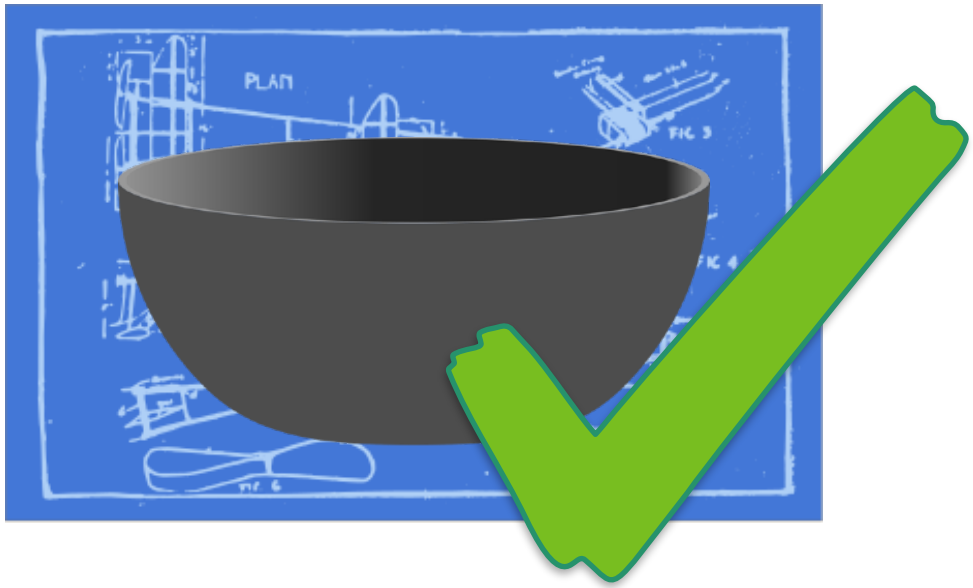
Verifying that a compiler preserves concurrent value-dependent information-flow security

Robert Sison (UNSW Sydney, Data61) and **Toby Murray** (University of Melbourne)

September 2019

www.data61.csiro.au

So you've proved your program *doesn't leak secrets*…



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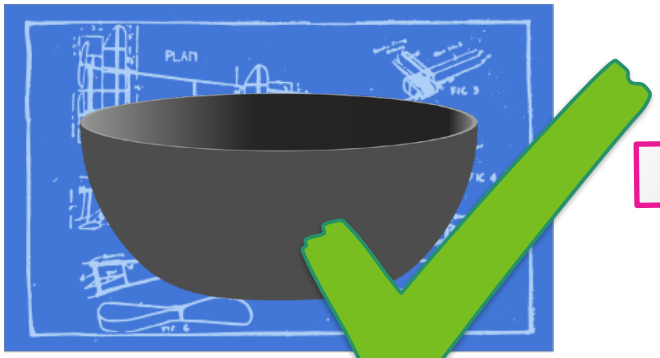

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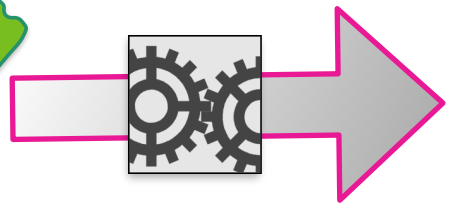

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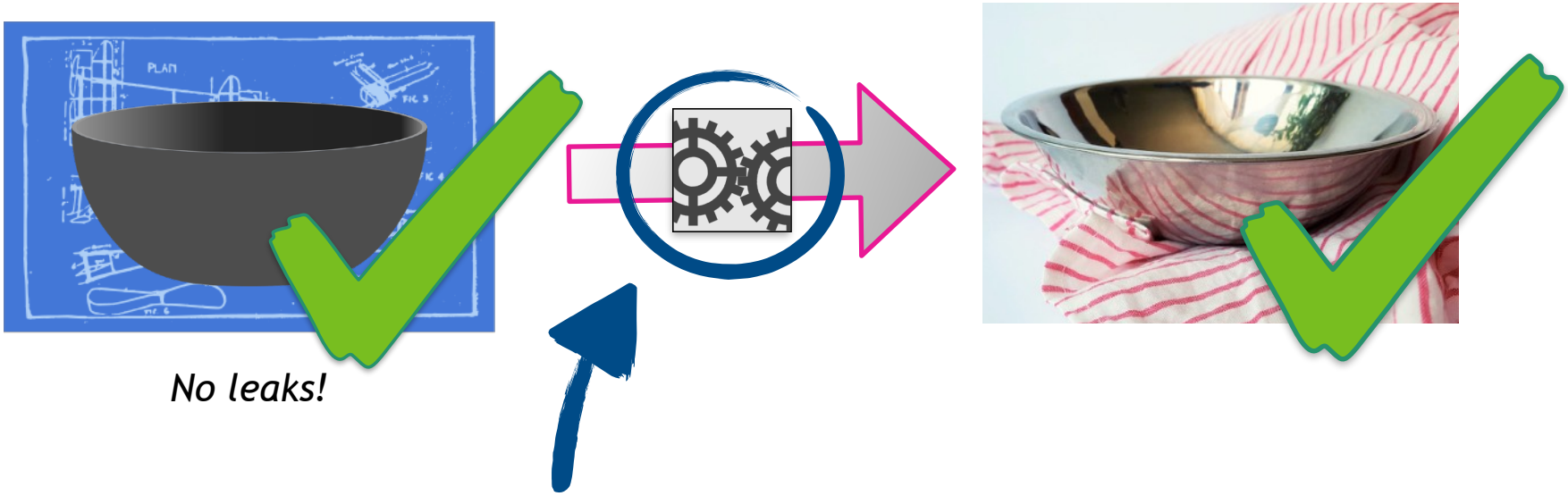

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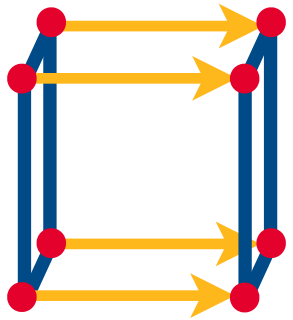

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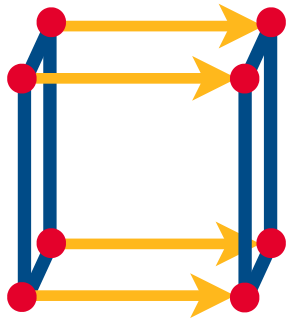

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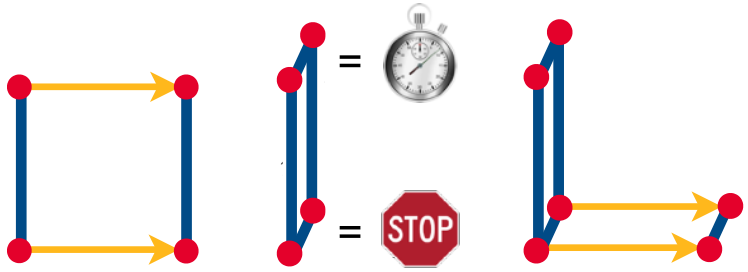

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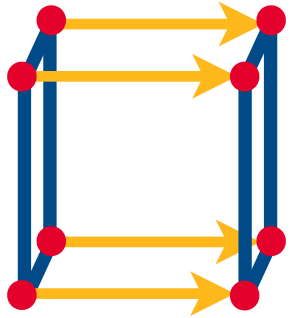

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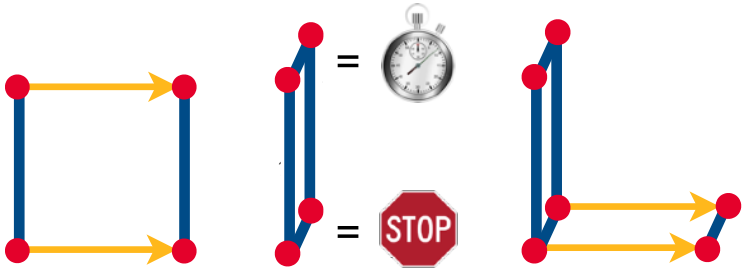

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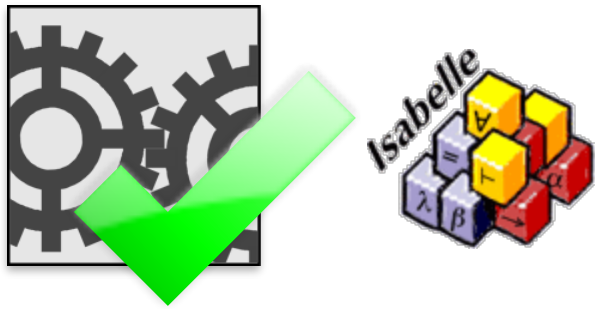

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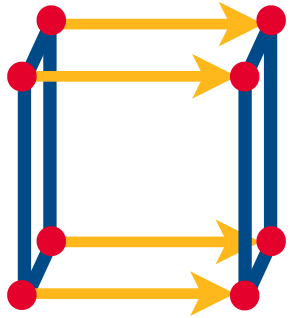

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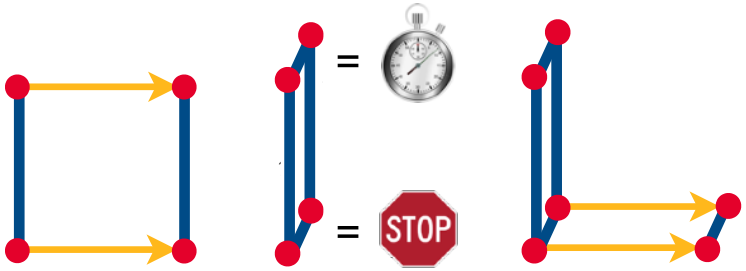

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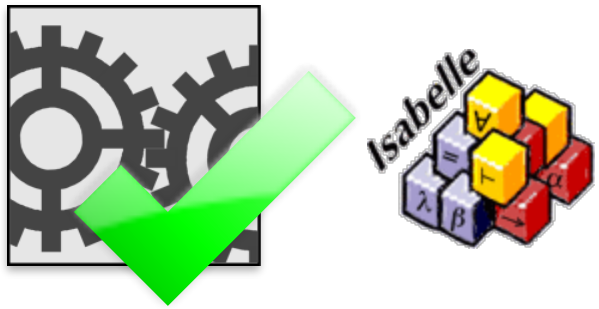

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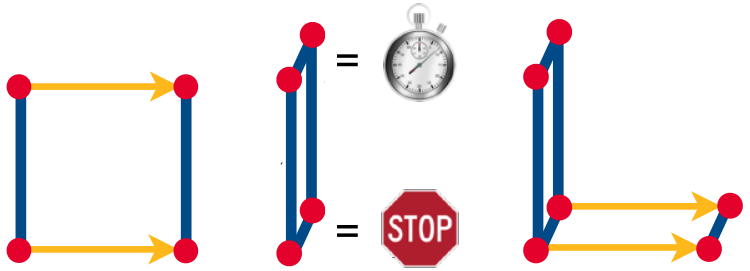
Goal

Prove a compiler *preserves proofs* of confidentiality — in an interactive theorem prover!

Results

1. Decomposition principle

for *confidentiality-preserving refinement*



(Technique)

2. Verified compiler

While-language to RISC-style assembly

(Proof-of-concept for technique)

(Formalisation: https://covern.org/itp19.html)

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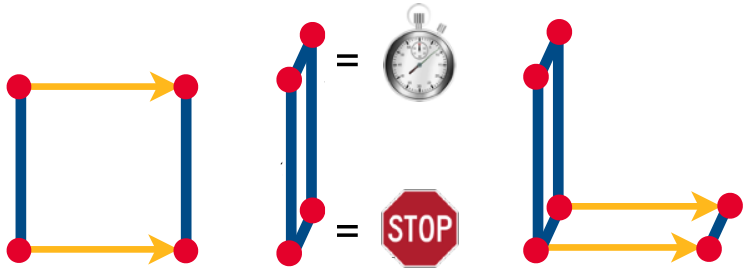

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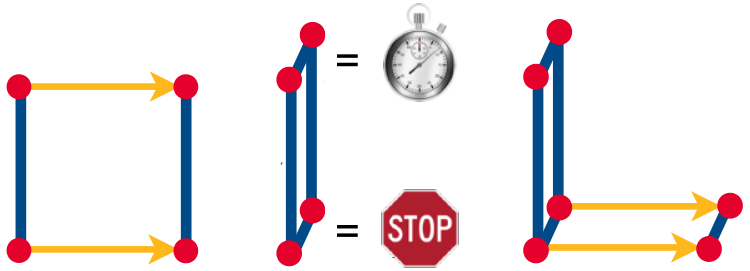

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Background: Murray et al. (CSF'16)
(Why *still* hard?)

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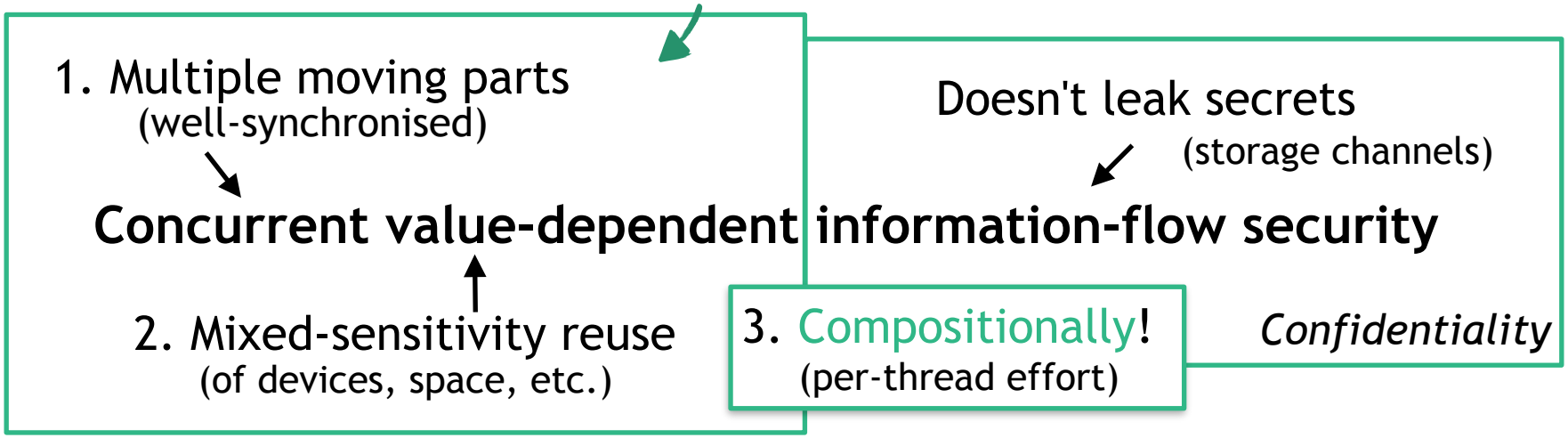

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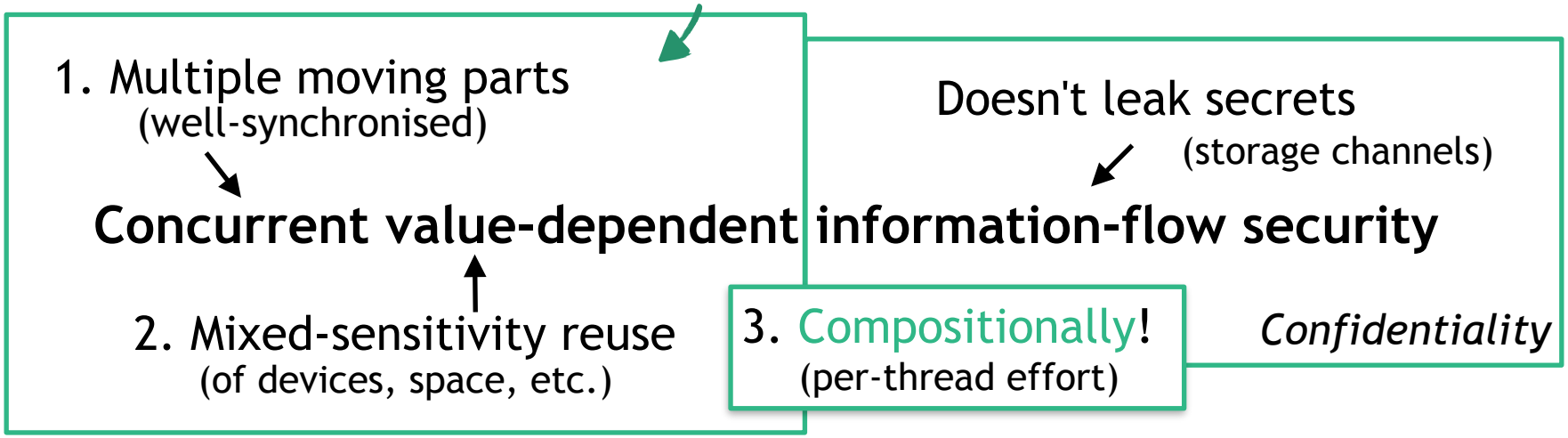

Beaumont et al.
(ACSAC'16)

Example

(DSTG + Data61 collaboration)

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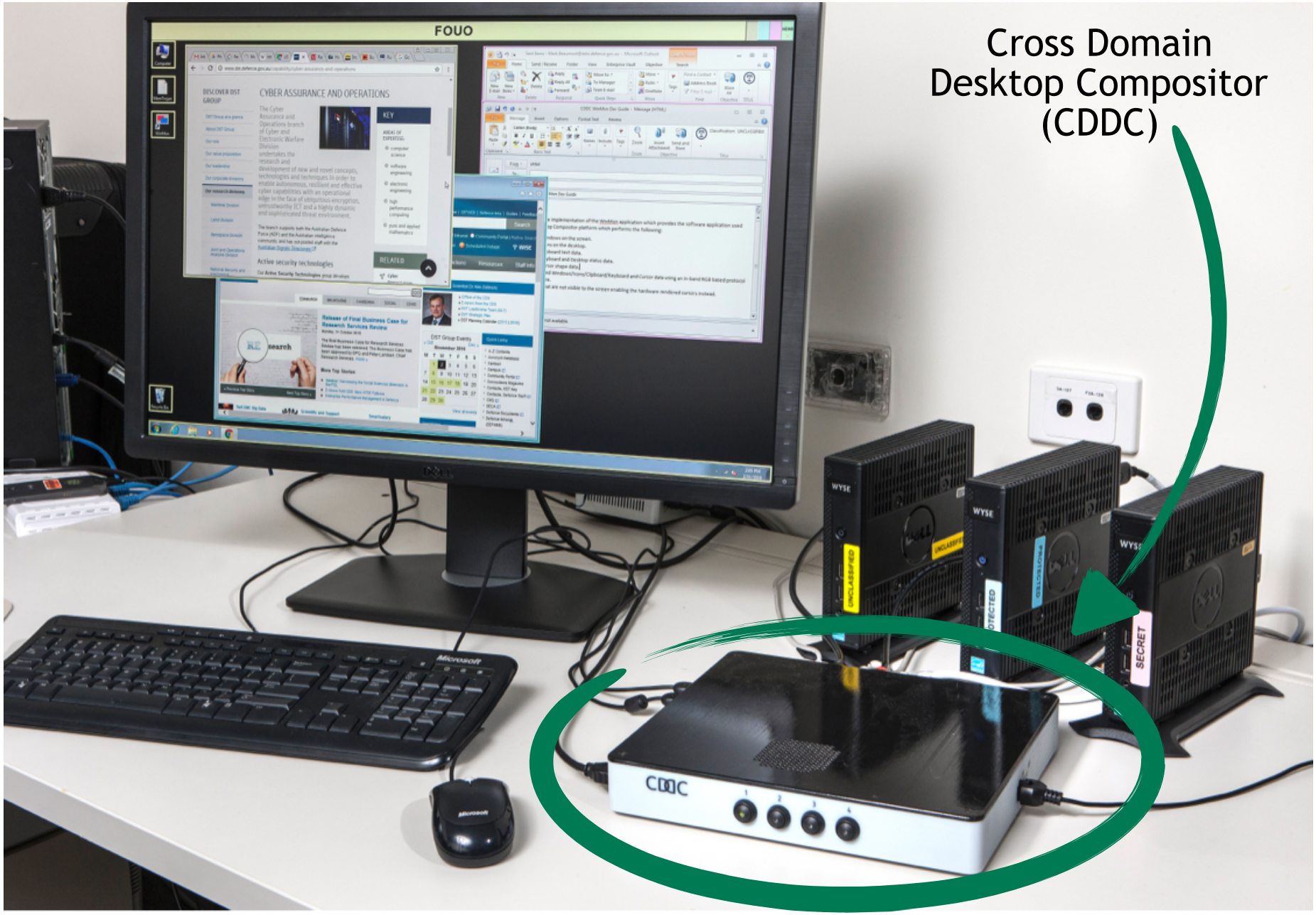
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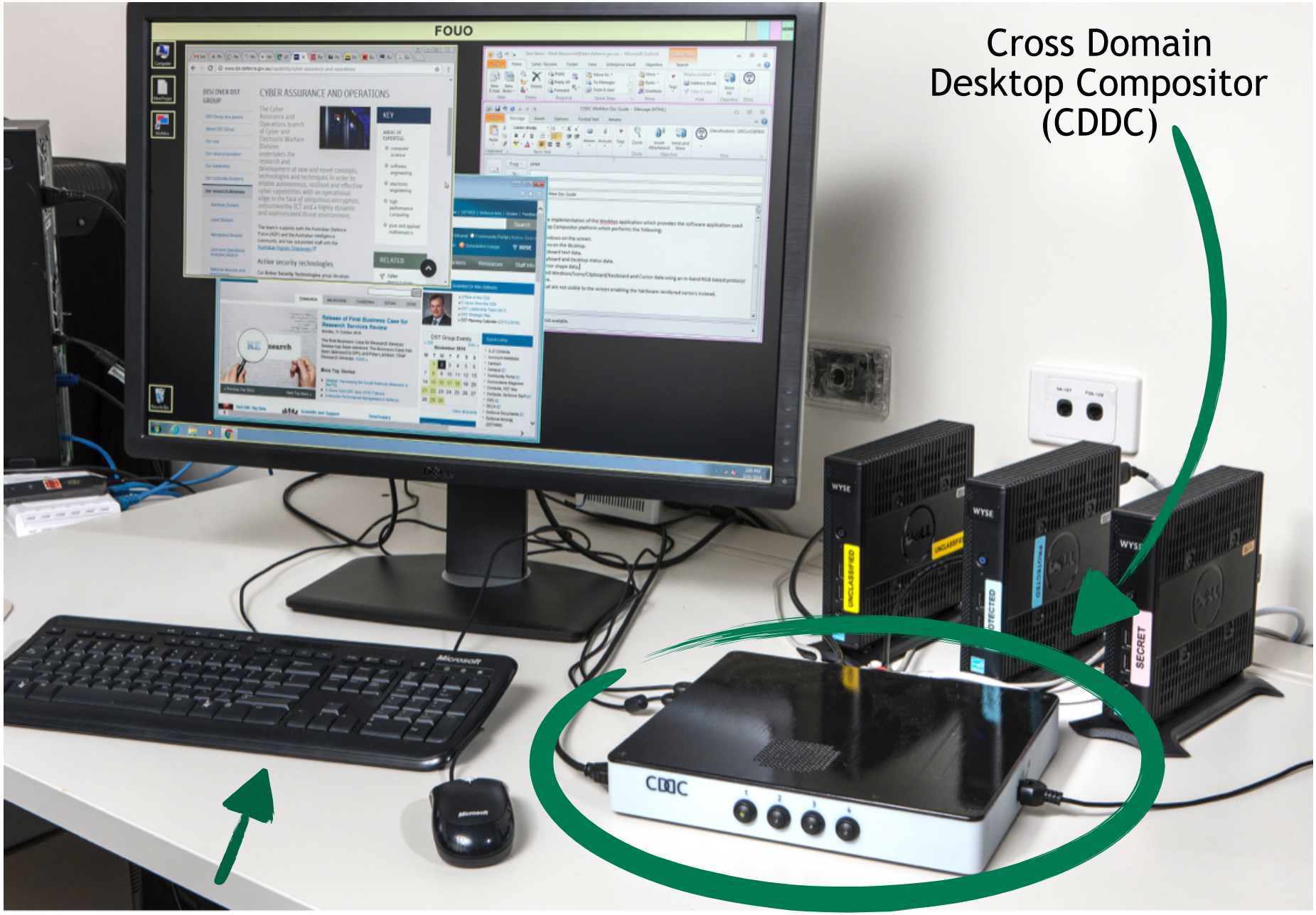
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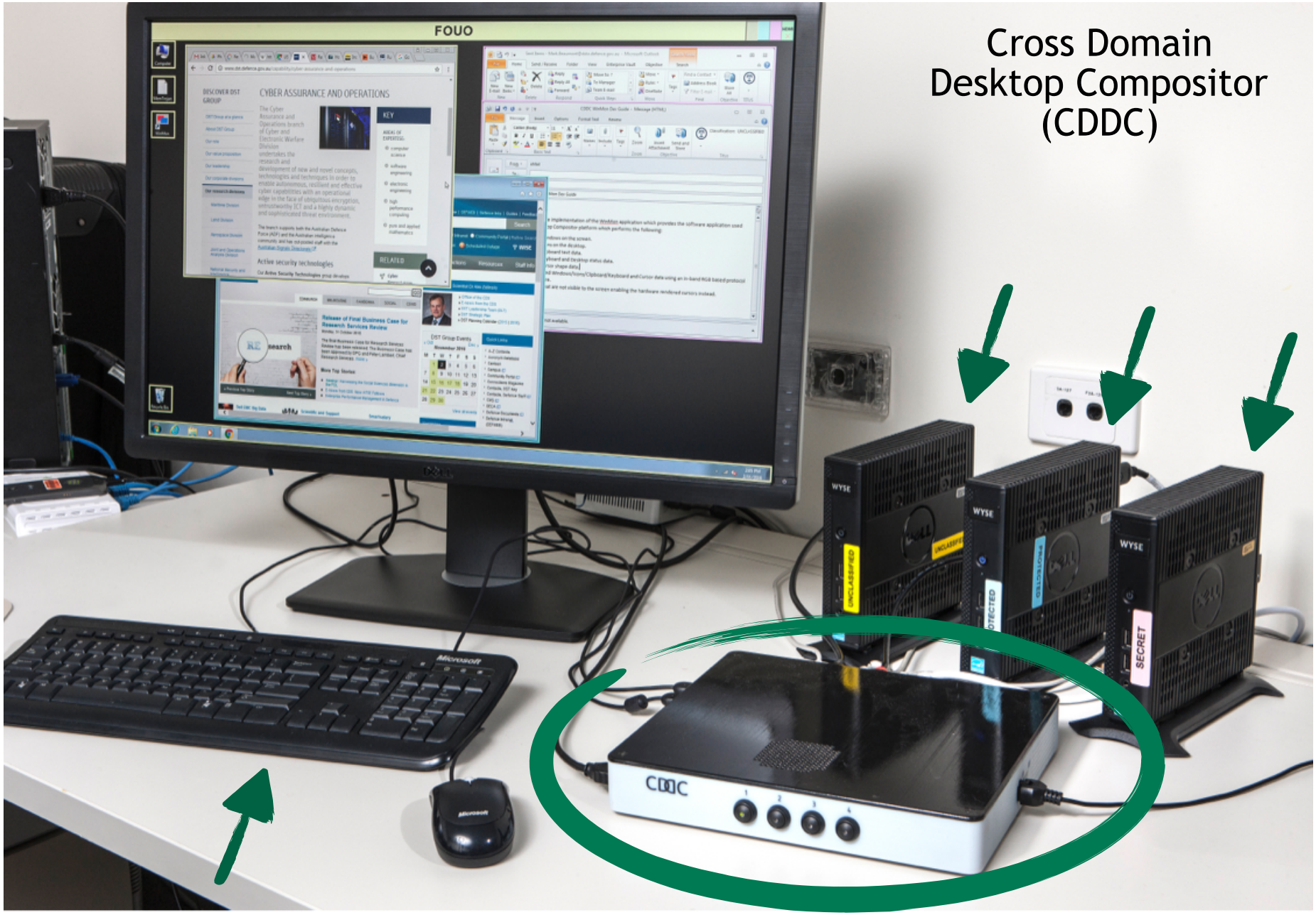
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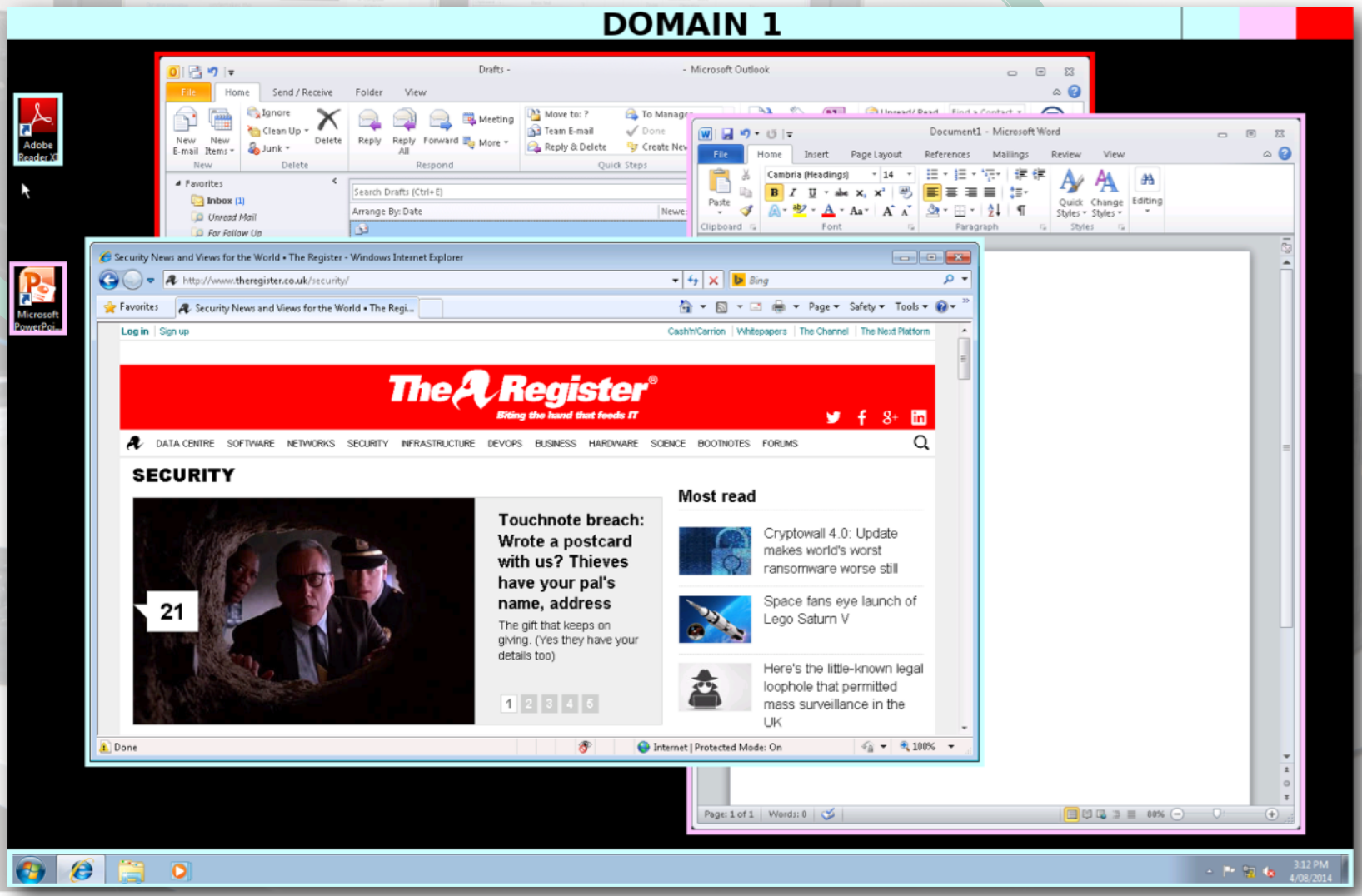

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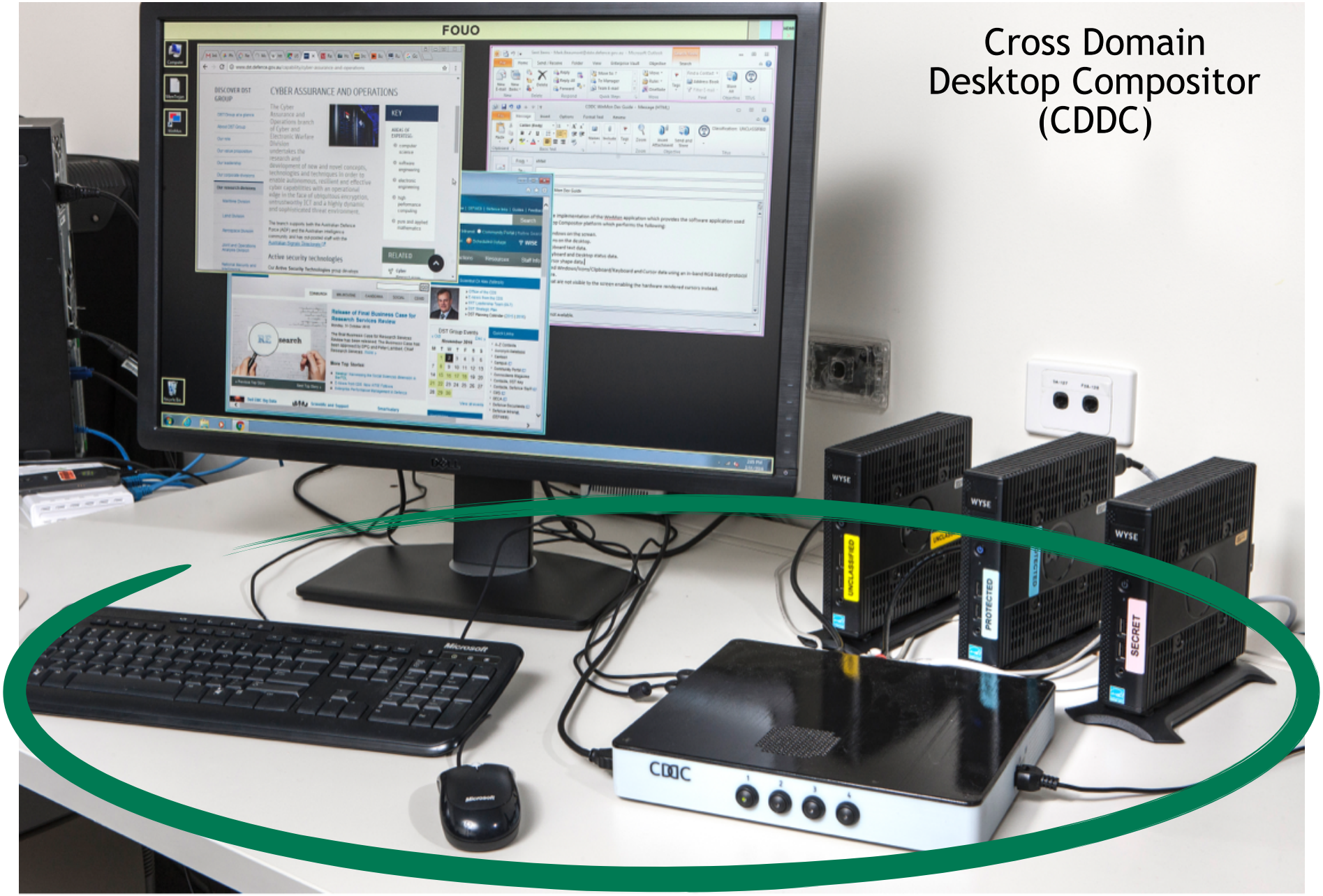

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Concurrent **value-dependent information-flow security**

2. Mixed-sensitivity reuse
(of devices, space, etc.)

Doesn't leak secrets
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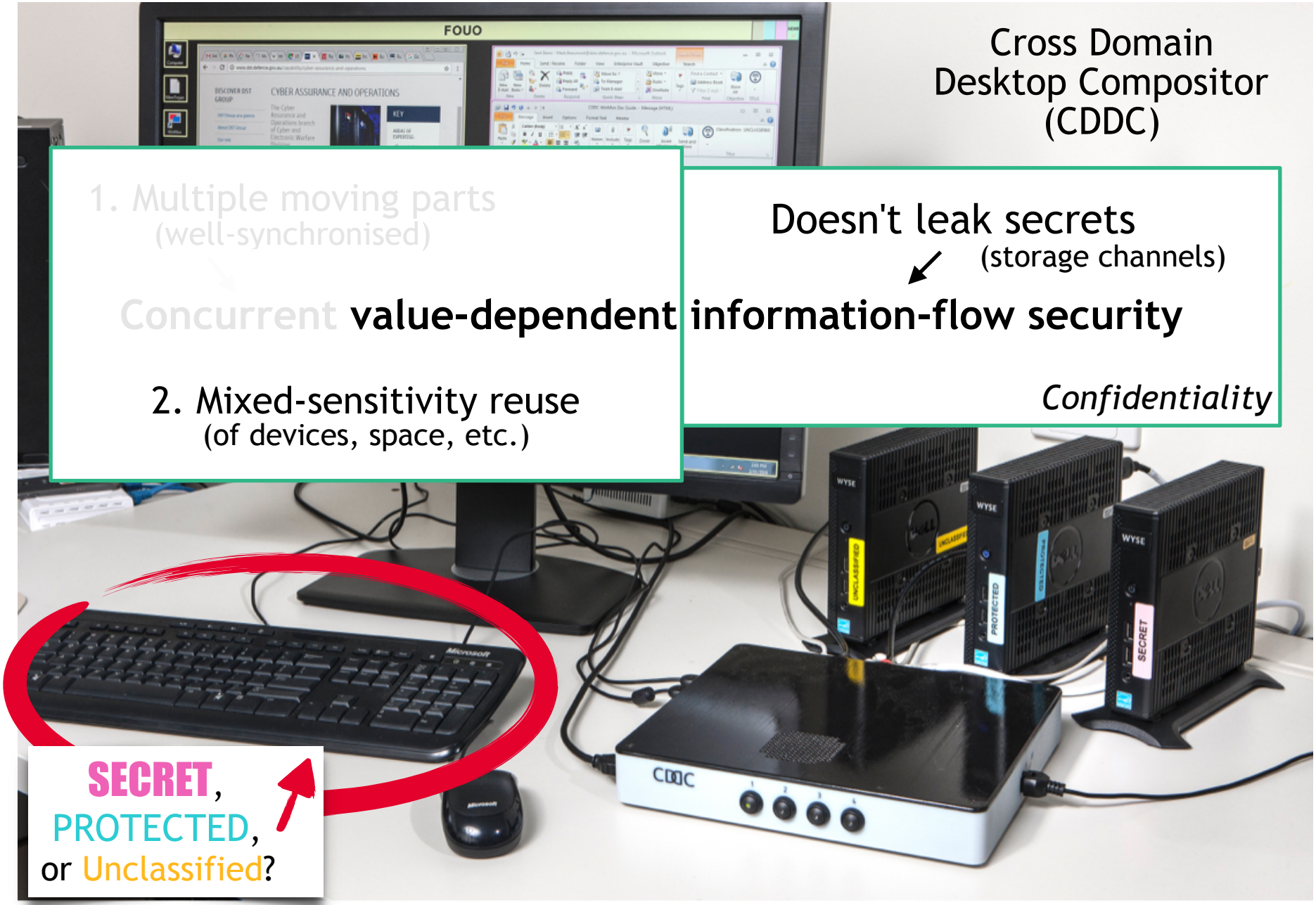

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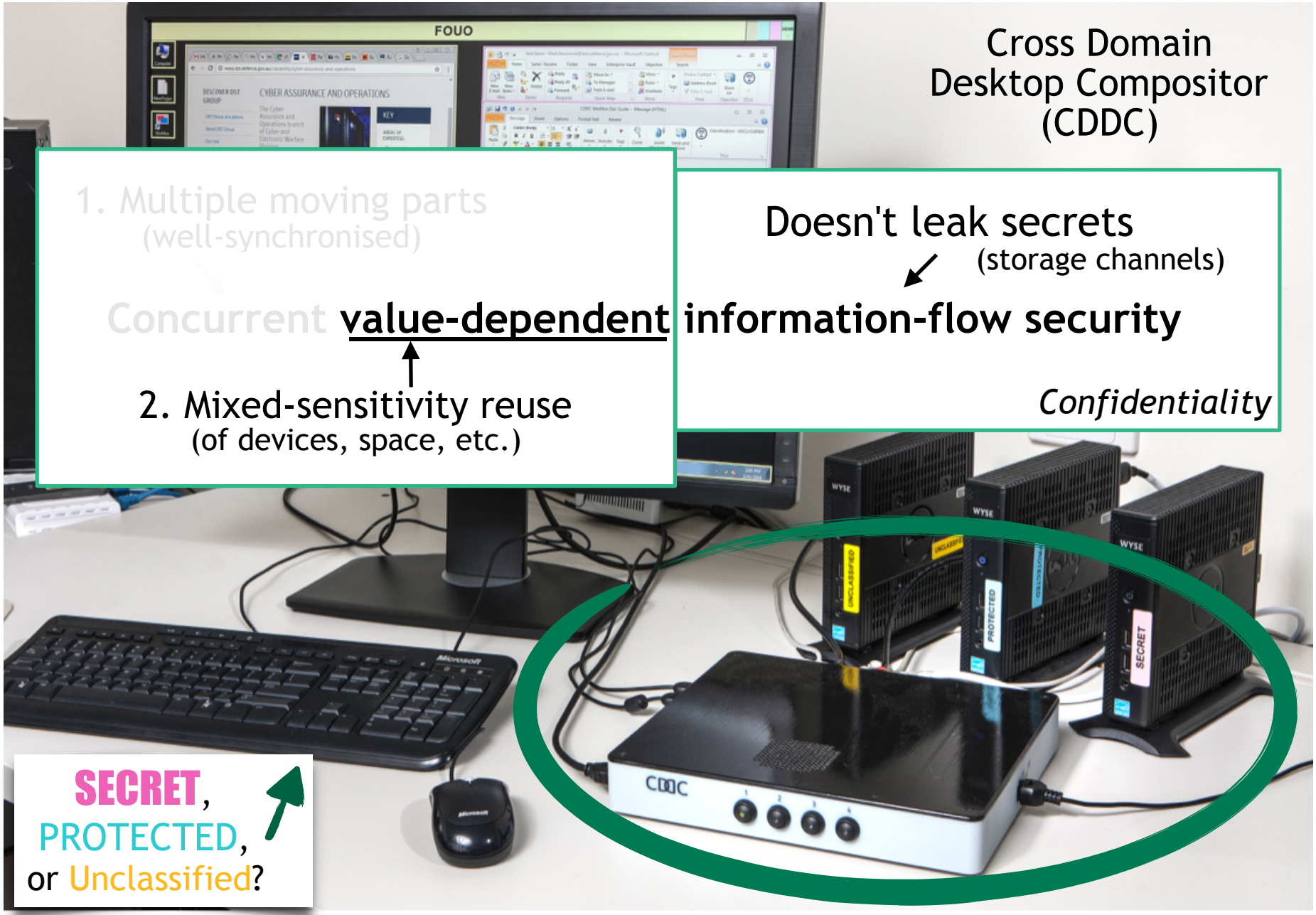

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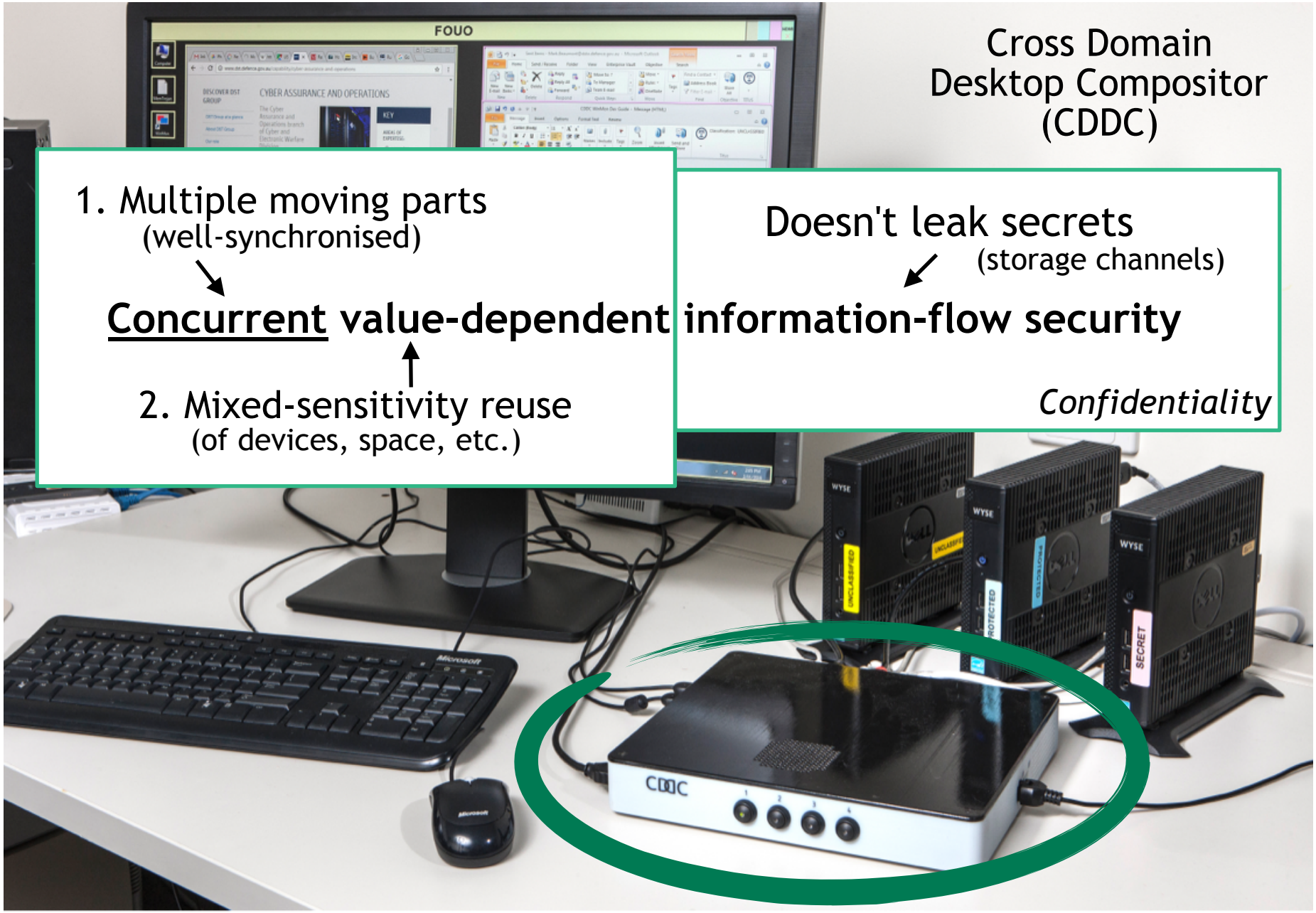

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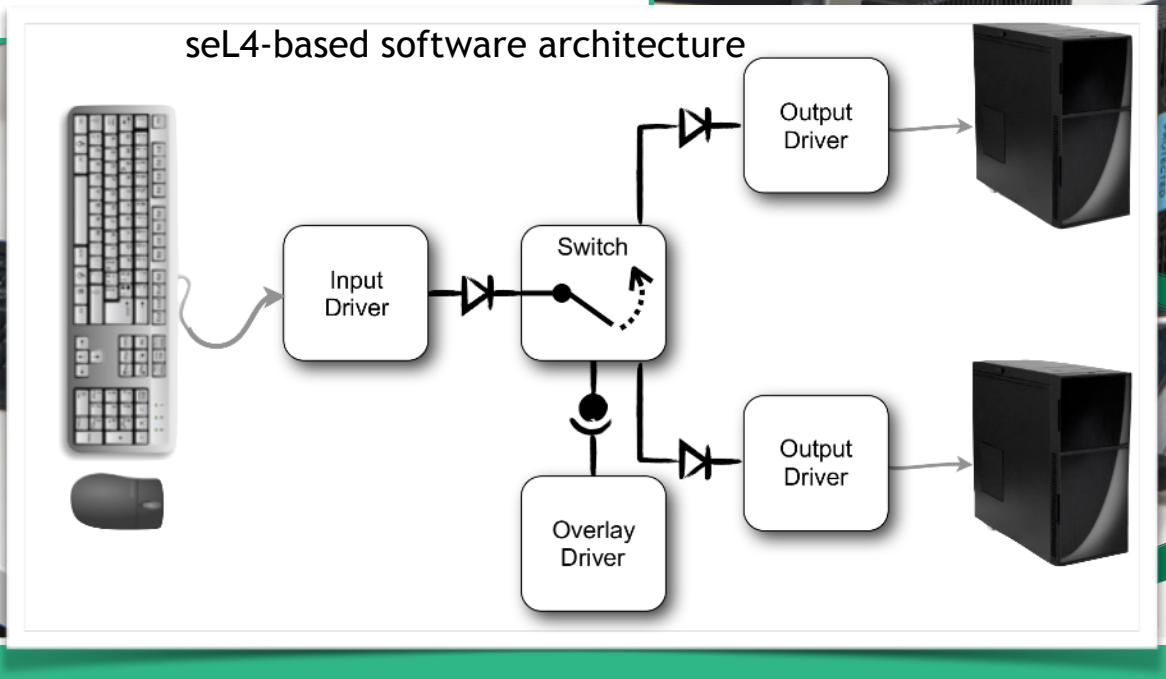

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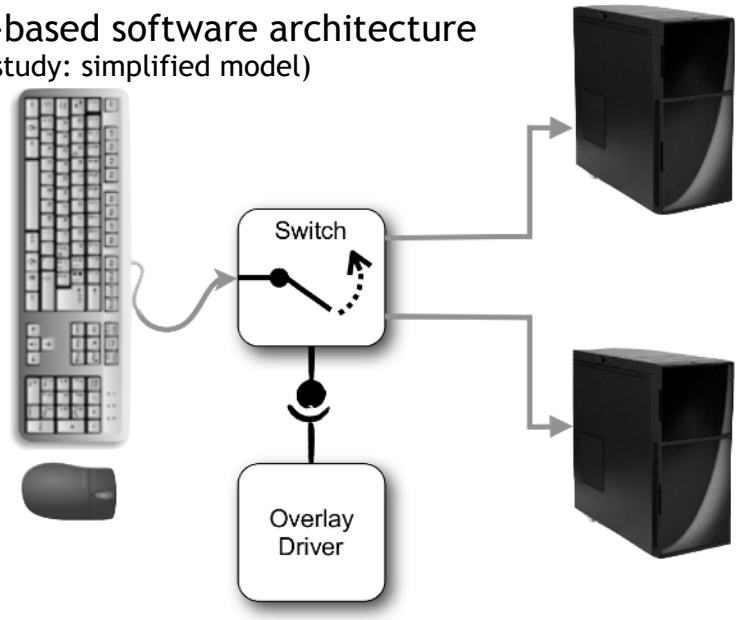
(Case study: simplified model)



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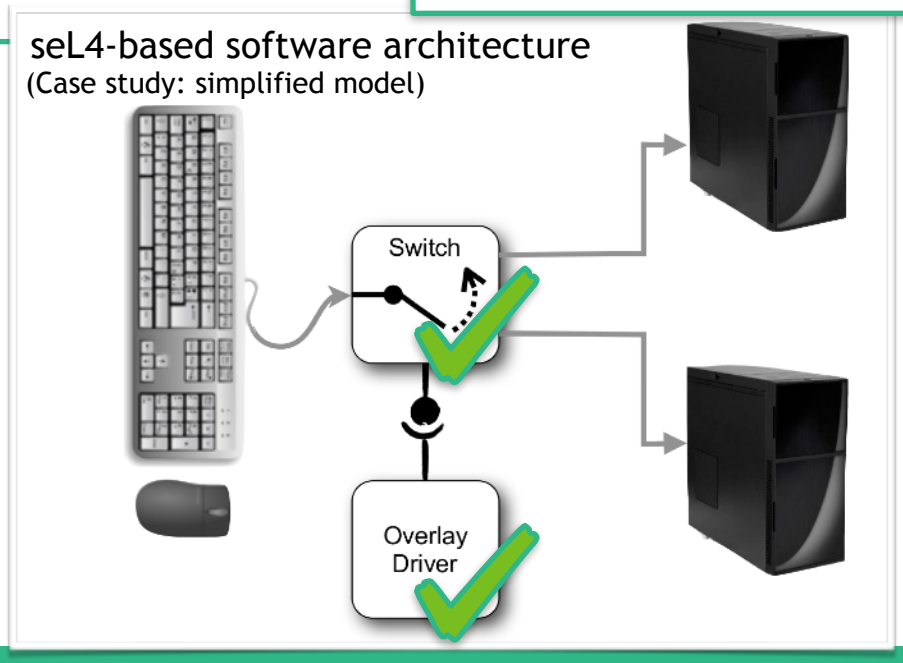

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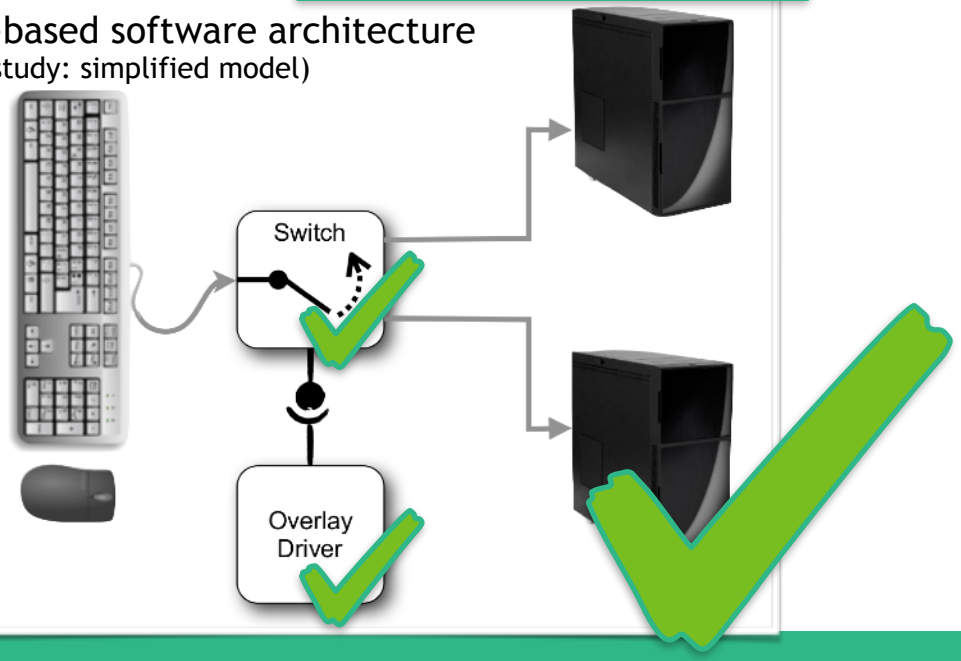

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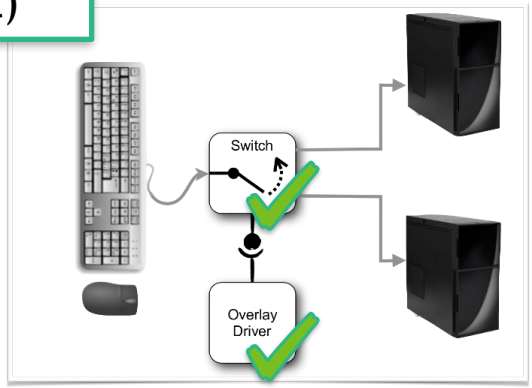

Can a compiler preserve it?

Motivation

Why wouldn't a compiler preserve it? (CSF'16)

Concurrent value-dependent information-flow security

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Murray et al. CSF'16

control variable contents
(*sensitivity-switching*)

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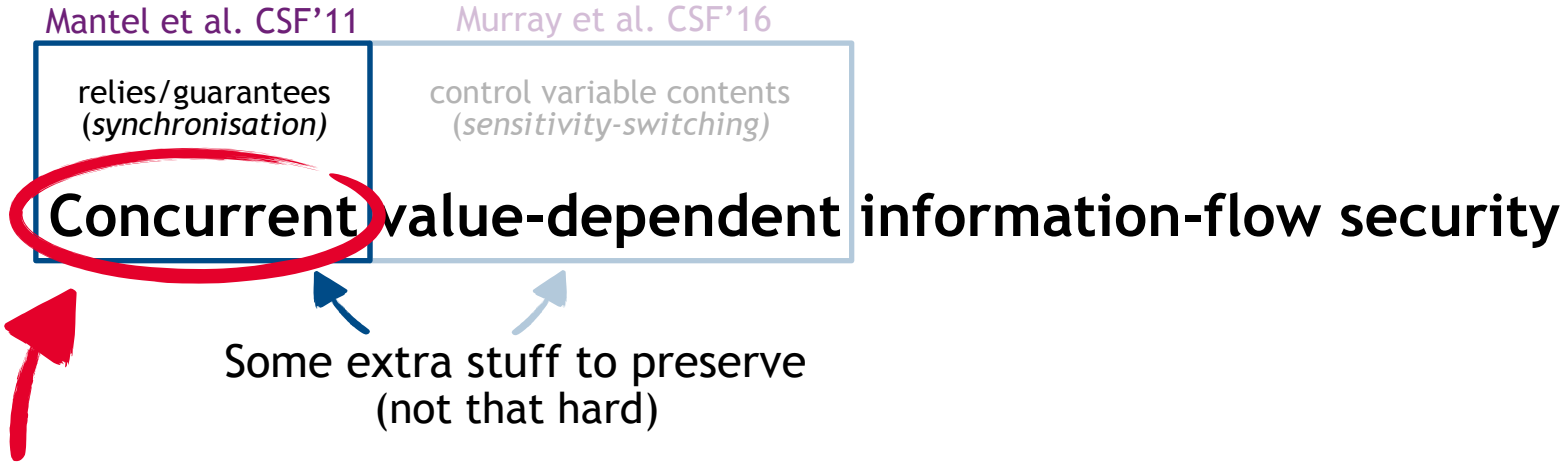

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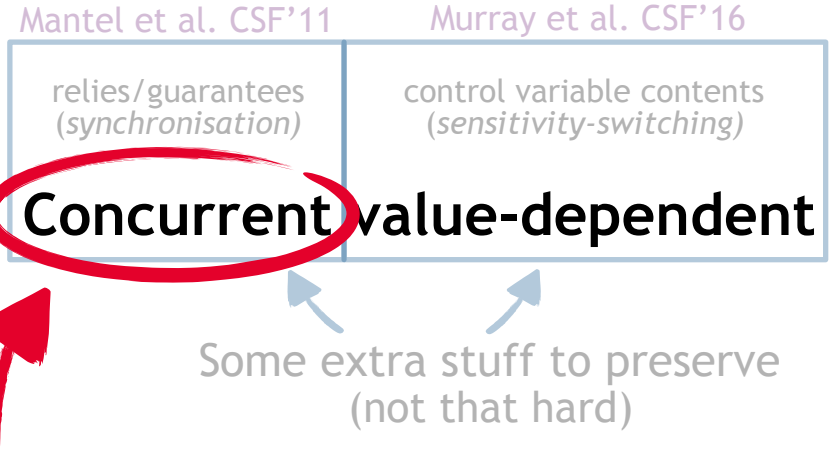

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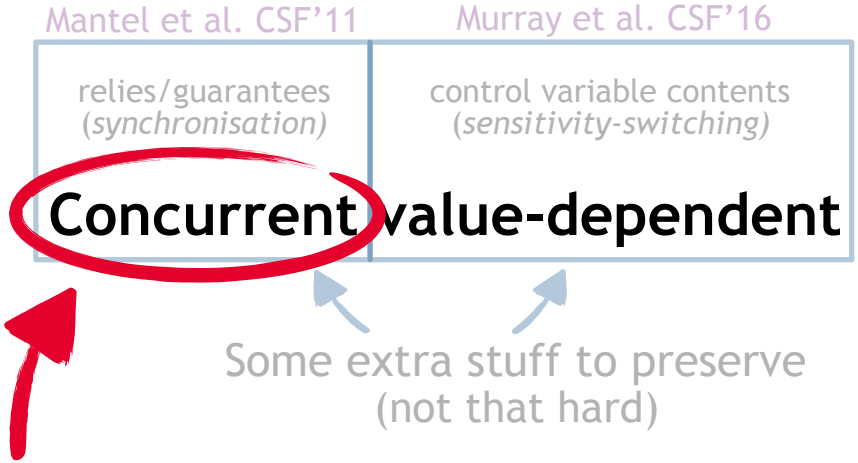

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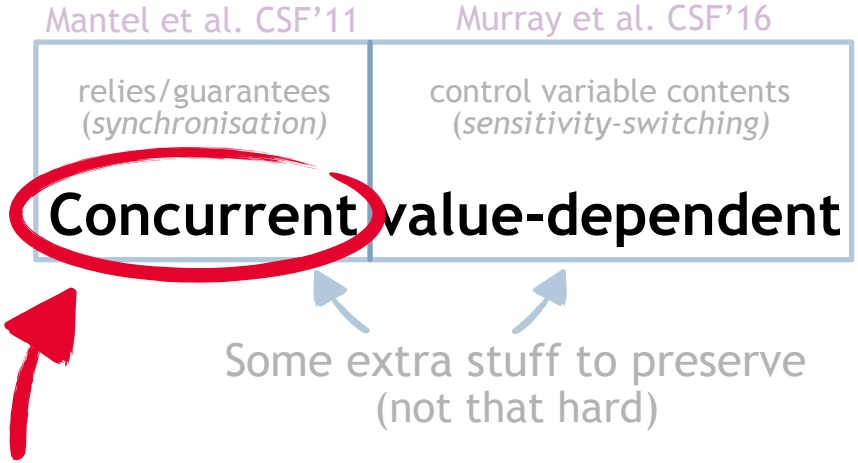

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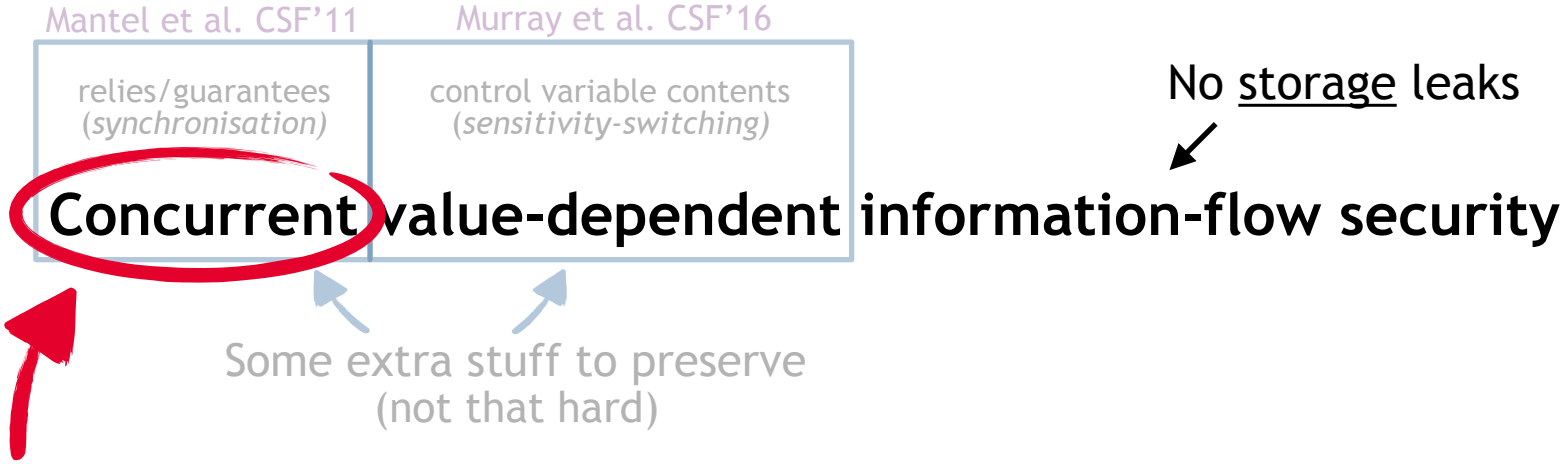

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Minimal example:

Program A

```
// Initially, v = 0
if (h) then
  skip
else
  skip; skip
fi
v := 1
```

Program B

```
l := v
```

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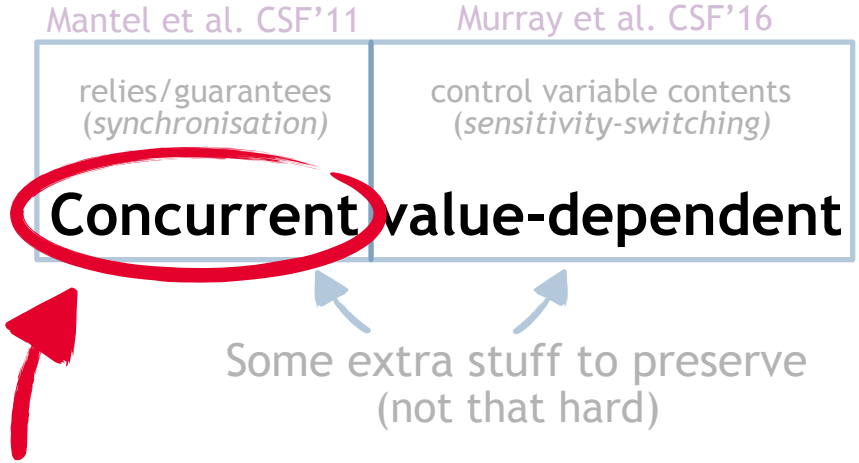

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Minimal example:

Program A

```
// Initially, v = 0
if (h) then
  skip
else
  skip; skip
fi
v := 1
```

✓ h isn't assigned to anything

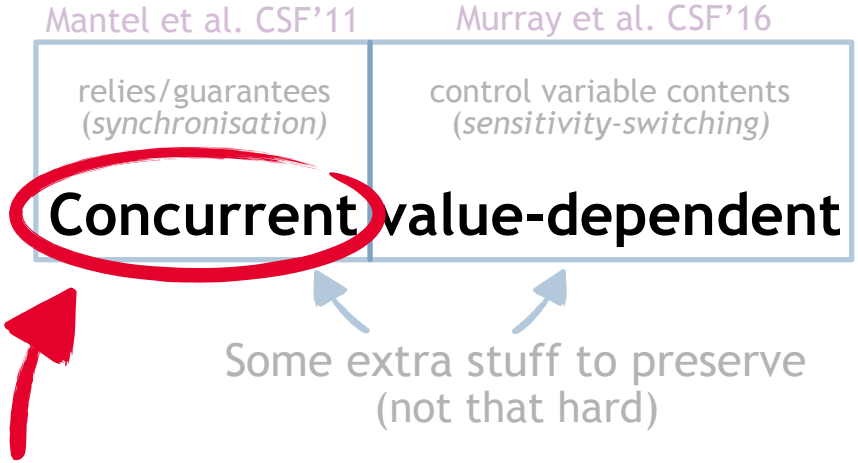
Program B

```
l := v
```

✓ h isn't even here!

Motivation

Why wouldn't a compiler preserve it? (CSF'16)



No storage leaks ✓

This particularly makes it harder!

Interference-resilience (tricky)

+

Each thread must prevent (scheduler-relative) timing leaks!

Volpano & Smith, CSFW'98

Minimal example:

Thread A		Thread B
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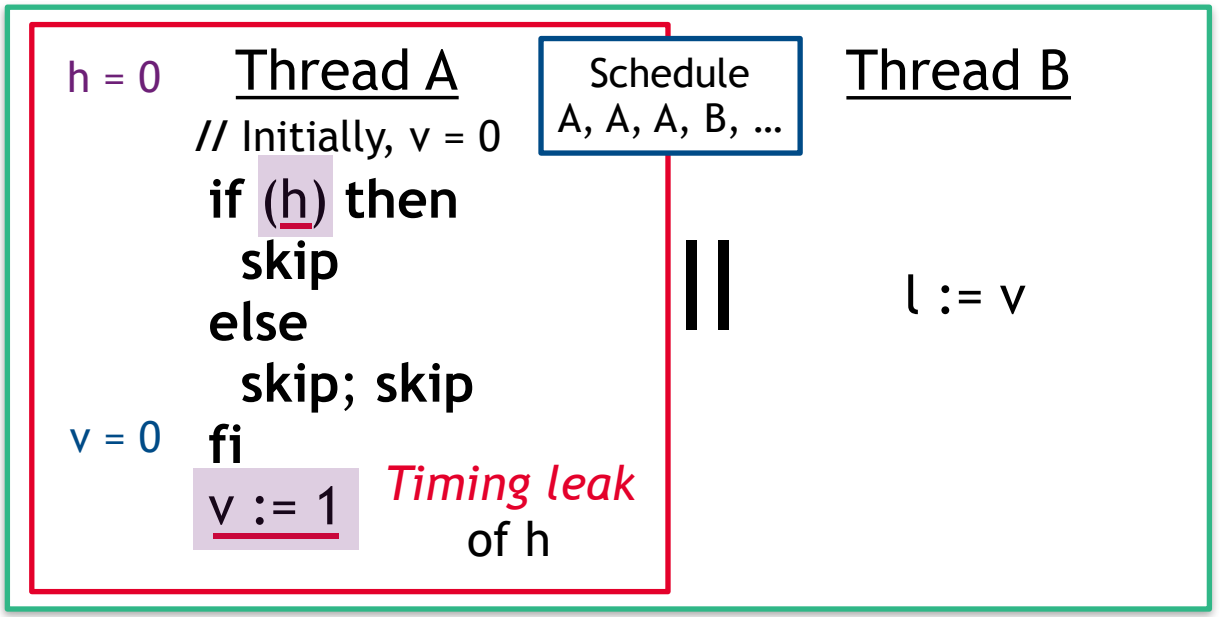

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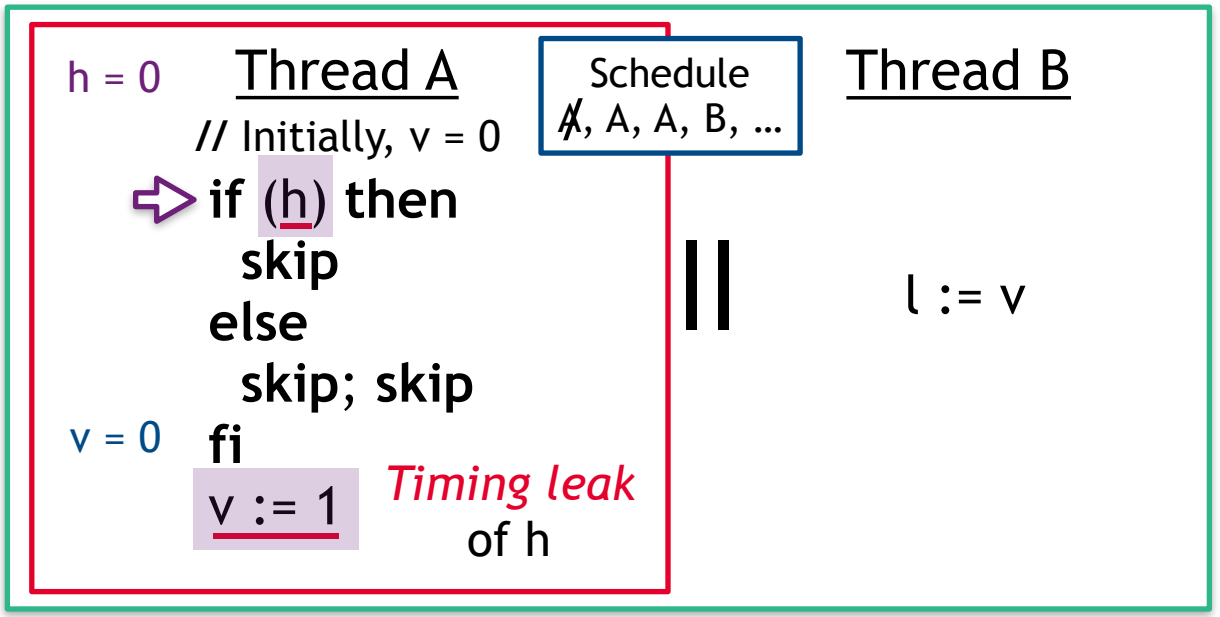

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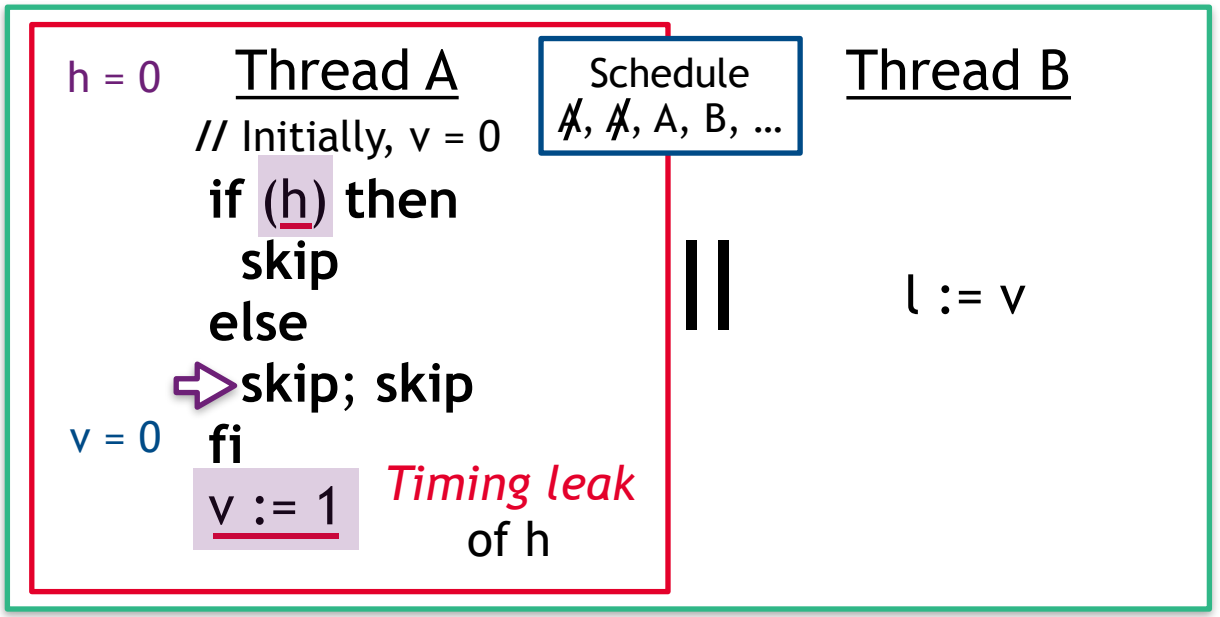

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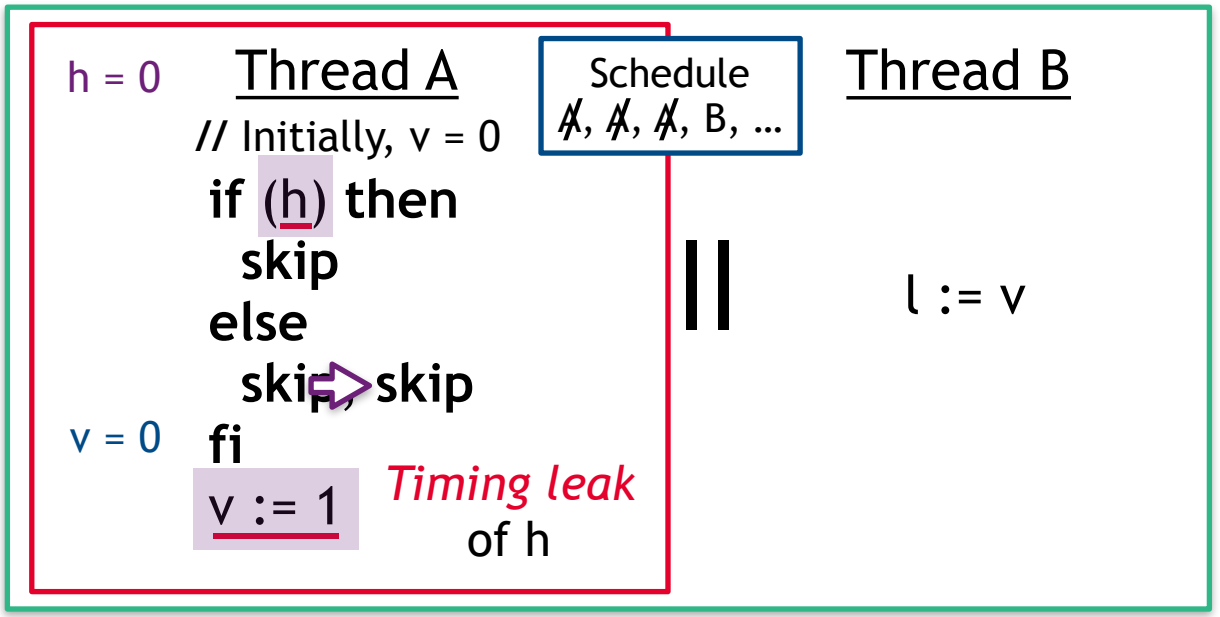

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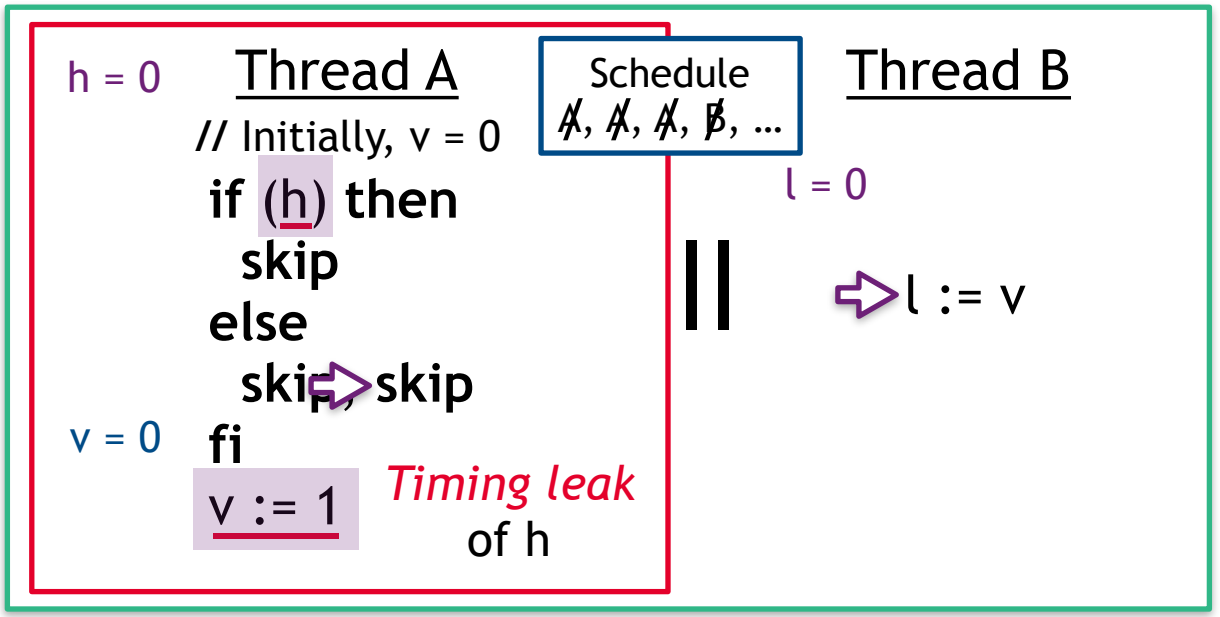

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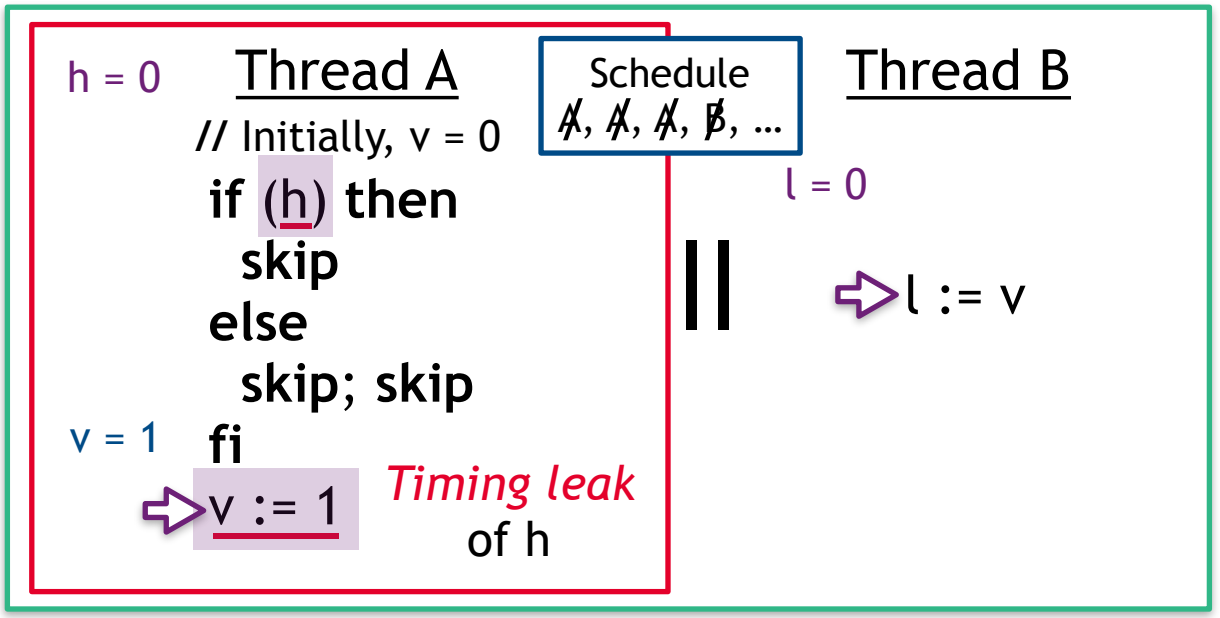

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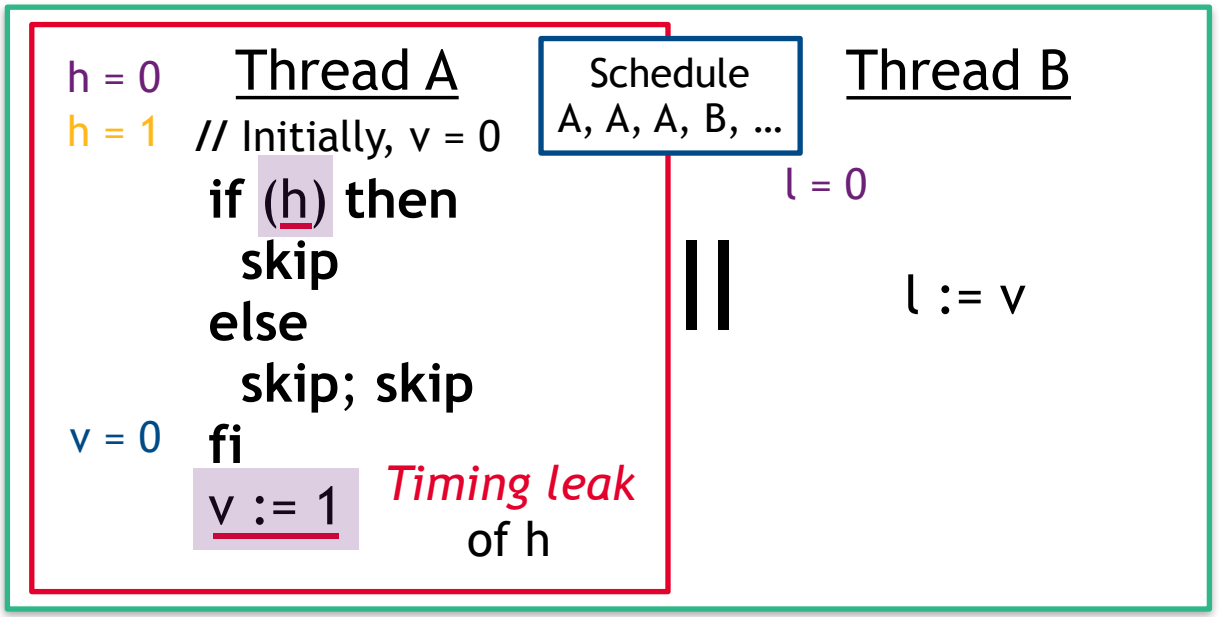

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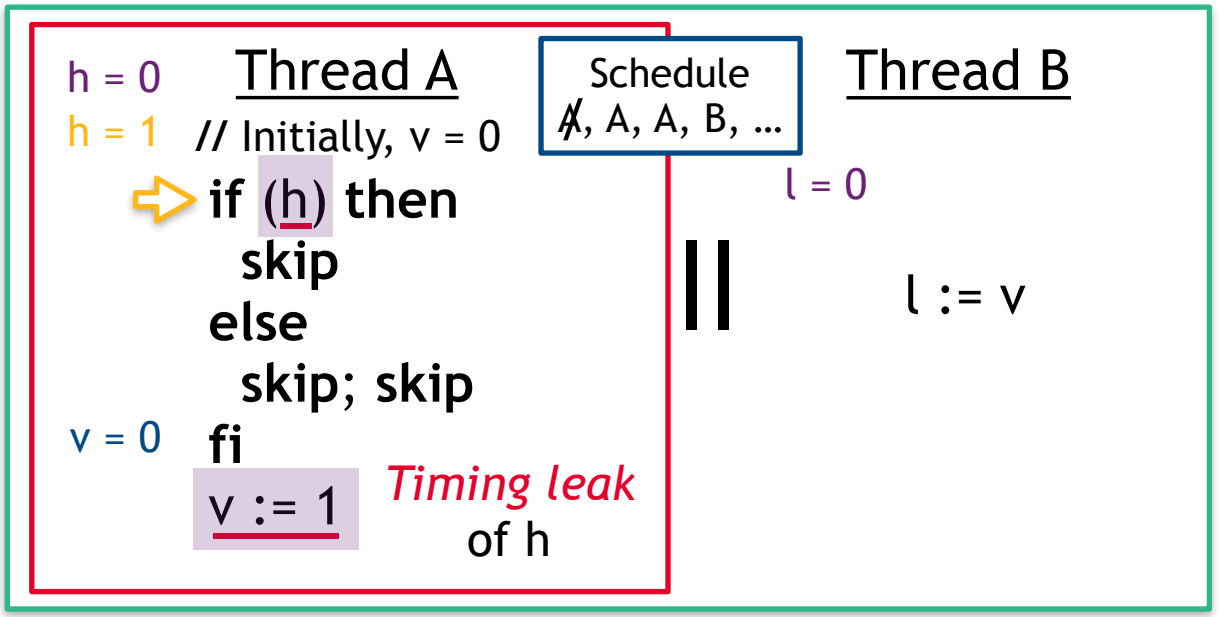

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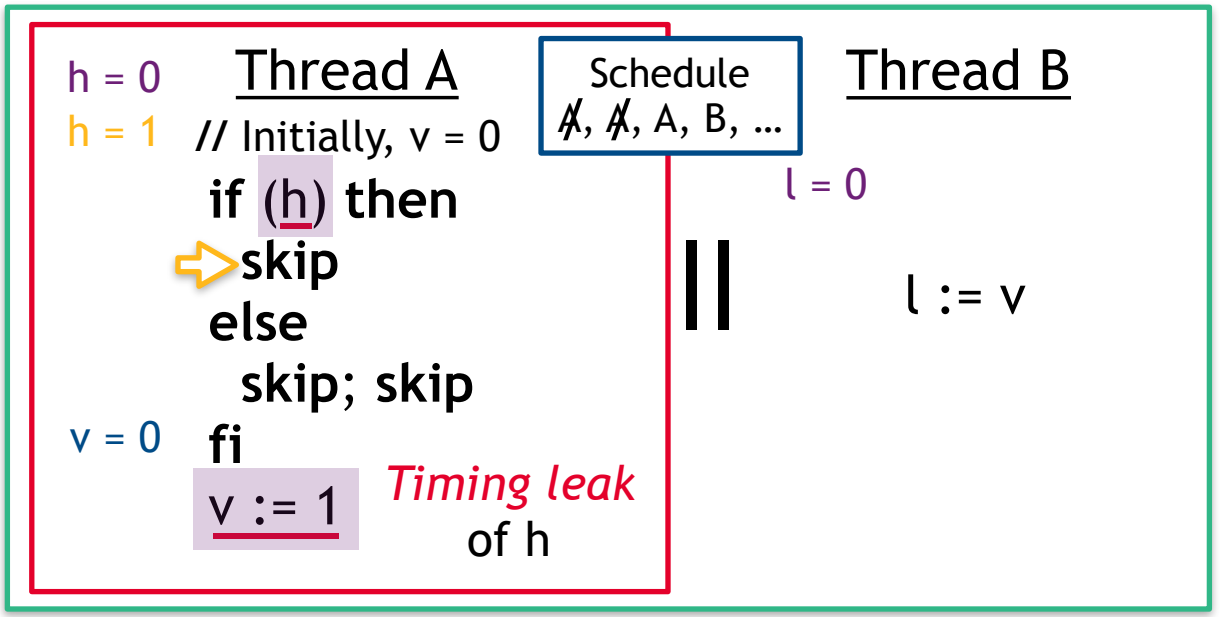

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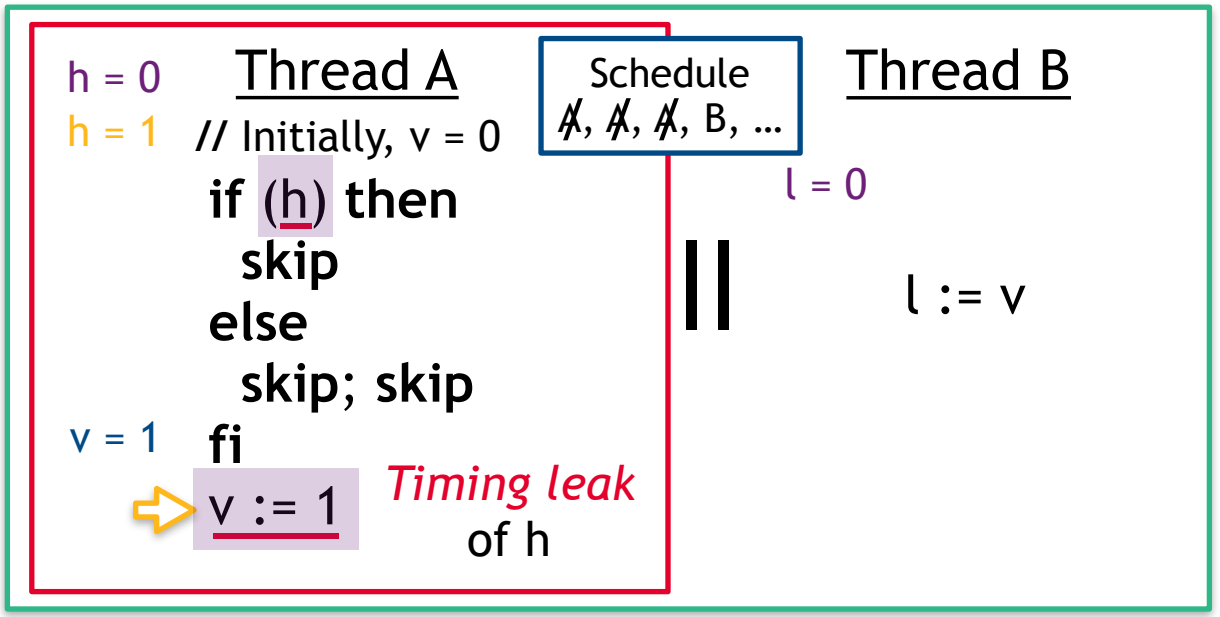

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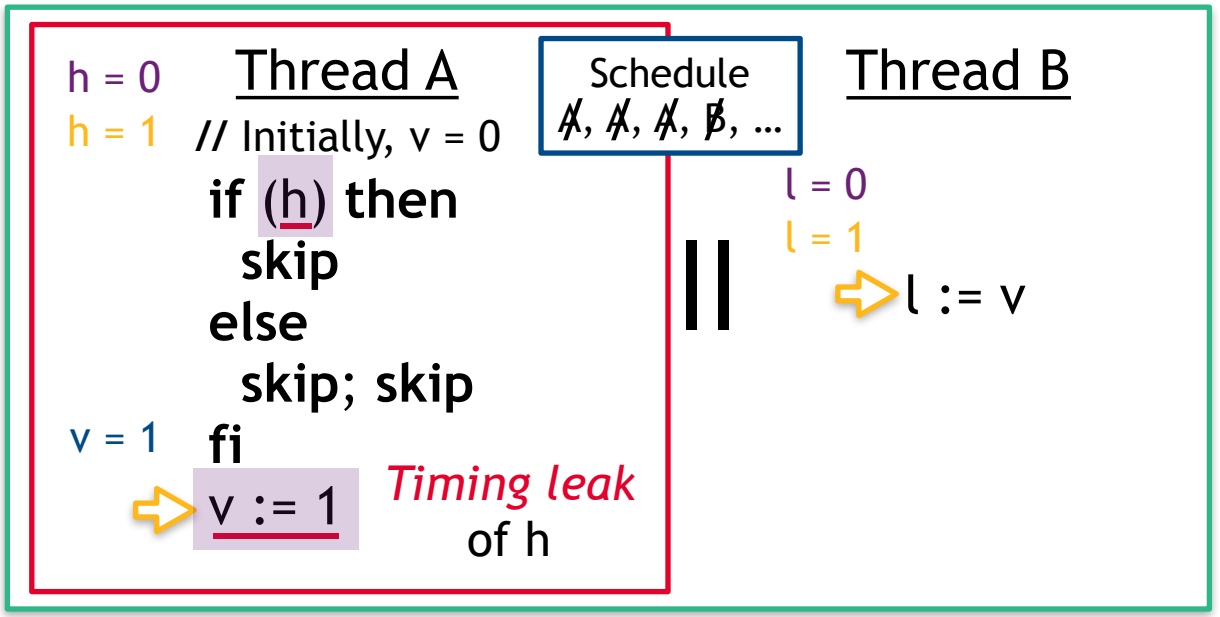

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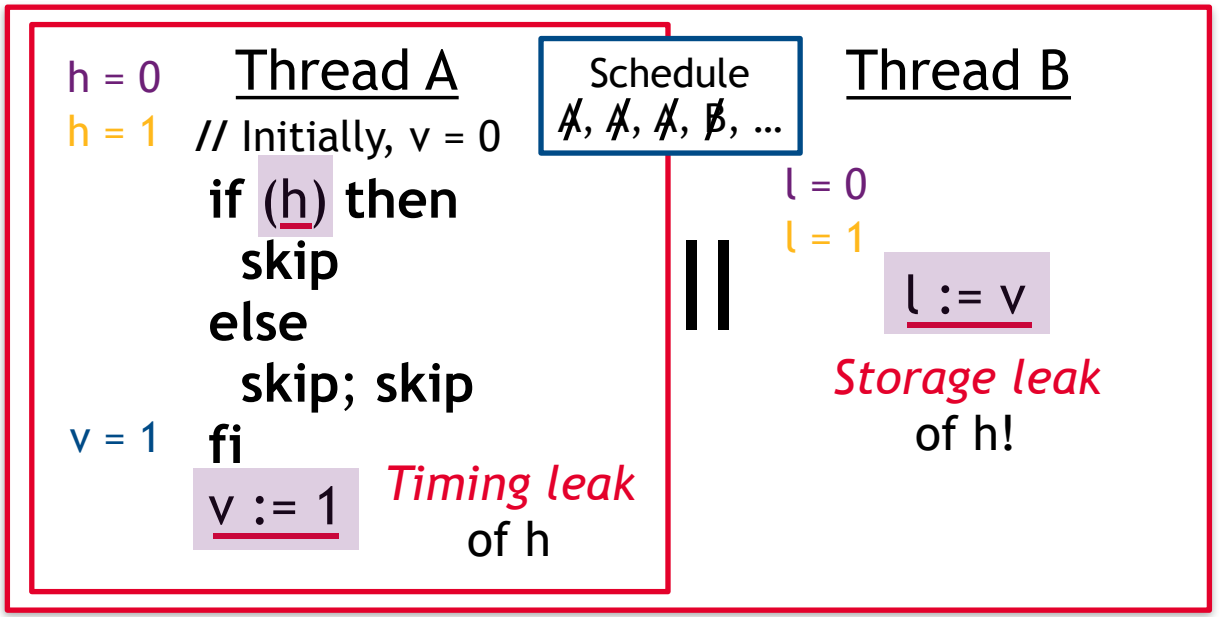

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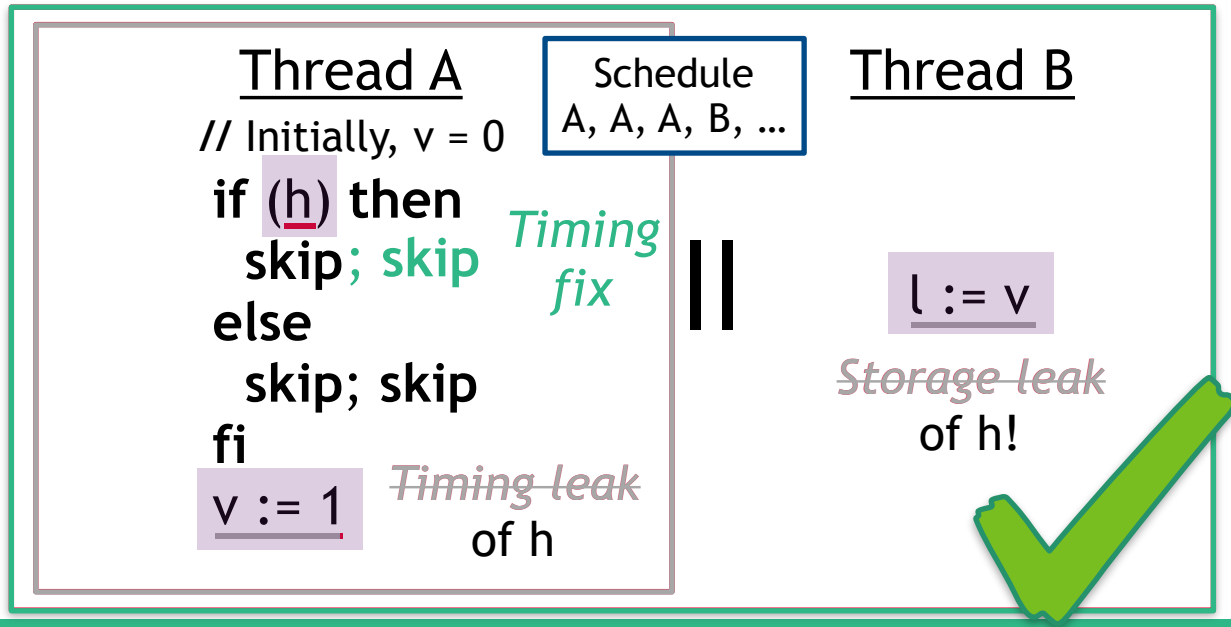

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But: Compiler may eliminate it!

This particularly makes it harder!

Interference-resilience (tricky)

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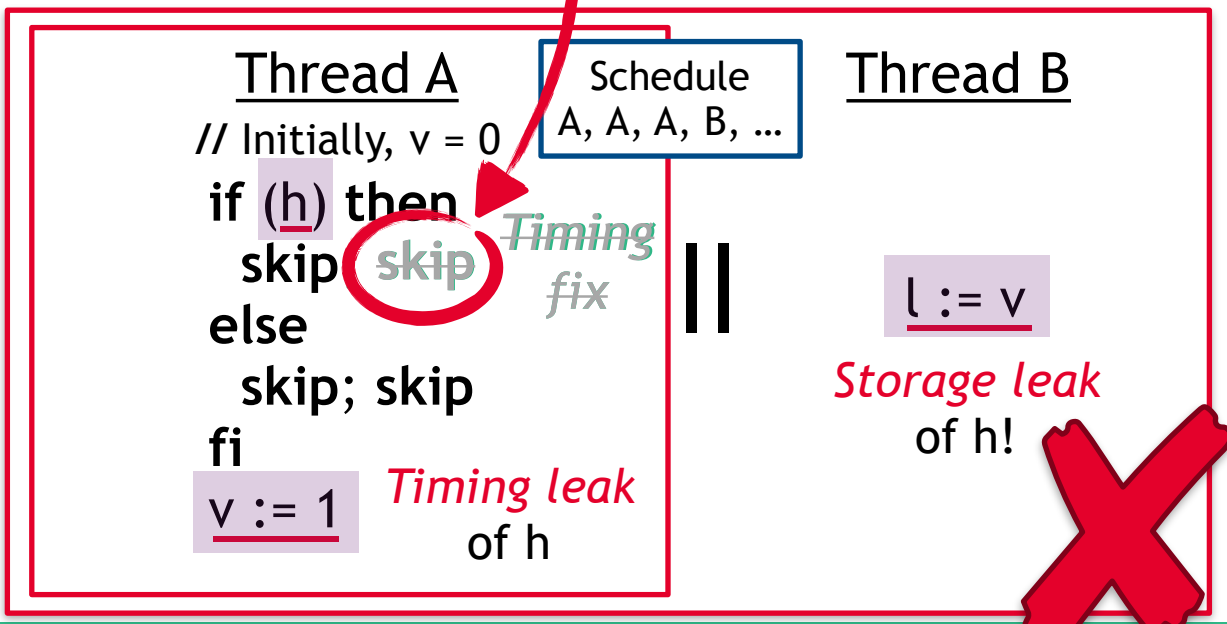

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But: Compiler may eliminate it!

(or, introduce *new* "**if** (h)"!)

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Interference-resilience (tricky)

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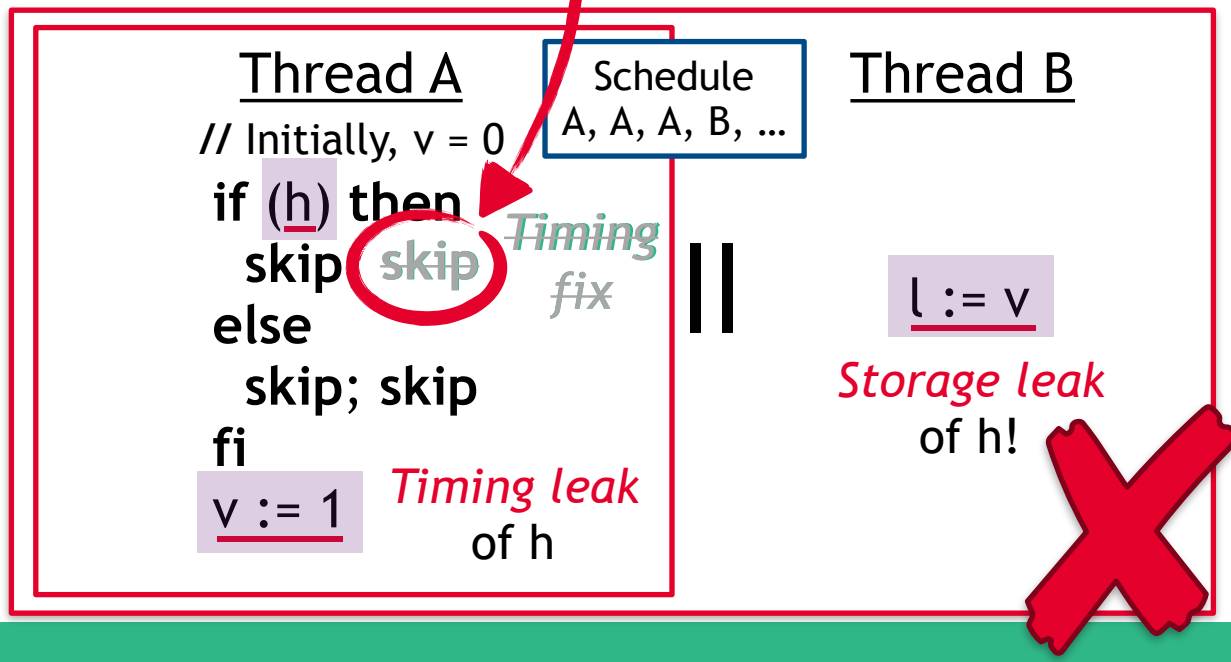
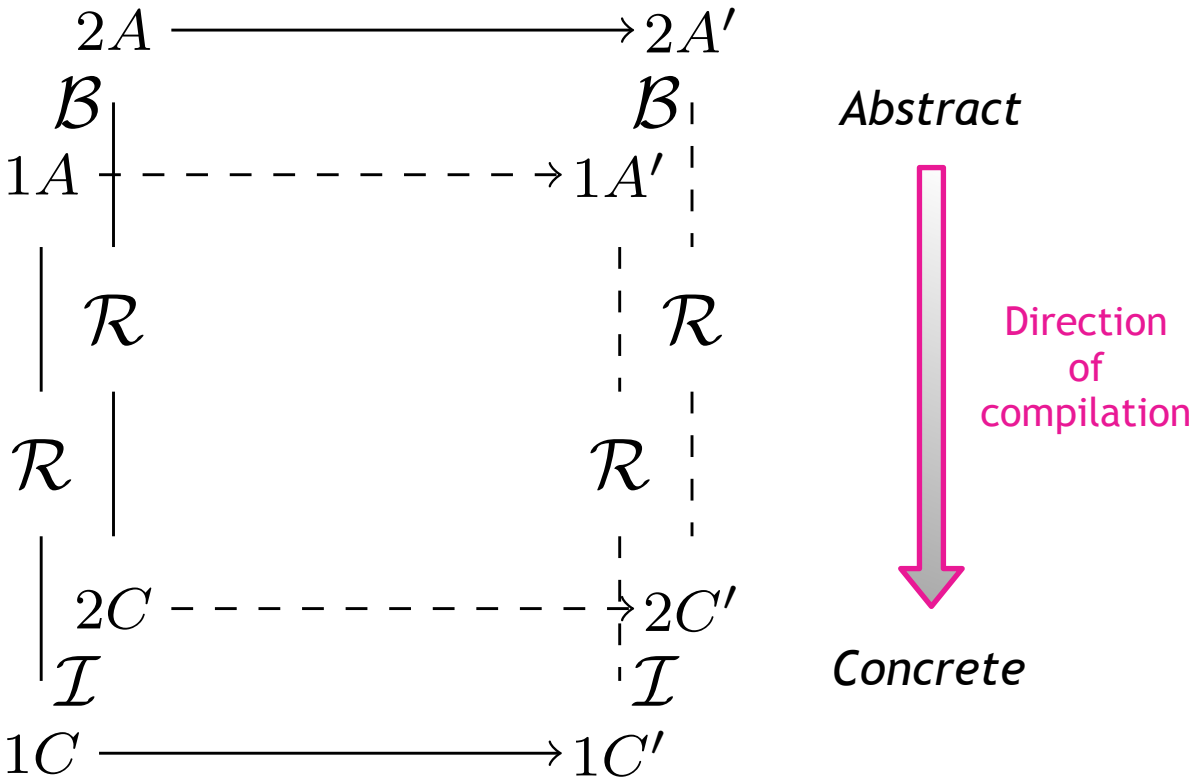


Background

Why is it hard to prove? (CSF'16)

Concurrent value-dependent information-flow security

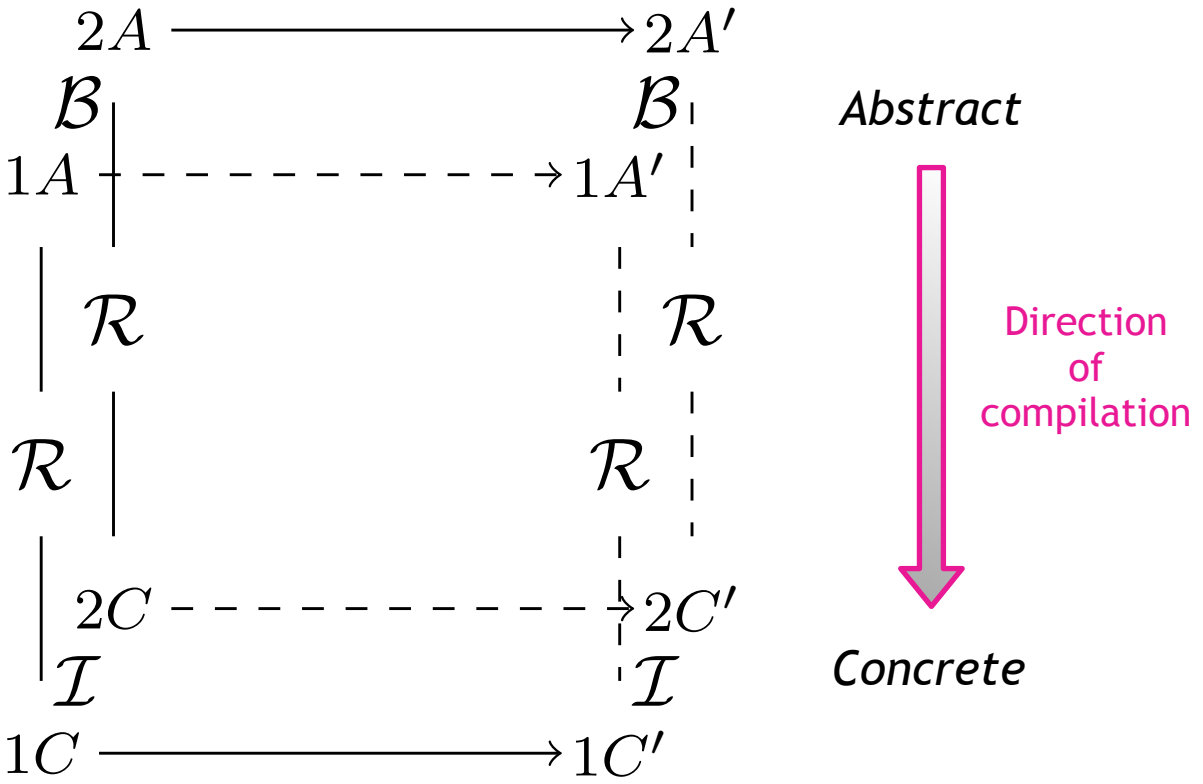
-preserving refinement



Background

Why is it hard to prove? (CSF'16)

Confidentiality-preserving refinement



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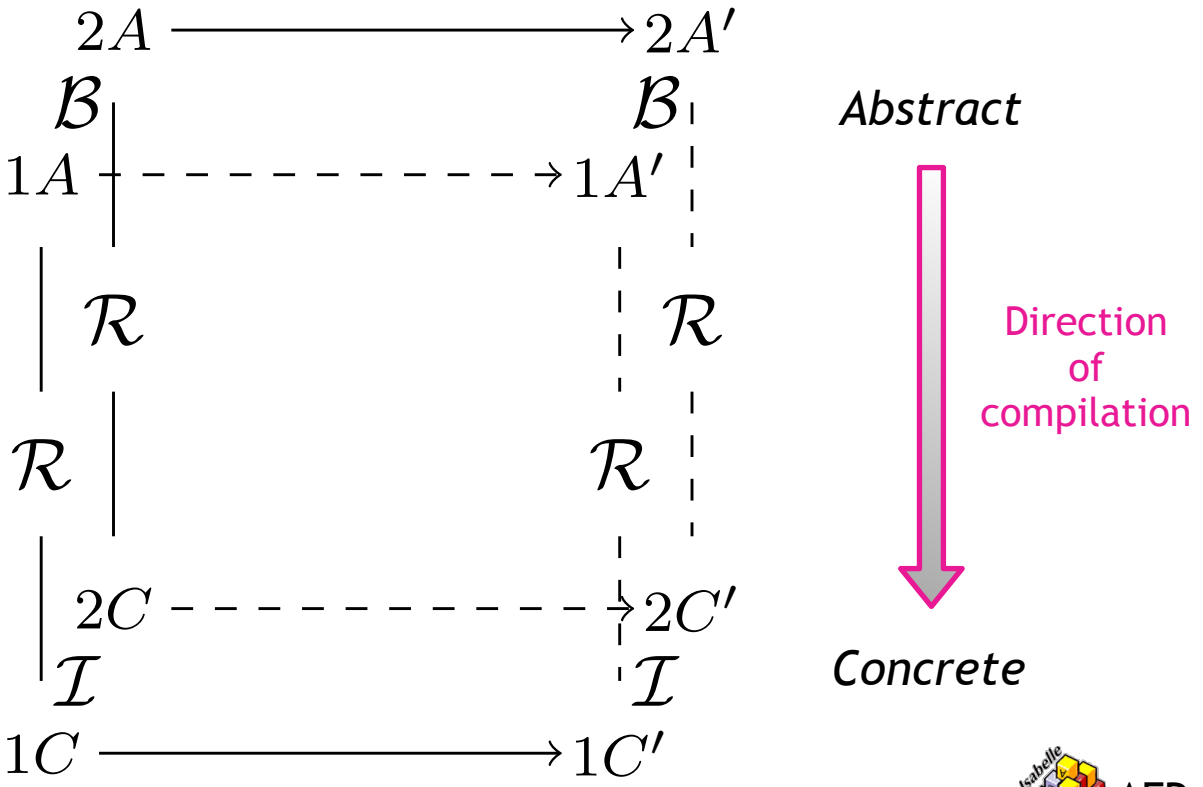
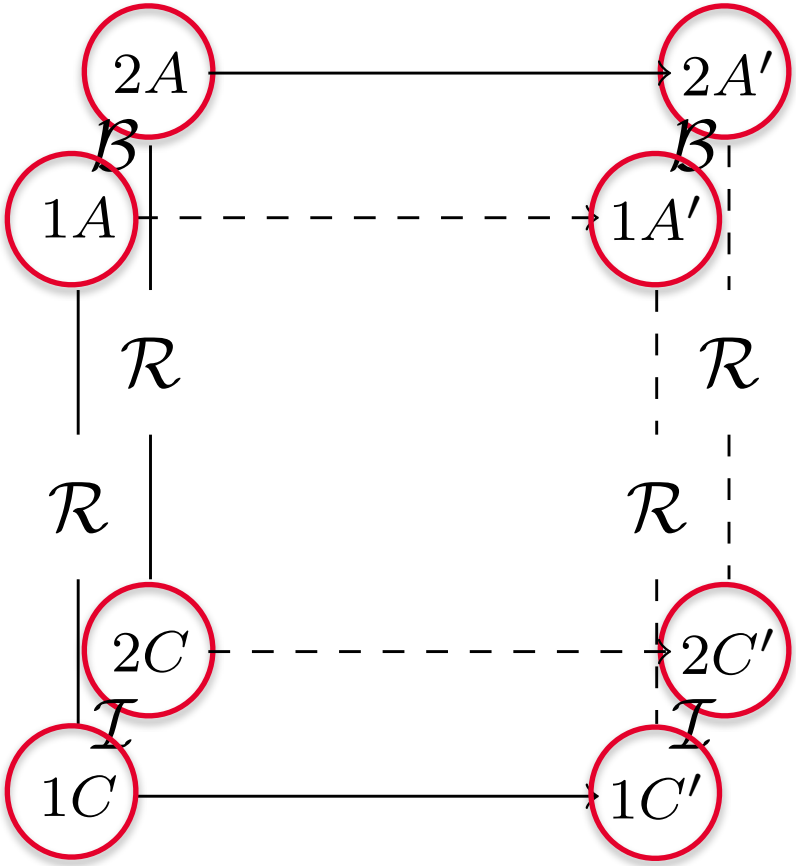


AFP entry:
`Dependent_SIFUM_Refinement`

Background

Why is it hard to prove? (CSF'16)

Confidentiality-preserving refinement



Program configurations

Abstract

Direction of compilation

Concrete

AFP entry:
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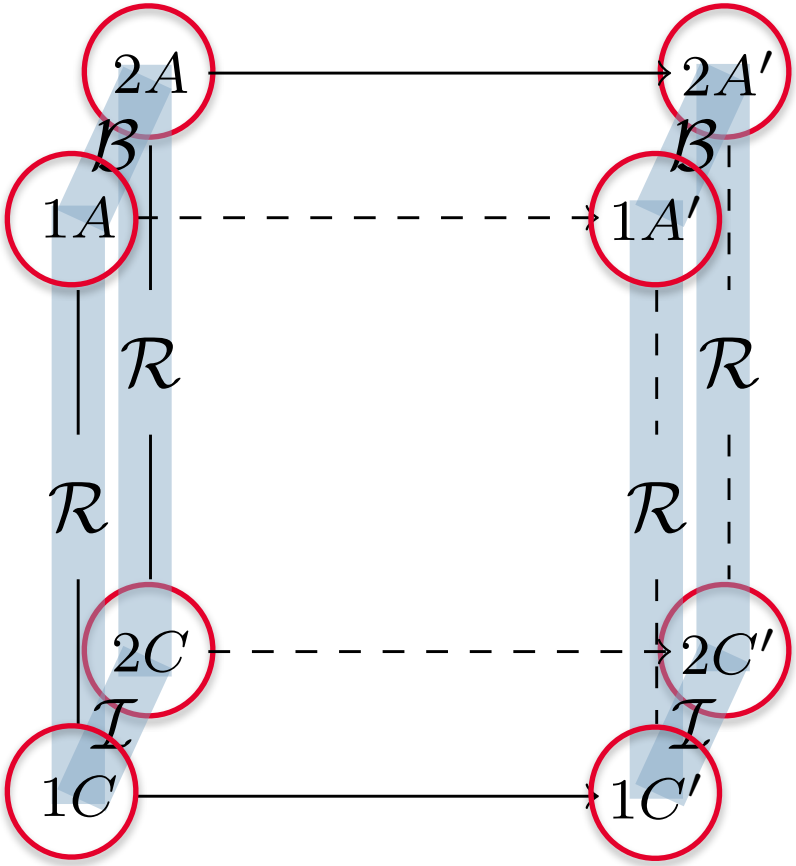
Background
Why is it hard to prove? (CSF'16)

Confidentiality-preserving refinement

Relations

(between)

Program configurations



Abstract

Direction of compilation

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Execution steps

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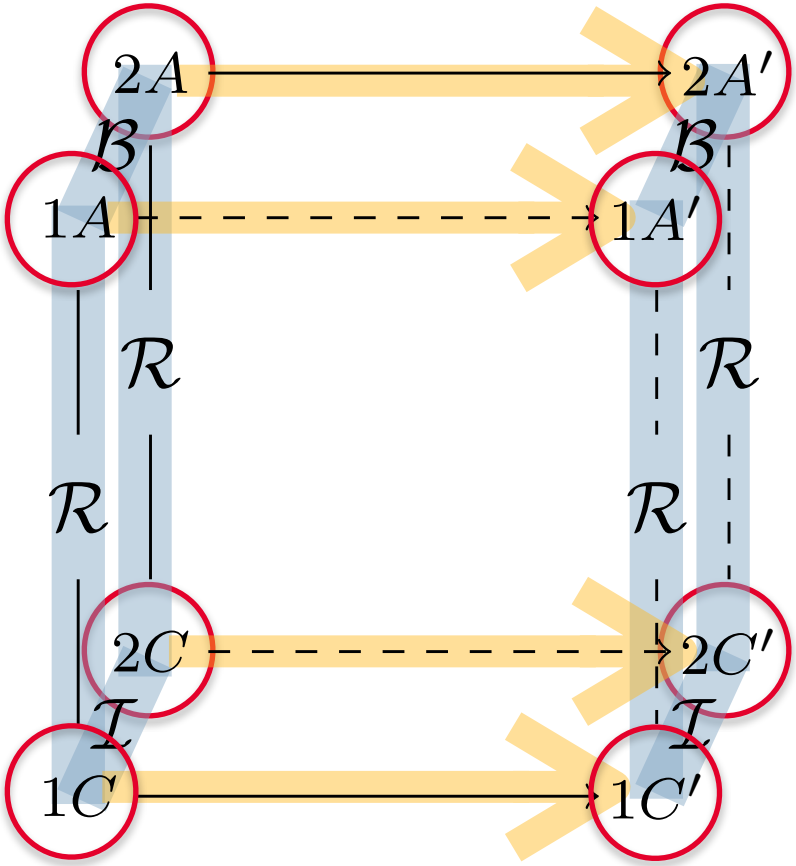

Abstract

Direction of compilation

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AFP entry:

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Background

Why is it hard to prove? (CSF'16)

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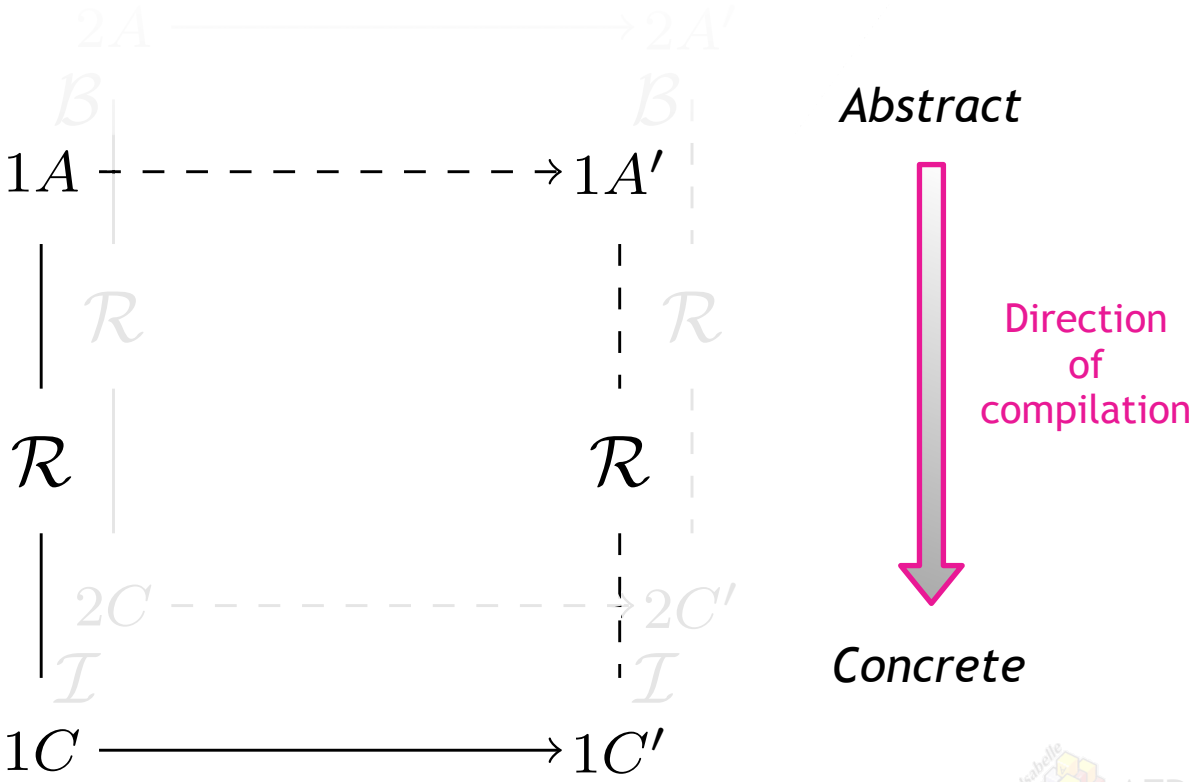
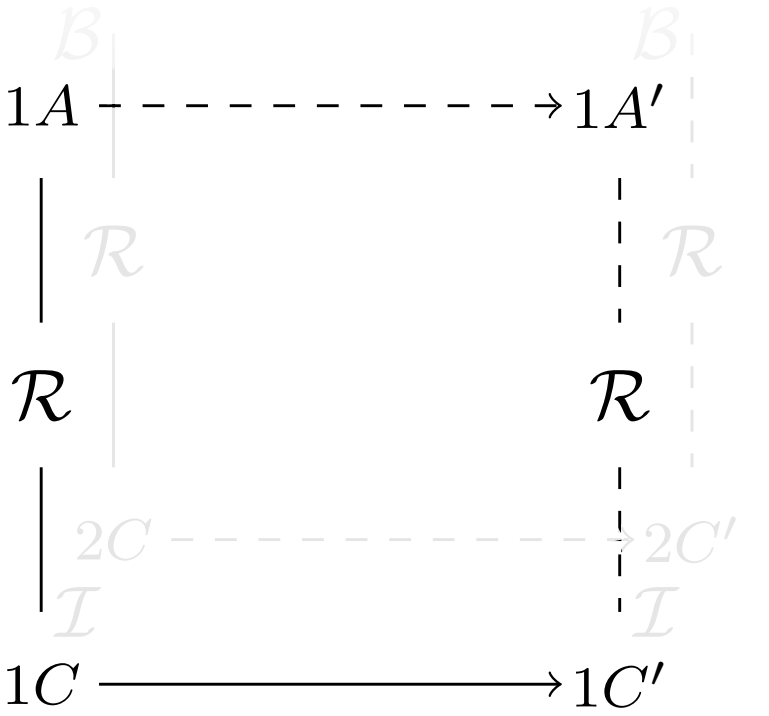


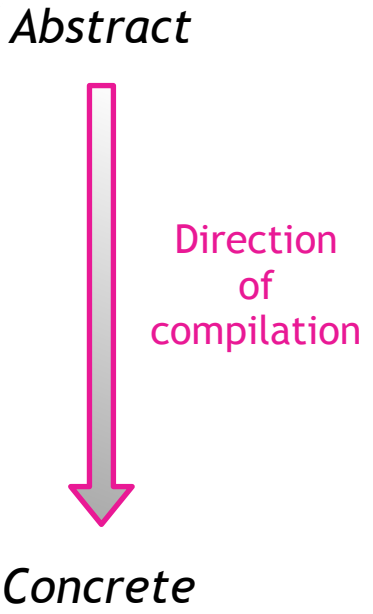
AFP entry: Dependent_SIFUM_Refinement

Background
Why is it hard to prove? (CSF'16)

"Usual" refinement:

A simulates C ⇒ C refines A





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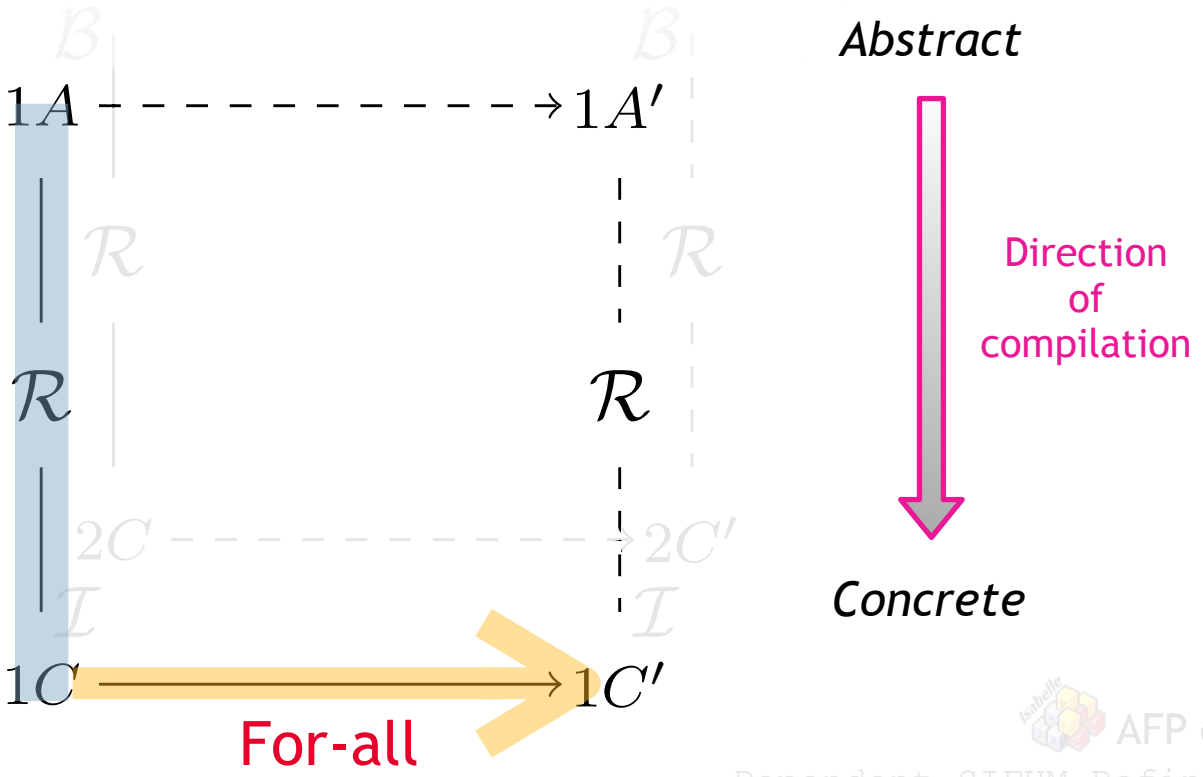

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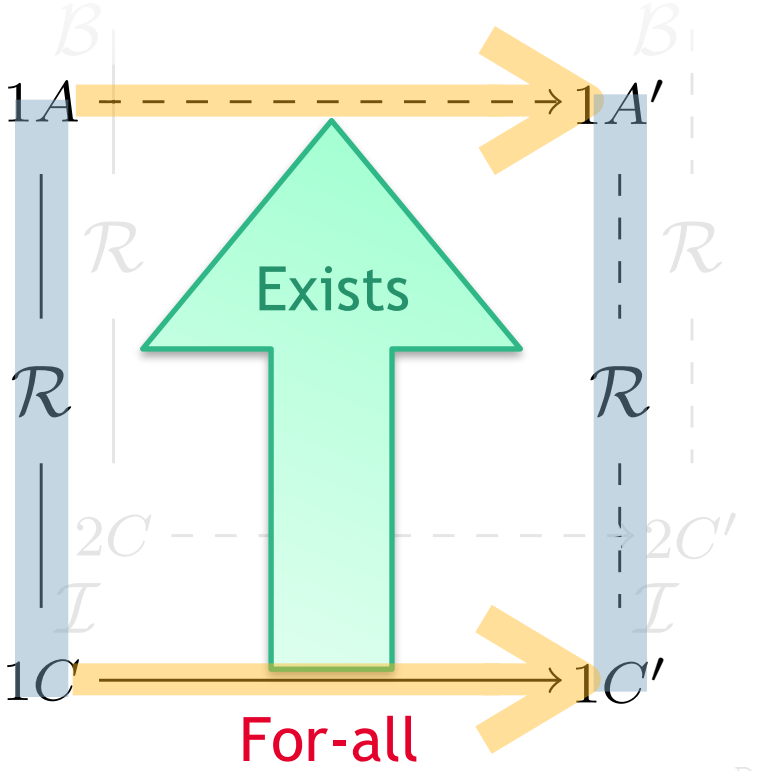

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Direction of compilation

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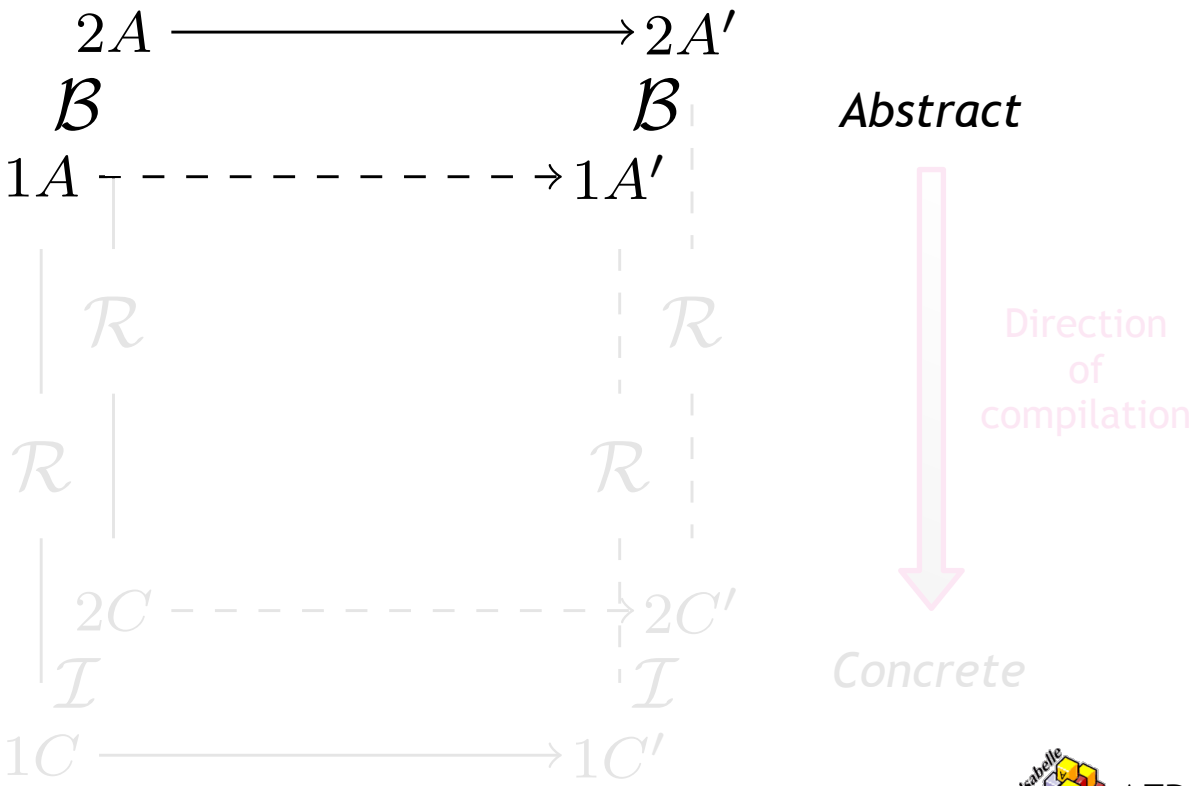
AFP entry: Dependent_SIFUM_Refinement

Background
Why is it hard to prove? (CSF'16)

From compiler front-end

Security proof (Bisimulation B)

Confidentiality-preserving refinement



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Background

Why is it hard to prove? (CSF'16)

From compiler front-end

Security proof (Bisimulation B)

+

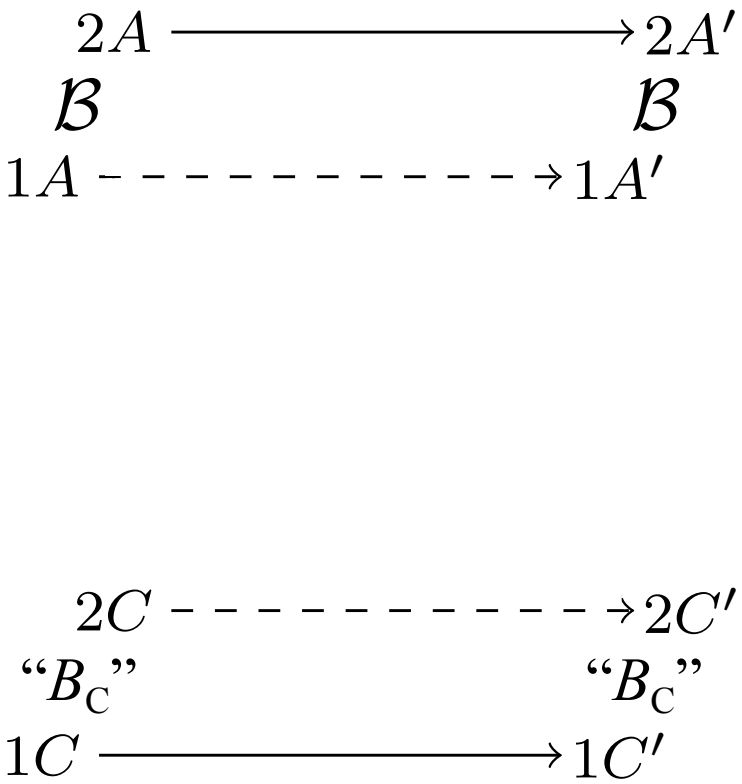
?

⇒

For *free* ?

Security proof (Bisimulation "B_C")

Confidentiality-preserving refinement



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Security proof (Bisimulation B)

+

Compiler correctness proof (Refinement R)

⇒ "For free"*

Security proof (Bisimulation $\mathrm{B_c of}\ B\ R\ I$)

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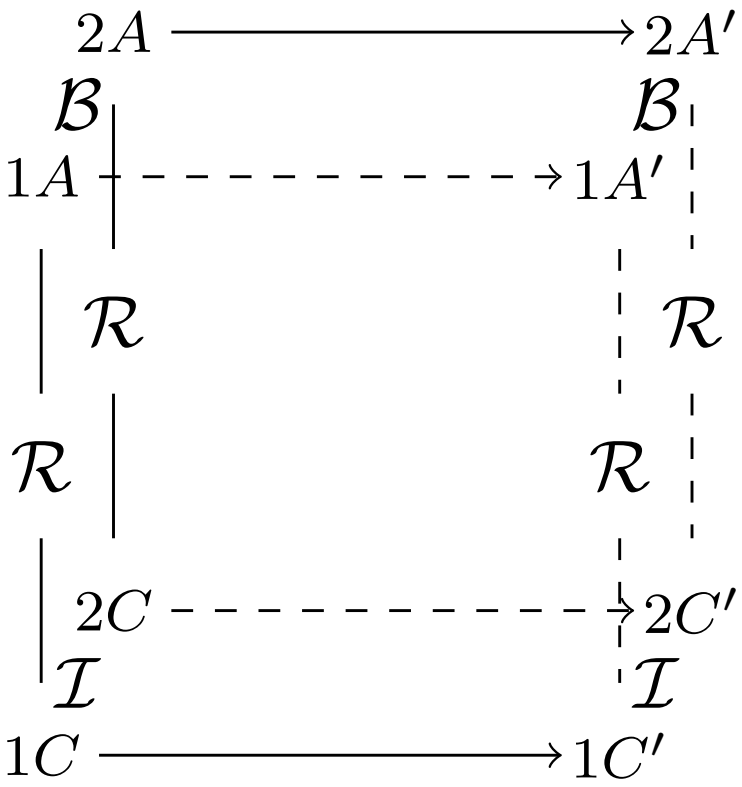

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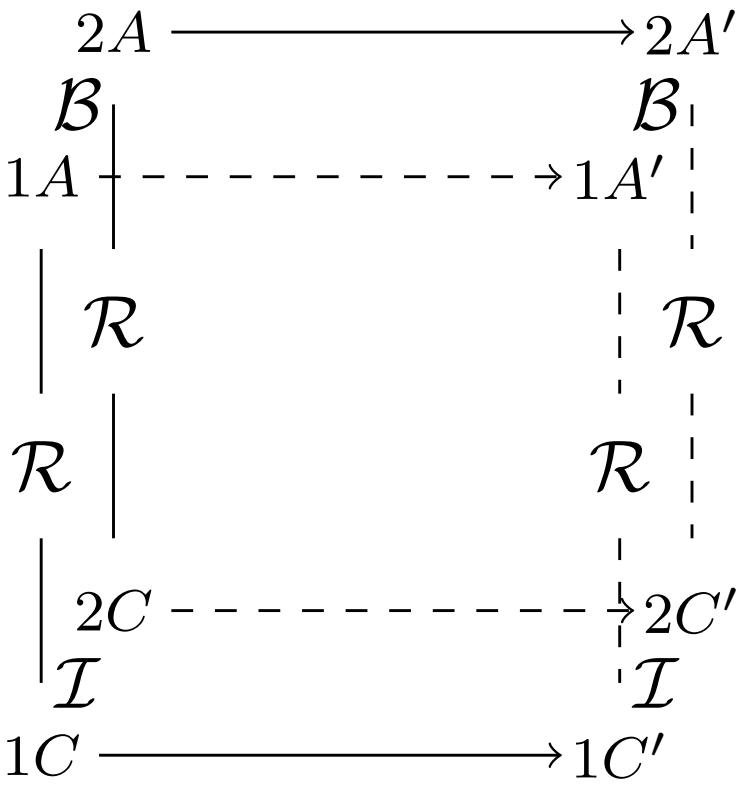

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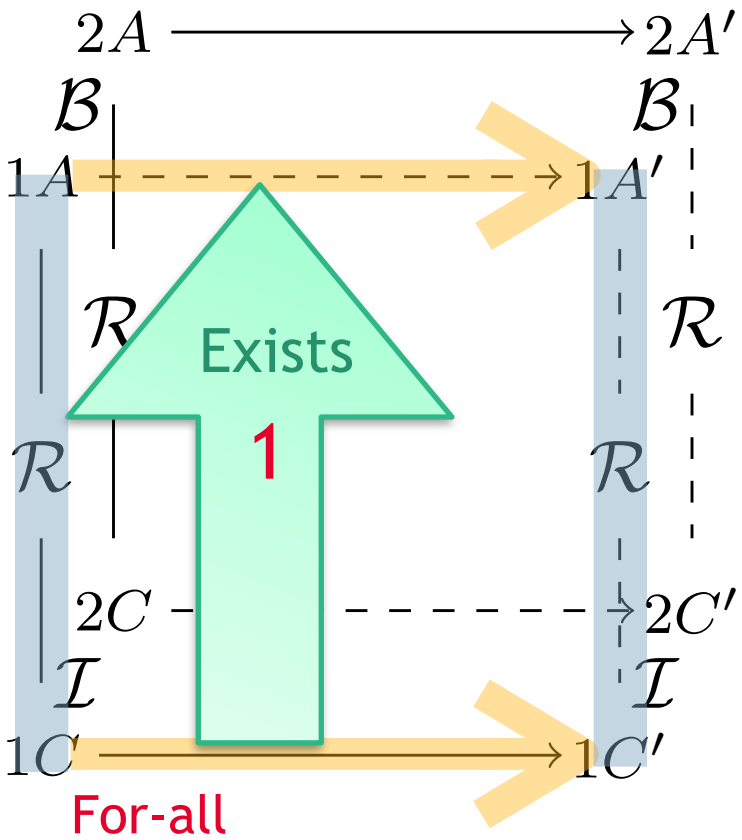

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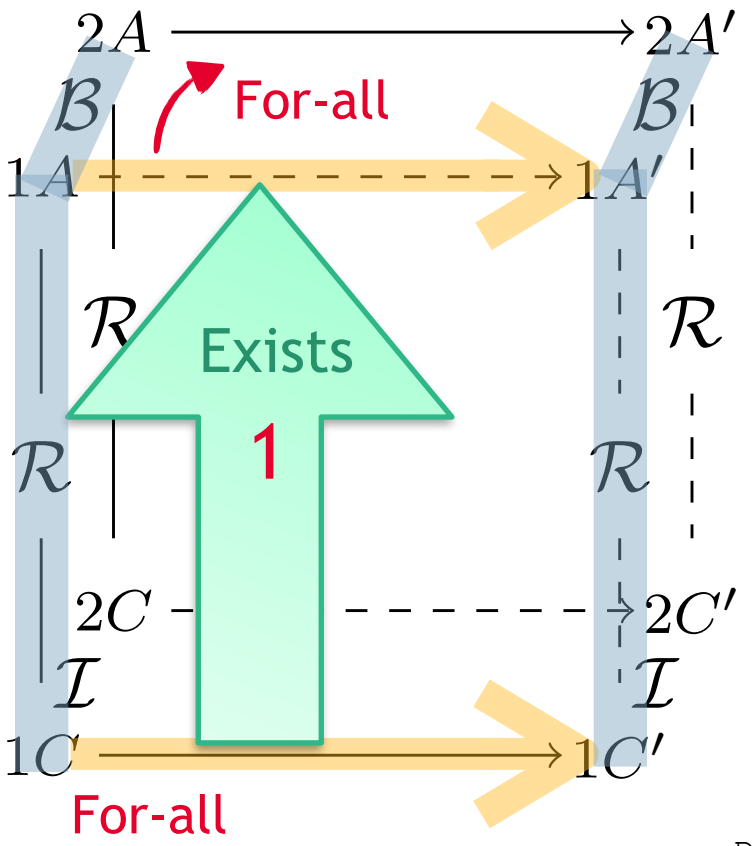

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Why is it hard to prove? (CSF'16)

From compiler front-end

Security proof (Bisimulation B)

+

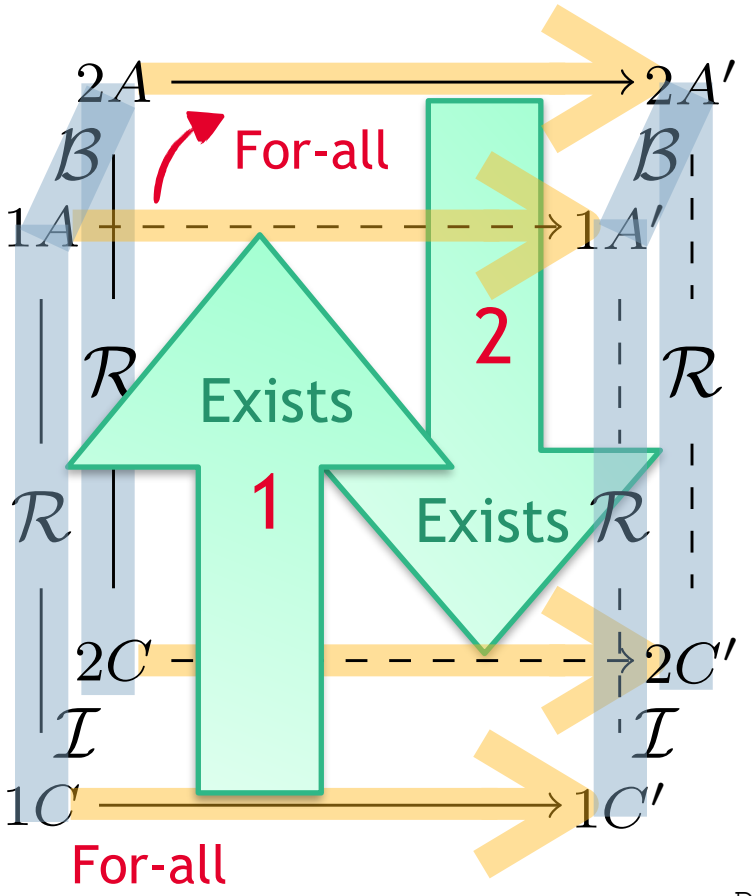
Compiler correctness proof (Refinement R)

⇒ "For free"*

Security proof (Bisimulation $\mathrm{B_c of}\ B\ R\ I$)

*Confidentiality-preserving refinement

(Two-sided!)



Abstract

Direction of compilation

Concrete

AFP entry:
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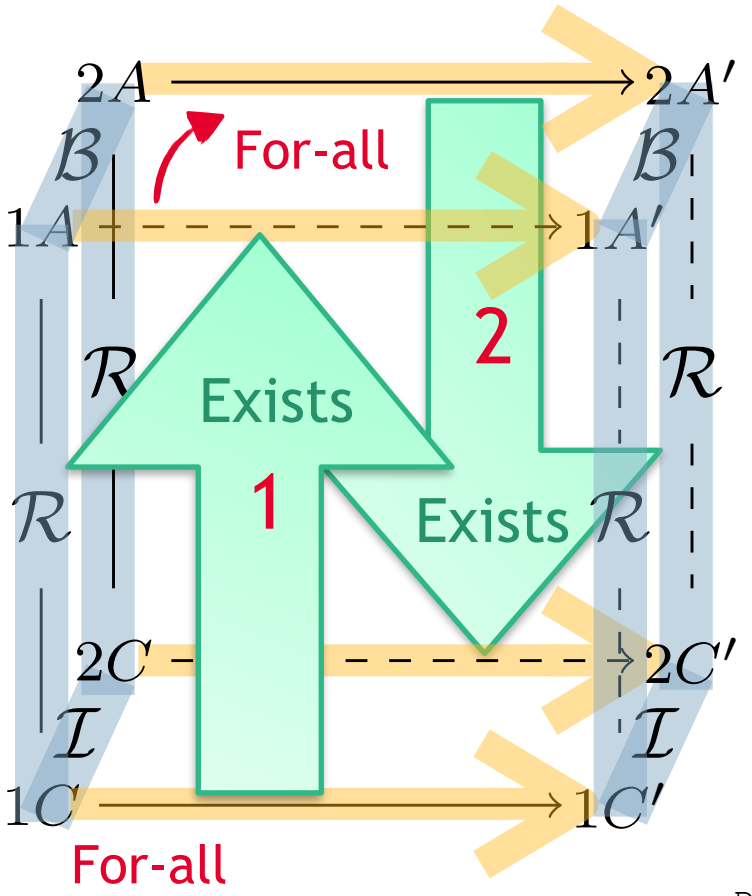

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(**Compare:** Barthe et al. CSF'18)

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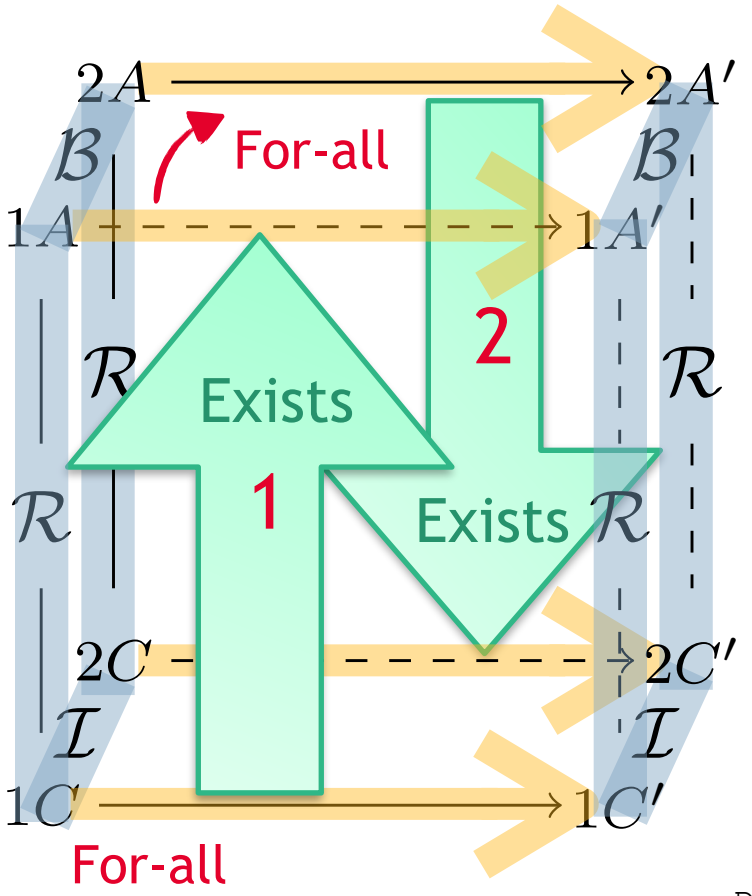

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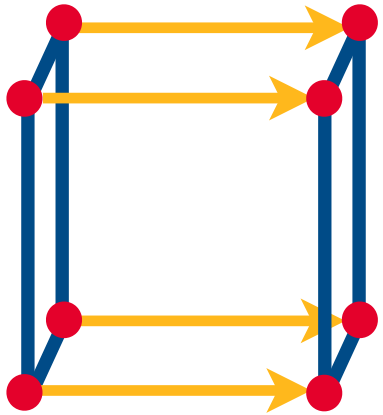
Our contributions

Goal

Prove a compiler *preserves proofs* of concurrent value-dependent information-flow security

Plan: Use *confidentiality-preserving refinement*



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Results

1. Decomposition principle

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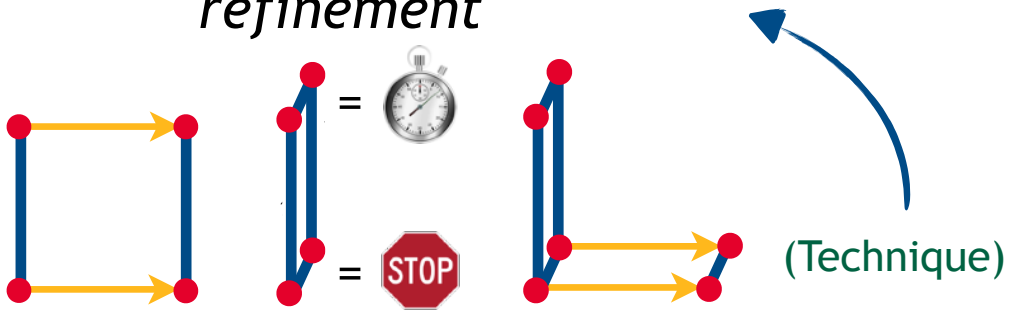

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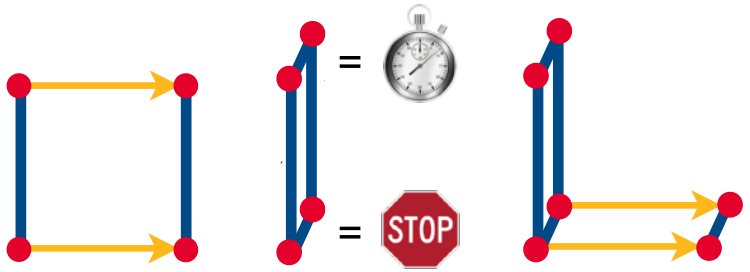

(Technique)

2. Verified compiler

While-language to RISC-style assembly

(Proof-of-concept for technique)

Impact

1st such proofs carried to assembly-level model by compiler

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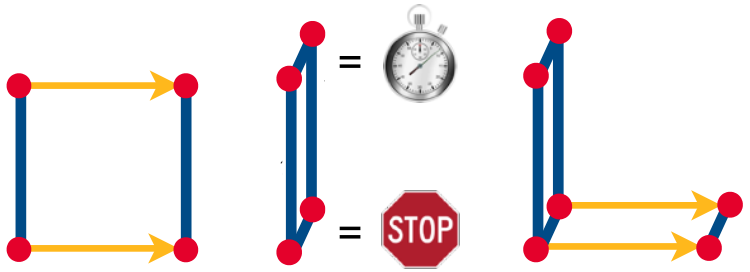

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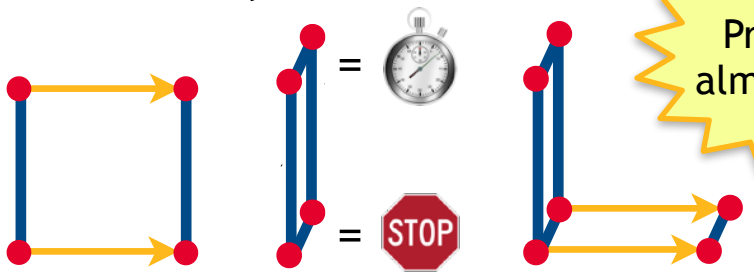

Proof effort almost *halved*!

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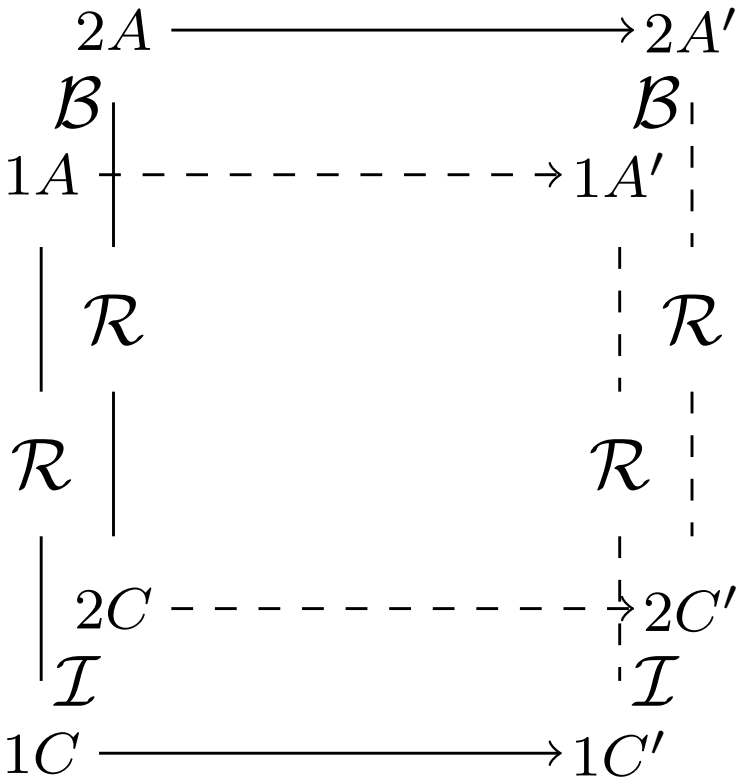
The “cube”, decomposed

Simpler confidentiality-preserving refinement



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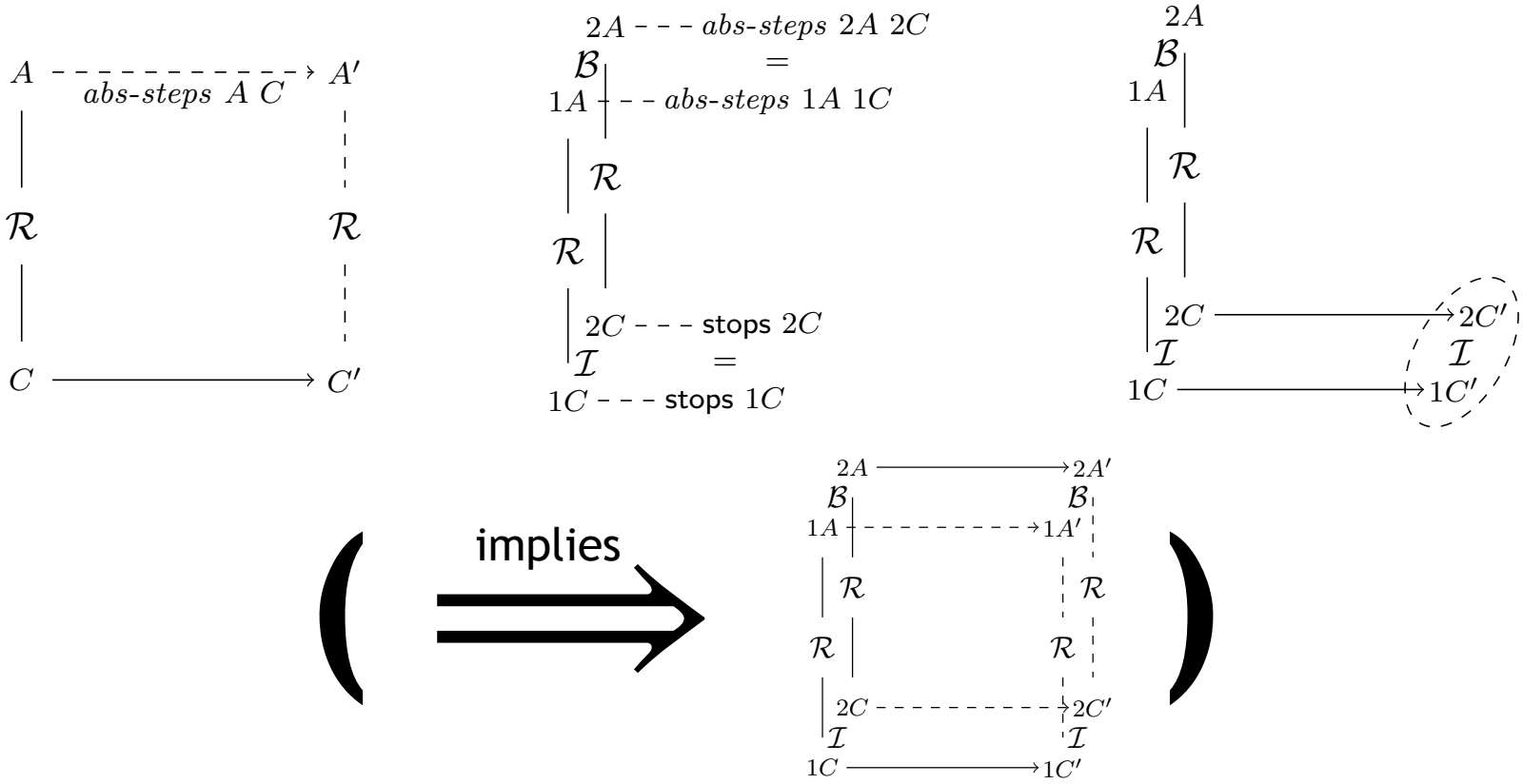

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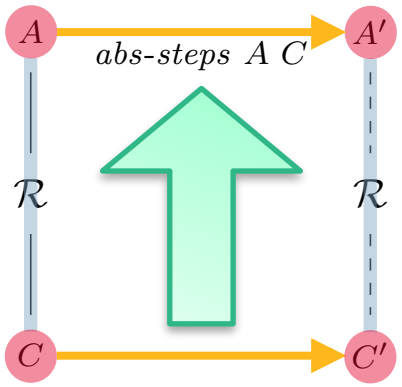

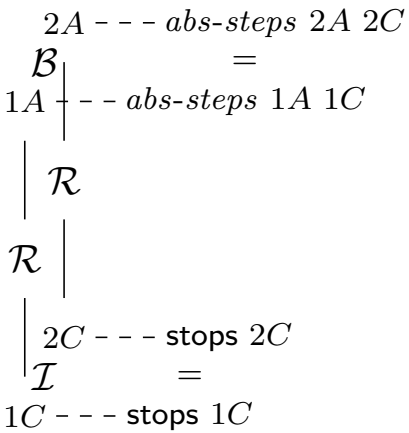

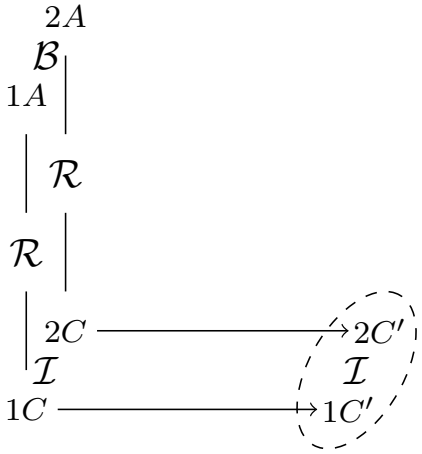

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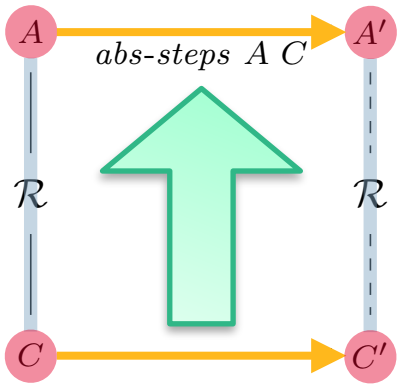

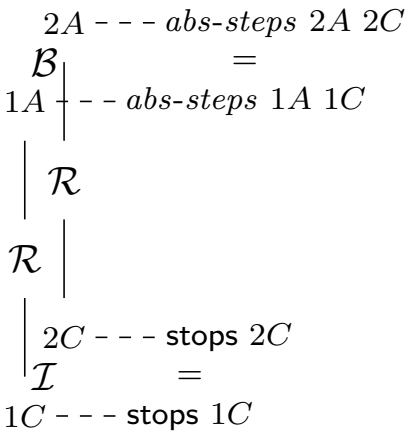

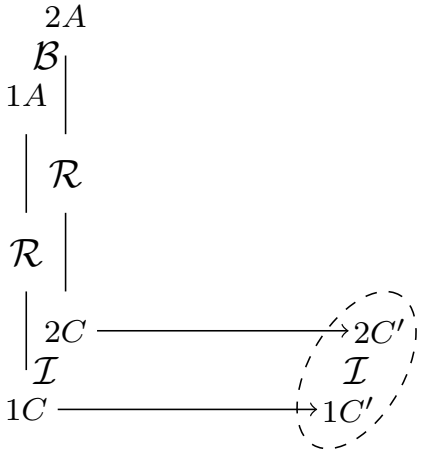

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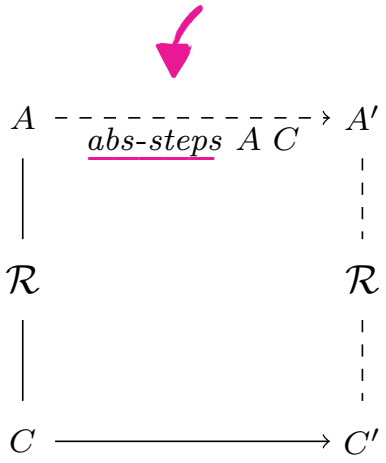

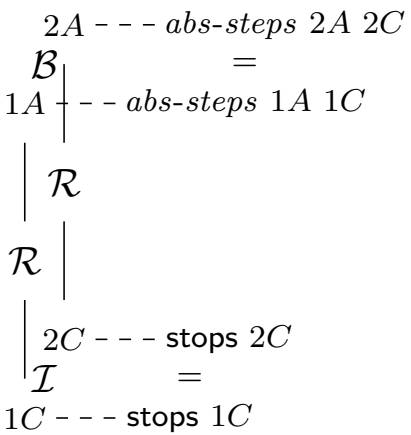

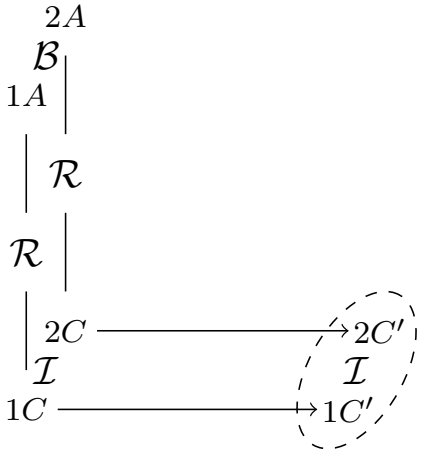

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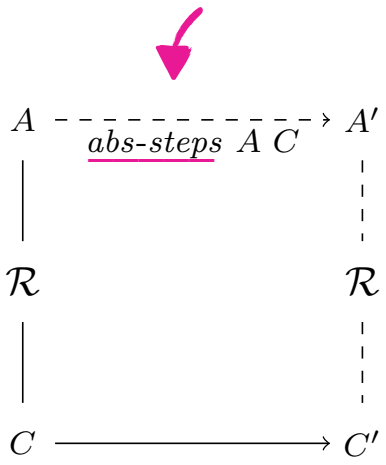

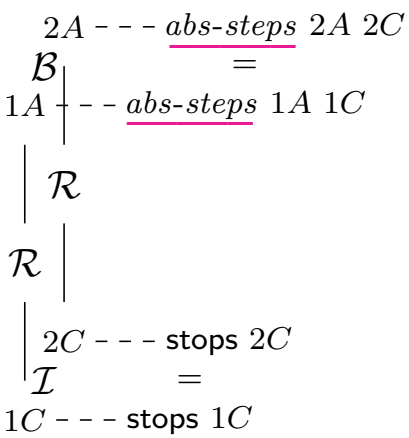

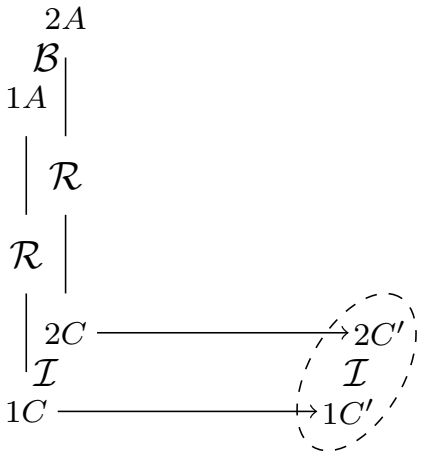

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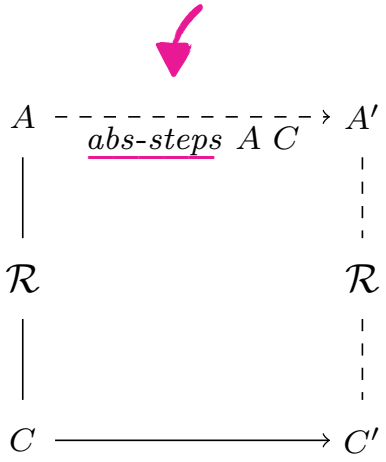

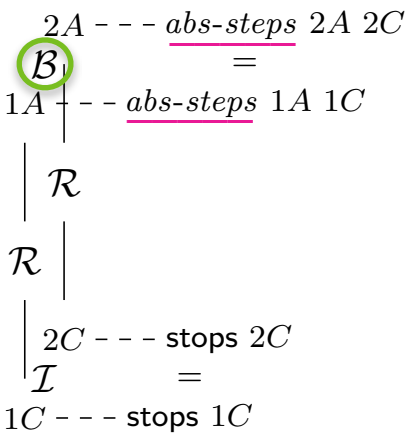

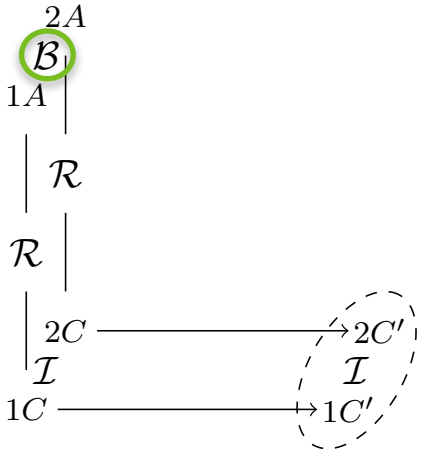

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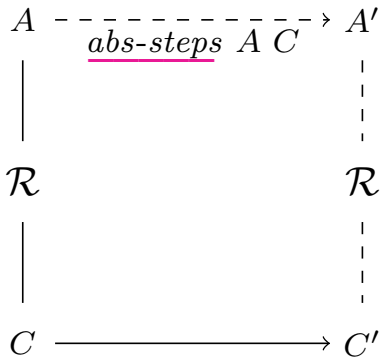

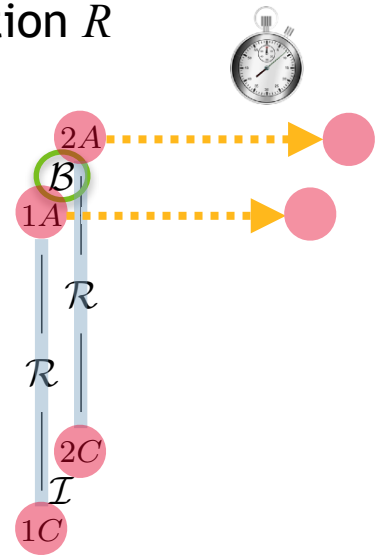

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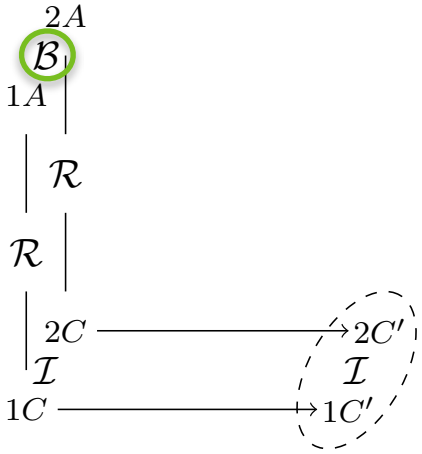

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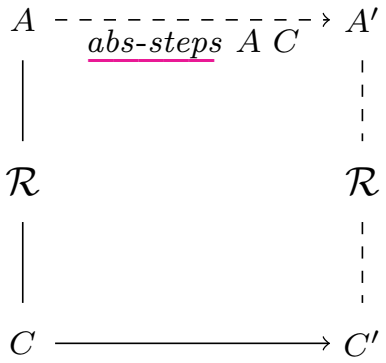

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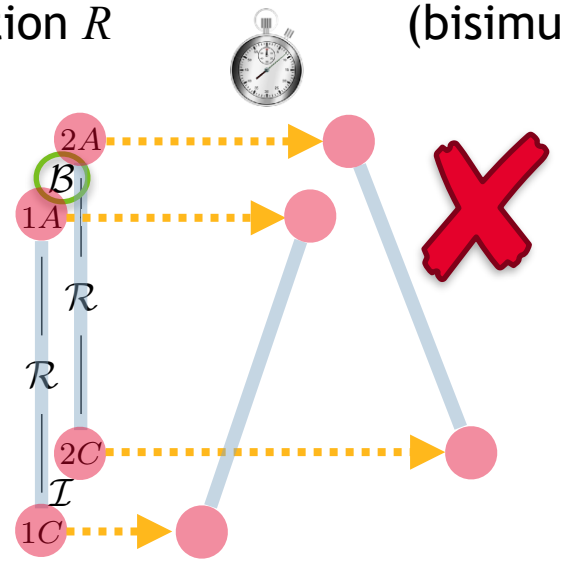

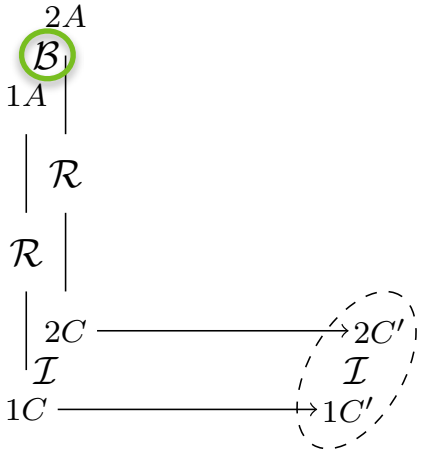

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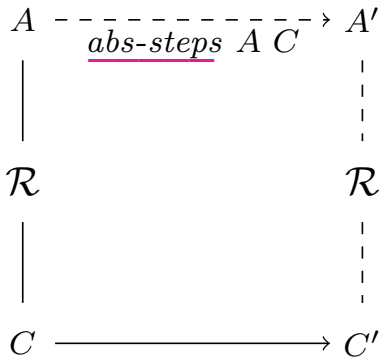

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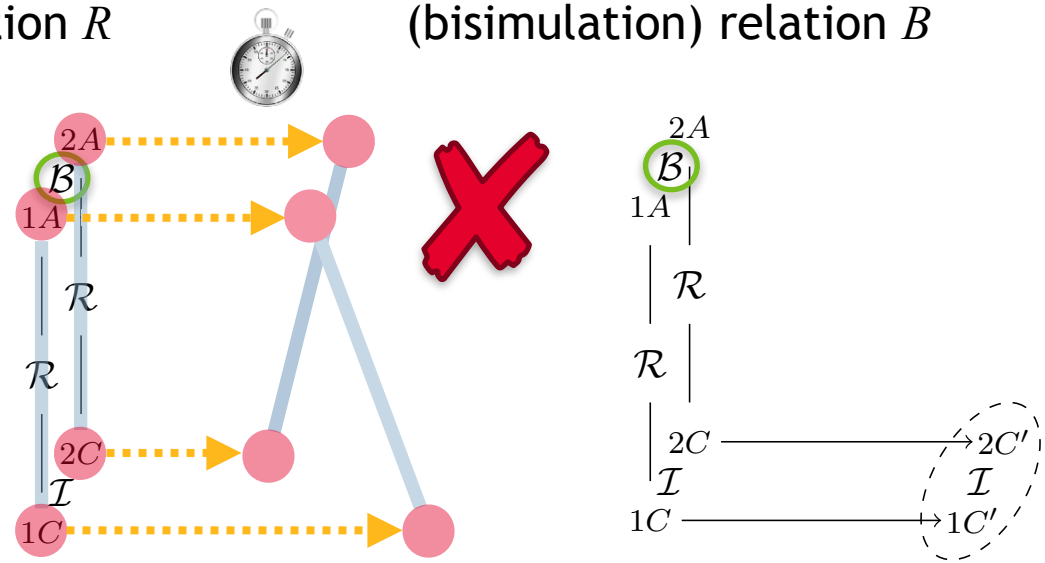

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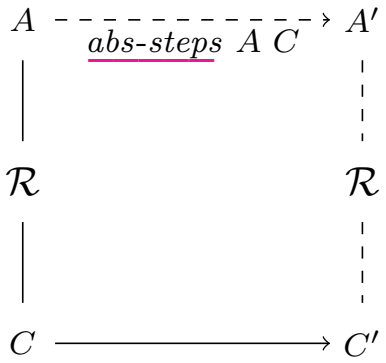

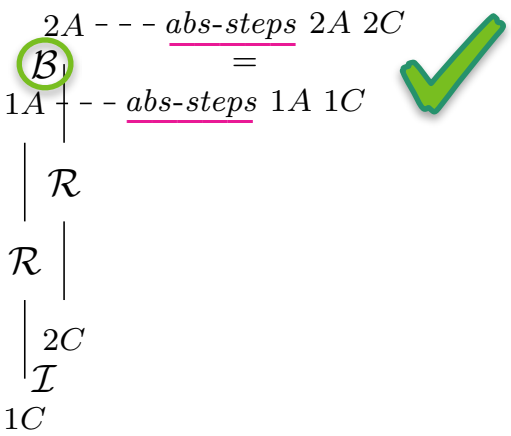

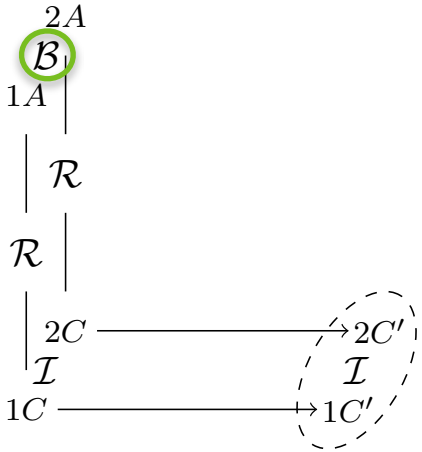

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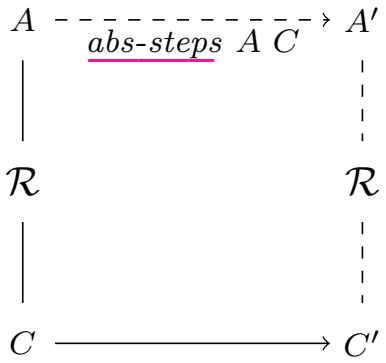

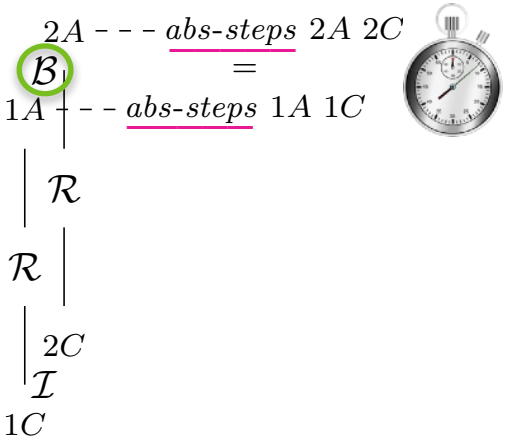

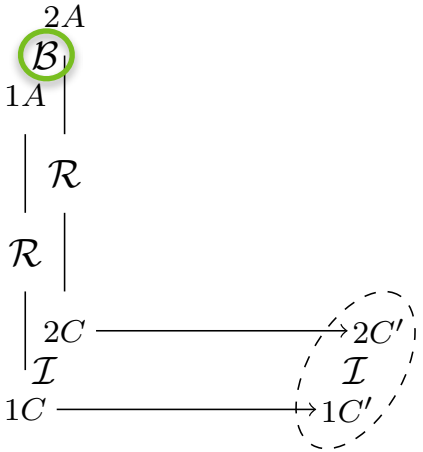

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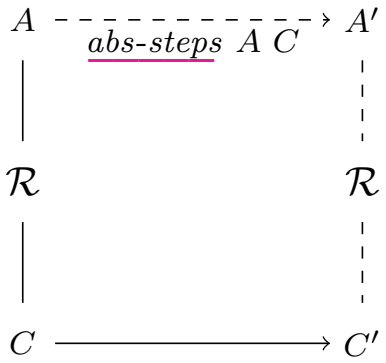

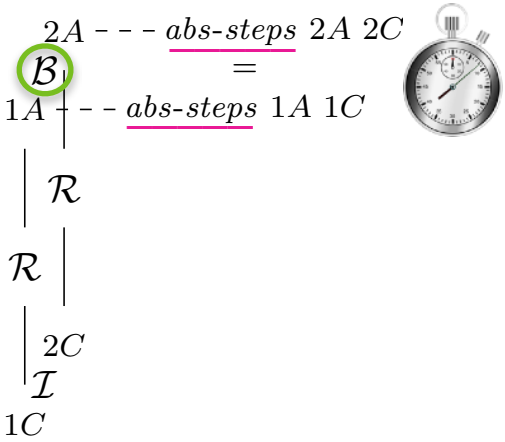

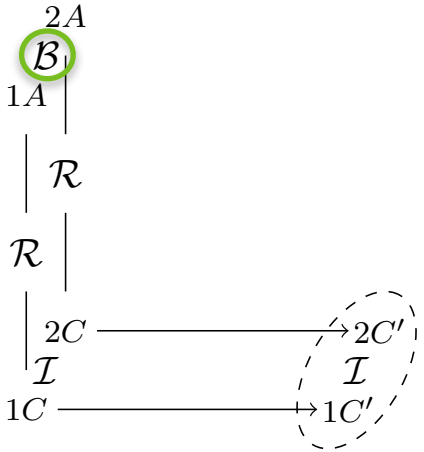

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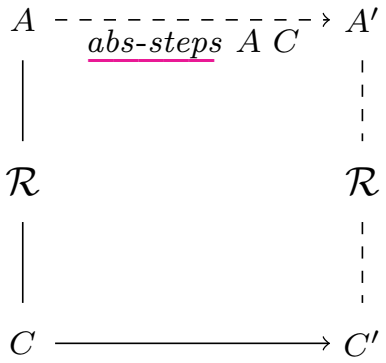

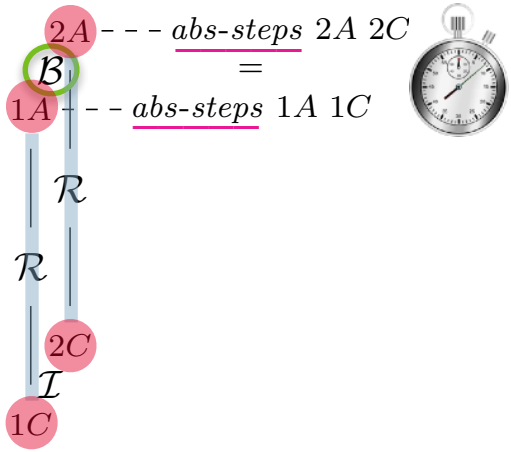

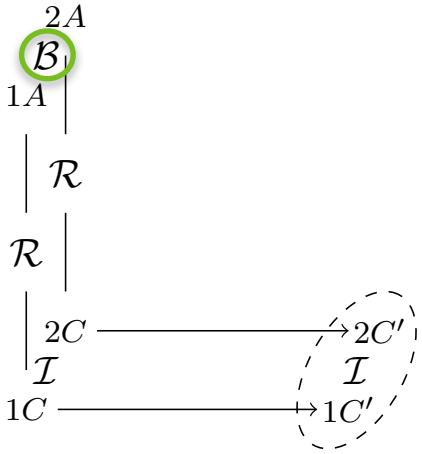

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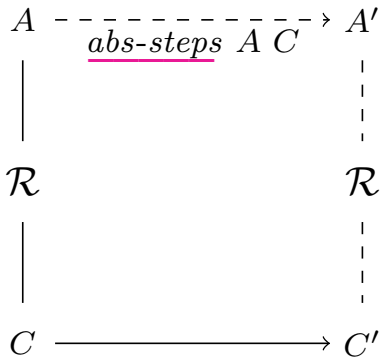

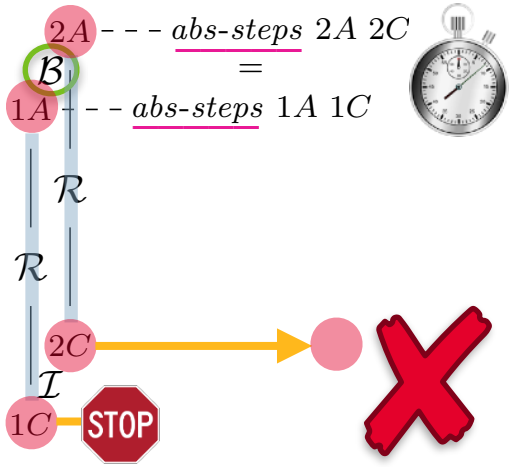

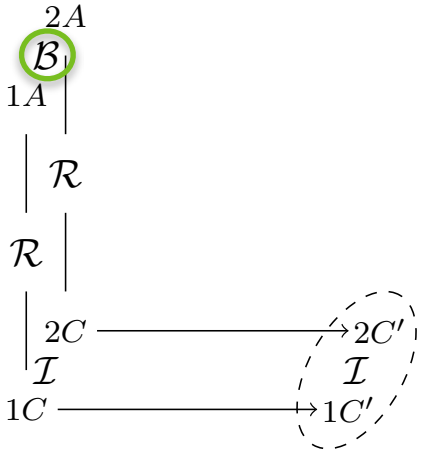

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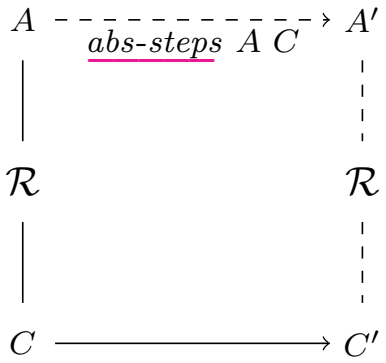

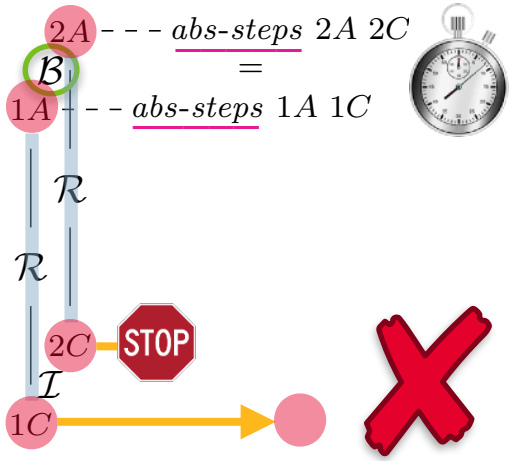

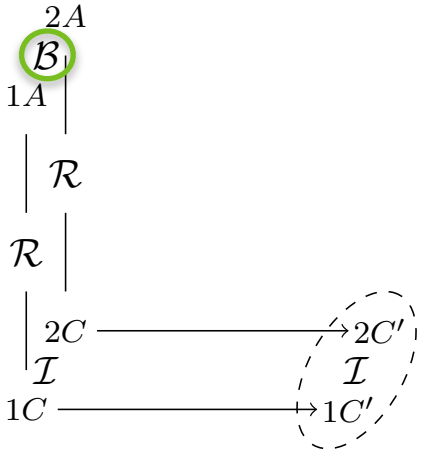

1. “Usual” proof of refinement

2. Consistent pacing
and
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Standard compiler correctness!

(+ “extra stuff” for conc, val-dep)

The “cube”, decomposed

Simpler confidentiality-preserving refinement

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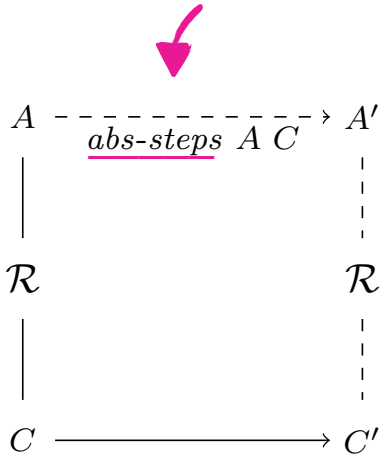

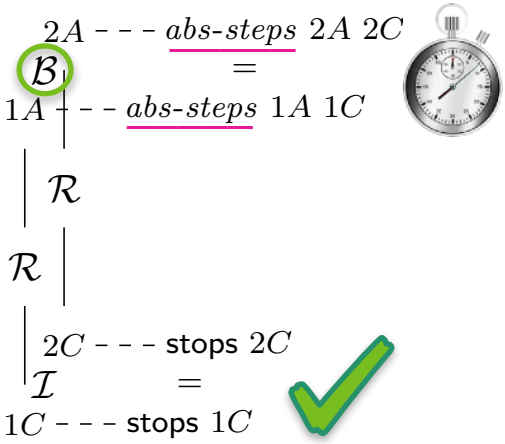

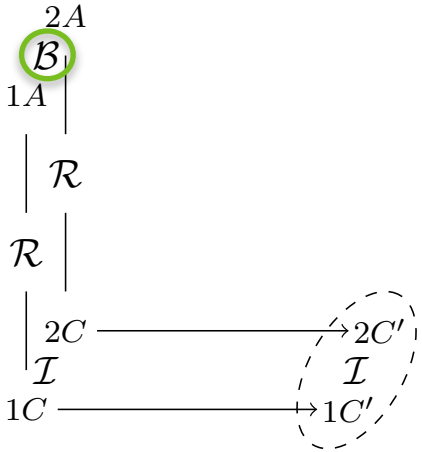

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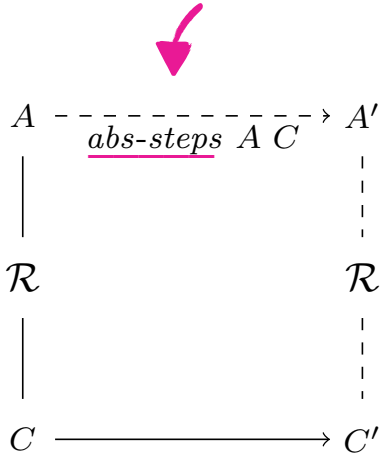

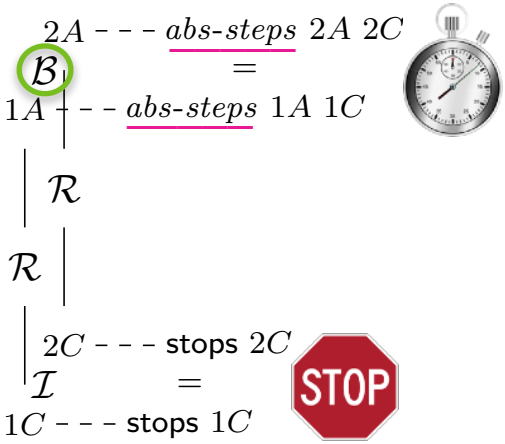

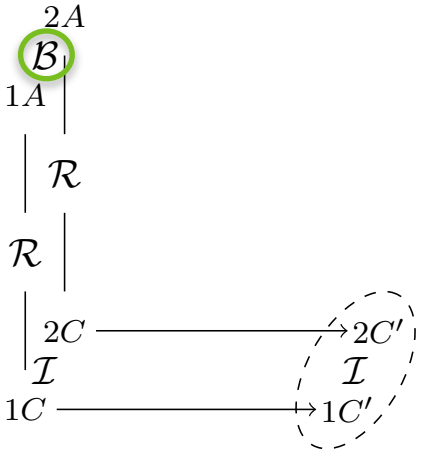

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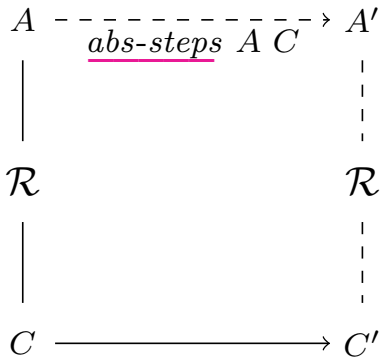

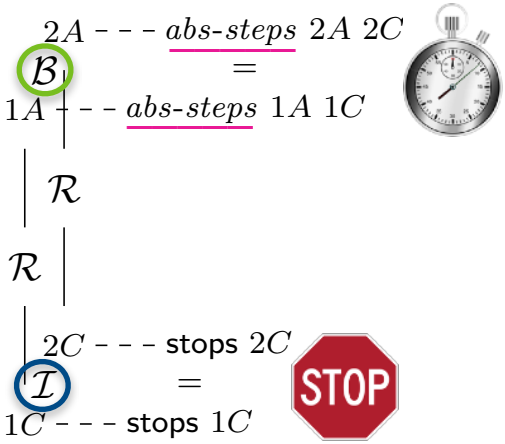

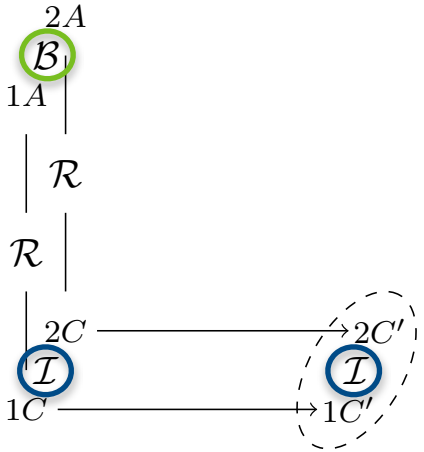

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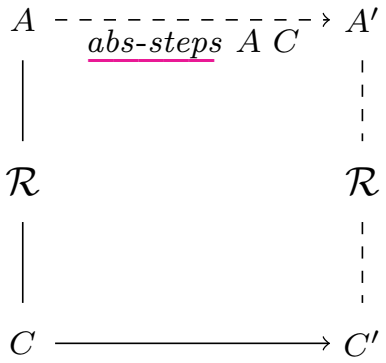

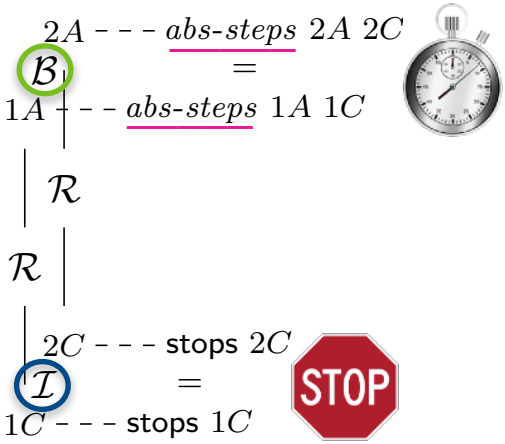

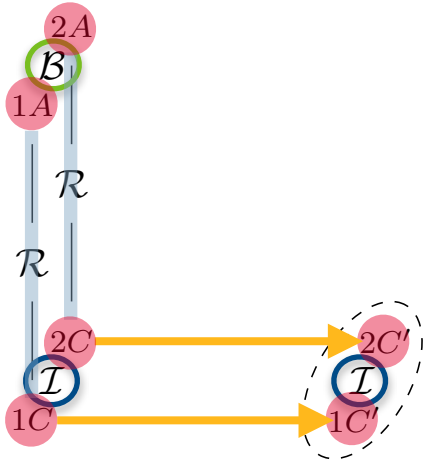

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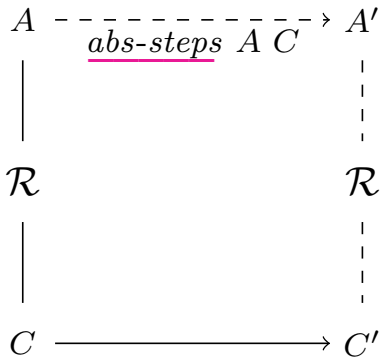

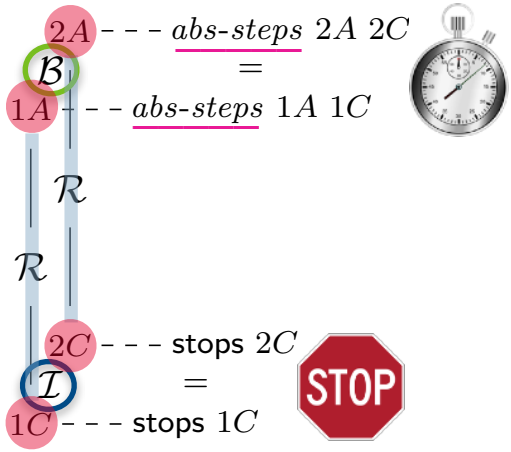

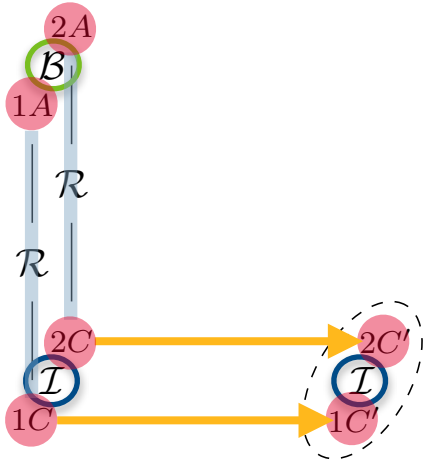

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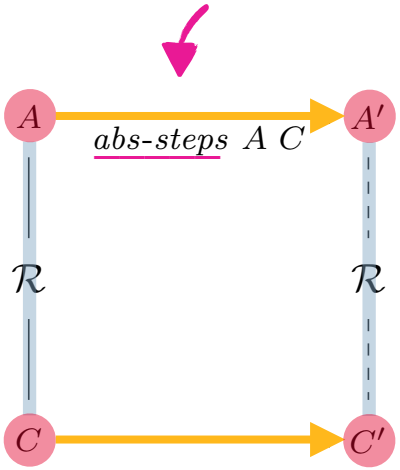

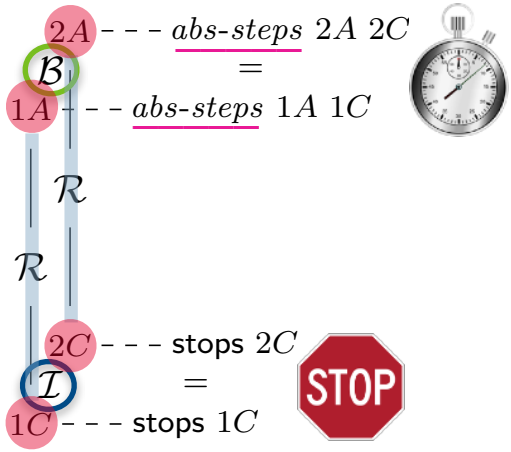

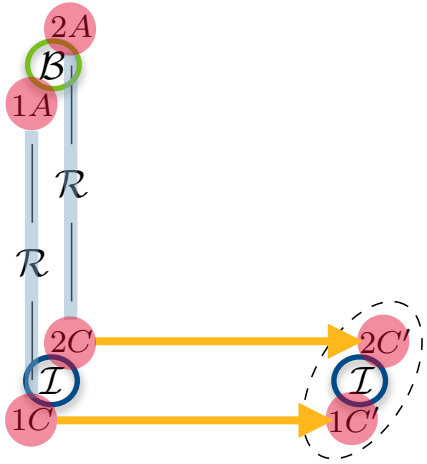

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Proof effort comparison

Refinement example (excerpt) from CSF'16

```
if h ≠ 0 then
    x := y
else
    x := y + z
fi
```

Abstract program

```
reg3 := h;
if reg3 ≠ 0 then
    skip;
    skip;
    reg0 := y;
    x := reg0
else
    reg1 := y;
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Concrete program

formalisation artifact:
https://covern.org/itp19.html

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branch on secret

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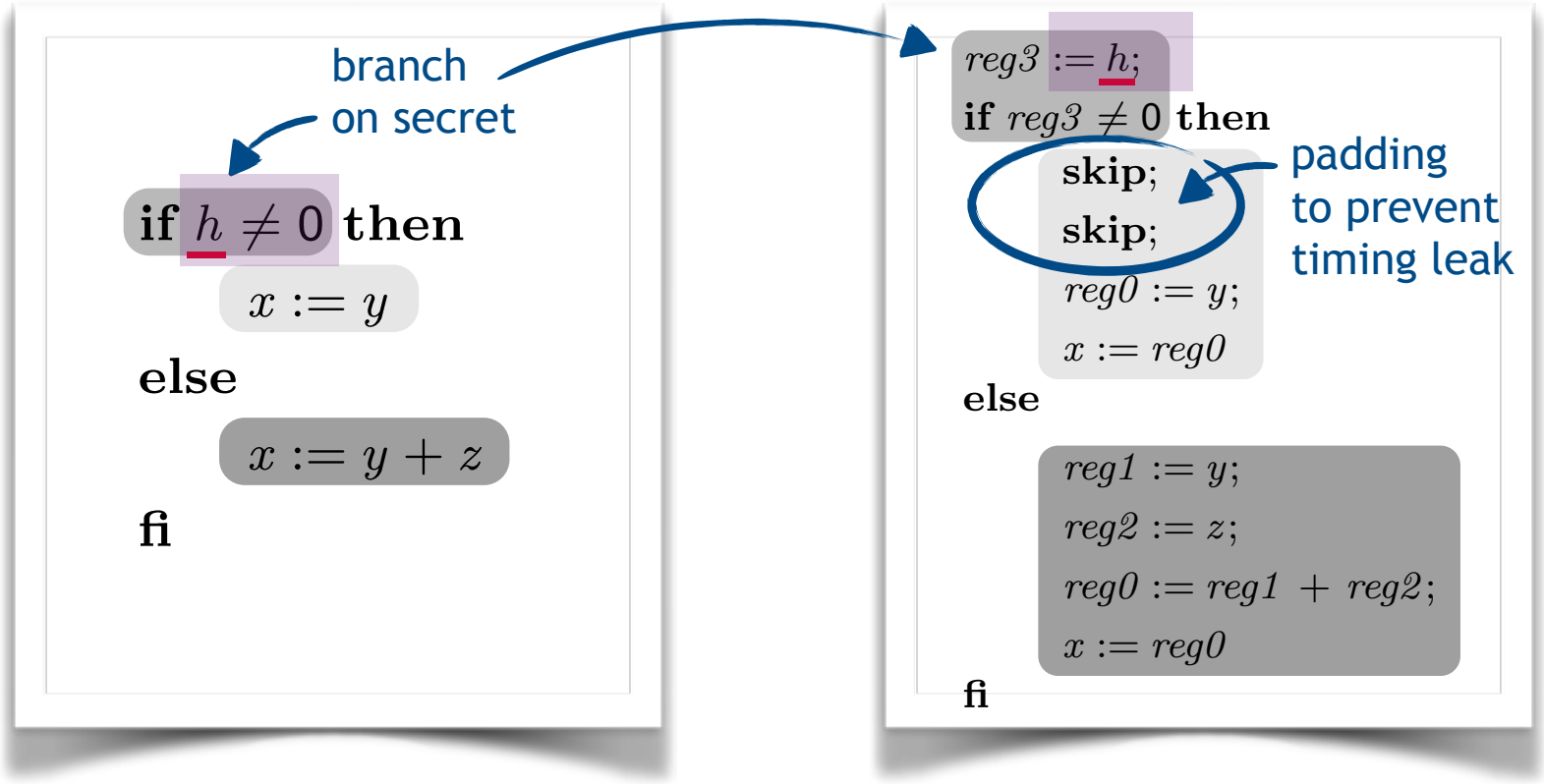

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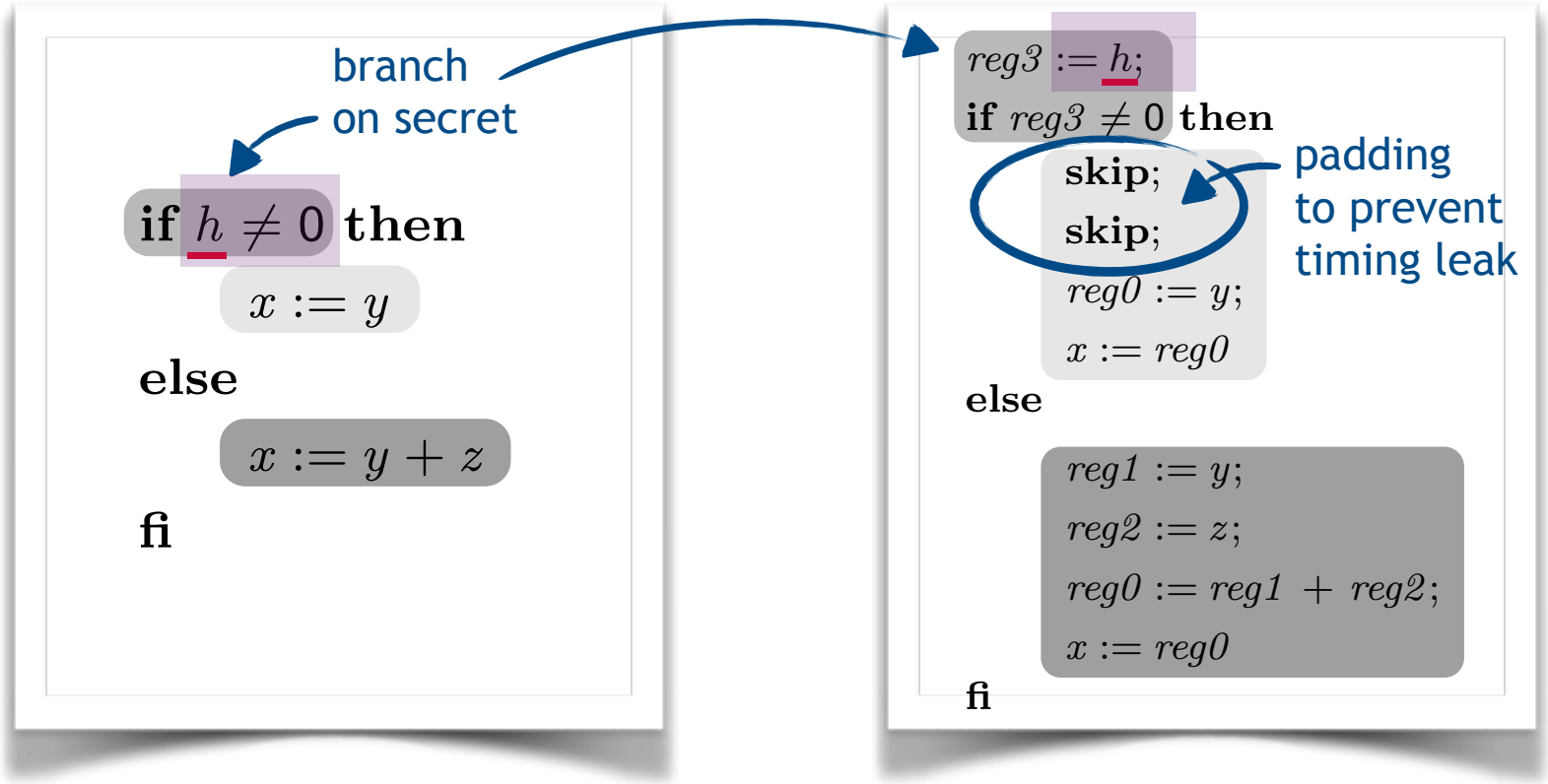

Abstract program

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- 44% shorter proof of secure refinement
  (~3.6K to ~2K lines of Isabelle/HOL proofs)

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Our contributions

Goal

Prove a compiler *preserves proofs* of concurrent value-dependent information-flow security

Results

1. Decomposition principle

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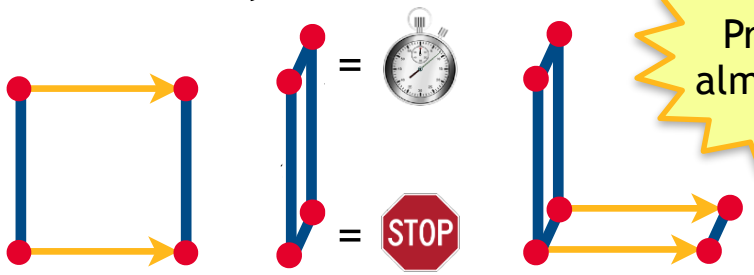

Proof effort almost *halved*!

(Technique)

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While-language to RISC-style assembly

(Proof-of-concept for technique)

Impact

1st such proofs carried to assembly-level model by compiler

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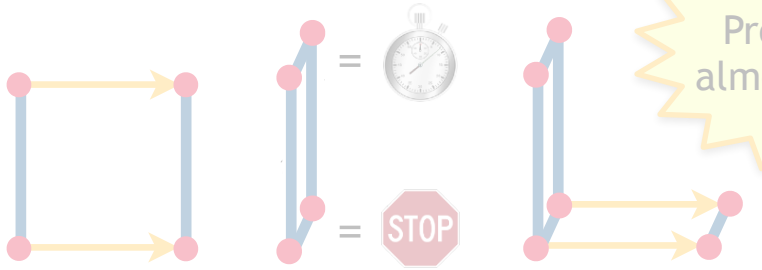

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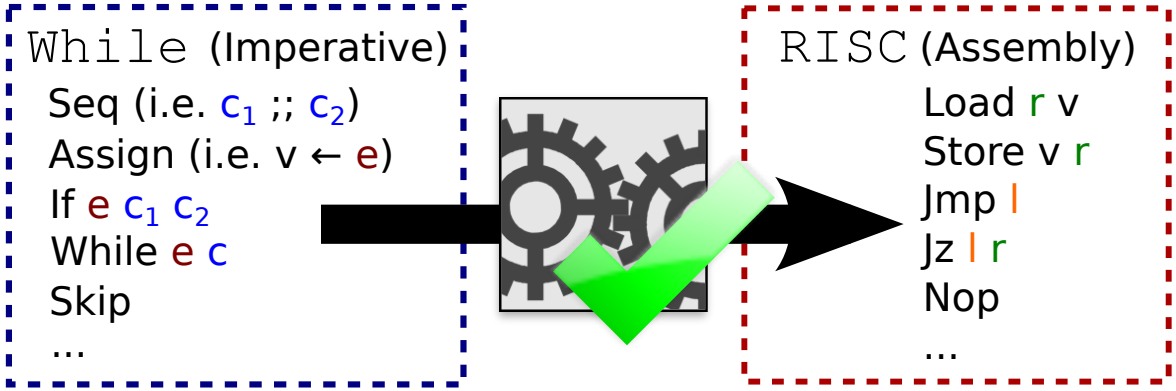
Verified compiler

Overview

An Isabelle/HOL *primrec* function



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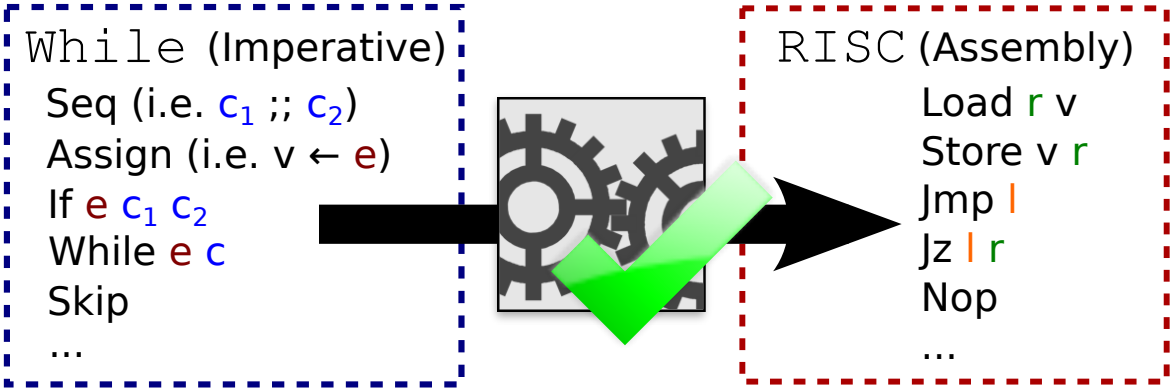

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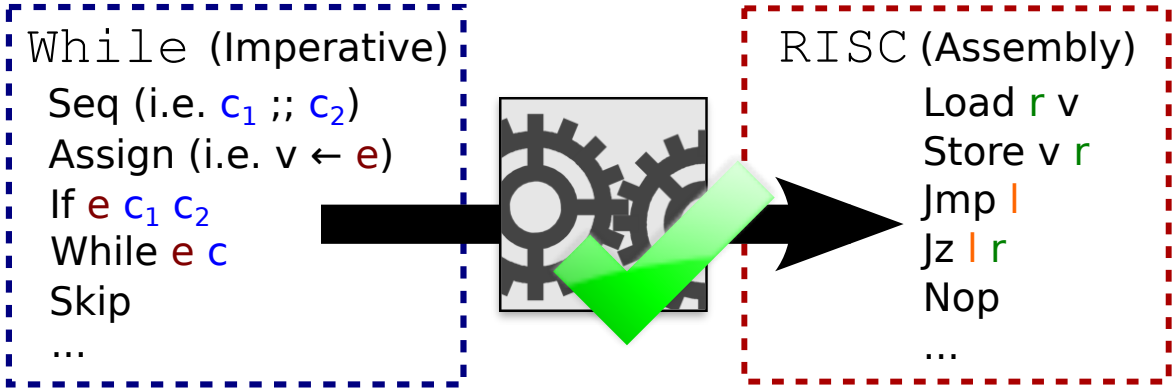

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  - Prevents data races on shared memory
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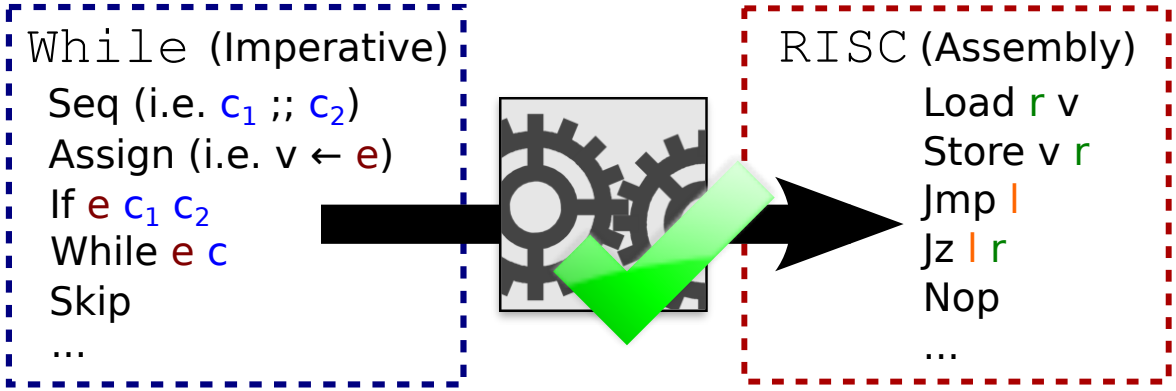

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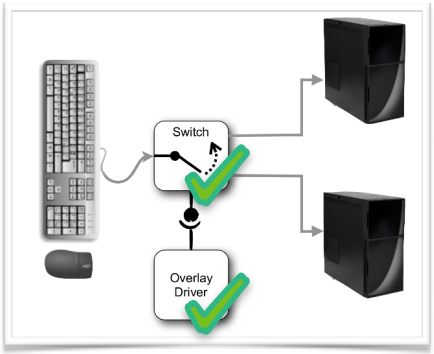

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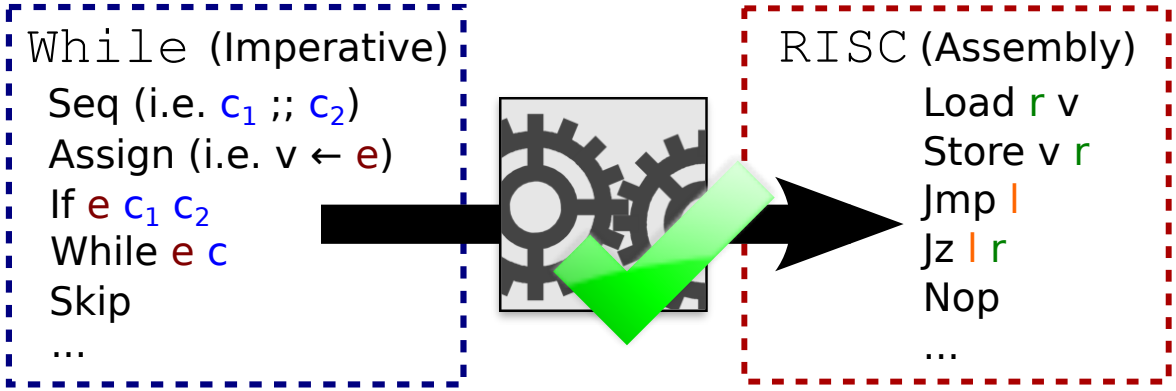

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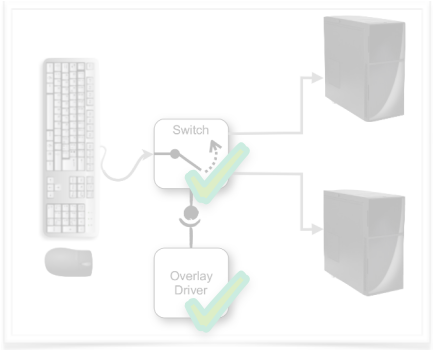

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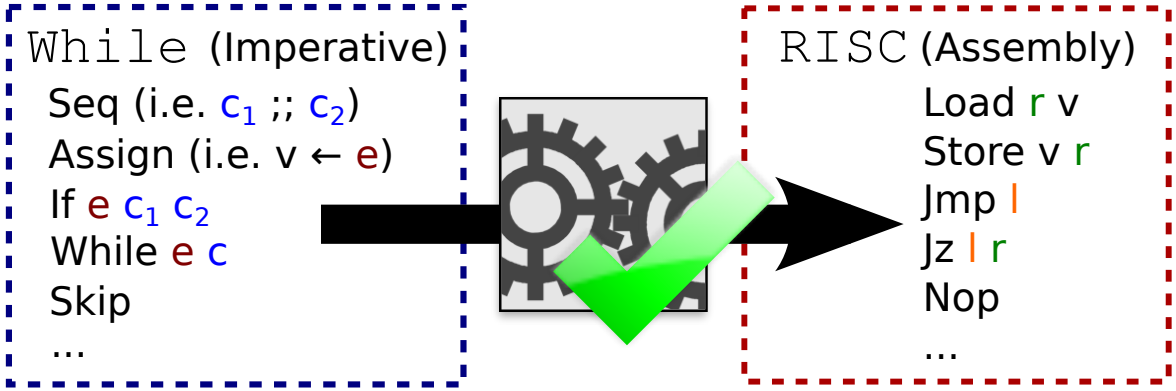

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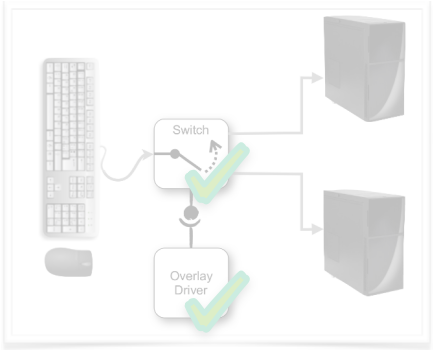

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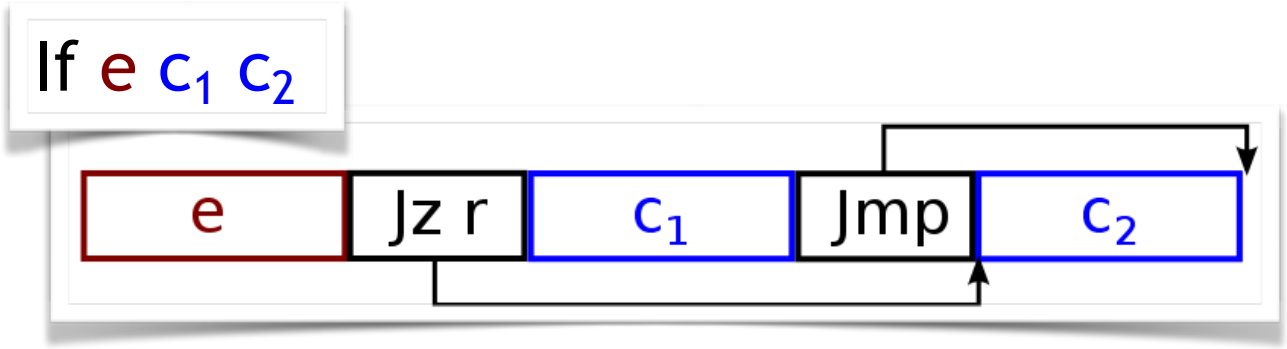

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RISC

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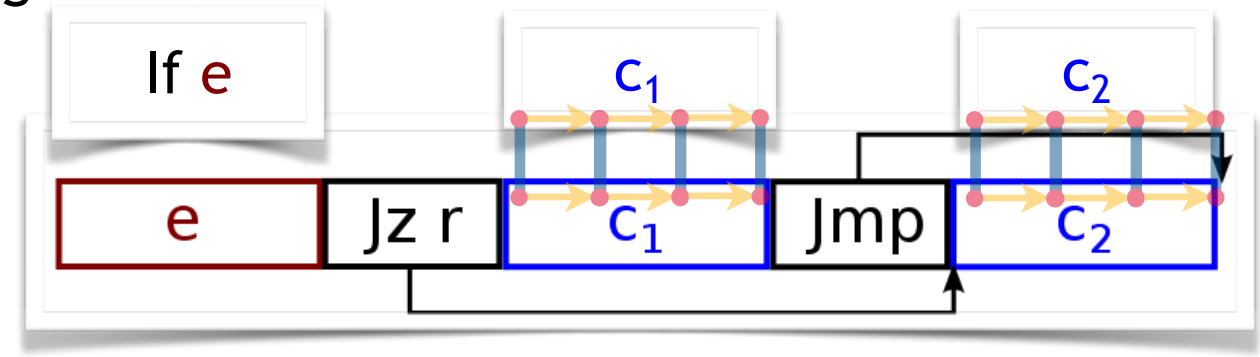

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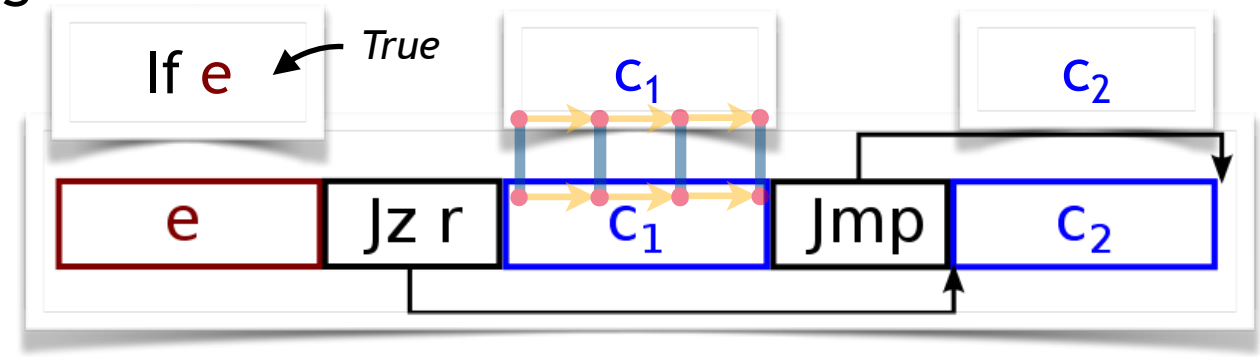

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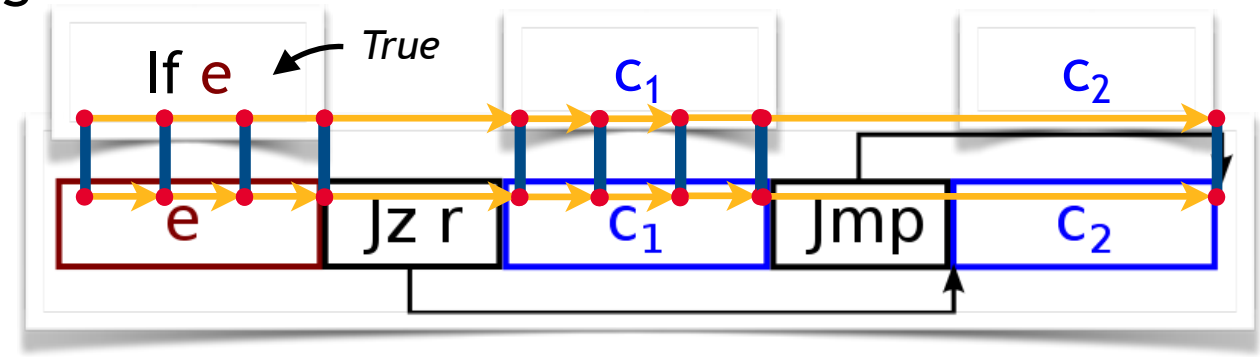

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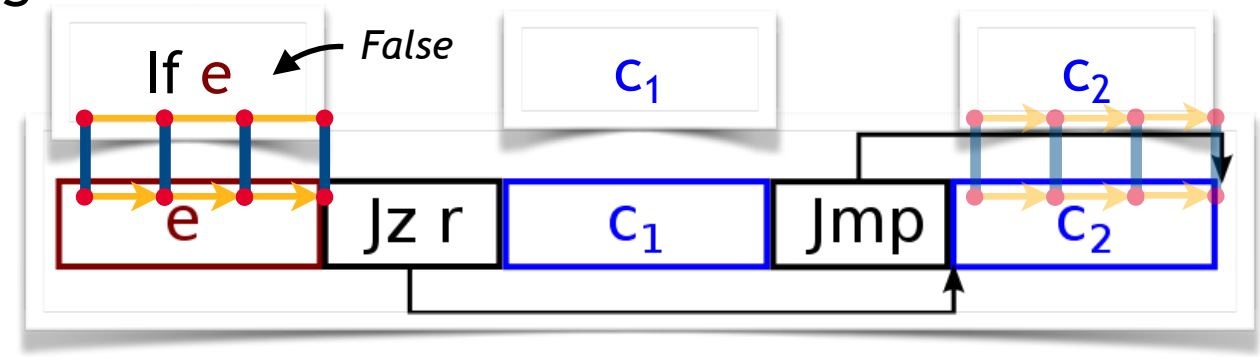

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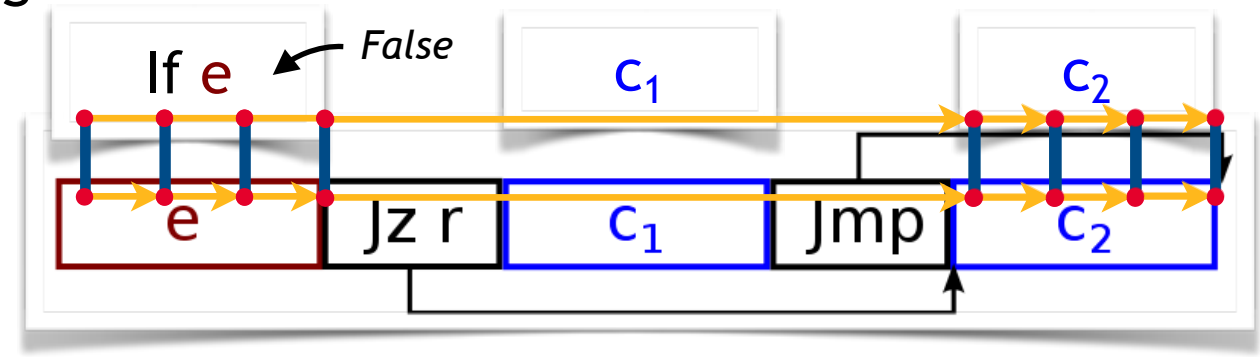

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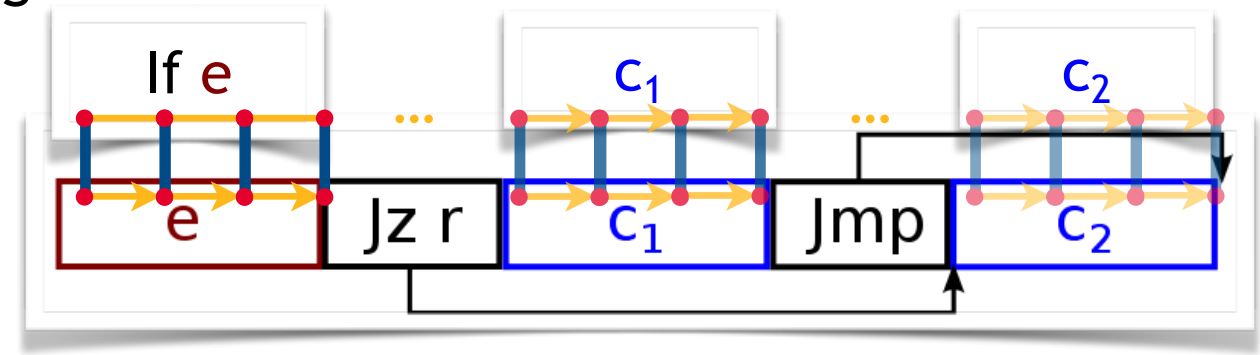

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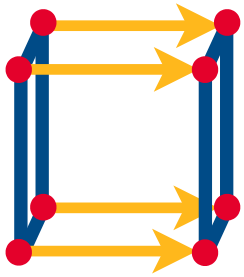
- Theorem: R (for B, with I) is a secure refinement



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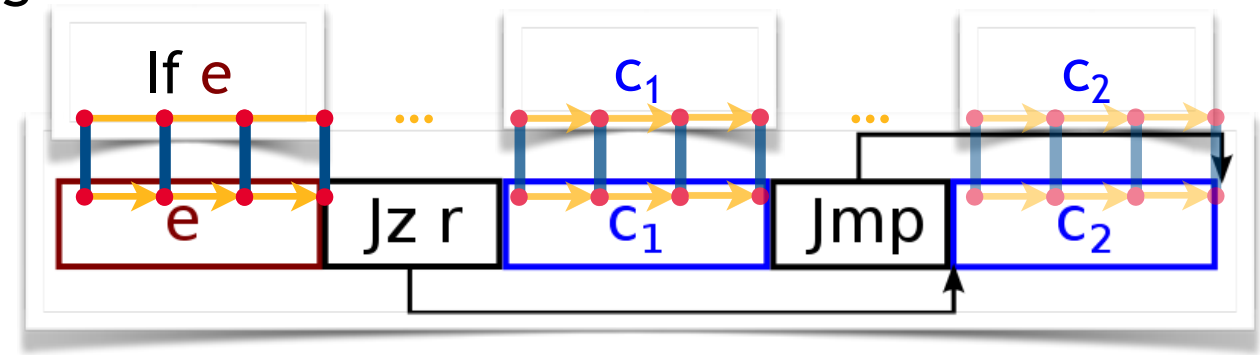
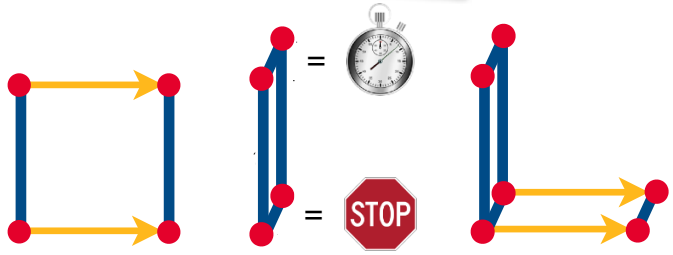


While
RISC

- Theorem: R (for B, with I) is a secure refinement
  (via *decomposition principle*)



While
RISC

(Formalisation: https://covern.org/itp19.html)

Verified compiler

Proof approach

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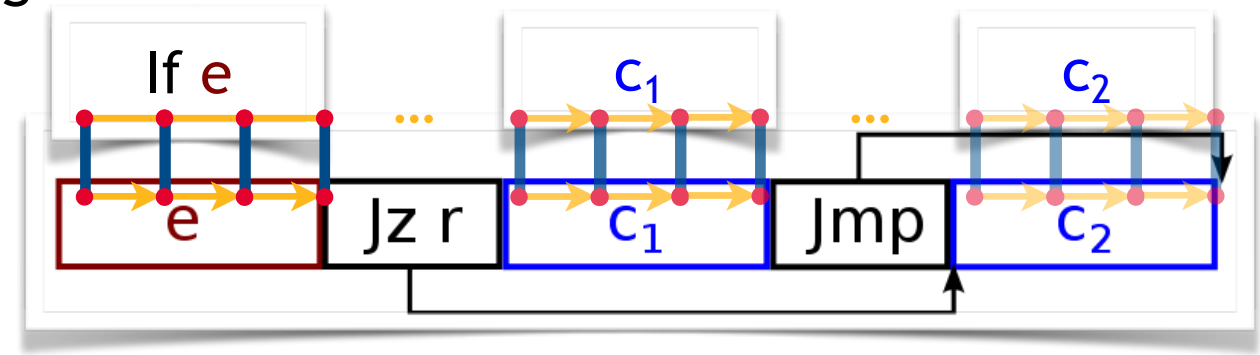

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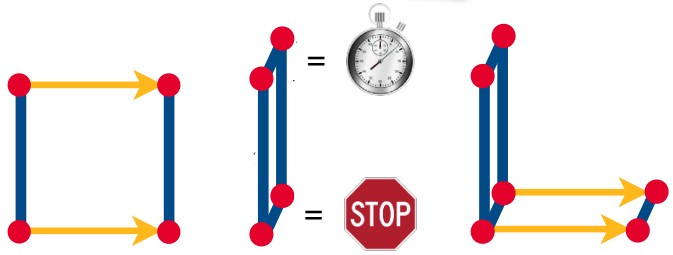

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- Theorem: Compiler input related to output by R

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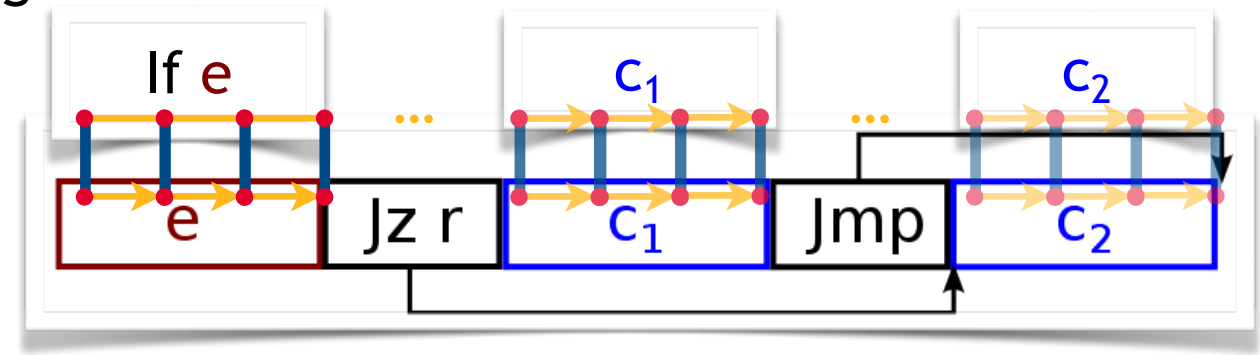

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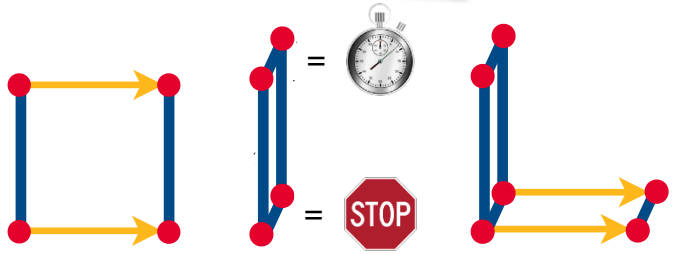

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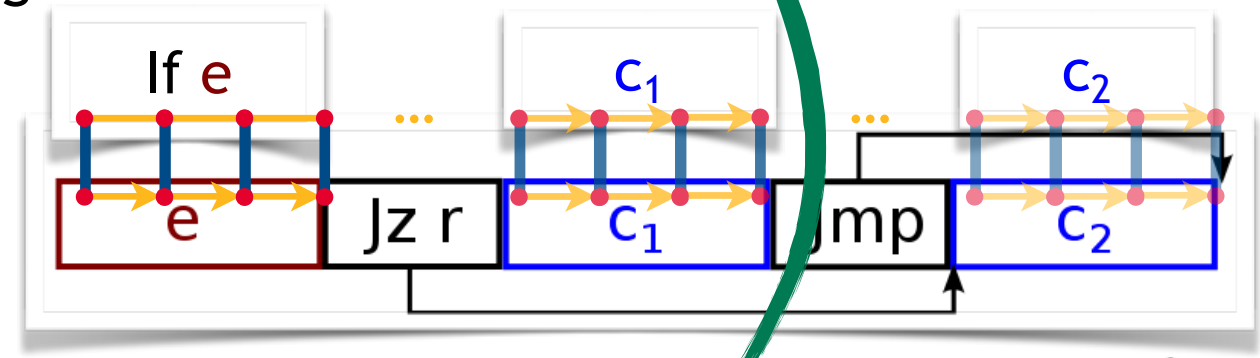

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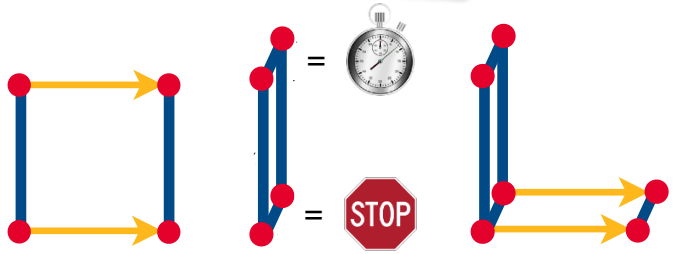

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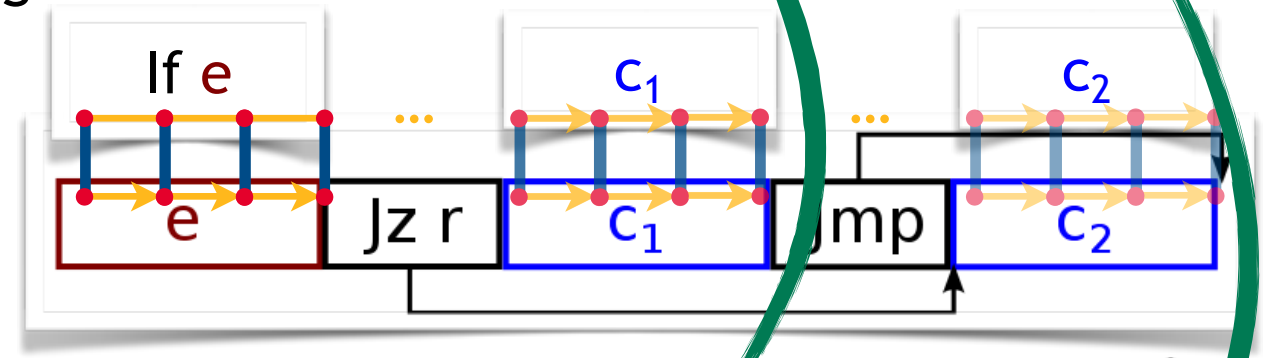

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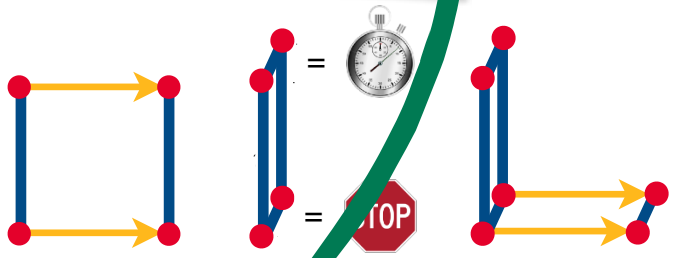

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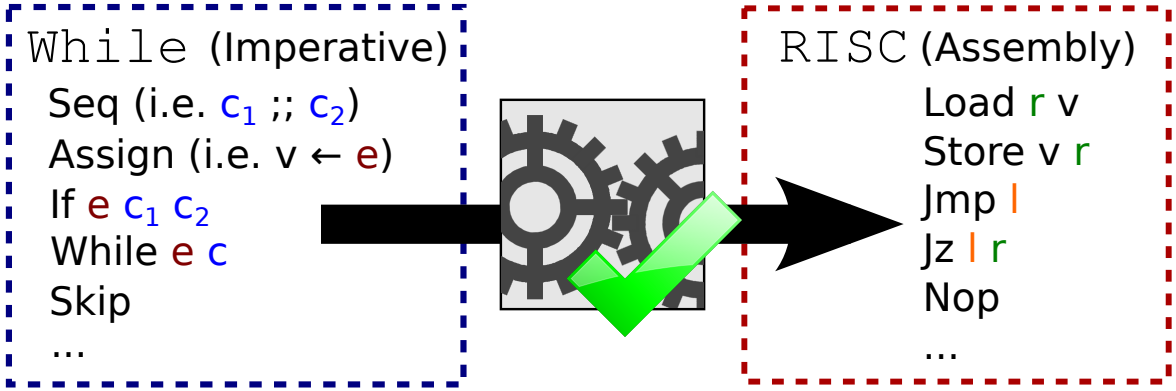
Verified compiler

Overview

(Based on: Tedesco et al. CSF'16)

An Isabelle/HOL *primrec* function



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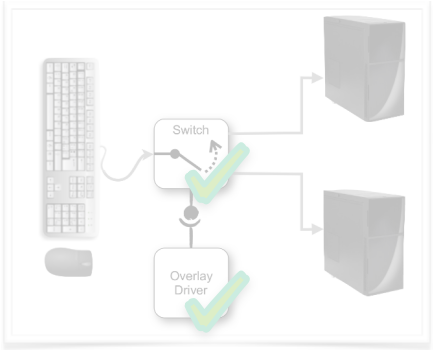
- Application: 2-thread input-handling model of *Cross Domain Desktop Compositor*



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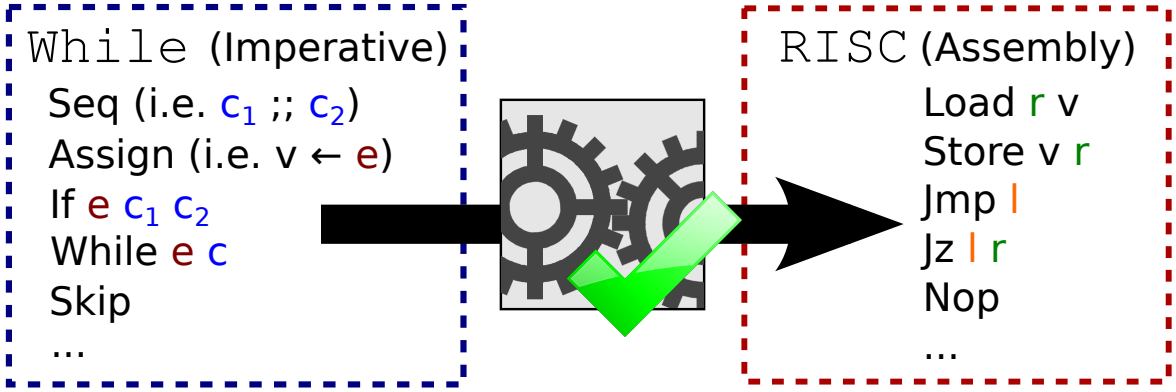

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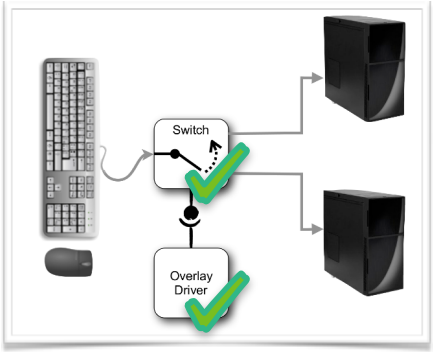

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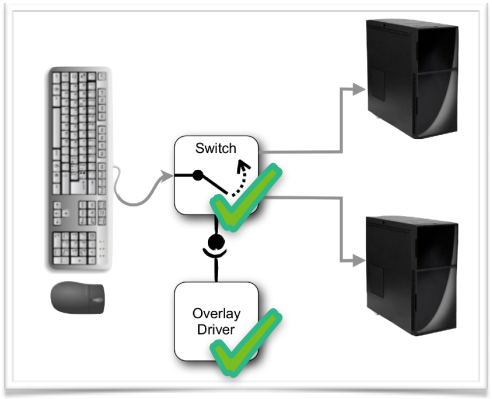
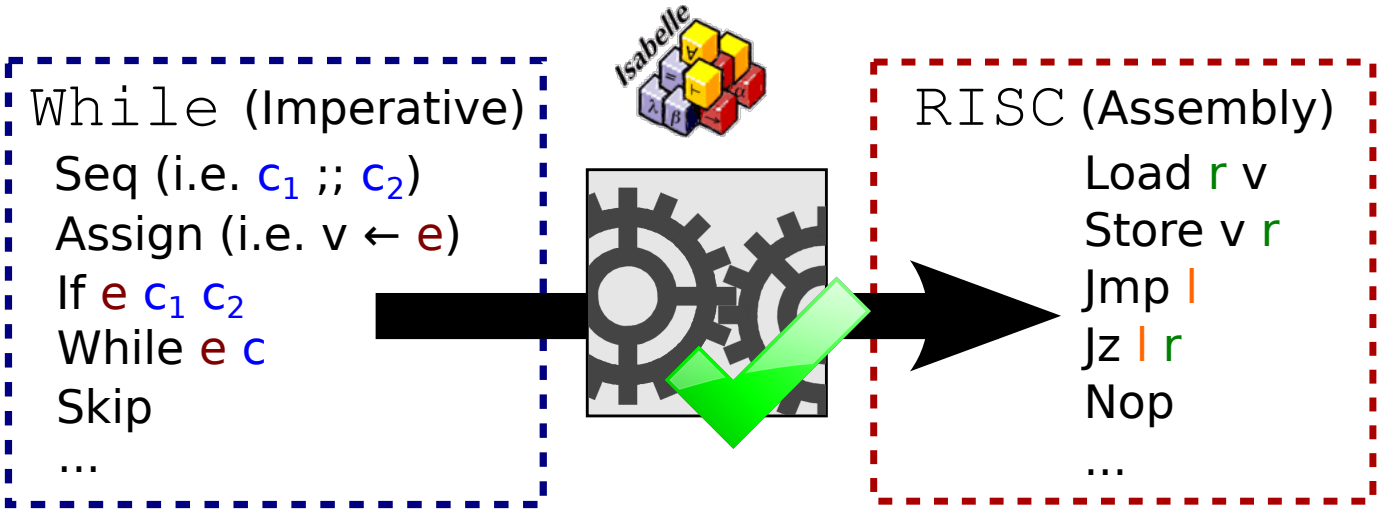
Verified compiler

Application: CDDC input-handling model





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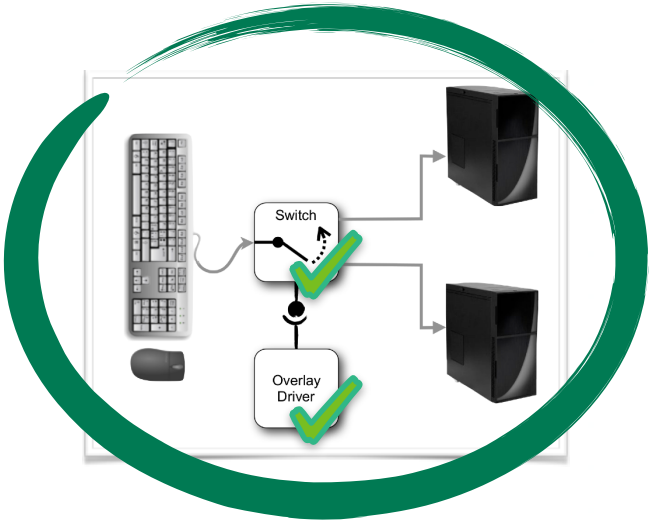

`While` (Imperative)
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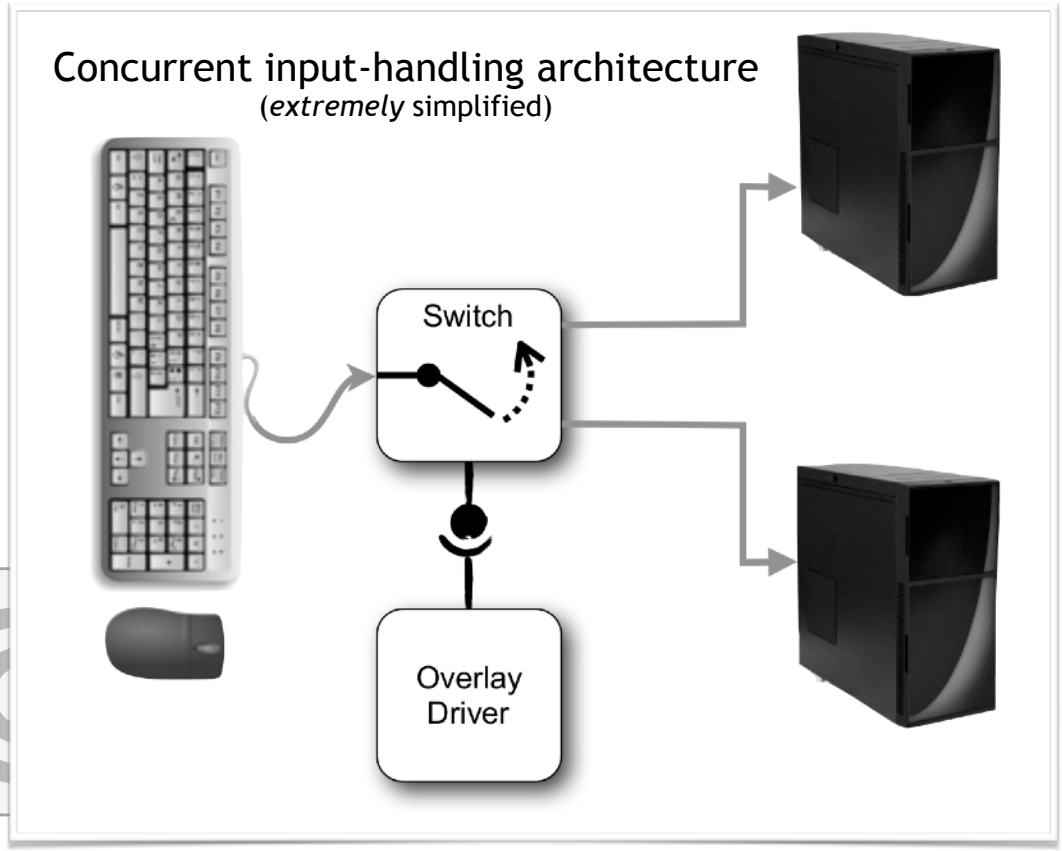

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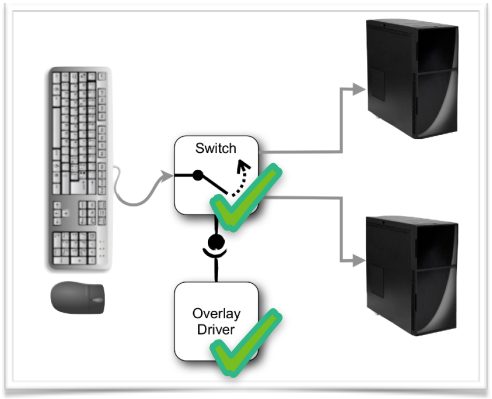
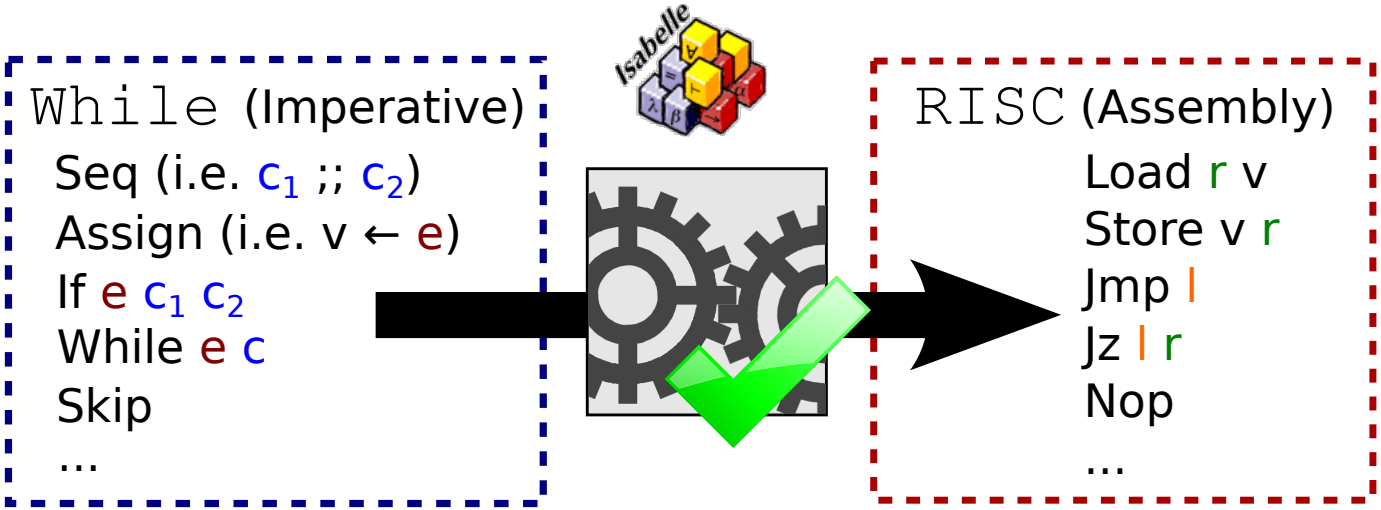
Verified compiler

Application: CDDC input-handling model

~150 lines `While`





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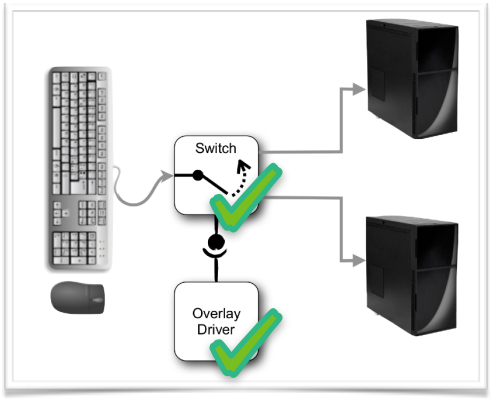

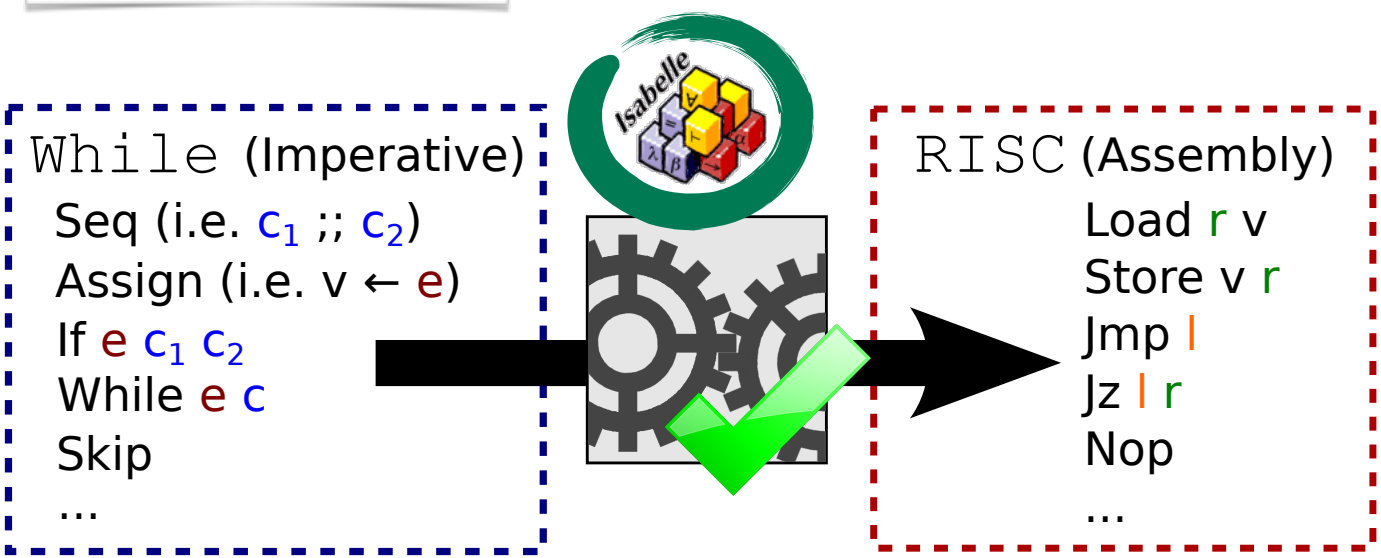

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Application: CDDC input-handling model

~150 lines `While`

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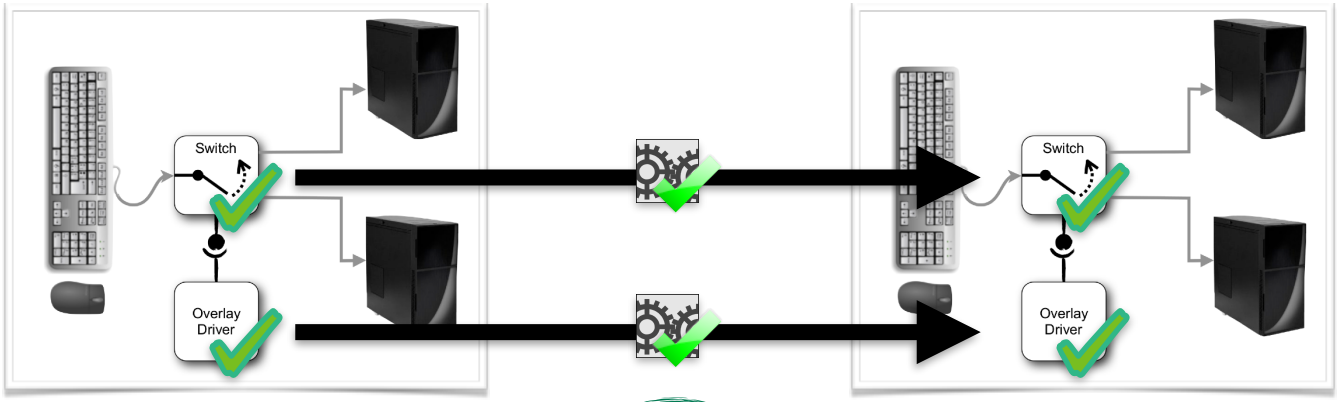

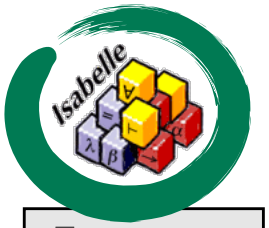

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- Load r v
- Store v r
- Jmp l
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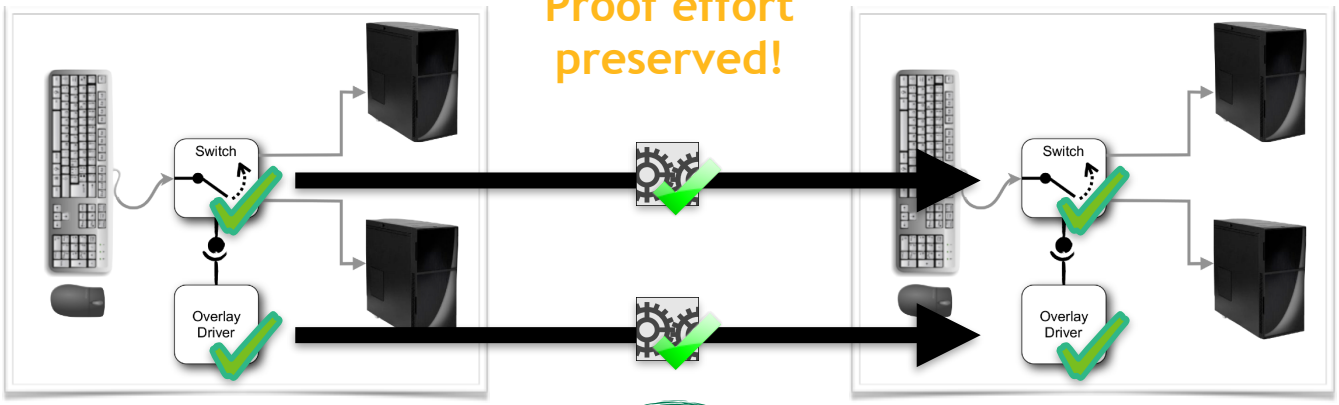

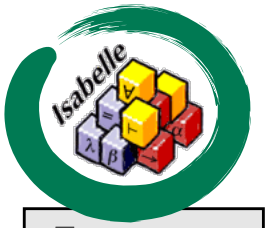

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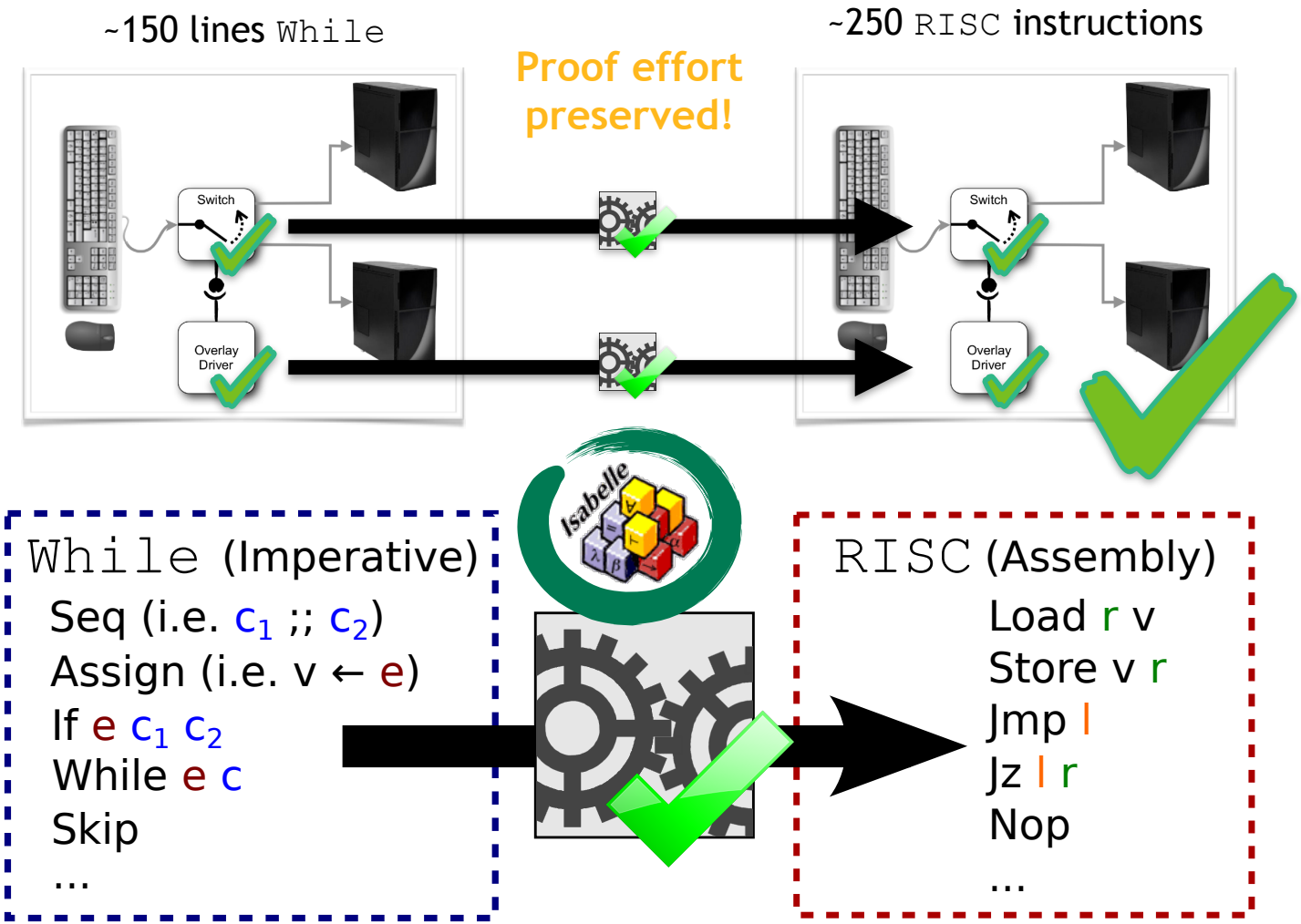

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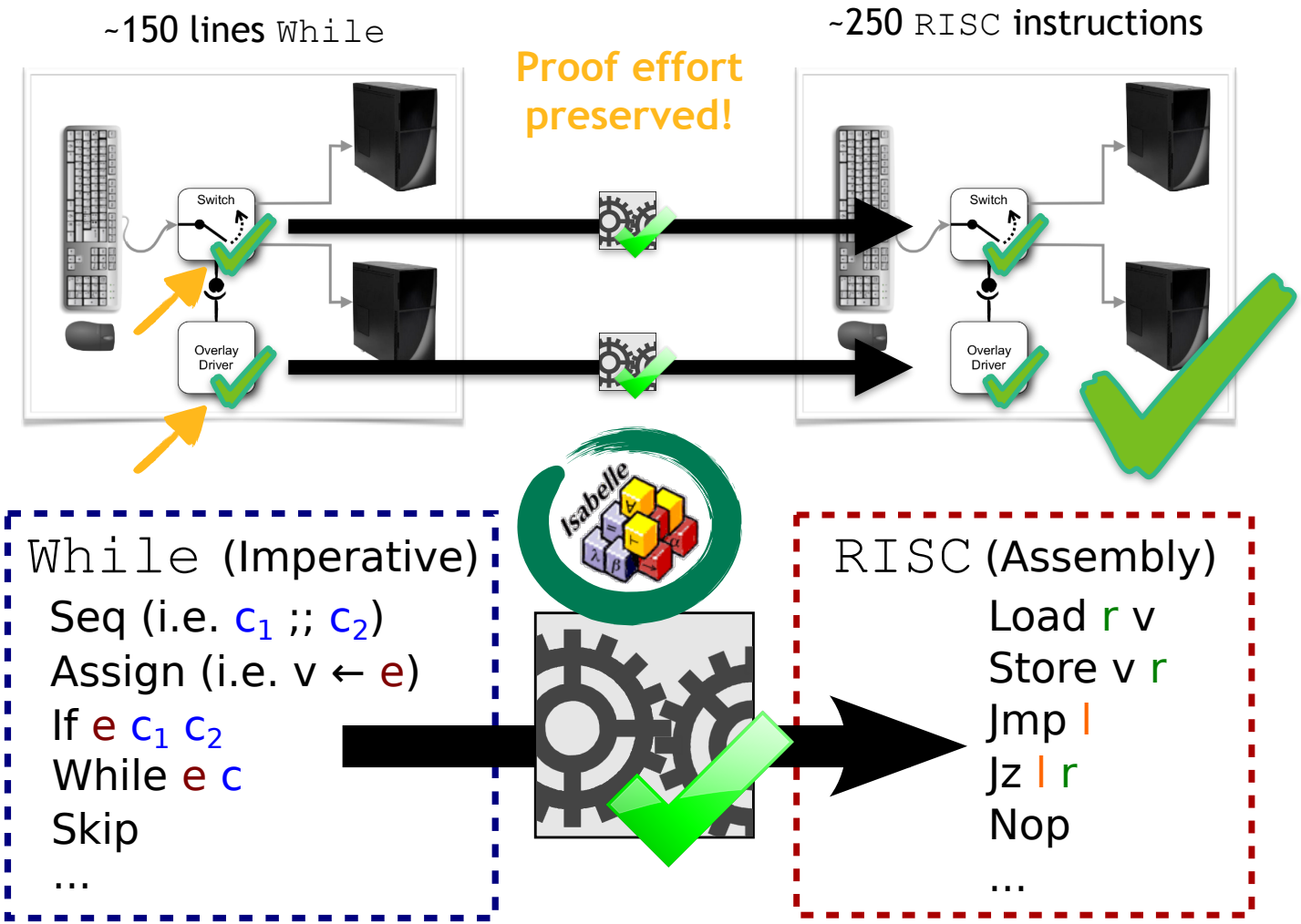

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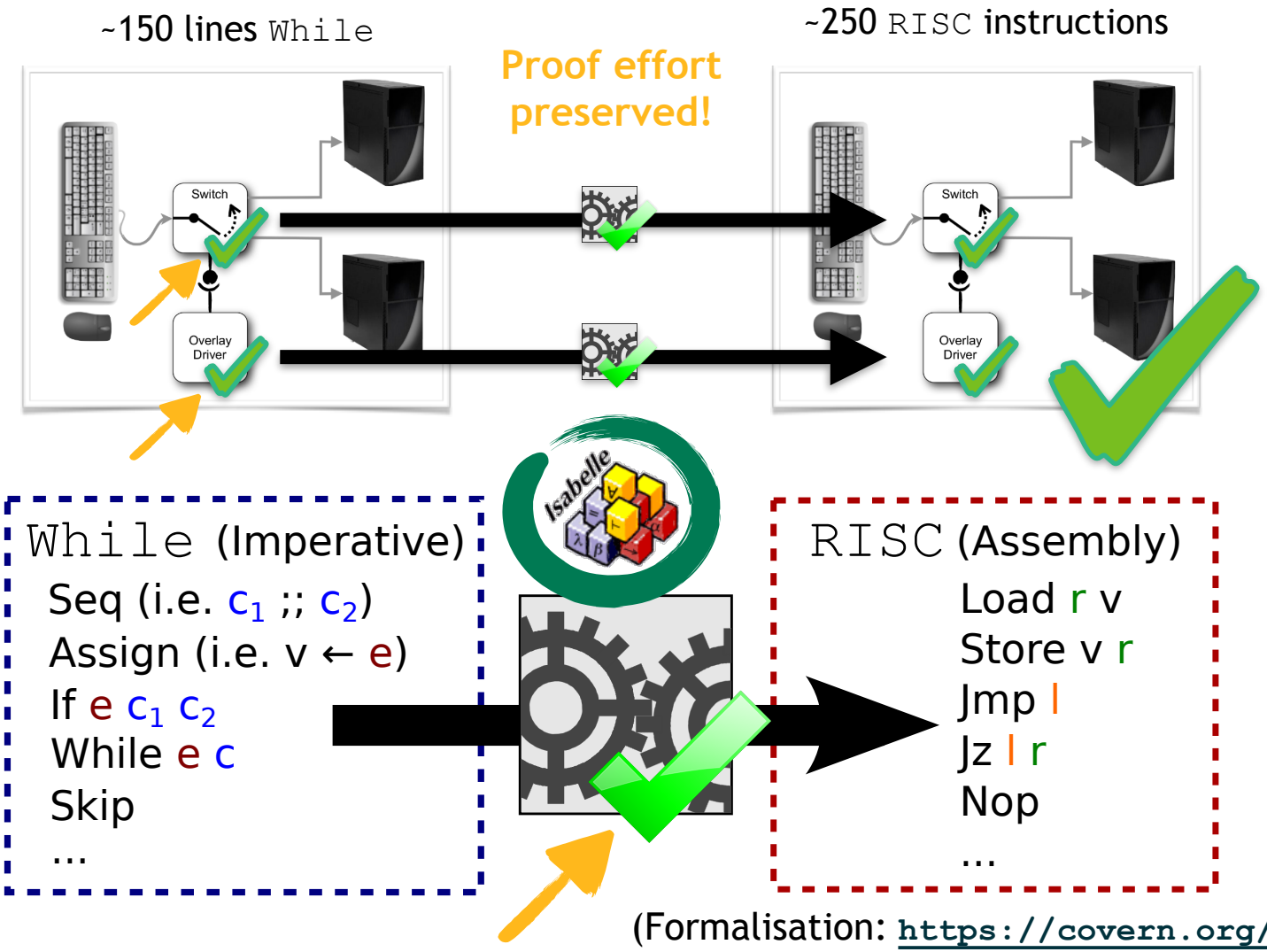

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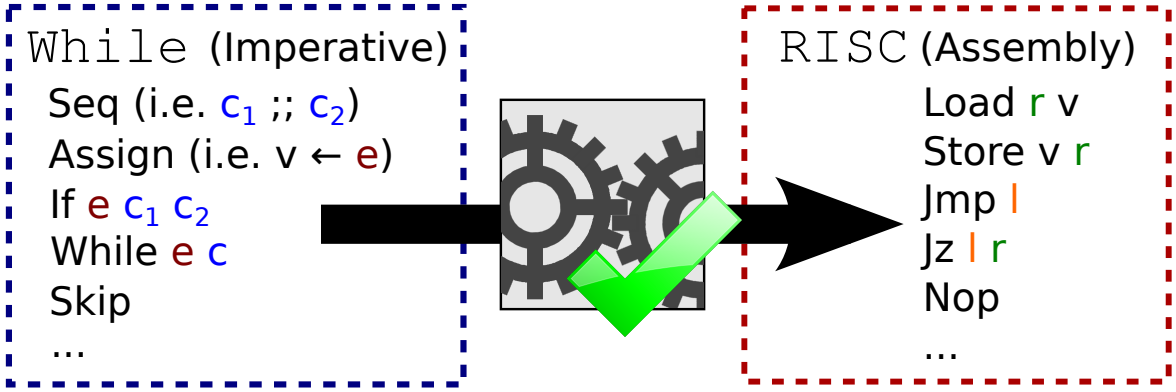
Verified compiler

Overview

(Based on: Tedesco et al. CSF'16)

An Isabelle/HOL *primrec* function



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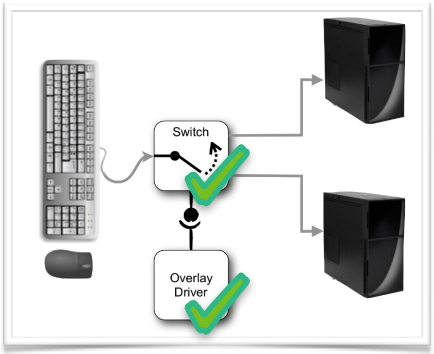

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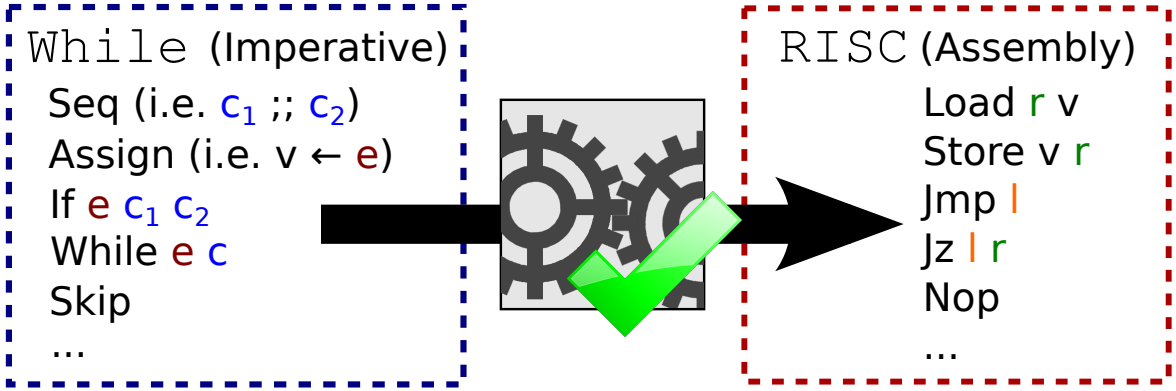

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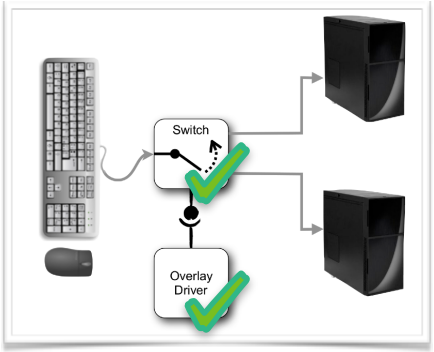

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Our contributions (Conclusion)

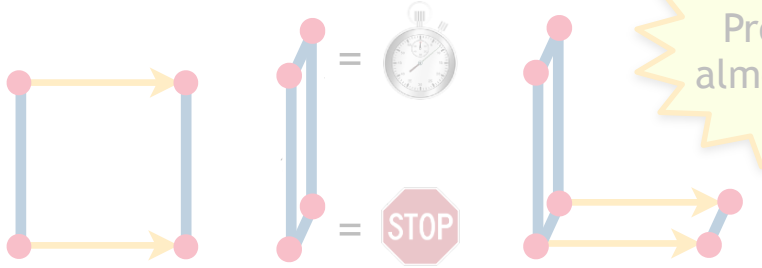
Goal

Prove a compiler *preserves proofs* of concurrent value-dependent information-flow security

Results

1. Decomposition principle

for *confidentiality-preserving refinement*



Proof effort almost *halved*!

(Technique)

2. Verified compiler

While-language to RISC-style assembly

(Proof-of-concept for technique)

Impact

1st such proofs carried to assembly-level model by compiler

(Formalisation: `https://covern.org/itp19.html`)

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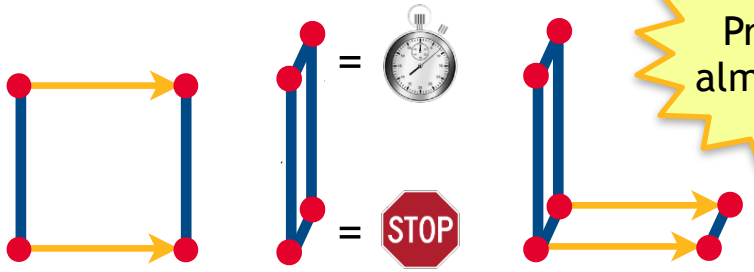

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Our contributions (Conclusion) + *Q & A*

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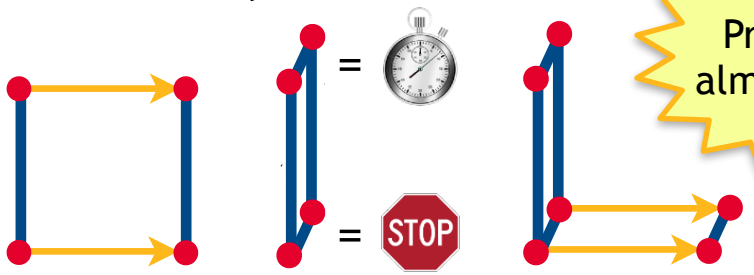

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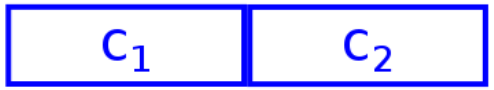
Thank you! Please see → (Formalisation: `https://covern.org/itp19.html`)

Appendix

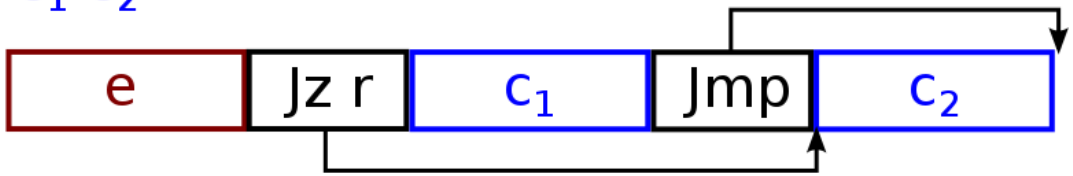
Differences from Tedesco et al. CSF'16 compilation scheme

- Seq (i.e. c_1 ;; c_2)



- Assign (i.e. v ← e)

- If e c_1 c_2



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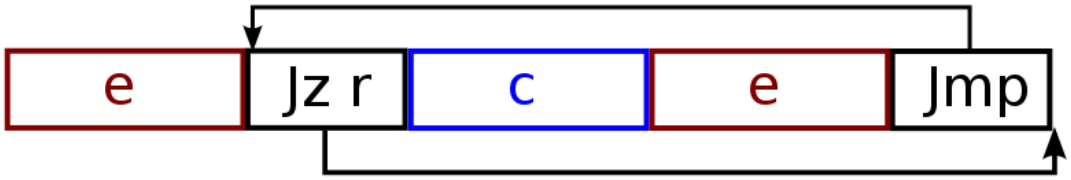
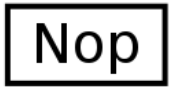


- ~~LockAcq l~~
- ~~LockRel l~~

- Skip



Tedesco et al. CSF'16

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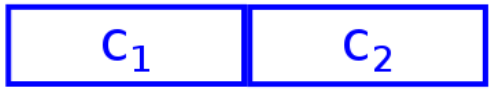
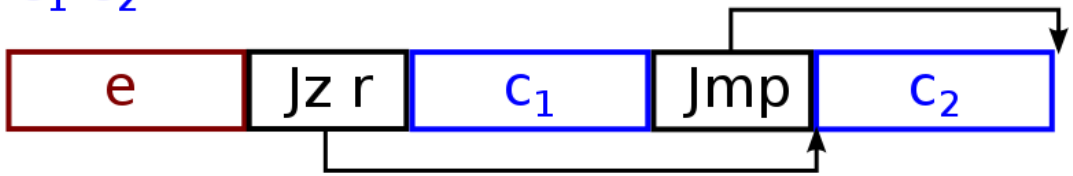


- Assign (i.e. v ← e)

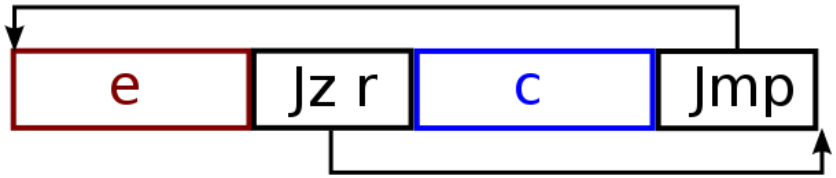
Fixed!

- If e c_1 c_2



- While e c

Simplified!

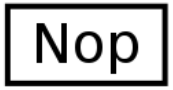


New!

- LockAcq l

- LockRel l

- Skip



Our While-to-RISC compiler