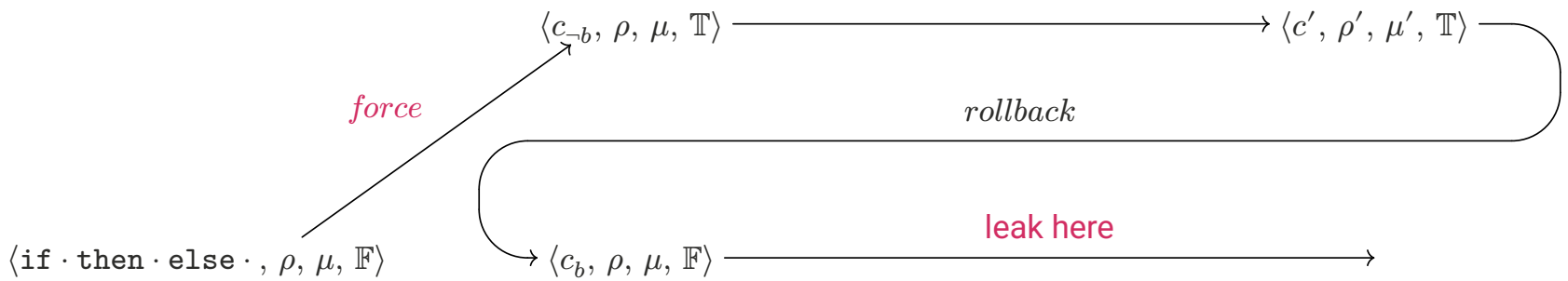

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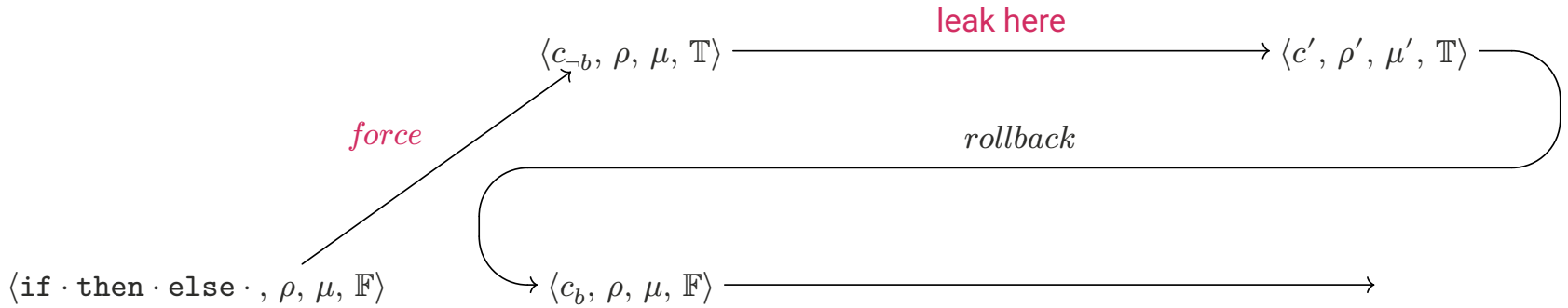

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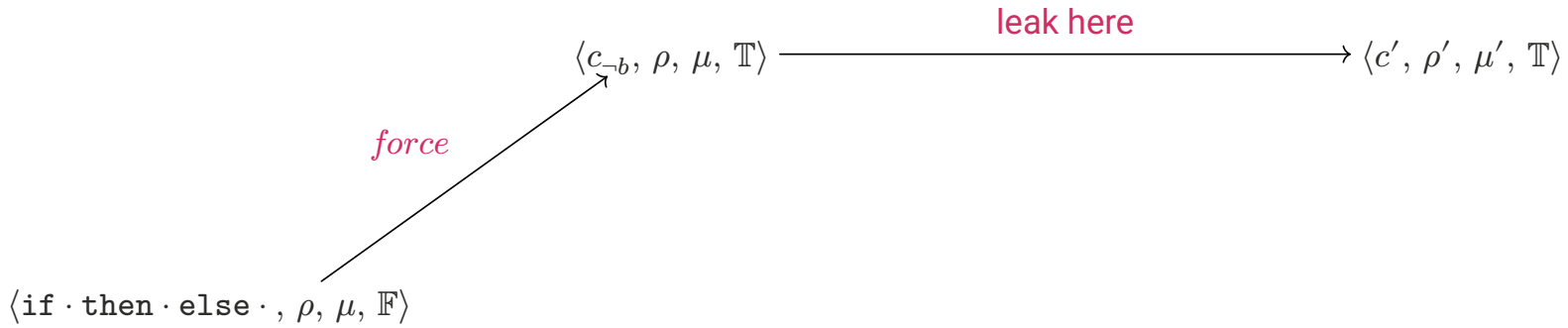

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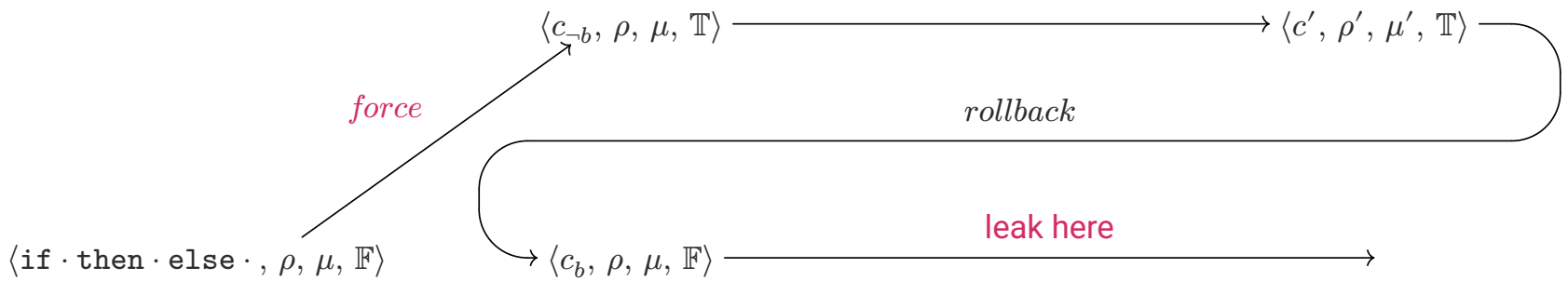

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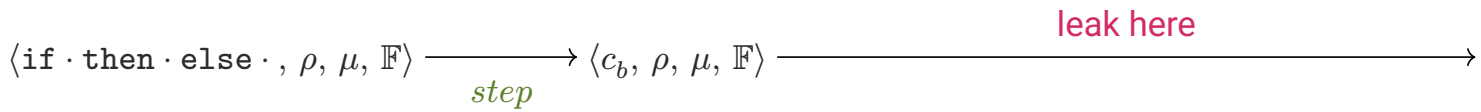

Always-Mispredict Semantics

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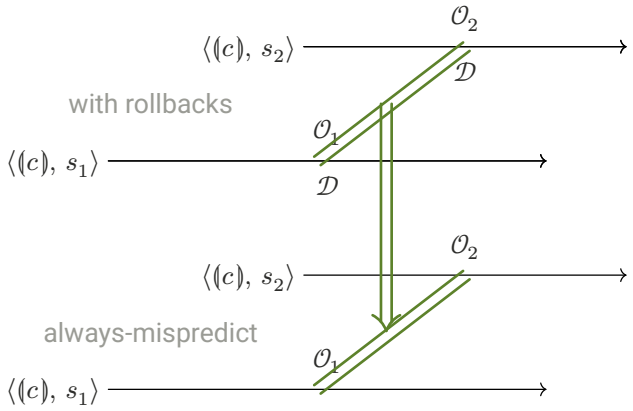
  - *idea:* vendor-guaranteed leakage model

From Directives to Always-Mispredict



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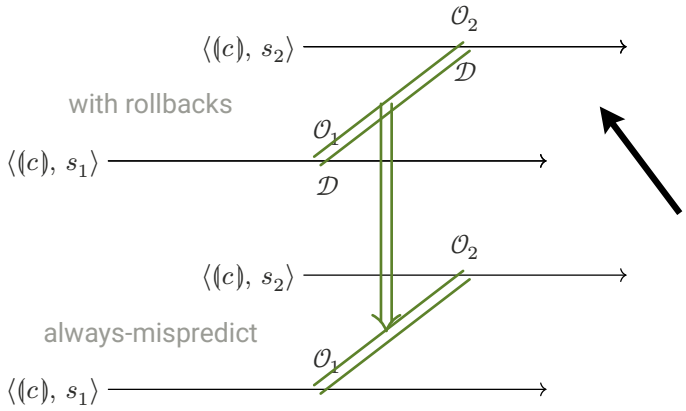

out-of-bounds accesses only in misspeculating execution

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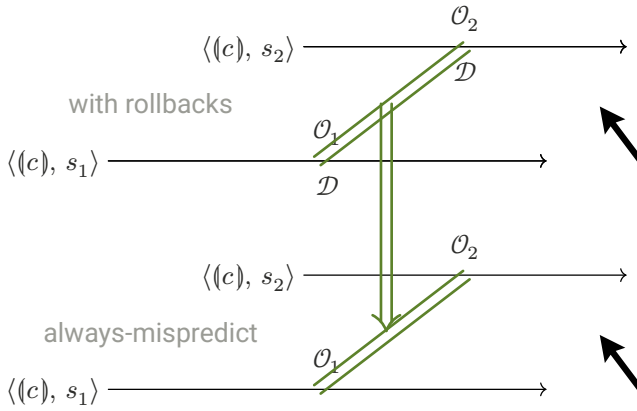

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flattened memory layout independent of speculation

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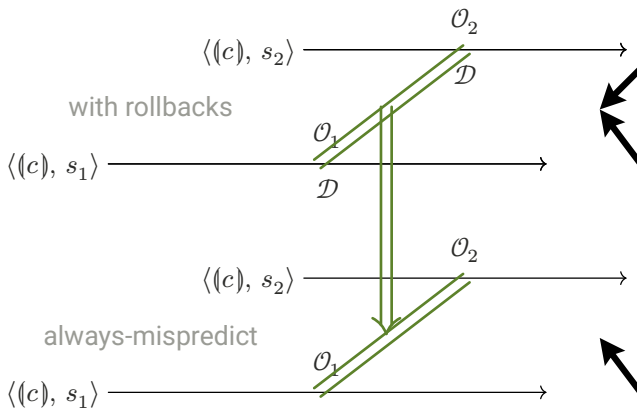

must assume sequential execution does not get stuck!

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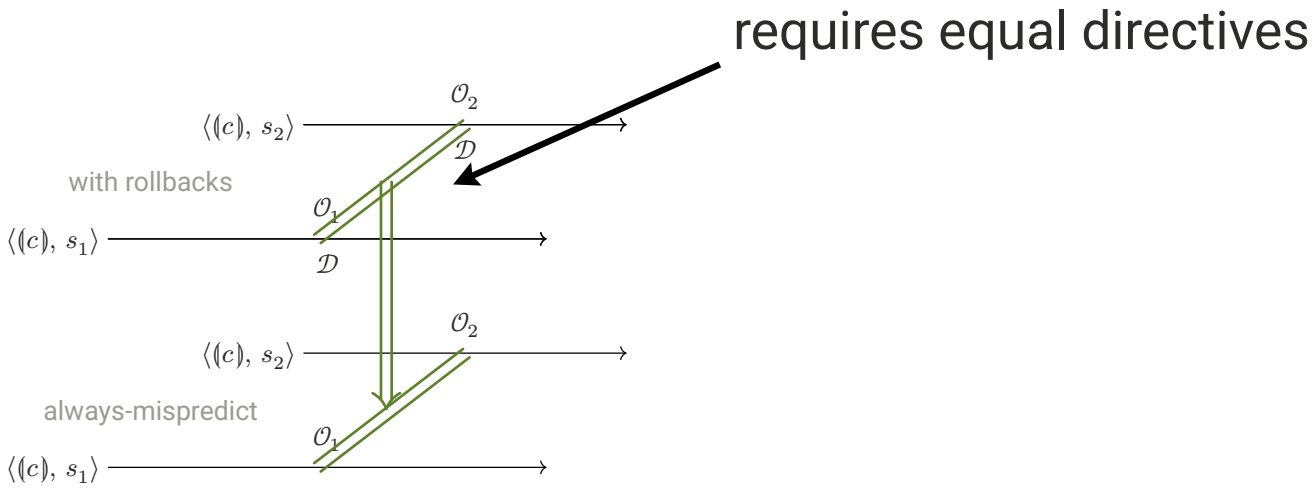
flattened memory layout independent of speculation

From Directives to Always-Mispredict



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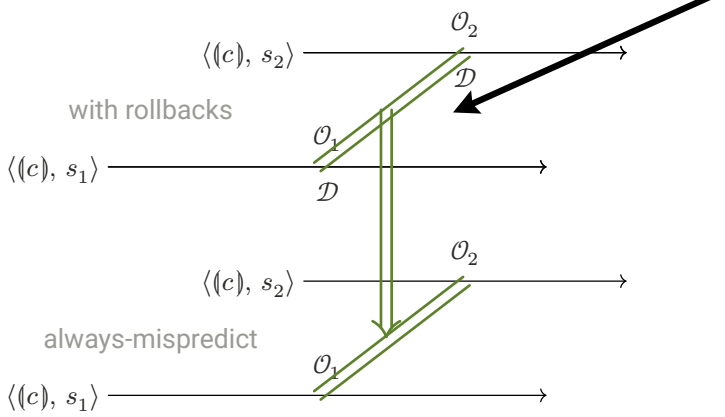

requires equal directives

- same out-of-bounds index must result in same location

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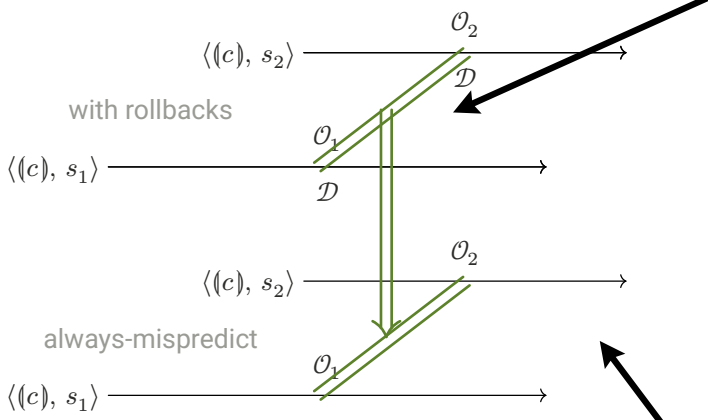

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memory access:
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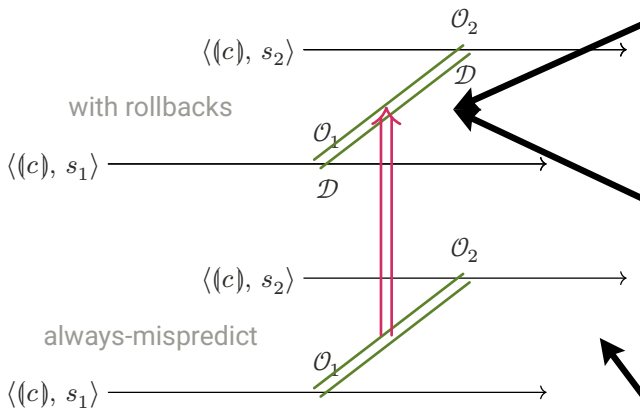

requires equal directives

no equality assumption
when different directives are used

memory access:
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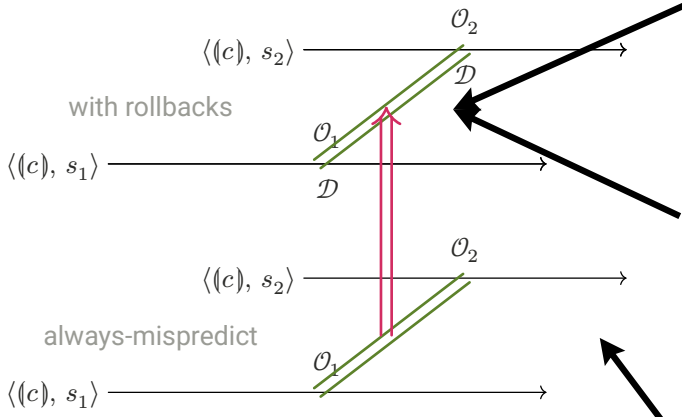

requires equal directives

one directive must allow
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From Directives to Always-Mispredict: Lessons Learned

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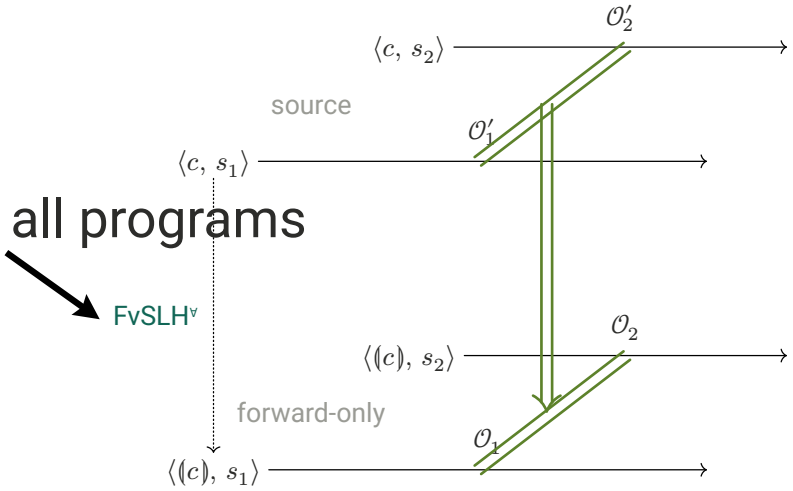
  - Easy to miss! Affects proofs of Selective and Flexible SLH

Conclusions

Efficient Mitigation for all programs



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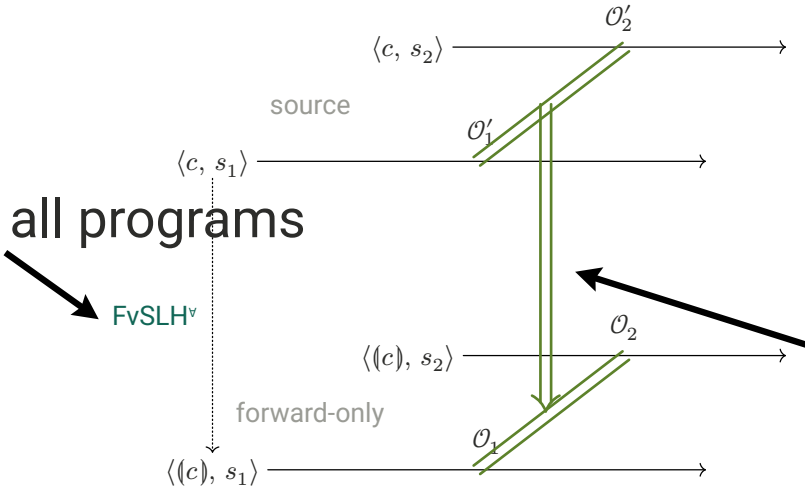

Formal relative security proof in Rocq

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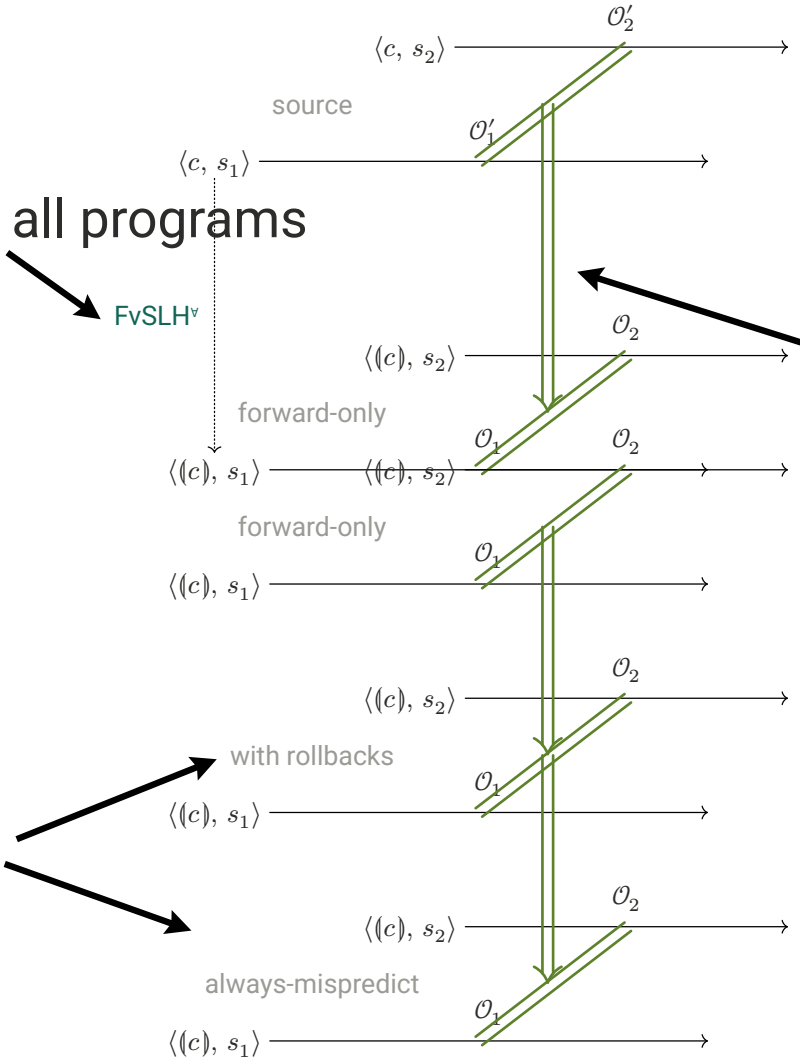

Formal relative security proof in Rocq

Proofs for more precise models (also in Rocq)

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FvSLH$^{\forall}$

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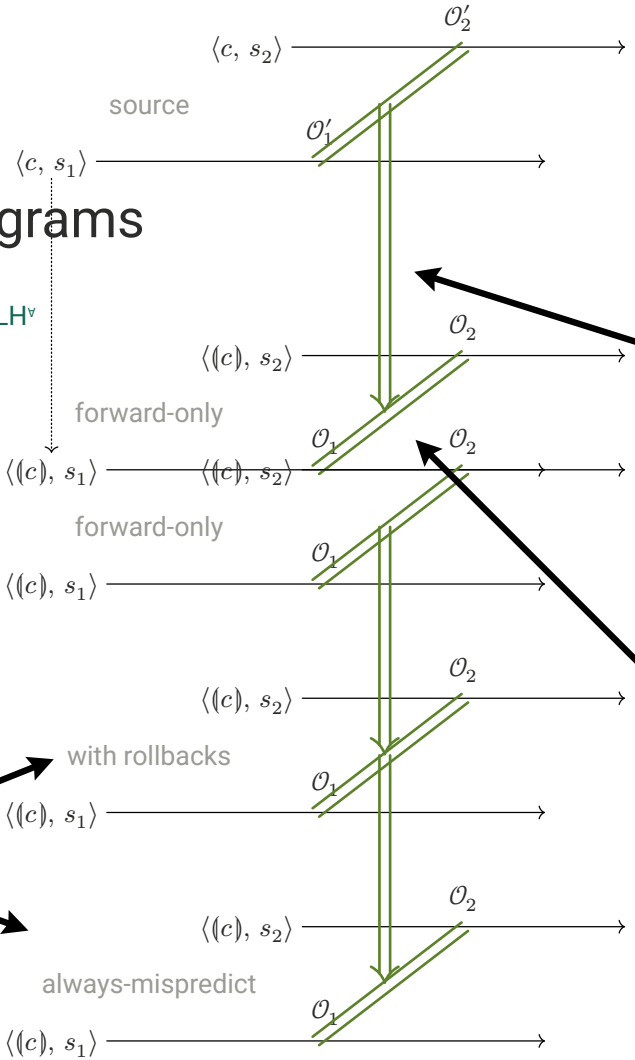

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work needed to connect here

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Bibliography

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