On Verifying Secret Control Flow Elimination

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Motivation

- 10^{13}€ annual cybercrime damage
- Vulnerabilities (Spectre/Meltdown)

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- Side-Channel Attacks

Image generated by ChatGPT

Timing Side-Channels

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- Execution time depends on secret password
- ~25 timing vulnerabilites on CVE since 2024

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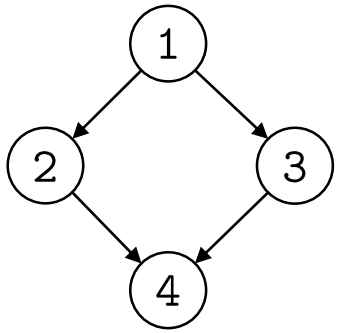

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Ferrante et al., 1987

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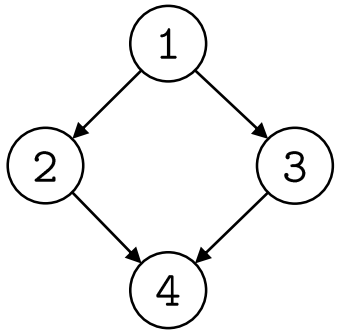

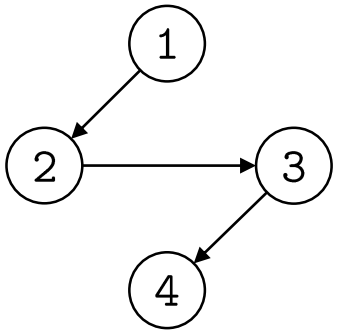

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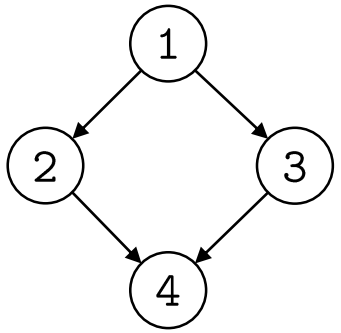
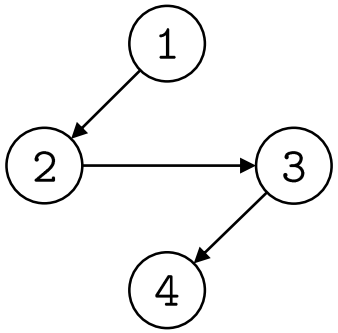
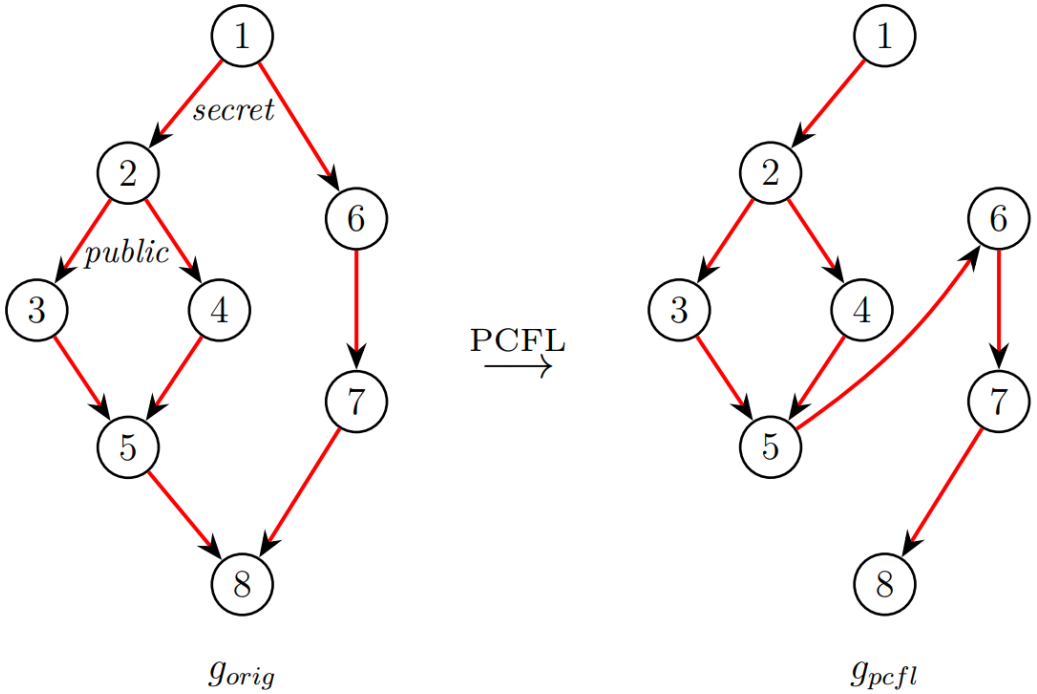




Goal: branch decisions should be independent of any secret parameters

Partial Control-Flow Linearization (PCFL)

Moll and Hack, 2018



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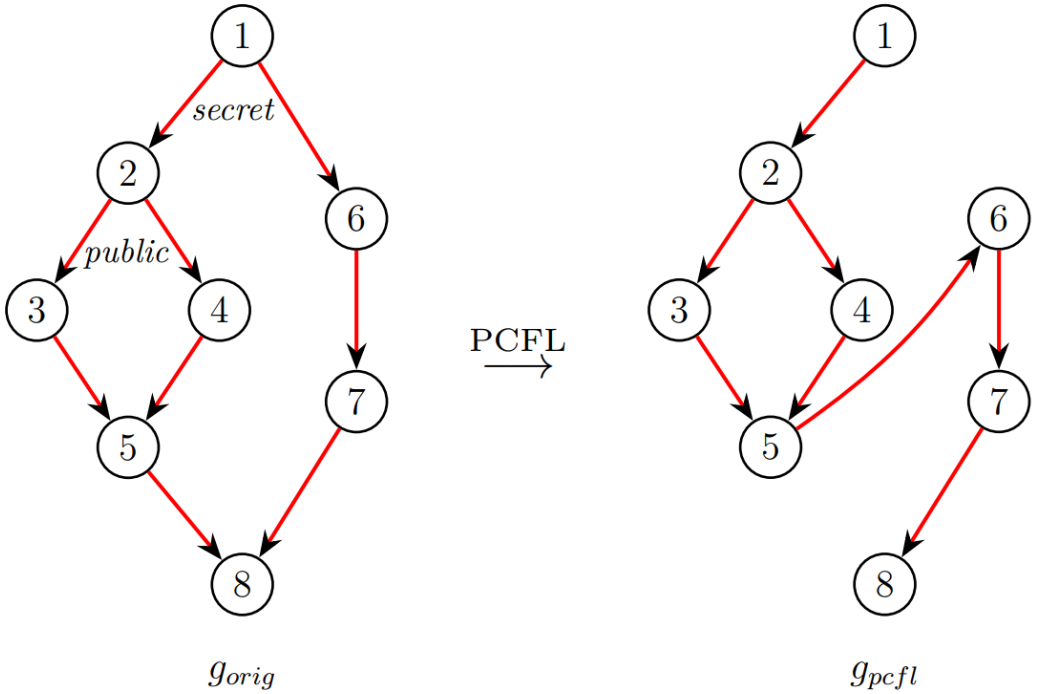

g_{orig} g_{pcfl}

$$\text{detour} : E \to V$$

$$\text{detour}(1, 6) = 2$$

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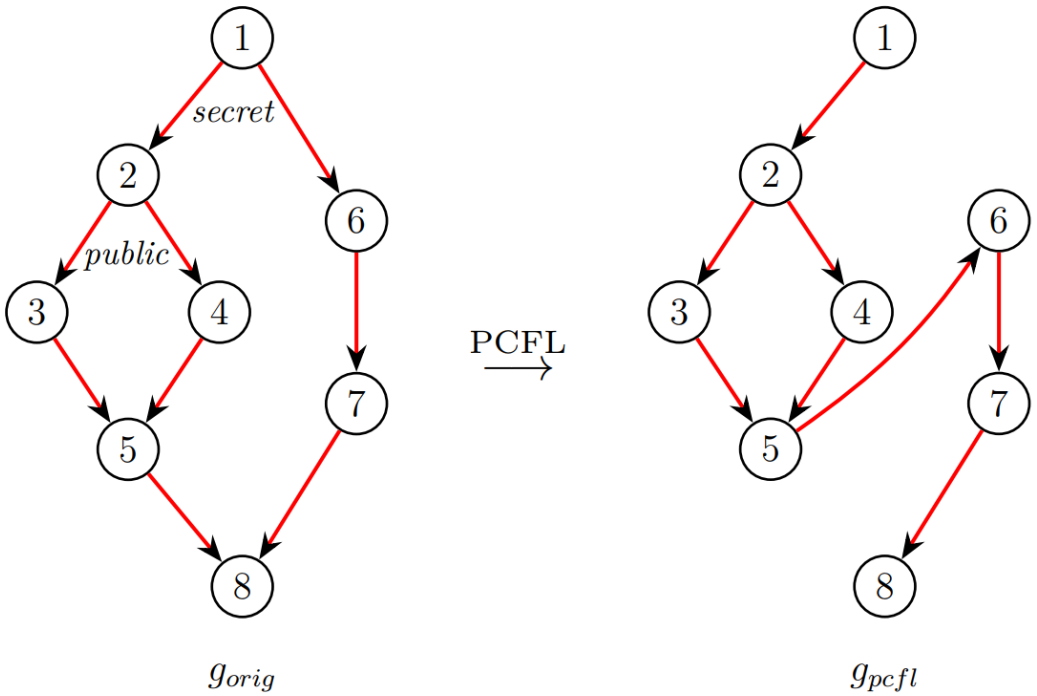

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$$\text{detour} : E \to V$$

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Lemma.

$$\forall (v, w) \in E, w \geq_{PD} \text{detour}(v, w)$$

Constant-Time Compilers

- SC-Eliminator (Wu et al., 2018)
- Constantine (Borello et al., 2021)
- PCFL (Hack and Moll, 2018) (Soares et al., 2023)

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Question: Can we formally verify a constant-time compiler transformation?

CompCert

Leroy, 2009

$$\texttt{Csem} \longrightarrow \ldots \longrightarrow \texttt{RTL} \longrightarrow \ldots \longrightarrow \texttt{Asm}$$

- has multiple intermediate languages

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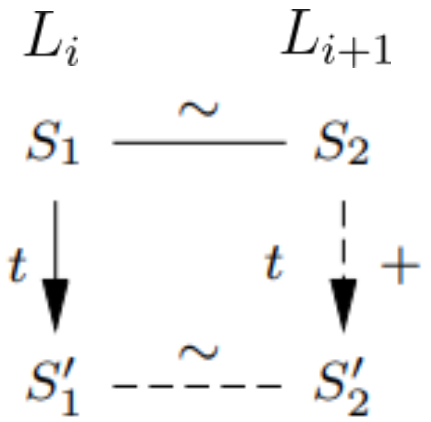

Image from Leroy, 2009

Contributions

- Verify a constant-time compiler transformation (PCFL) in CompCert

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  - Only for subset of C
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  - Only for subset of C
  - Eliminate secret *control flow*

1. Transformation is correct
2. Transformation removes secret control-flow

Approach

$$\texttt{Csem} \longrightarrow \ldots \longrightarrow \texttt{RTL} \longrightarrow \ldots \longrightarrow \texttt{Asm}$$

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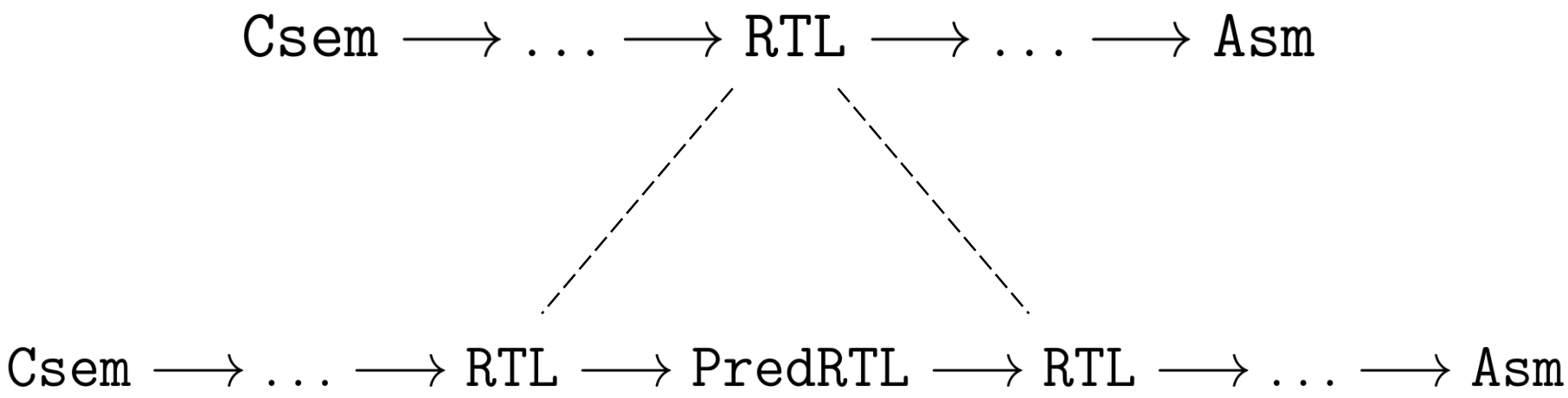

Approach

$$\texttt{Csem} \longrightarrow \ldots \longrightarrow \texttt{RTL} \longrightarrow \ldots \longrightarrow \texttt{Asm}$$

$$\texttt{Csem} \longrightarrow \ldots \longrightarrow \underset{g_{orig}}{\texttt{RTL}} \xrightarrow{\text{PCFL}} \underset{(g_{pcfl}, g_{orig})}{\texttt{PredRTL}} \xrightarrow{\text{predication}} \underset{g_{pcfl}}{\texttt{RTL}} \longrightarrow \ldots \longrightarrow \texttt{Asm}$$

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RTL state: $(v, regs) \in V \times val^{reg}$

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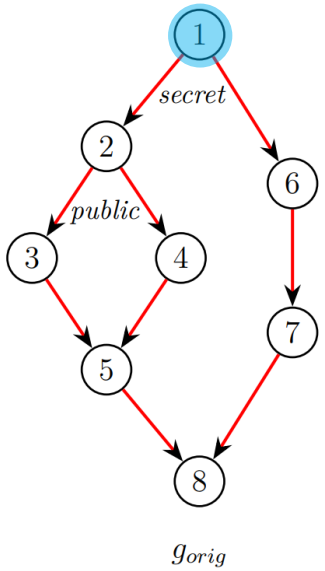

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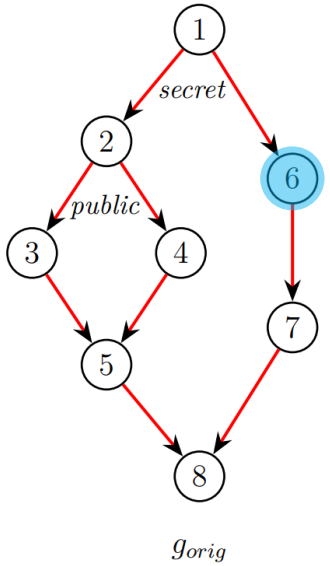

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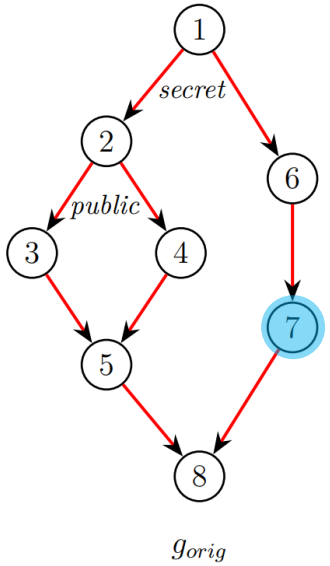

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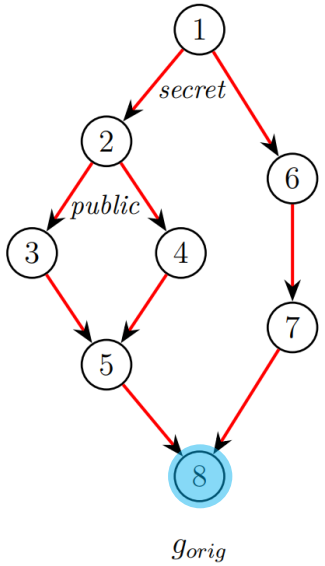

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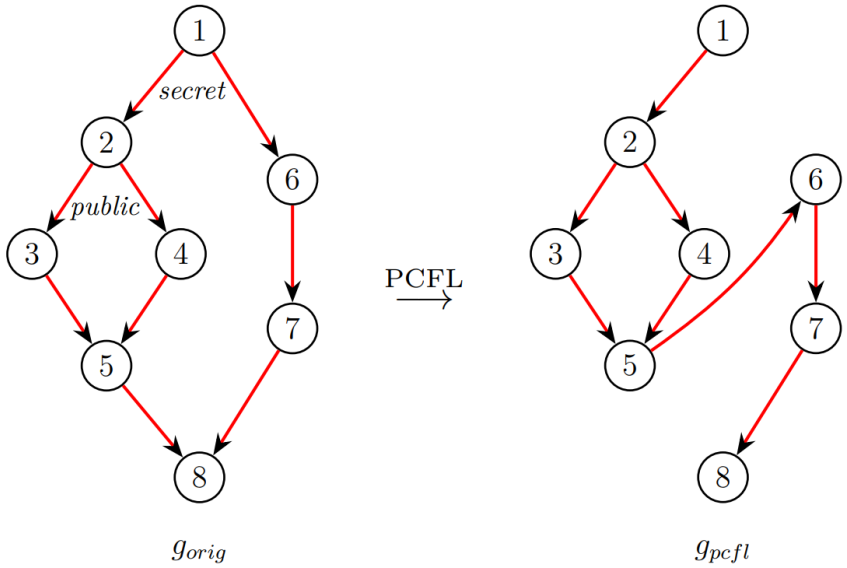

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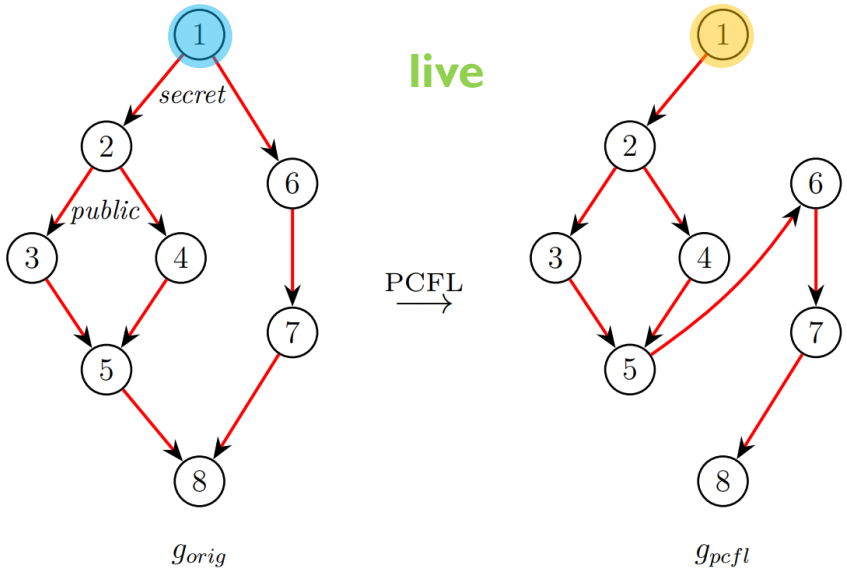

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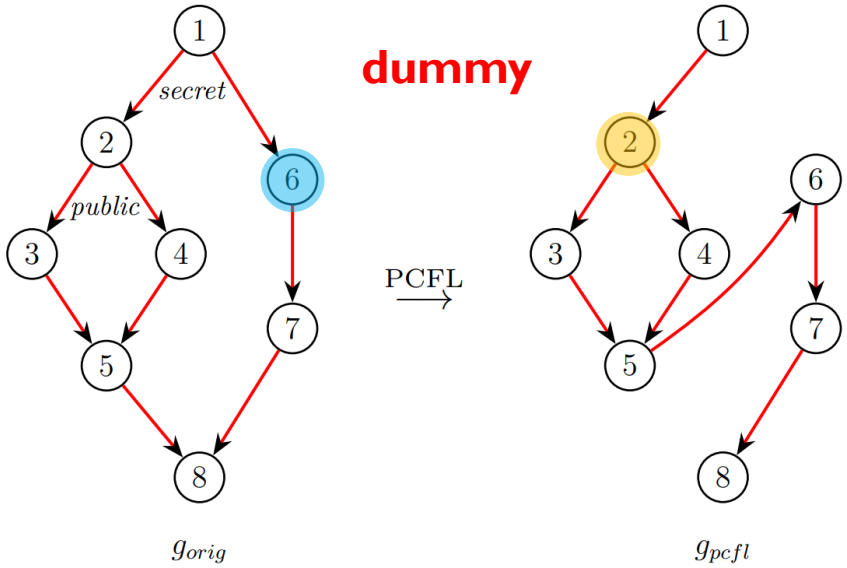

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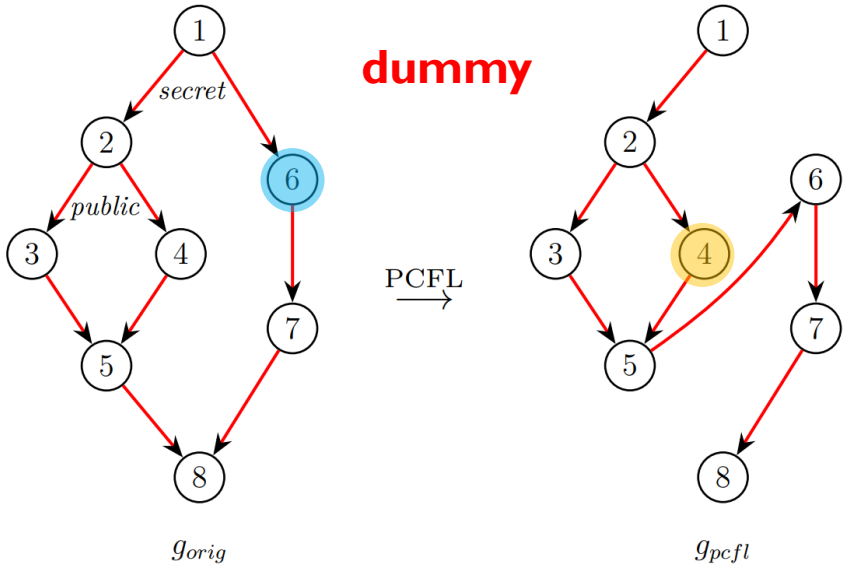

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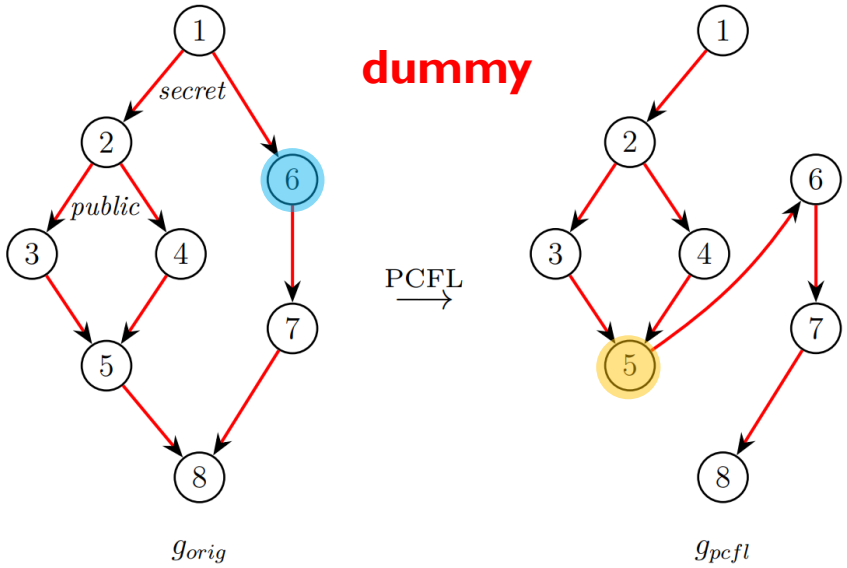

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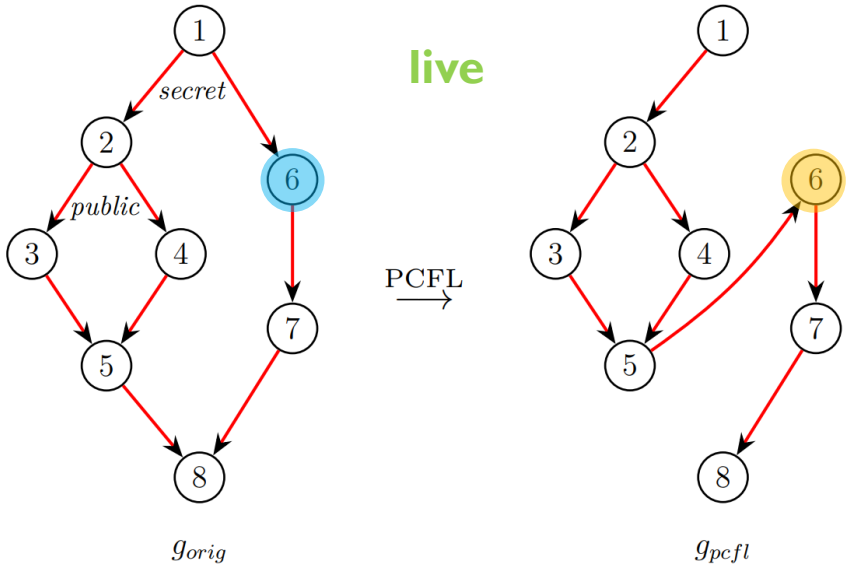

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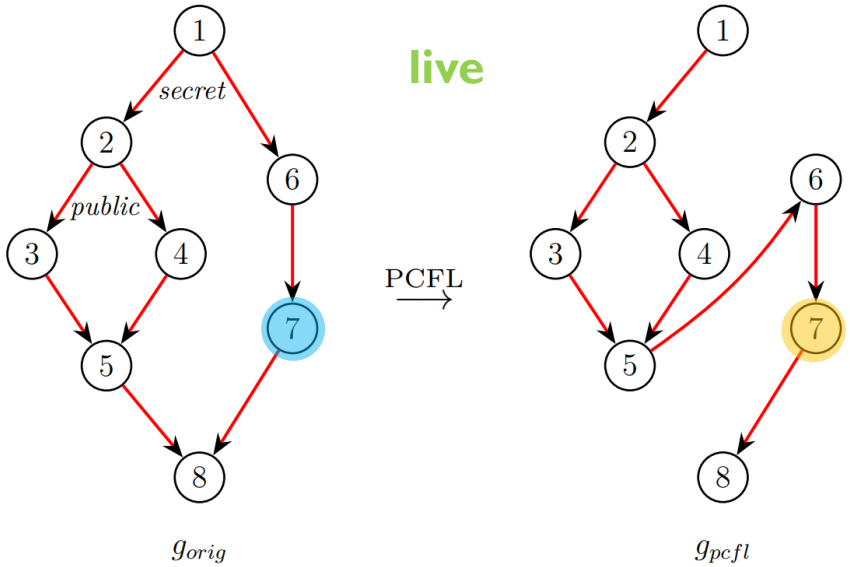

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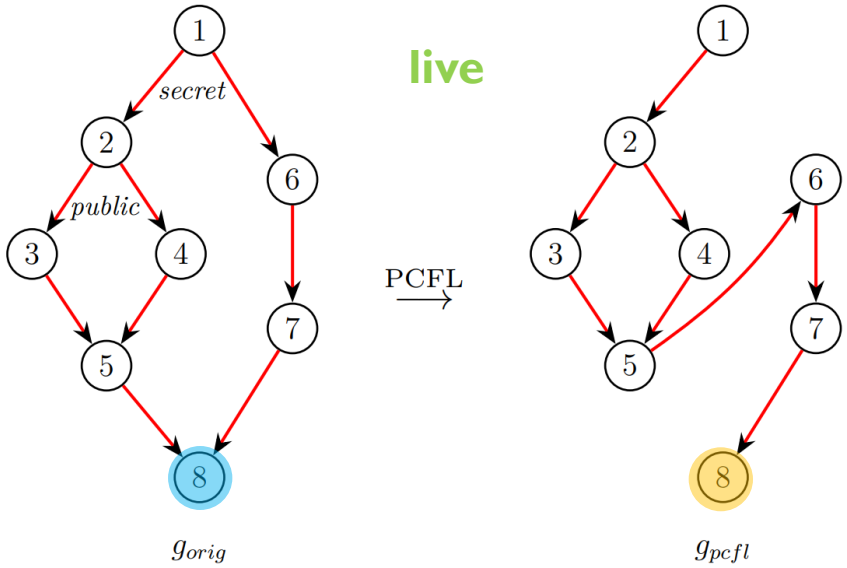

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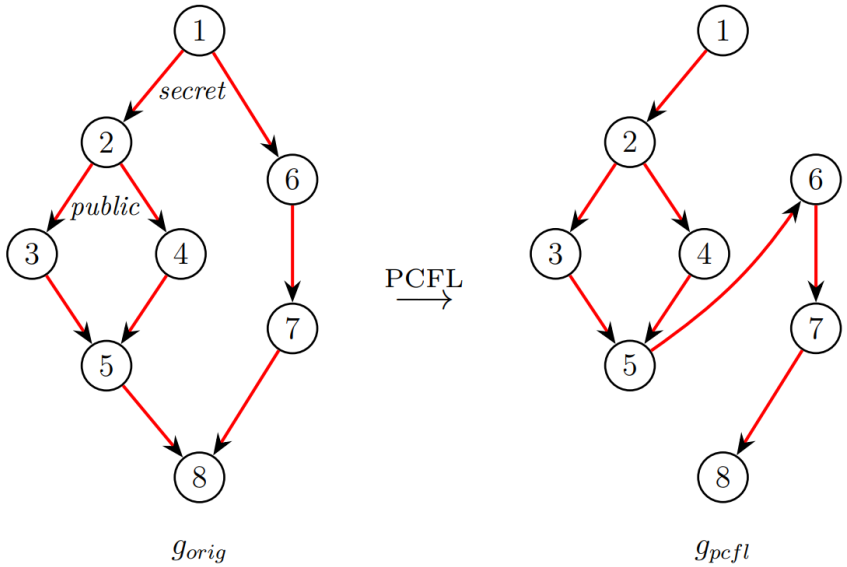

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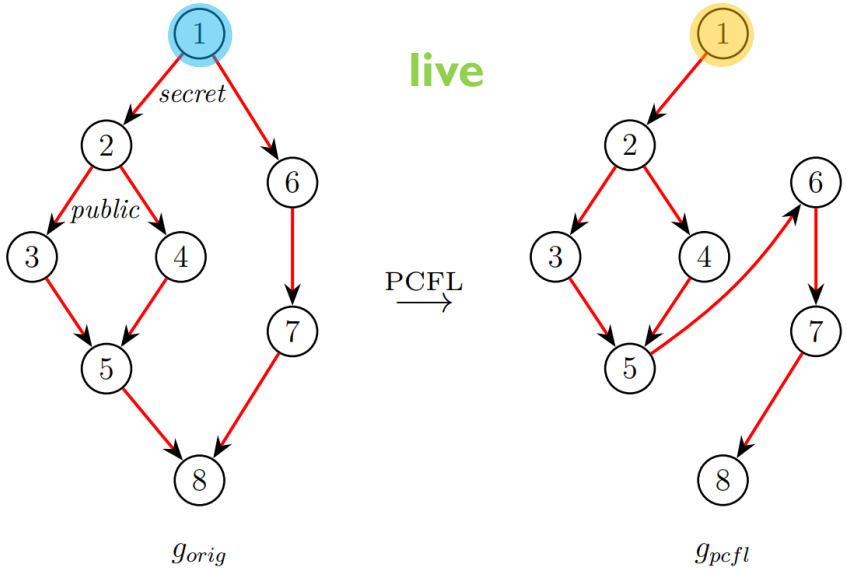

$$(1, r) \sim (1, 1, r)$$

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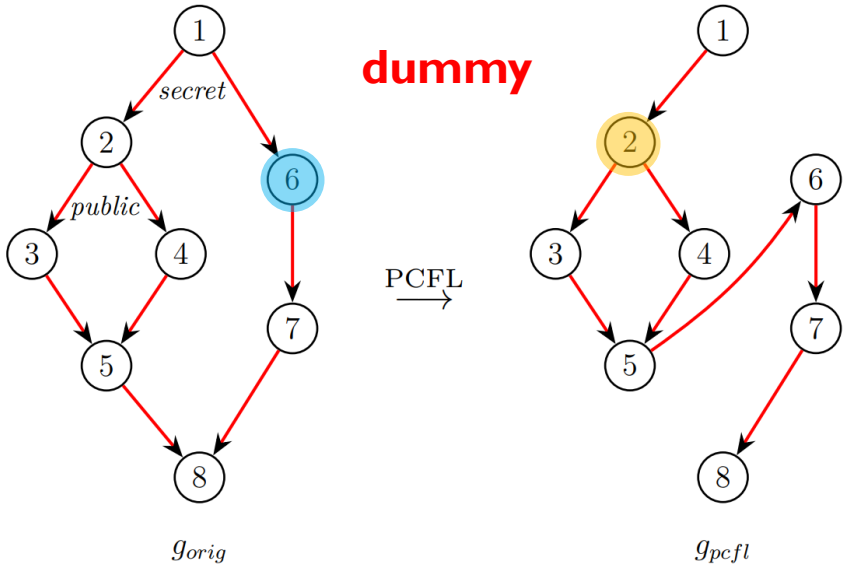

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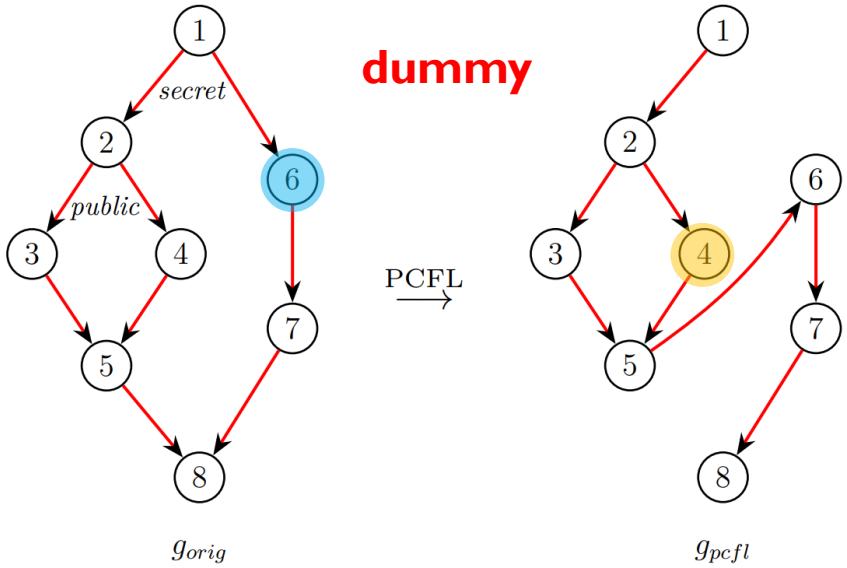

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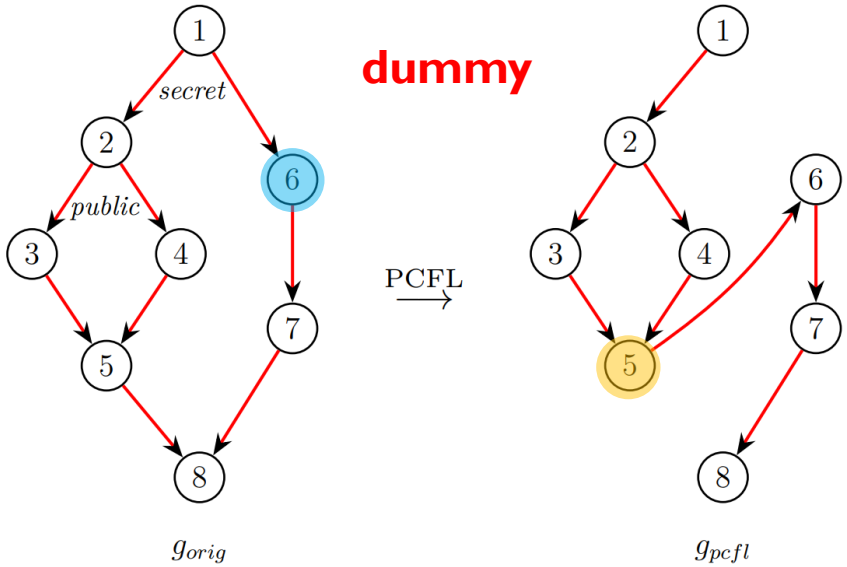

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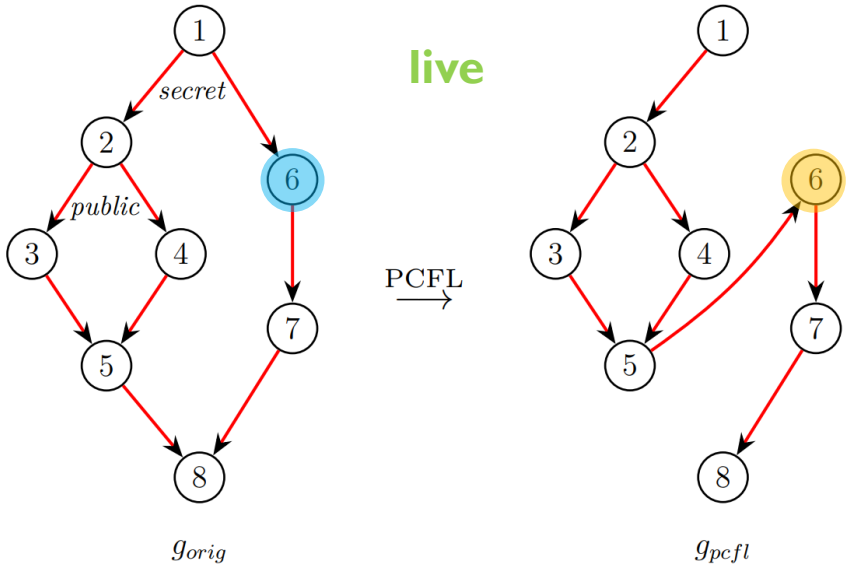

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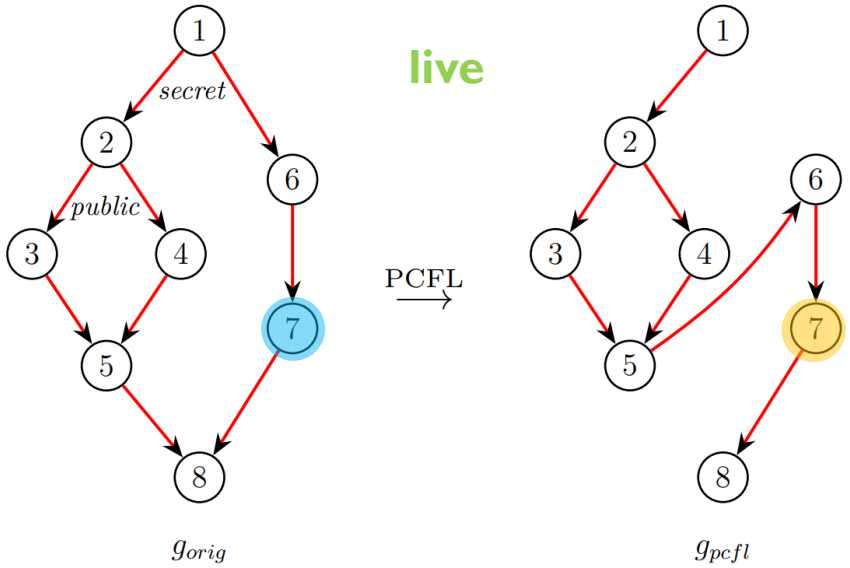

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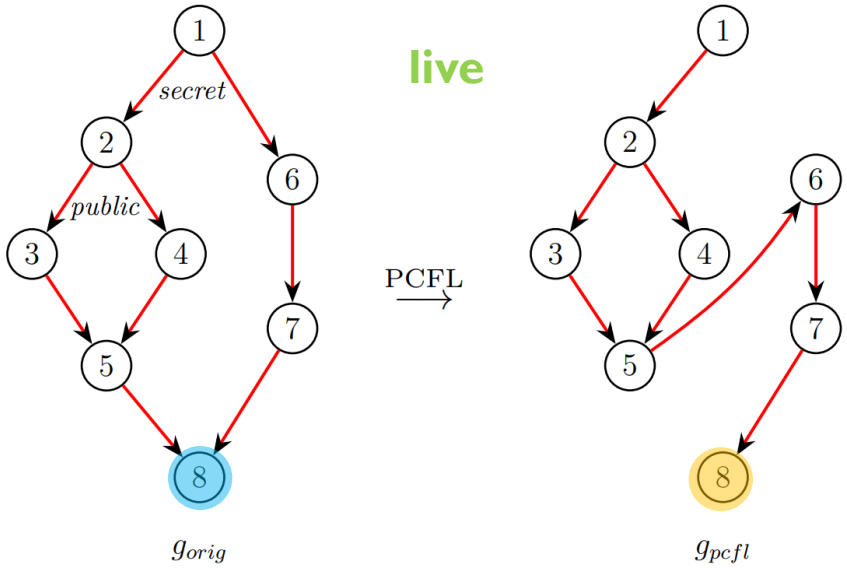

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1. Dummy states must not change registers
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2. Dummy states must always return
   - must not crash

Lemma.
$\forall (v, w) \in E, w \geq_{PD} \text{detour}(v, w)$

Unsafe Operations

```
if (t > 0):
  x = 1 / t
else:
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(a) Original code

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x1 = 1 / t
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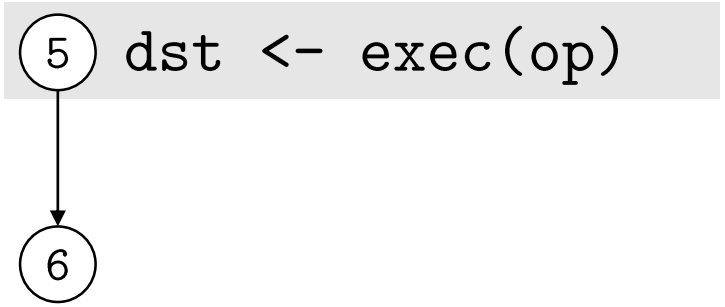
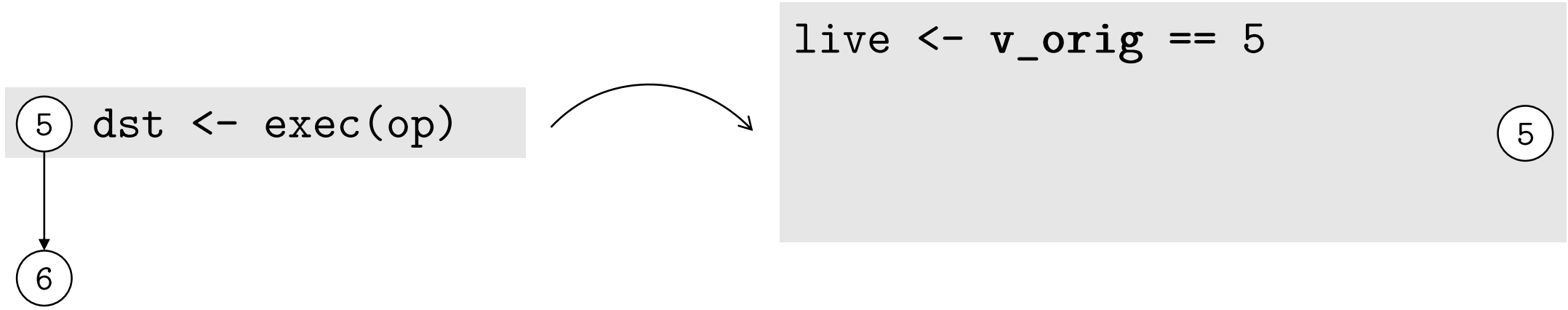
- Solution: restrict to *safe* operations
- can be relaxed to *non-uniform* vertices

Predication (PredRTL -> RTL)



Predication (PredRTL -> RTL)



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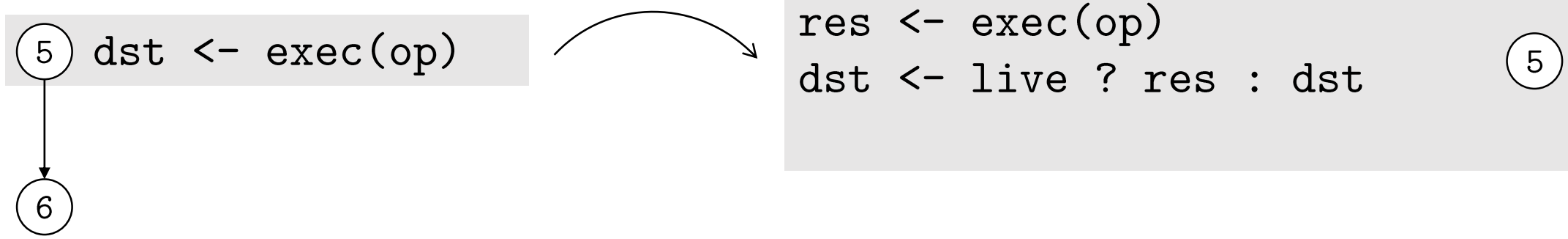

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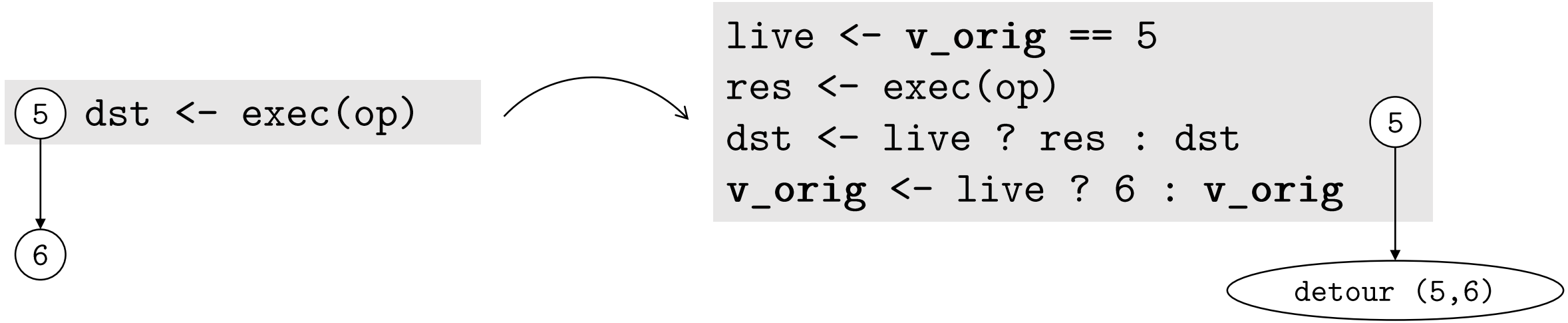

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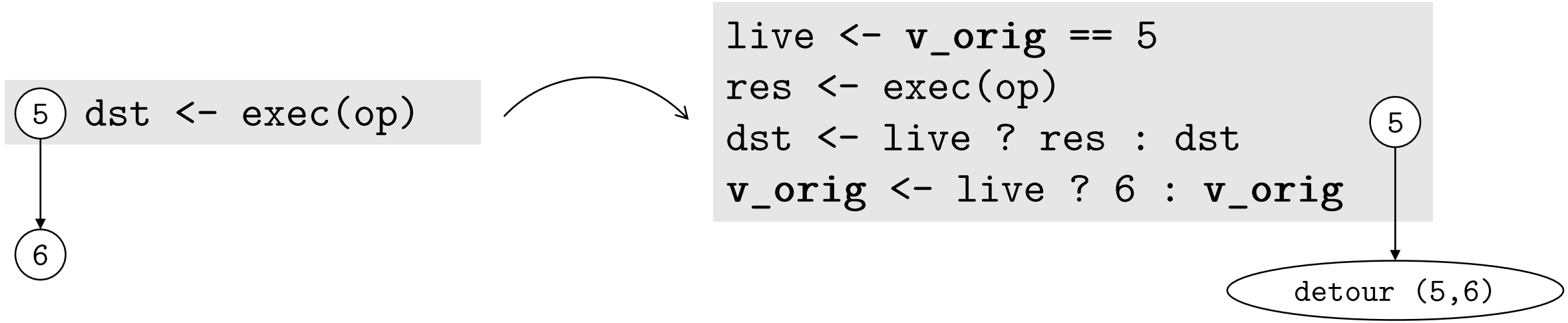

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  - → no need for boolean predicate

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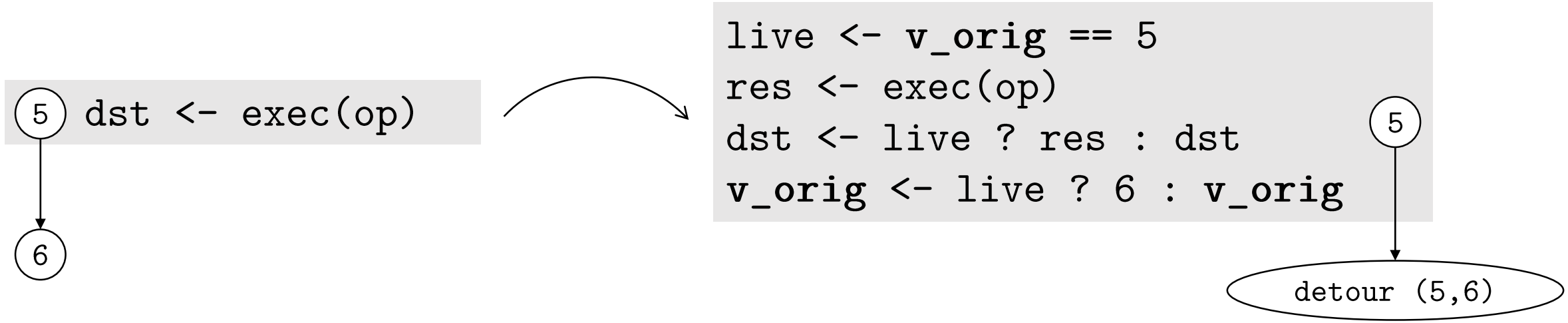

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Transformation is correct ✓

Control-Flow Security

Goal: branch decisions should be independent of any secret parameters

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- Proven for PredRTL
- Future: down to Asm

Conclusions

- Possible to verify a constant-time transformation for a subset of C
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Conclusions

- Possible to verify a constant-time transformation for a subset of C
- However, much effort (9000 LOC)
- Future: tackle remaining challenges
  - big-step semantics better suited?

Thank You!

Image generated by ChatGPT