Formal Validation of a Practical Verification Condition Generator

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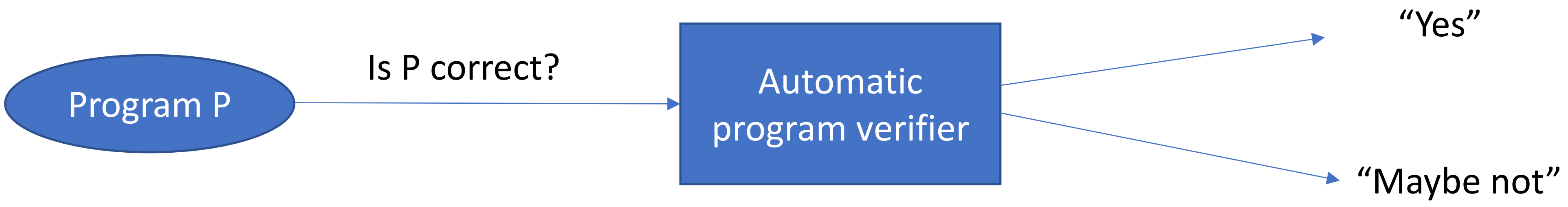
UBC

Motivation



Program P

Is P correct?

Automatic program verifier

“Yes”

“Maybe not”

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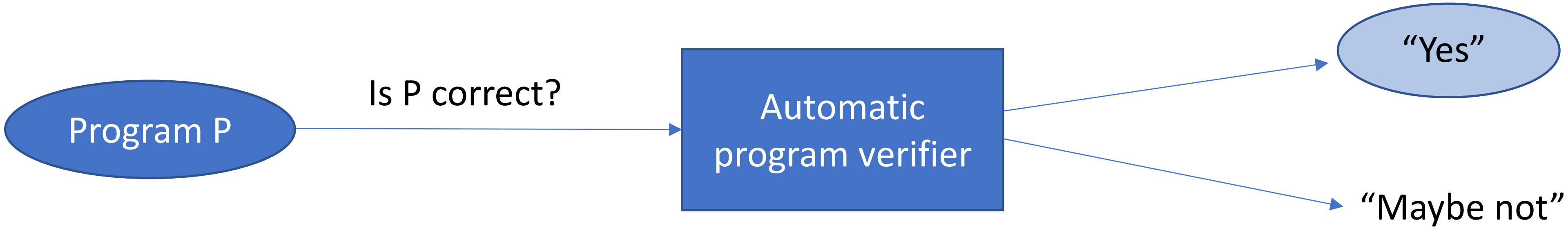

Soundness of a verifier: If the verifier says “Yes”, then P is indeed correct.

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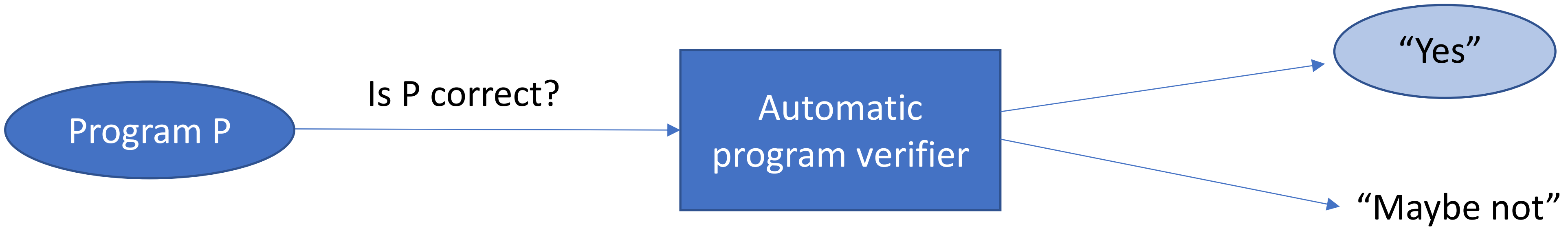

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Underlying logic of the verifier

- Sometimes formalised

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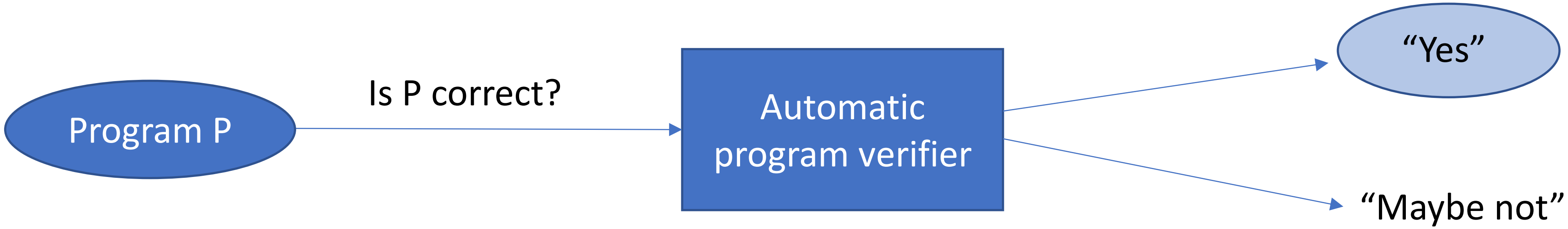

Soundness of a verifier: If the verifier says "Yes", then P is indeed correct.

Underlying logic of the verifier

- Sometimes formalised

Implementation of the verifier

- No formal guarantees
- Consists of many thousands of lines of code

Guarantees for verifier implementations

One possible approach: Prove verifier correct once and for all

- Impractical for existing verifiers, since implementation languages lack formalisation
- If reimplement in Coq or Isabelle, then lose benefits of modern languages

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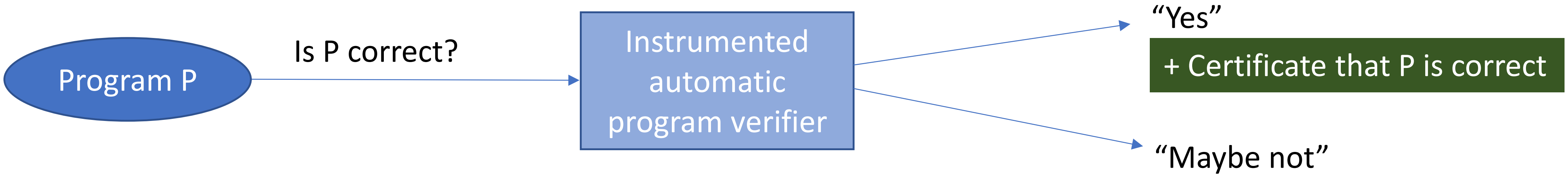
Our approach: Use a per-run validation strategy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“Yes”
+ Certificate that P is correct
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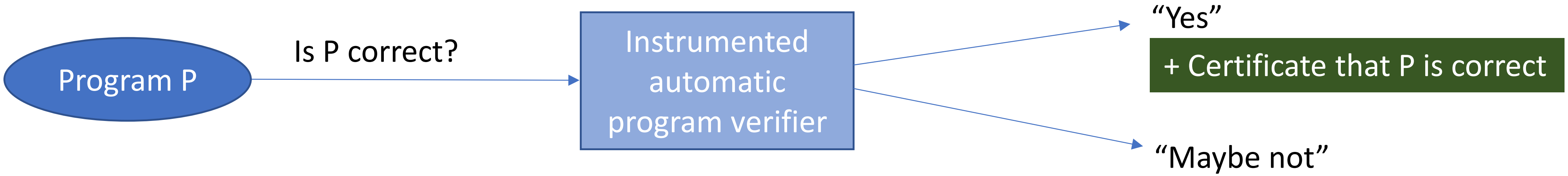
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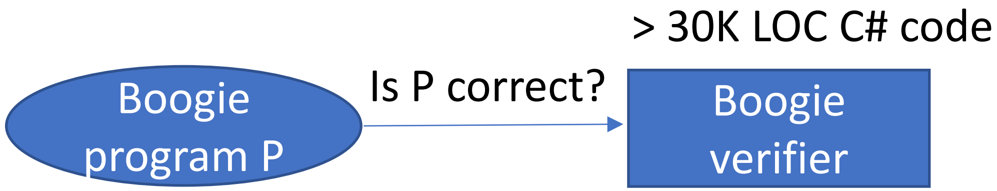
- We show it is feasible for an existing verifier
- Certificate generation is robust to implementation changes

Main contributions



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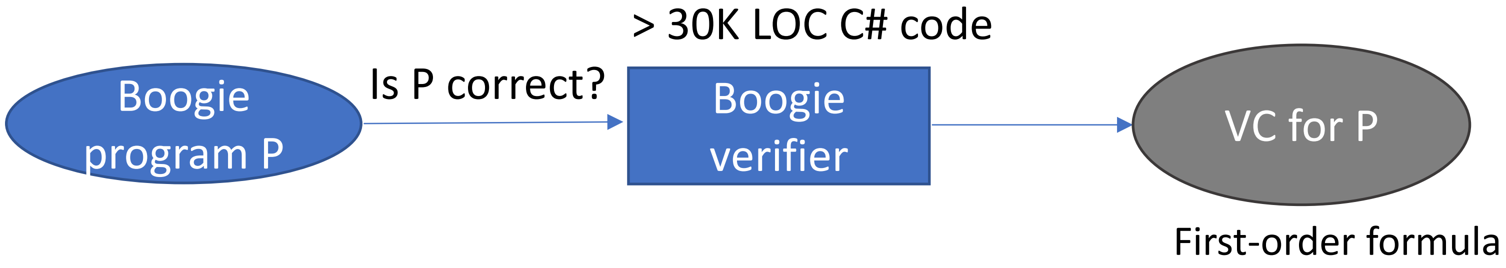

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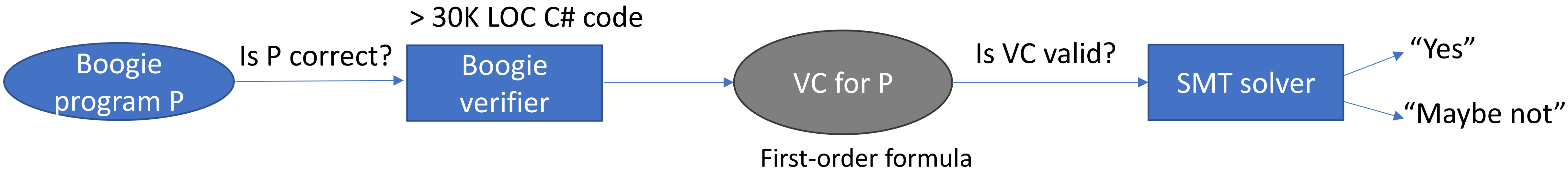

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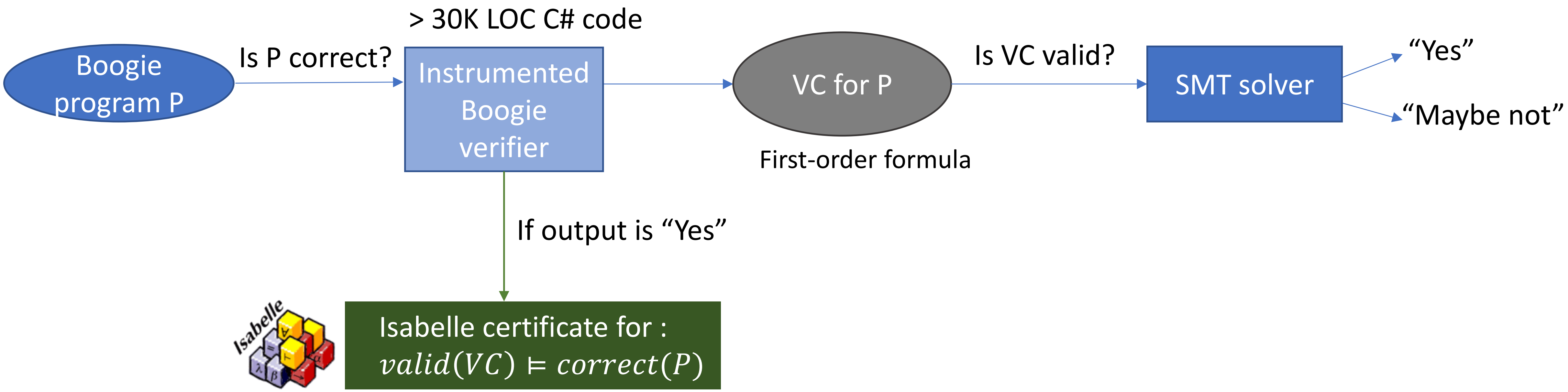
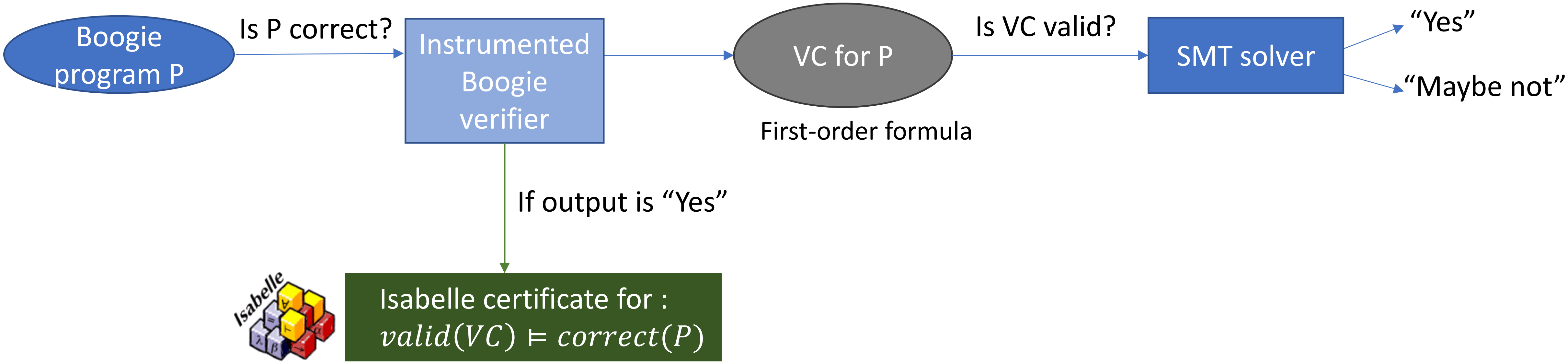


We formalise a subset of the Boogie language

Main contributions

low instrumentation effort (< 250 lines)

> 30K LOC C# code



Boogie program P

Is P correct?

Instrumented Boogie verifier

VC for P

First-order formula

Is VC valid?

SMT solver

“Yes”

“Maybe not”

If output is “Yes”

Isabelle certificate for : $valid(VC) \vDash correct(P)$

We formalise a subset of the Boogie language

Validating the Boogie verifier

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Verification of each procedure is decomposed into phases

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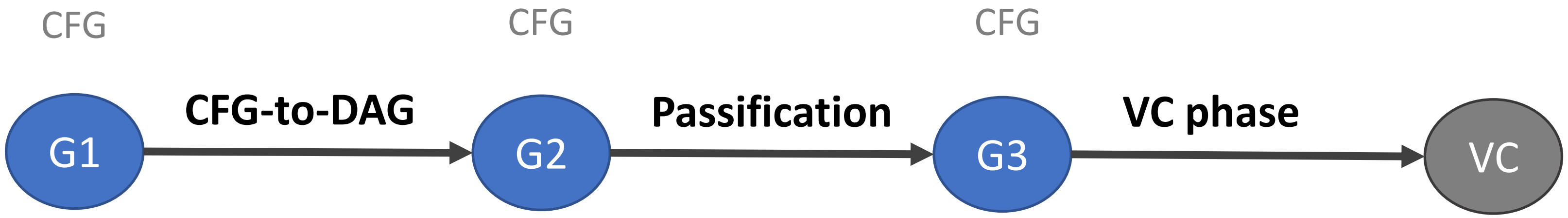
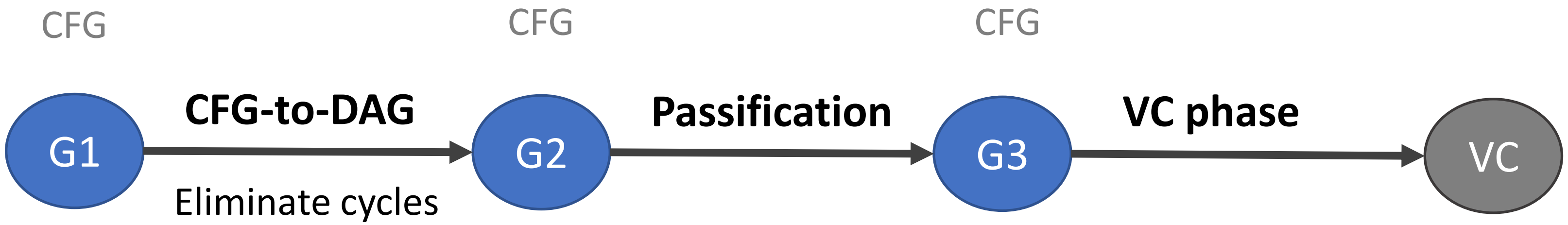


Validating the Boogie verifier

Verification of each procedure is decomposed into phases



Validating the Boogie verifier

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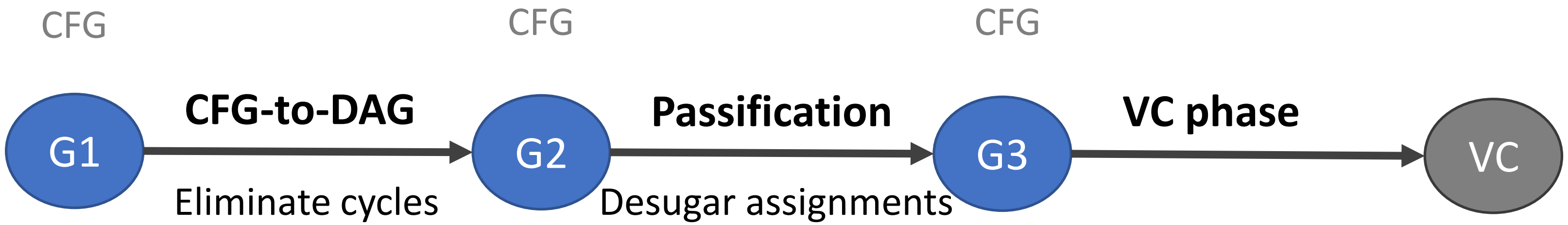


CFG

G1

CFG-to-DAG

Eliminate cycles

CFG

G2

Passification

Desugar assignments

CFG

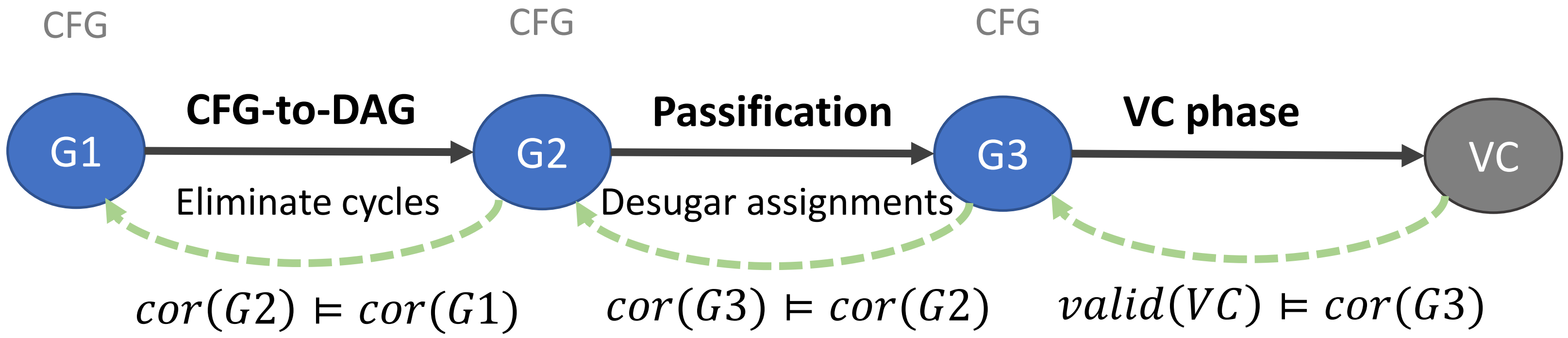
G3

VC phase

VC

Validating the Boogie verifier

Verification of each procedure is decomposed into phases



Validating the Boogie verifier

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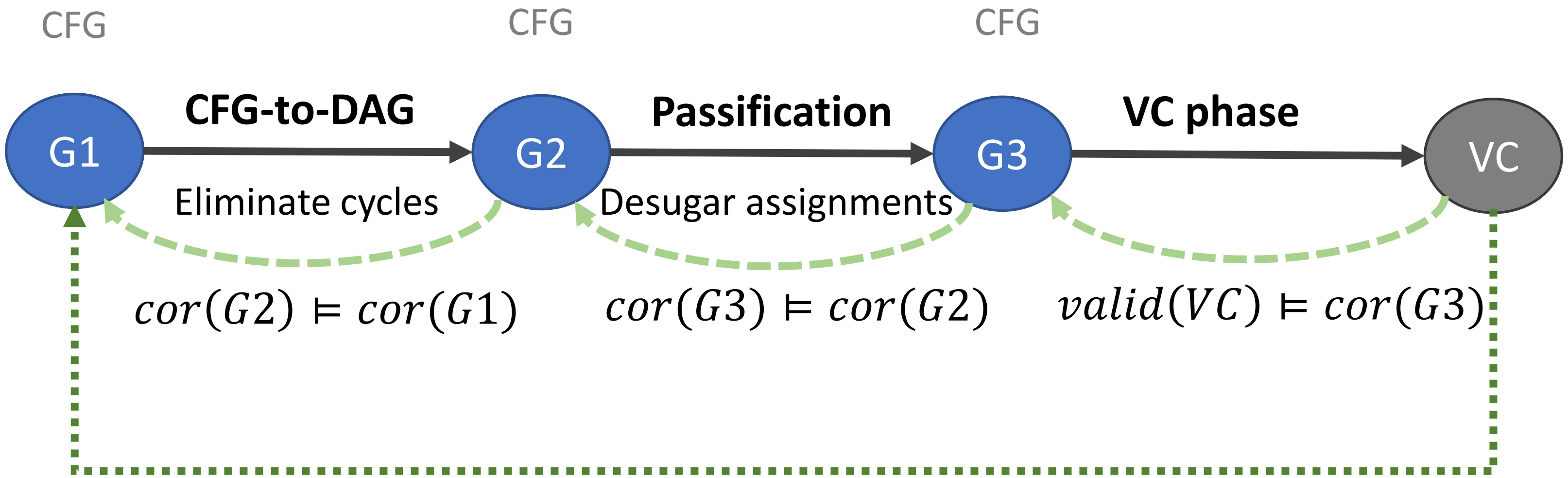

Final procedure certificate:
$valid(VC) \vDash cor(G1)$

Validating the Boogie verifier

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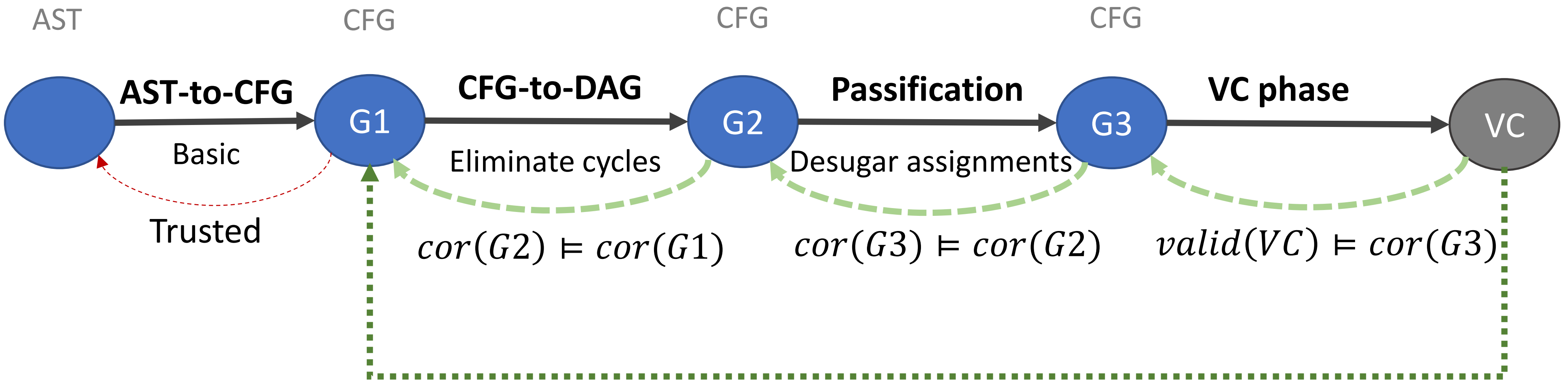

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Supported Boogie subset

Top-level	Procedures, (poly.) functions, axioms, type constructors, …

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Supported Boogie subset

Top-level	Procedures, (poly.) functions, axioms, type constructors, …
Types	Booleans, integers, uninterpreted types
Expressions	function calls, value and type quantification, …
Statements	x := E **assert** E **assume** E **havoc** x

Example

```
assume i != 0
j := 0

while (i != 0)
 invariant j >= 0 && (i == 0 ==> j > 0)
{
  j := j+1
  i := i-1
}

assert j > 0
…
```

Example

Consider all possible values for i and j

```
assume i != 0
j := 0

while (i != 0)
 invariant j >= 0 && (i == 0 ==> j > 0)
{
  j := j+1
  i := i-1
}

assert j > 0
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```

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Prune executions

Example

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while (i != 0)
 invariant j >= 0 && (i == 0 ==> j > 0)
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assert j > 0
…
```

Always satisfied here

CFG representation

```
assume i != 0
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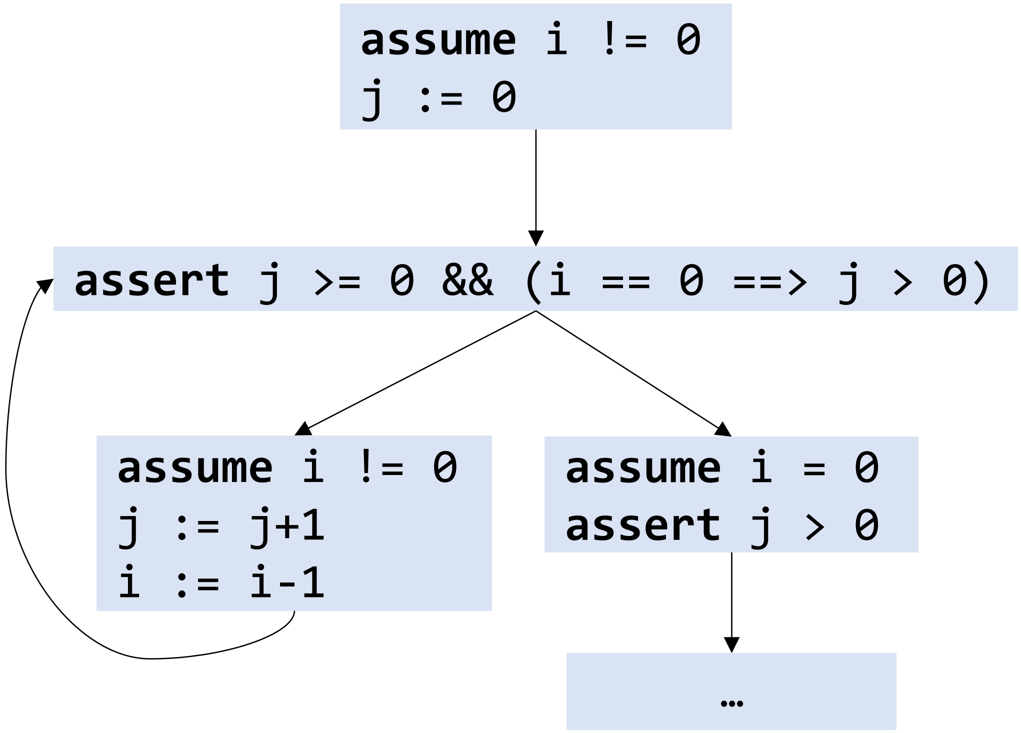

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assume i != 0
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```
assert j >= 0 && (i == 0 ==> j > 0)
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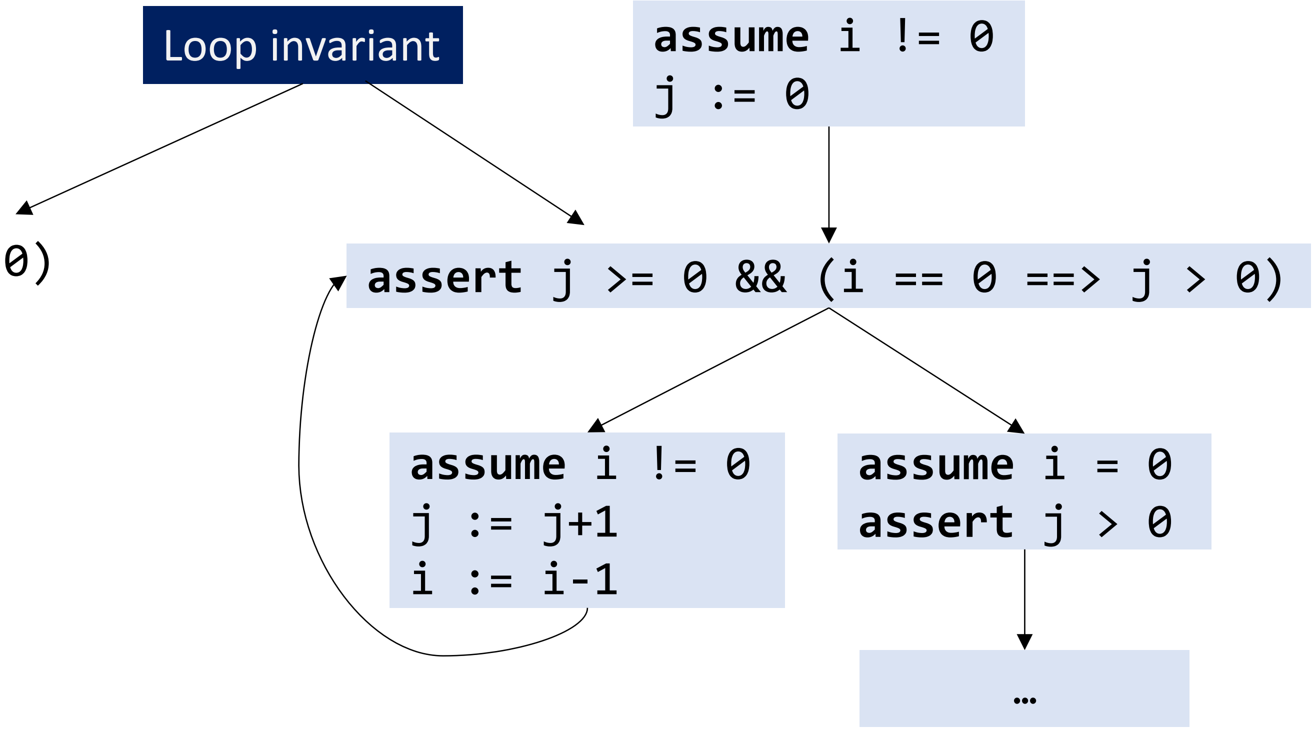

Loop invariant

```
assume i != 0
j := 0
```

```
assert j >= 0 && (i == 0 ==> j > 0)
```

```
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```

```
assume i = 0
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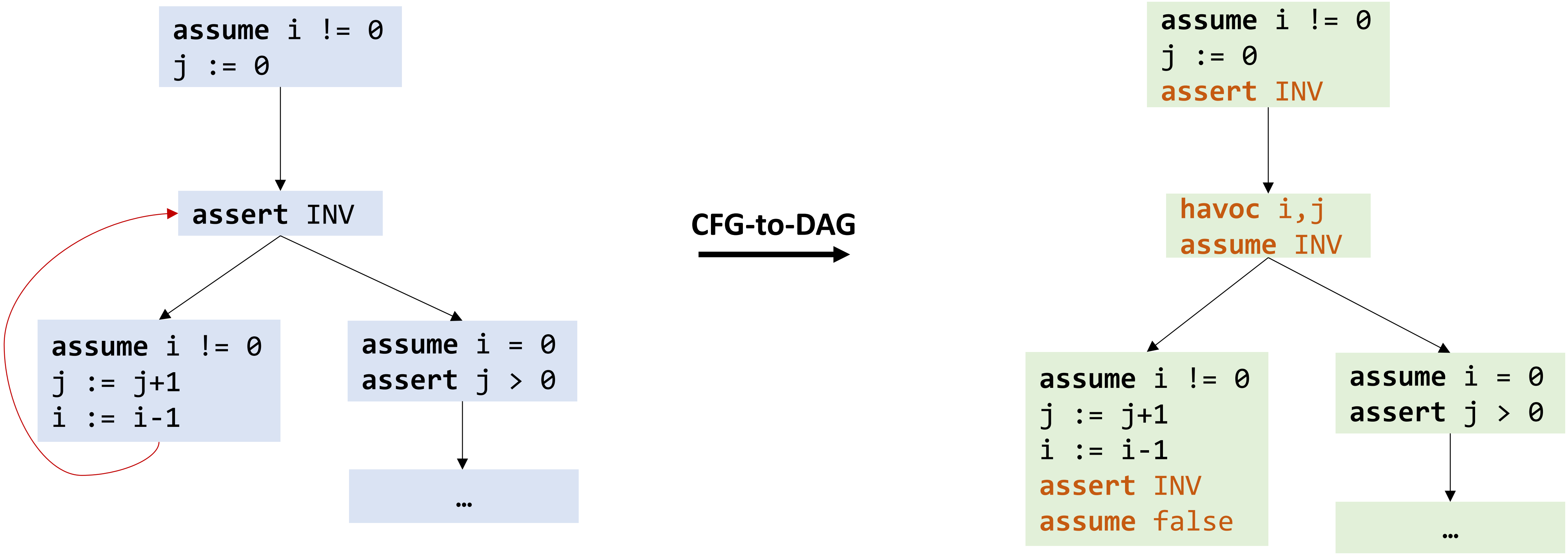
```

…

CFG-to-DAG phase



```
assume i != 0
j := 0
```

```
assert INV
```

```
assume i != 0
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i := i-1
```

```
assume i = 0
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```

```
…
```

CFG-to-DAG

```
assume i != 0
j := 0
assert INV
```

```
havoc i,j
assume INV
```

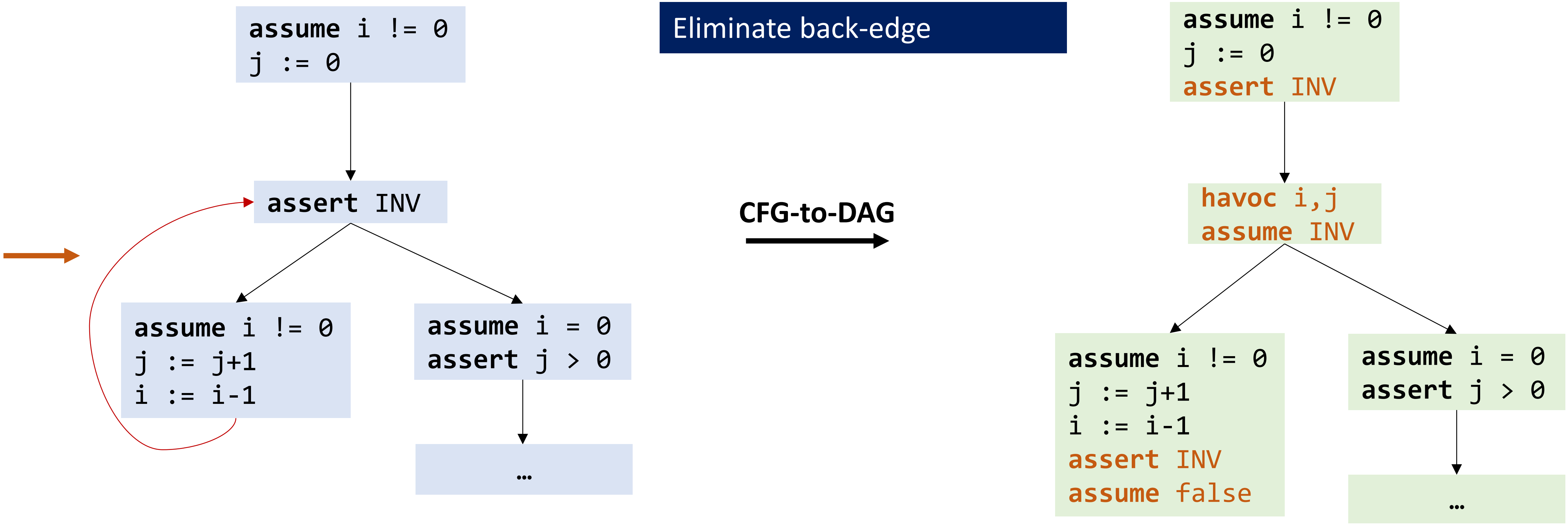
```
assume i != 0
j := j+1
i := i-1
assert INV
assume false
```

```
assume i = 0
assert j > 0
```

```
…
```

CFG-to-DAG phase

Eliminate back-edge



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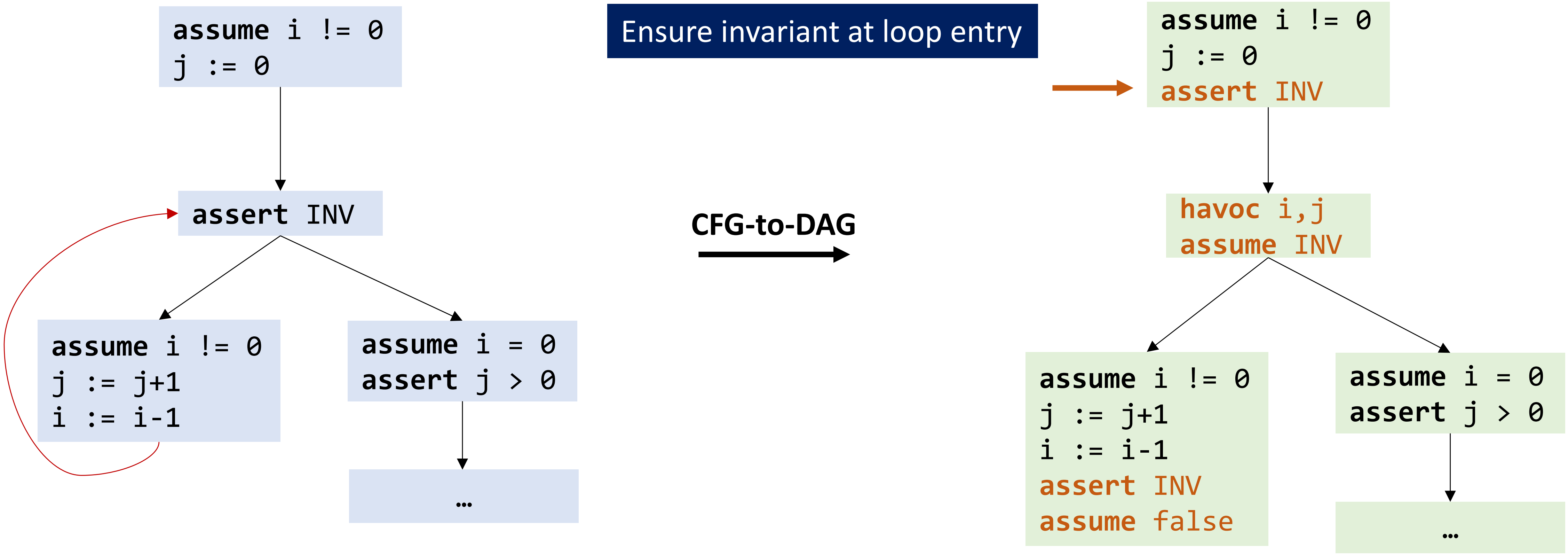

Ensure invariant at loop entry

```
assume i != 0
j := 0
```

```
assert INV
```

```
assume i != 0
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```

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```
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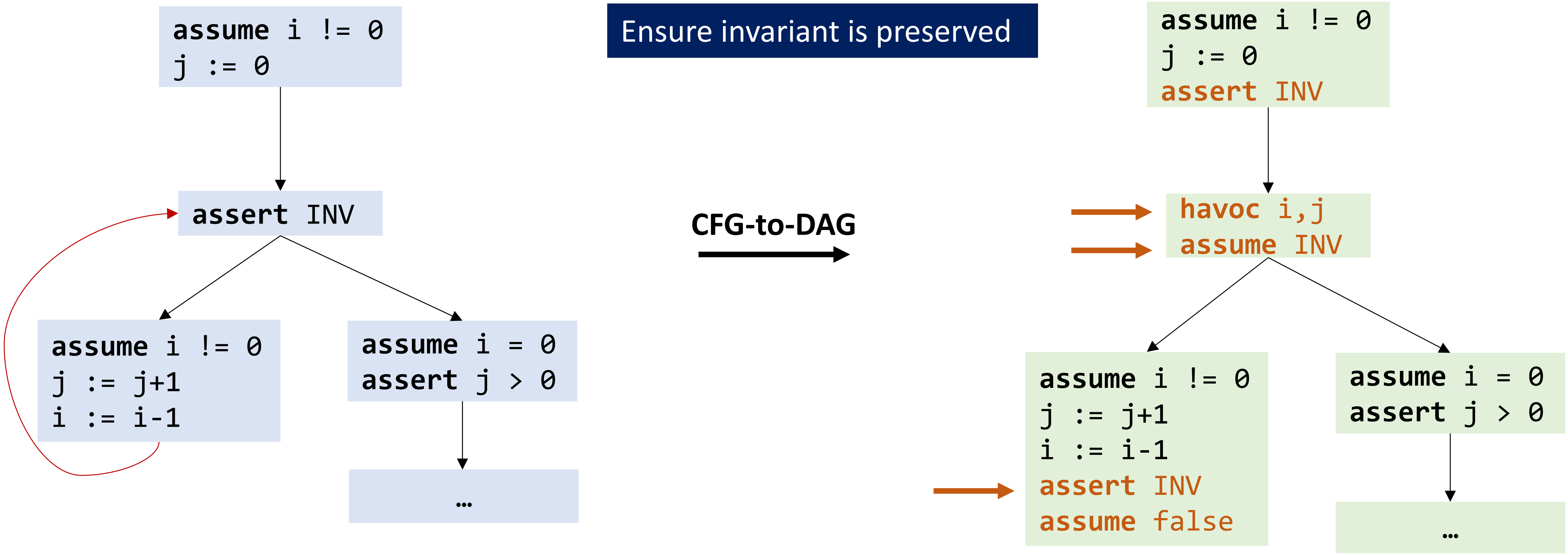

Ensure invariant is preserved

```
assume i != 0
j := 0
```

```
assert INV
```

```
assume i != 0
j := j+1
i := i-1
```

```
assume i = 0
assert j > 0
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```
…
```

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assume i != 0
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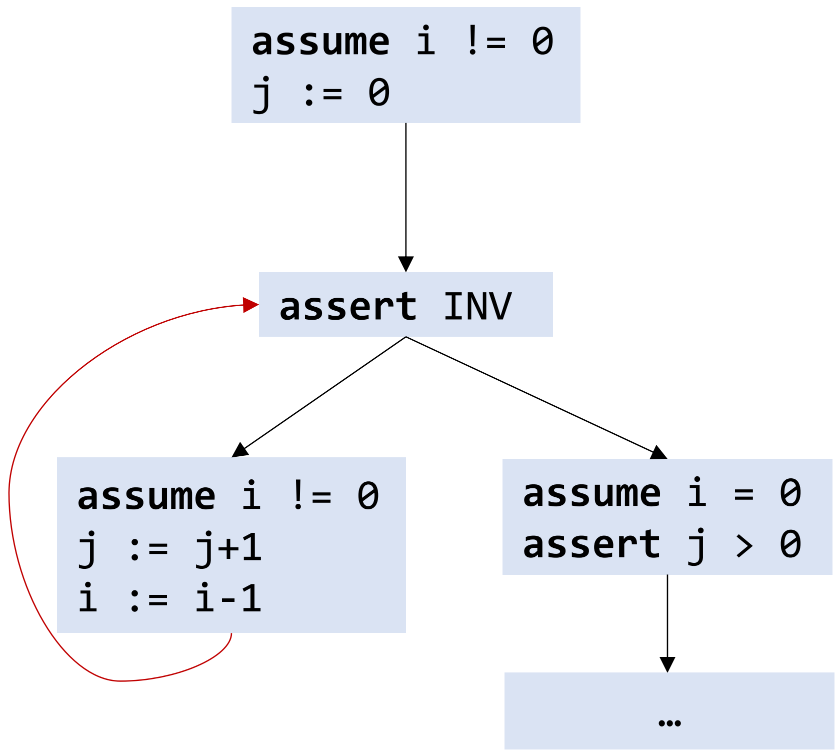

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Prune loop executions

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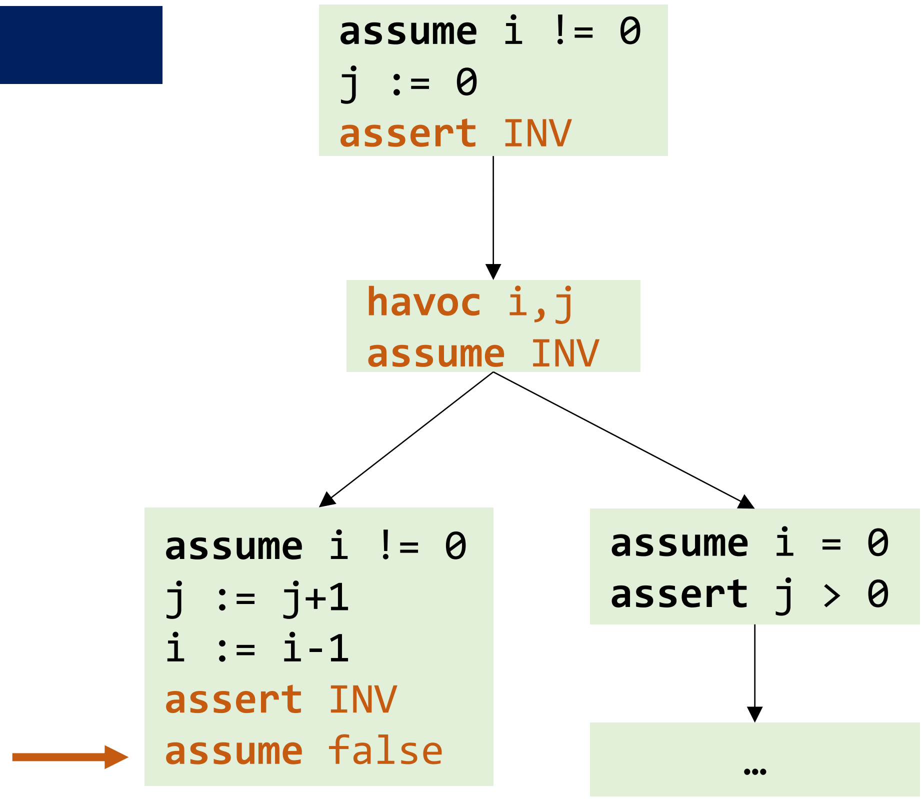

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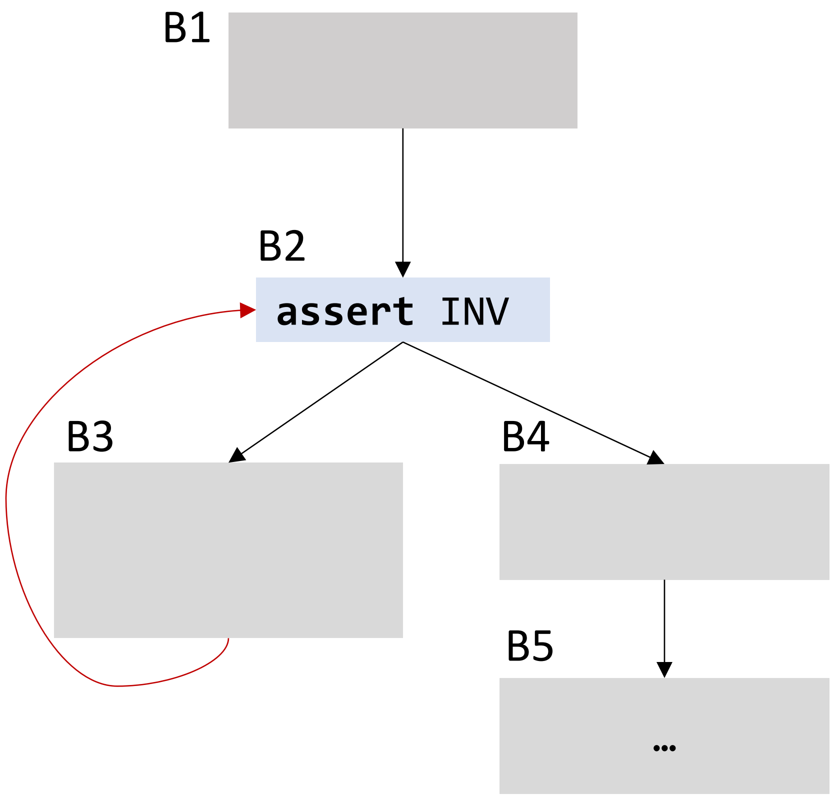
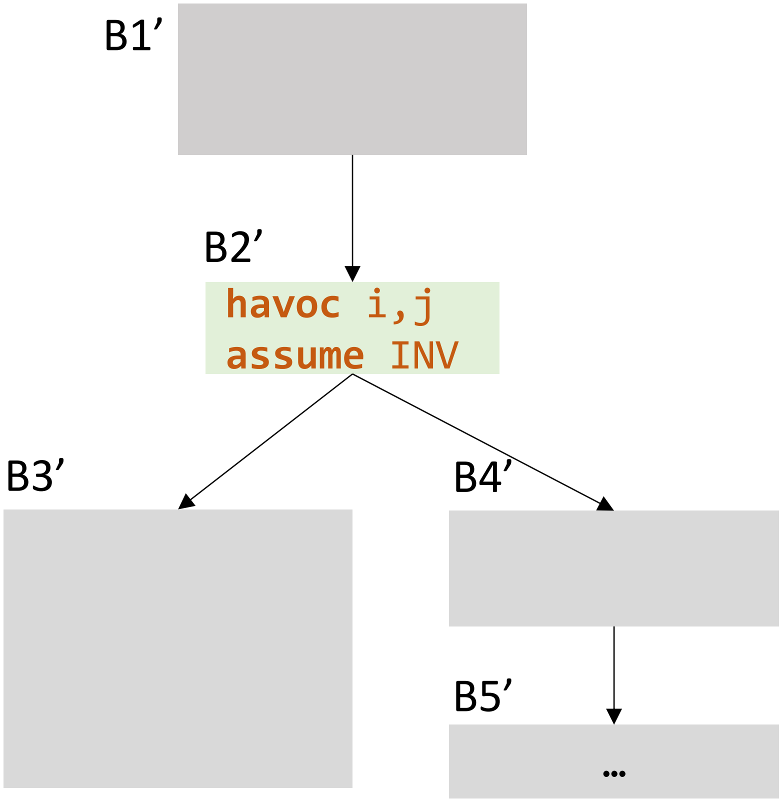
CFG-to-DAG validation: local results





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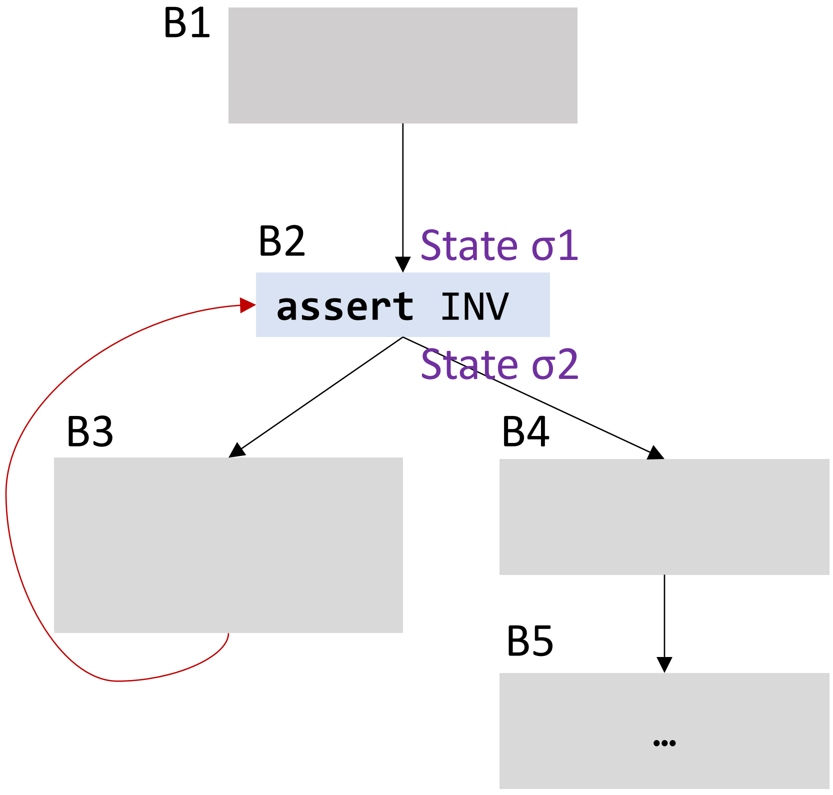

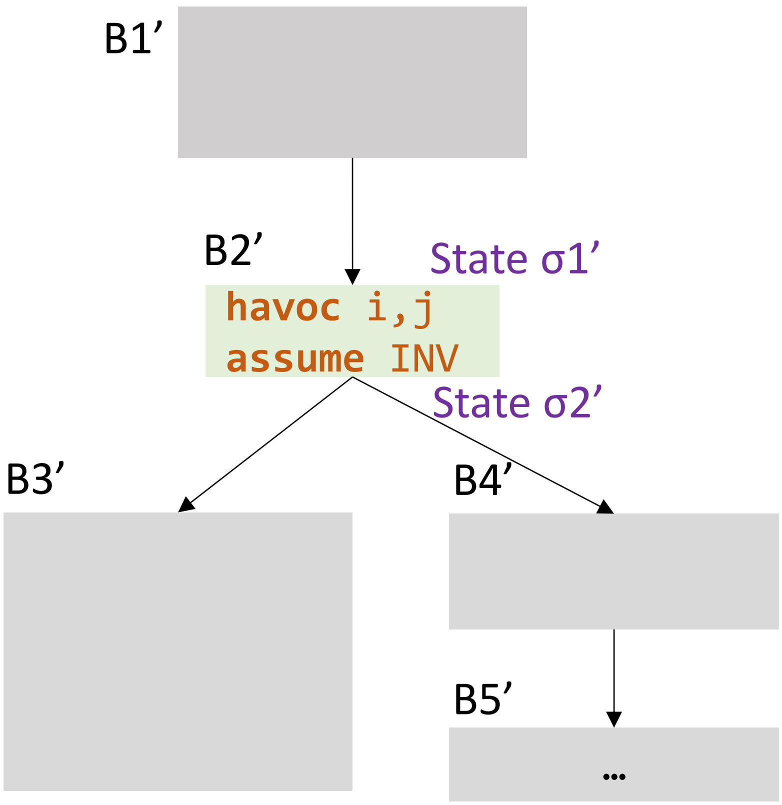

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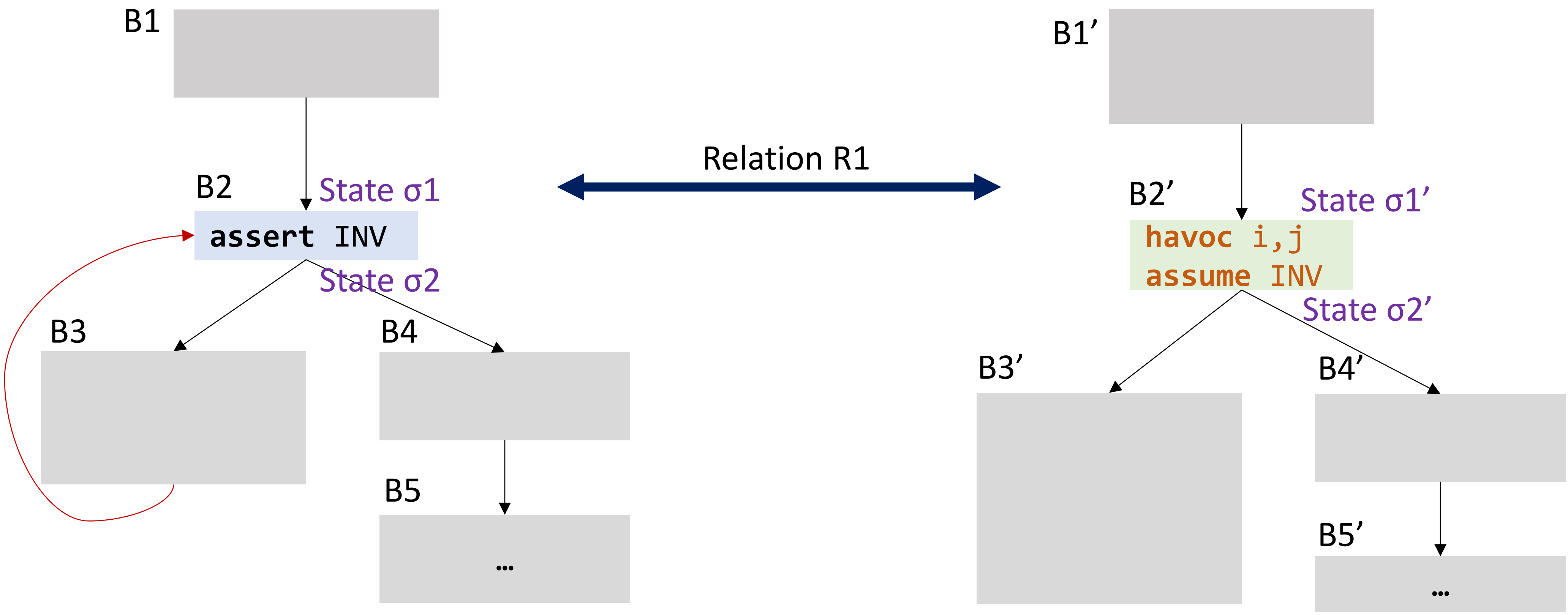

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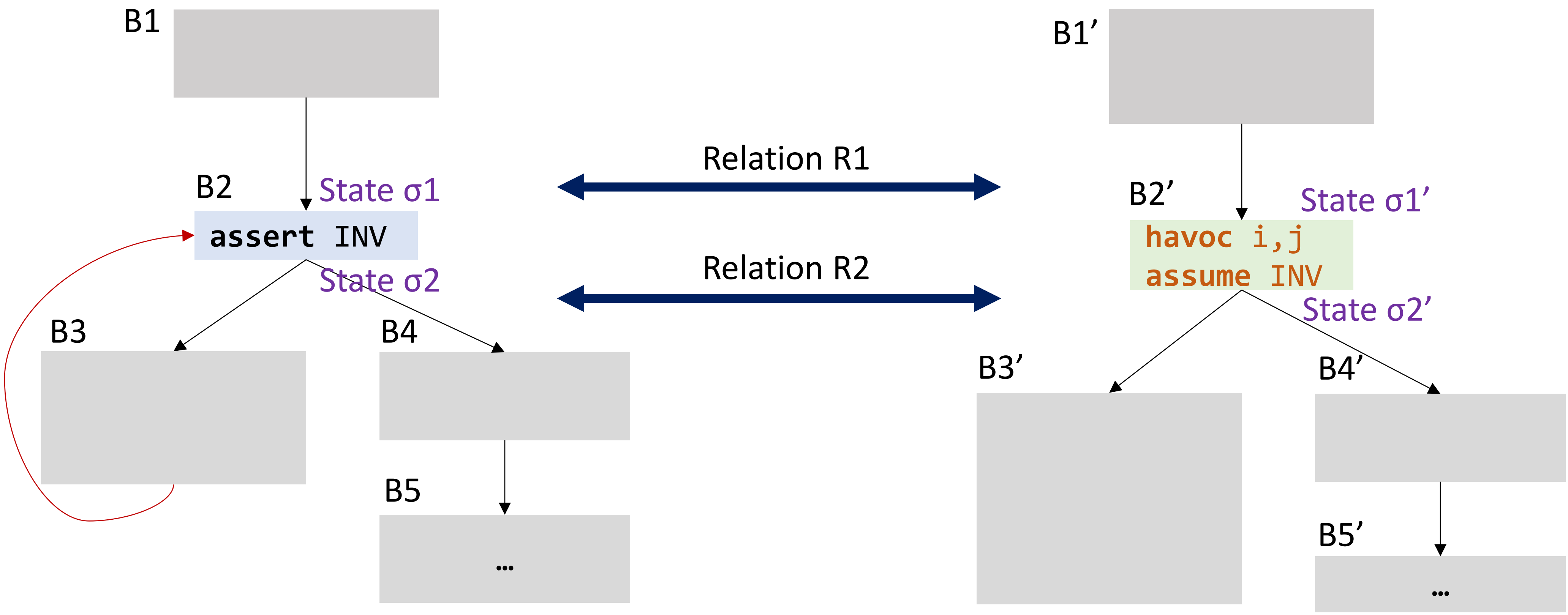
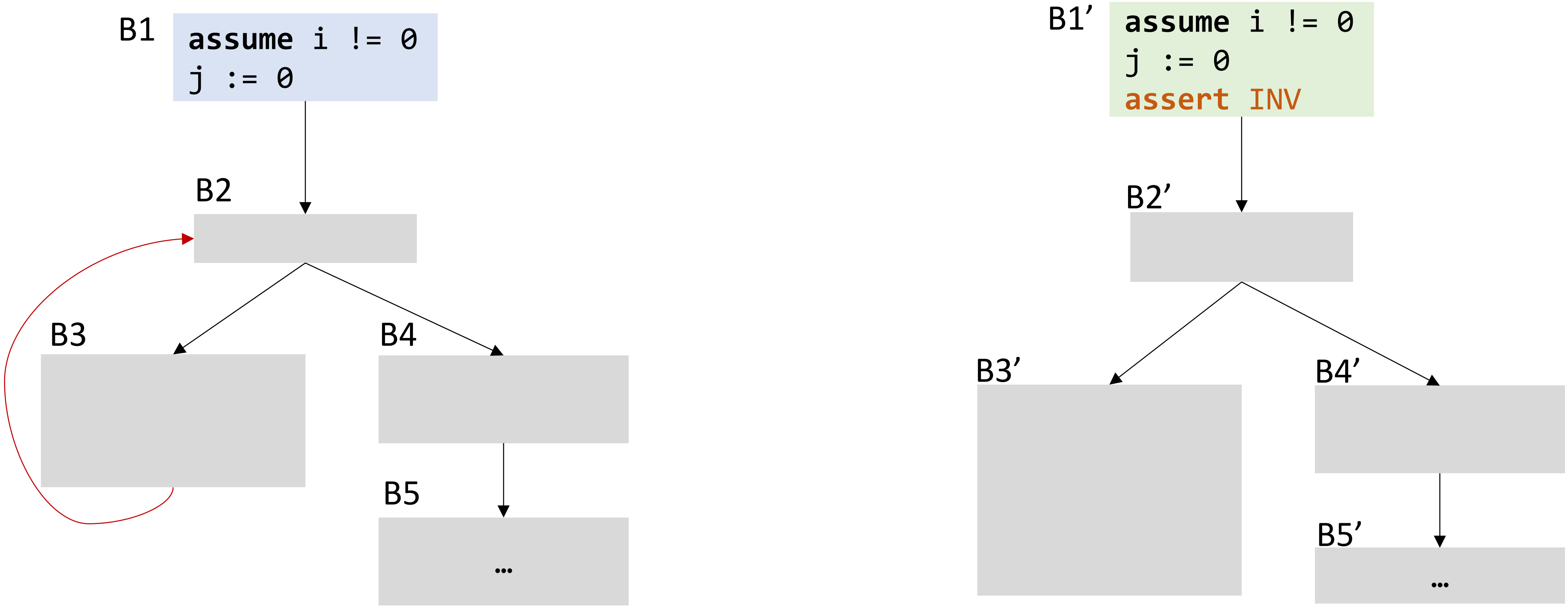


CFG-to-DAG validation: global result



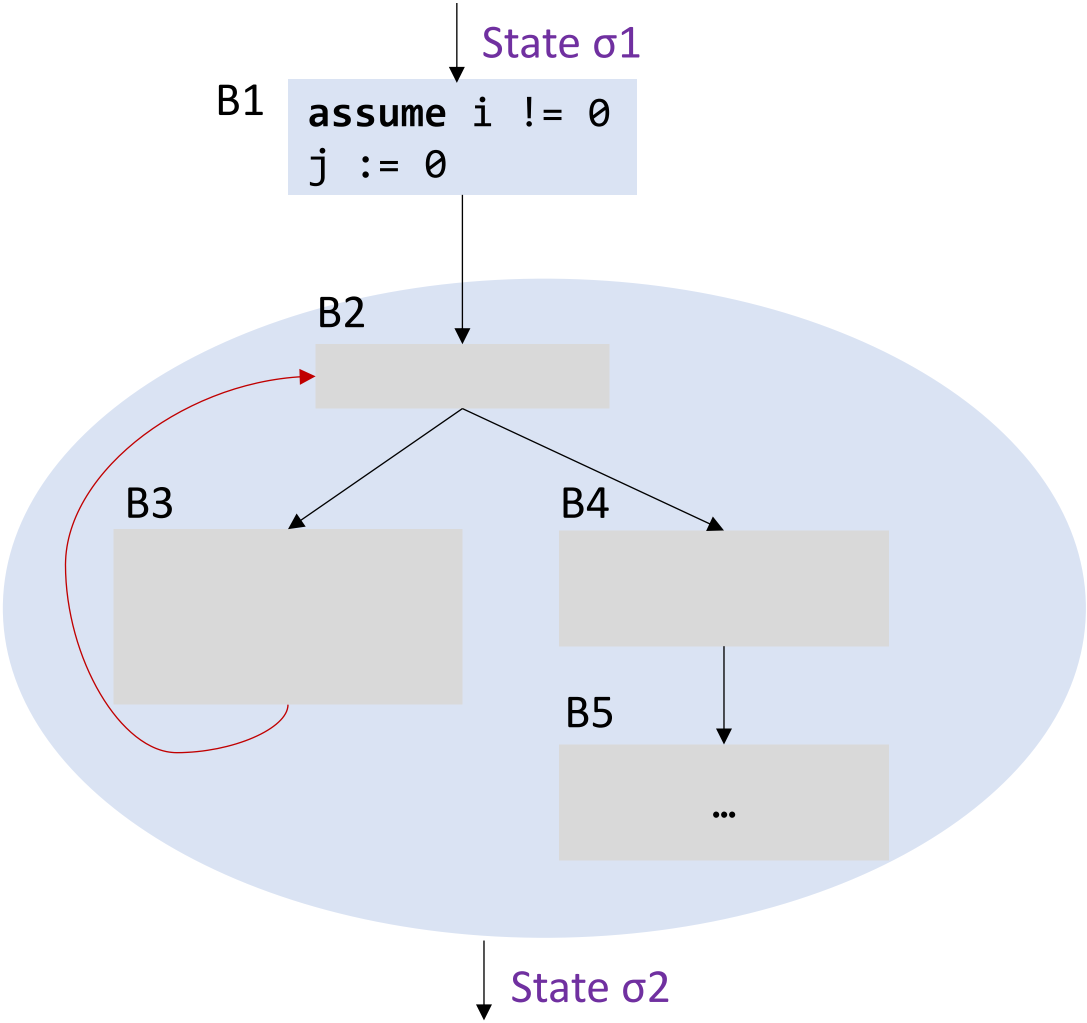
B1

```
assume i != 0
j := 0
```

B1’

```
assume i != 0
j := 0
assert INV
```

CFG-to-DAG validation: global result

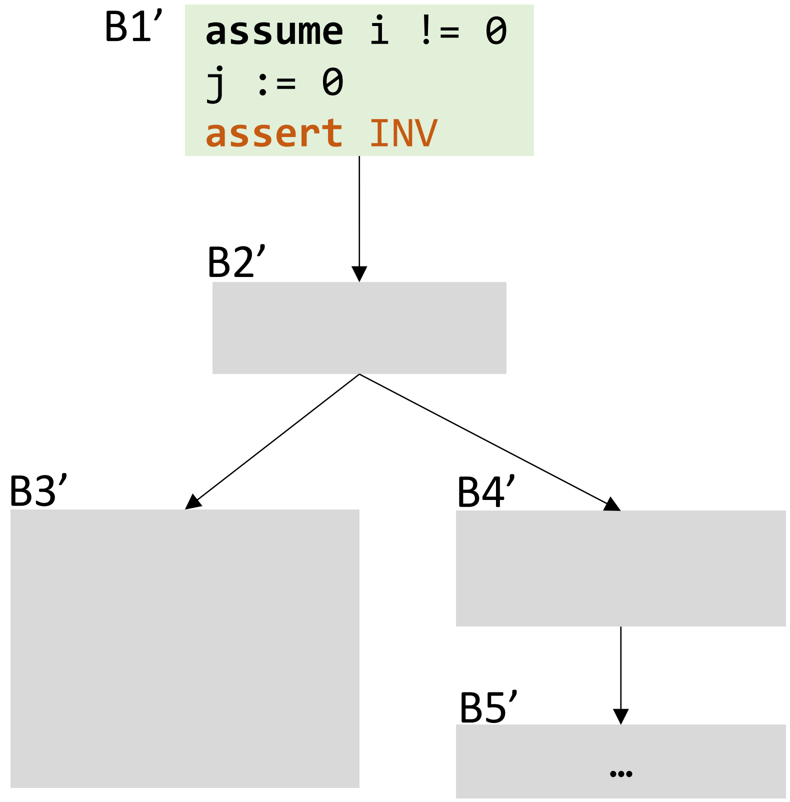


State σ1

B1

```
assume i != 0
j := 0
```

State σ2



B1’

```
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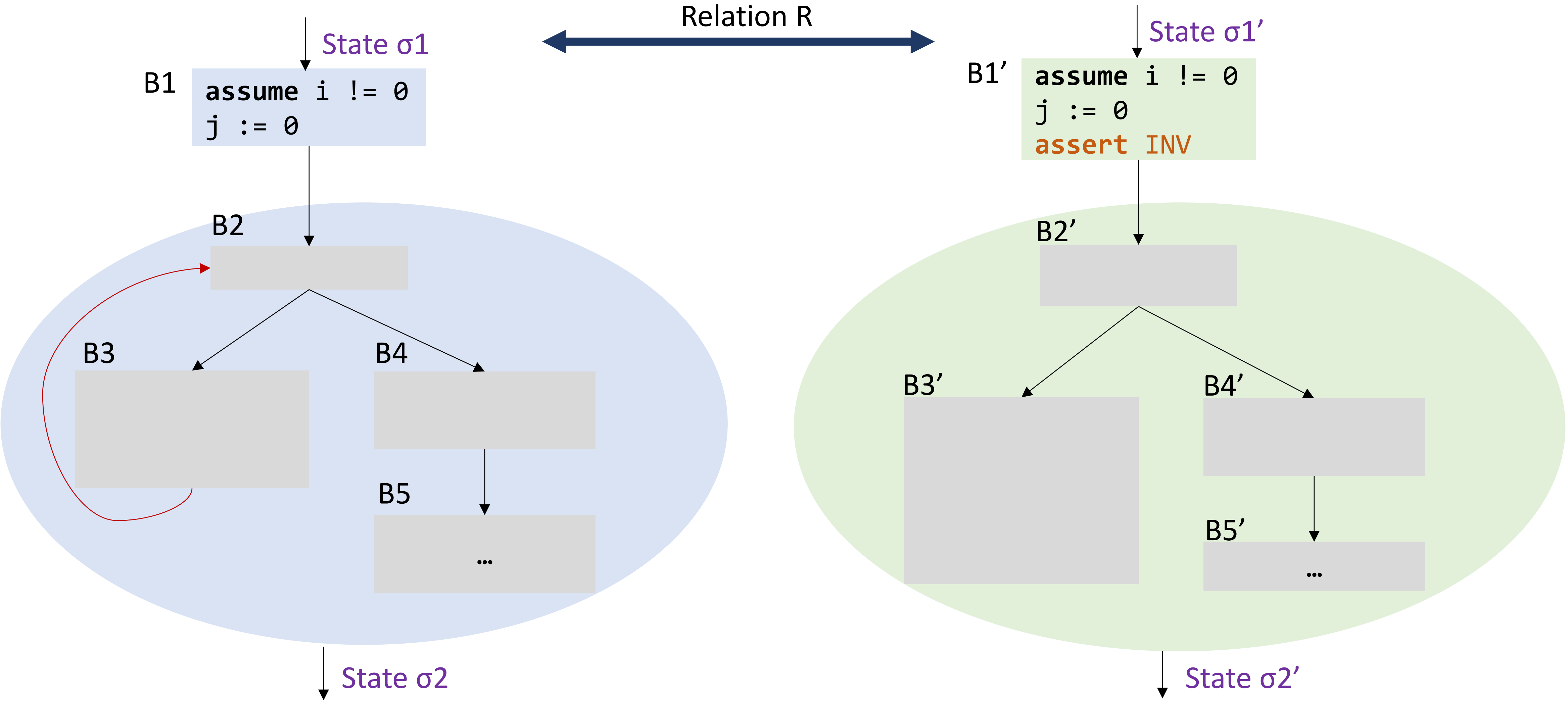
```

CFG-to-DAG validation: global result



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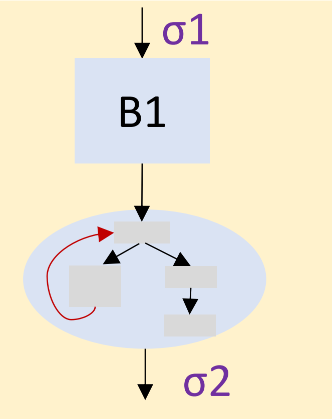
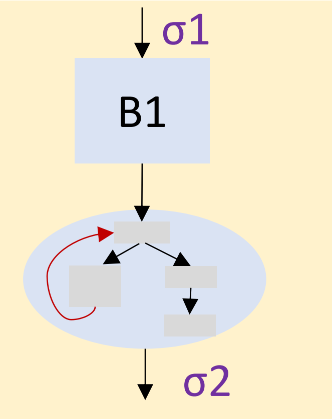
CFG-to-DAG validation: global block theorem

Assumptions



CFG-to-DAG validation: global block theorem

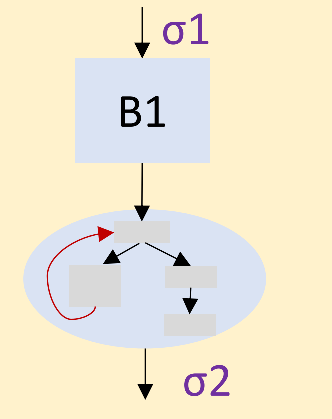
Assumptions



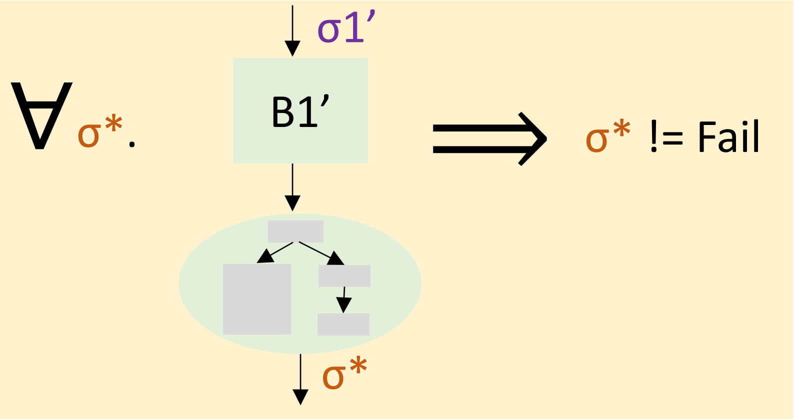
R(σ1, σ1’)

CFG-to-DAG validation: global block theorem

Assumptions

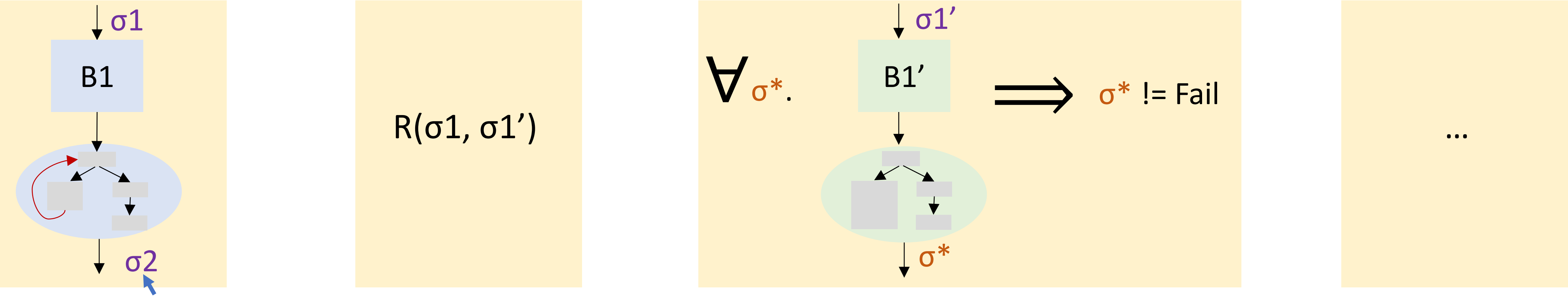


$R(\sigma1, \sigma1')$



CFG-to-DAG validation: global block theorem

Assumptions



σ1

B1

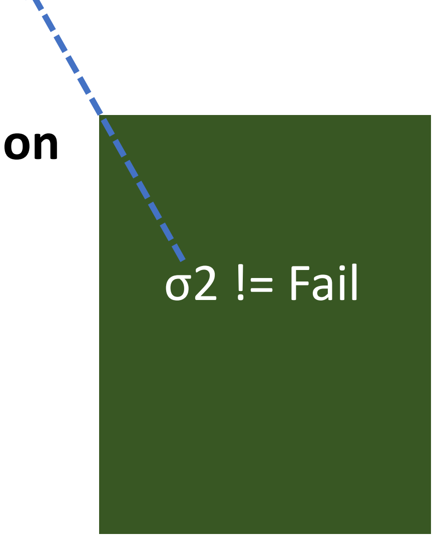
σ2

R(σ1, σ1’)

∀ σ*. σ1’ B1’ σ* ⟹ σ* != Fail

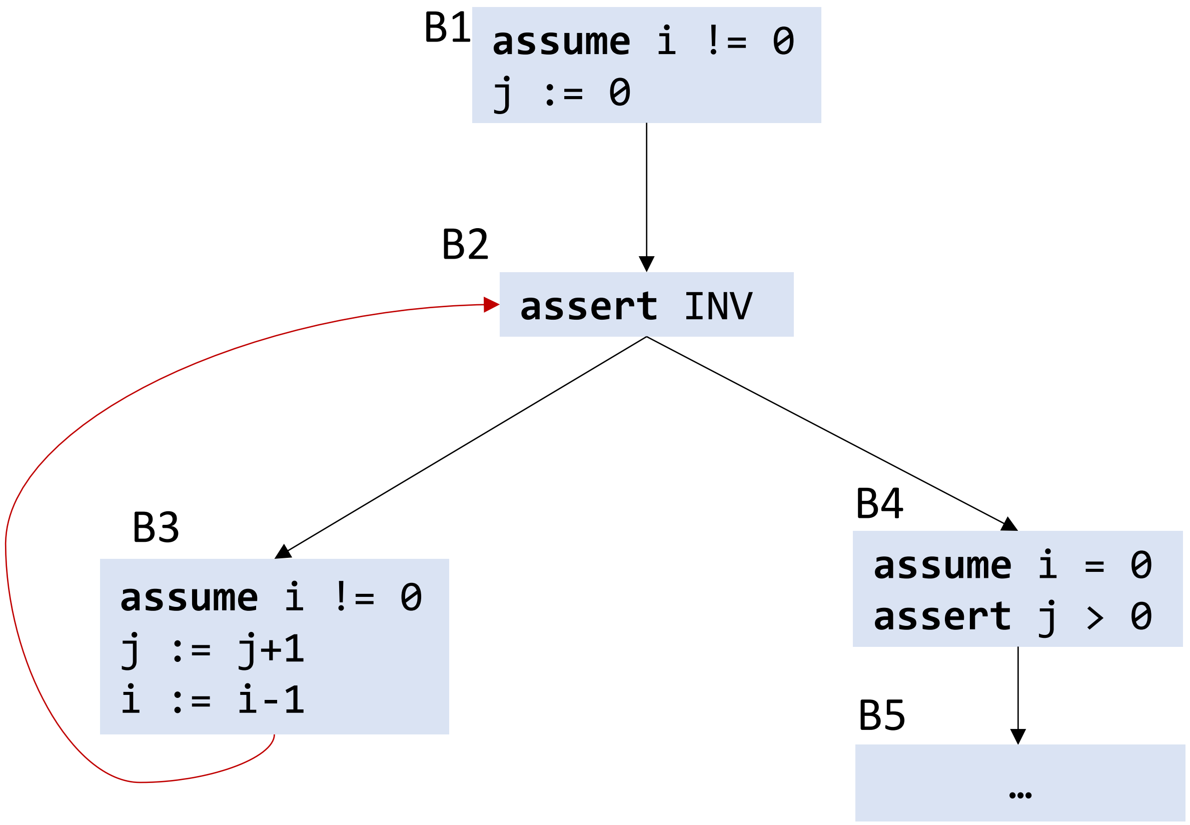
…

Conclusion



σ2 != Fail

CFG-to-DAG validation: global proof strategy



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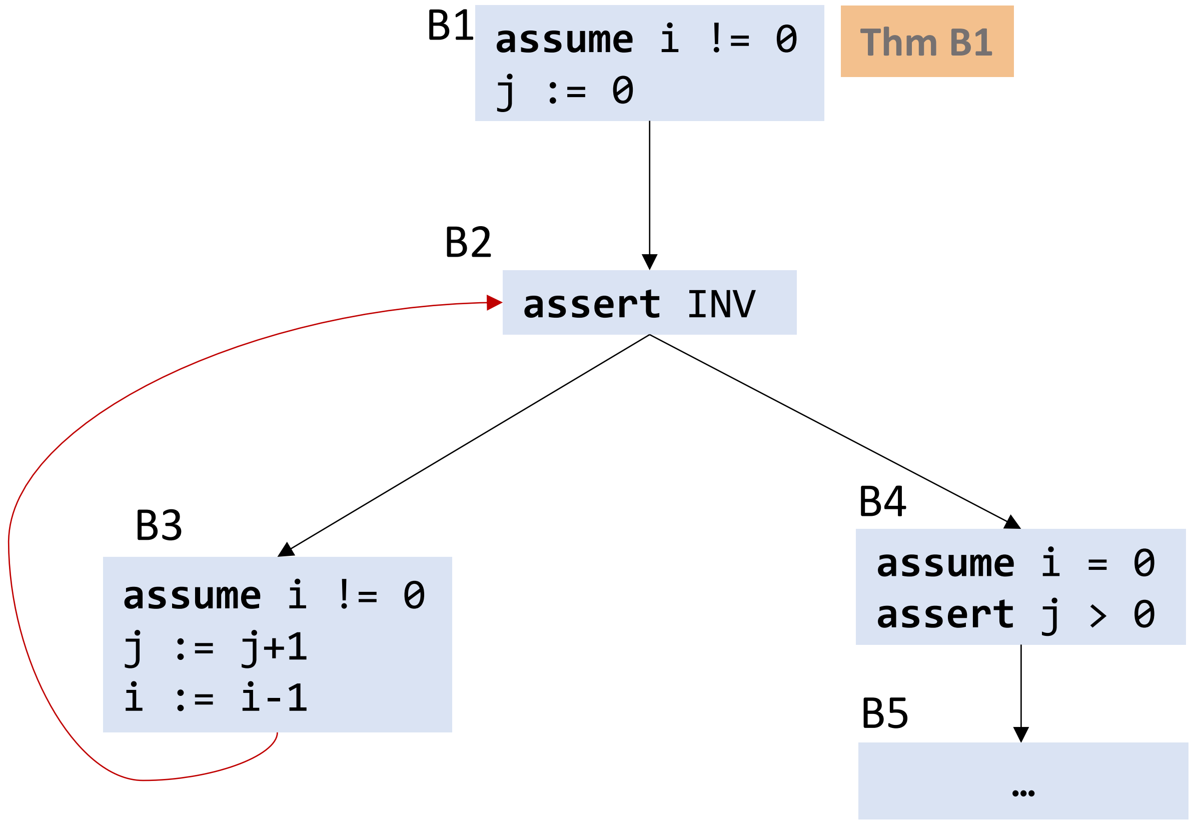

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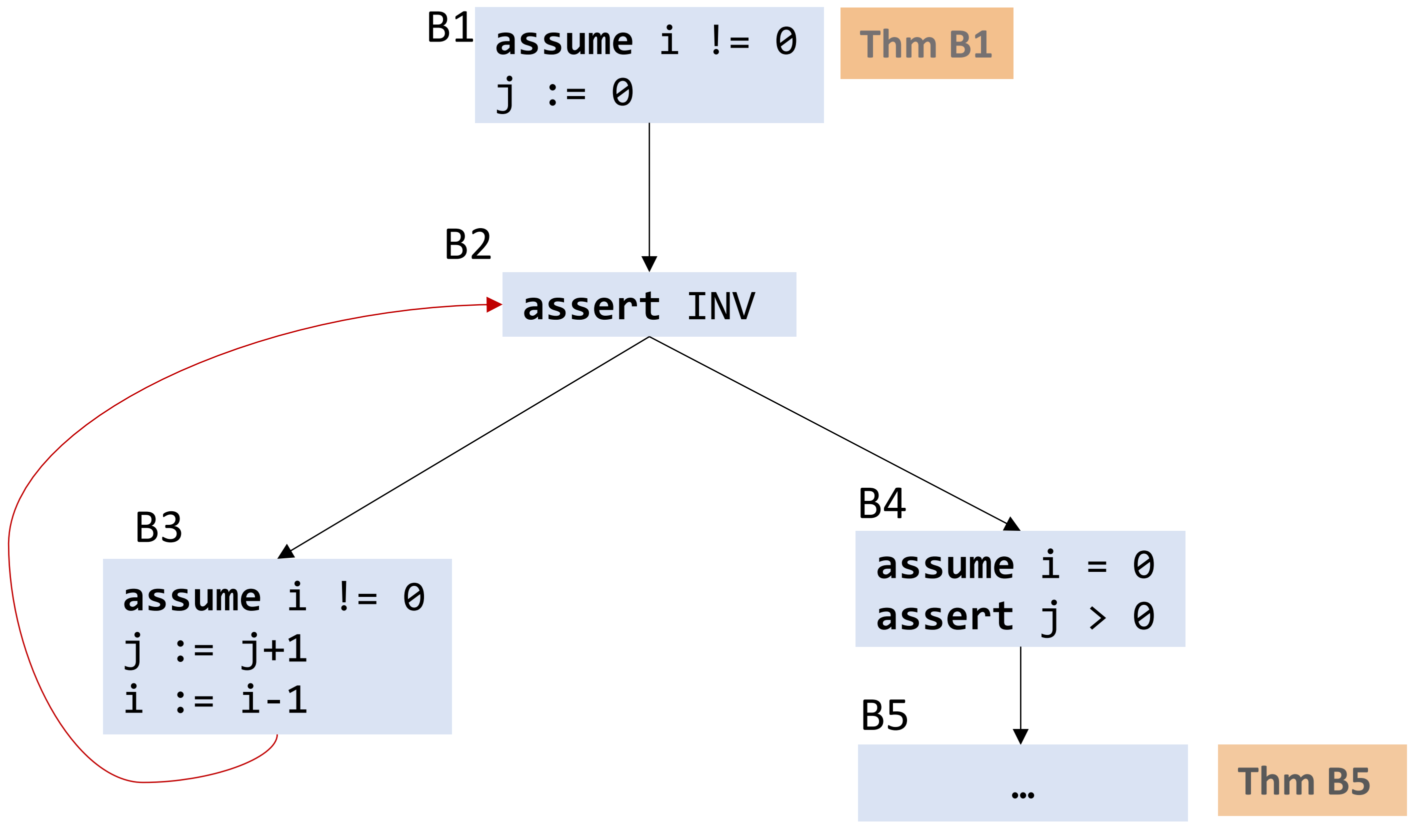

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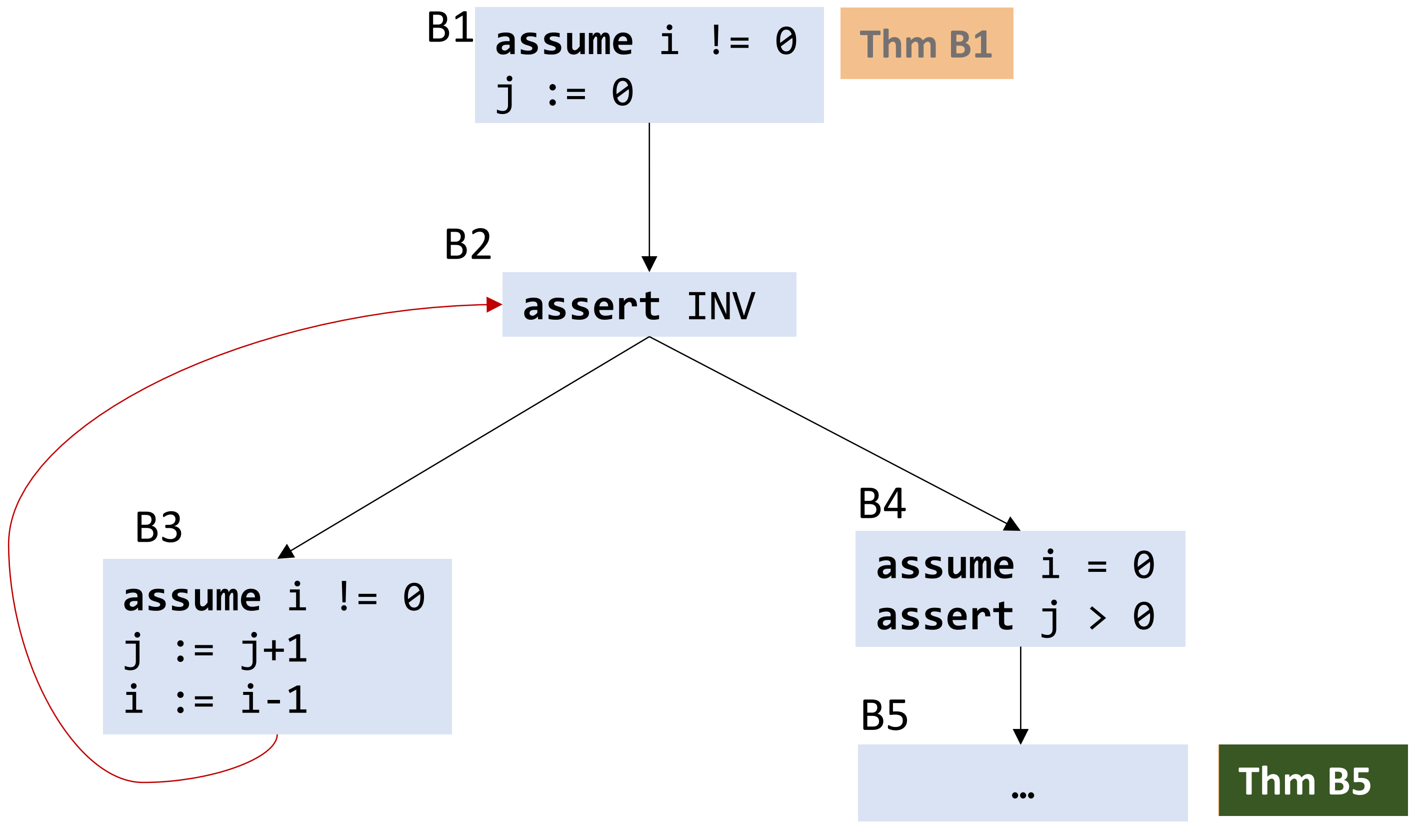

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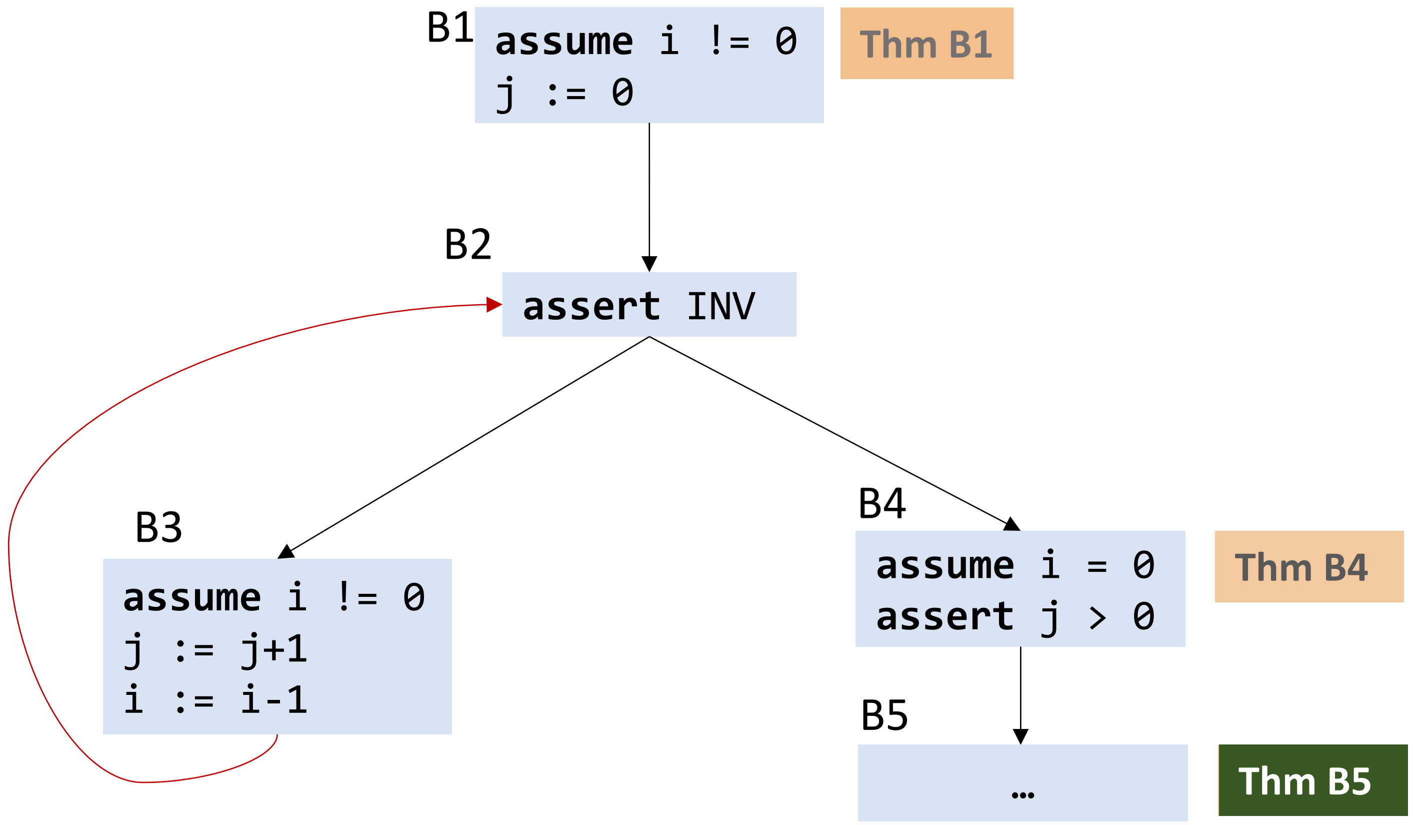
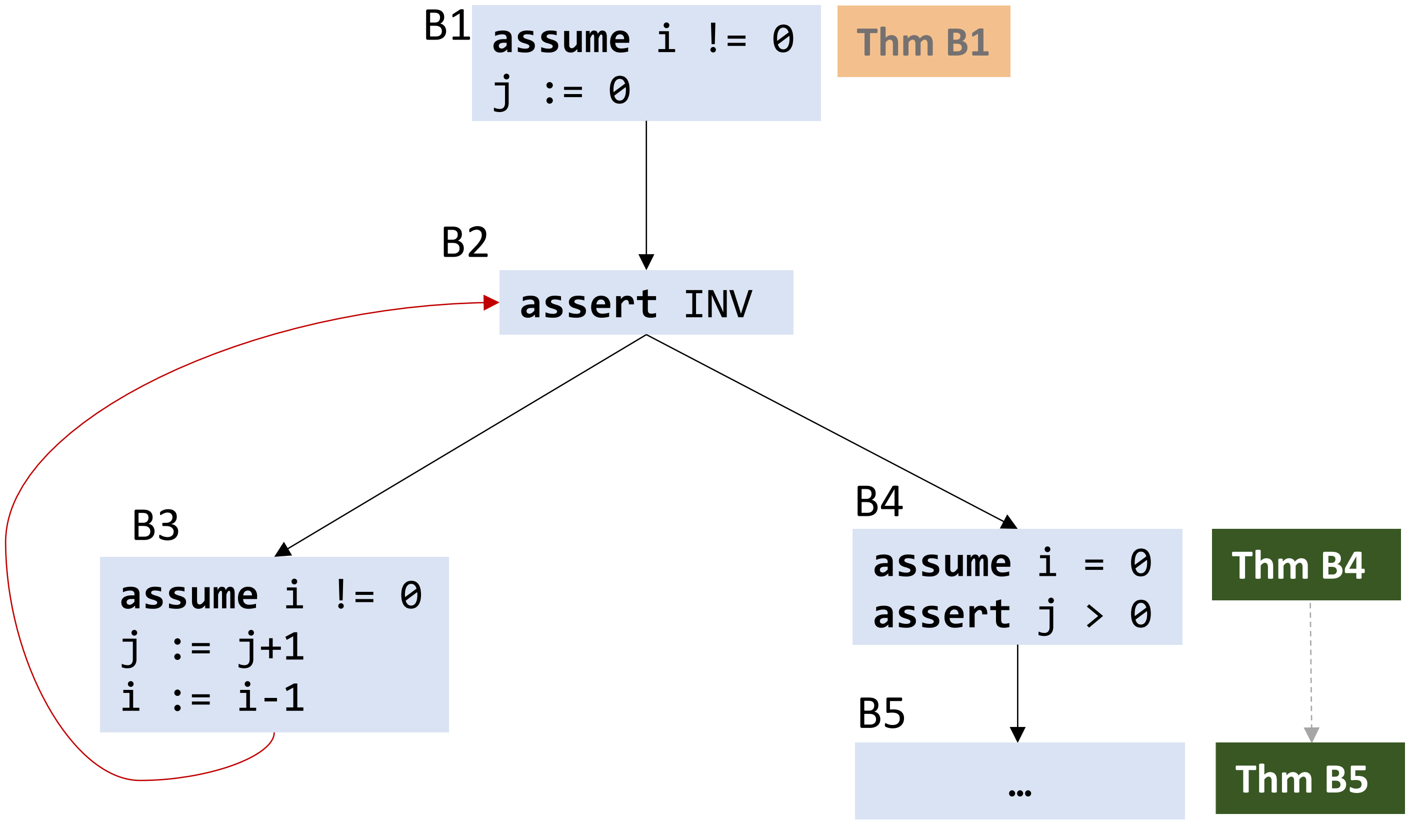
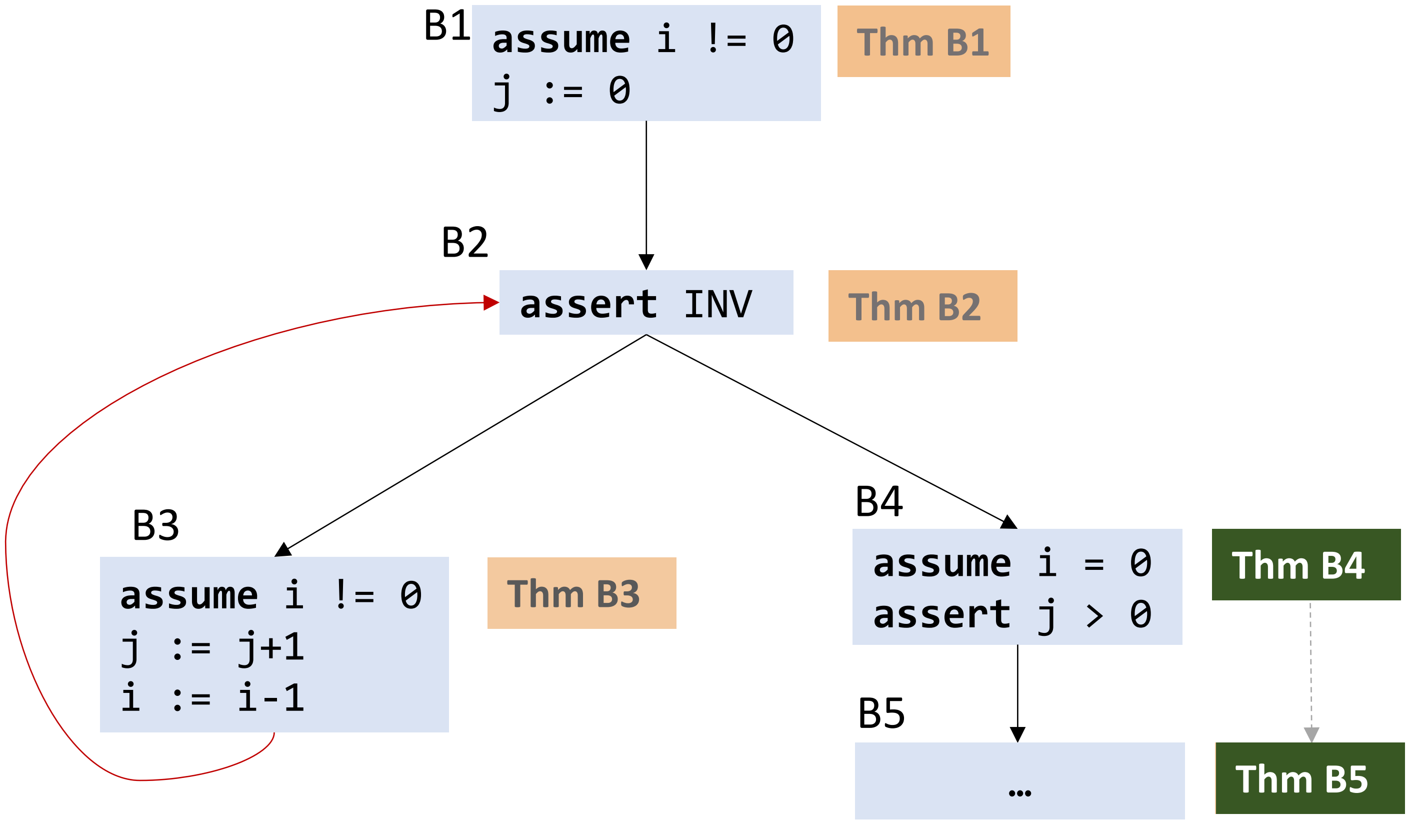


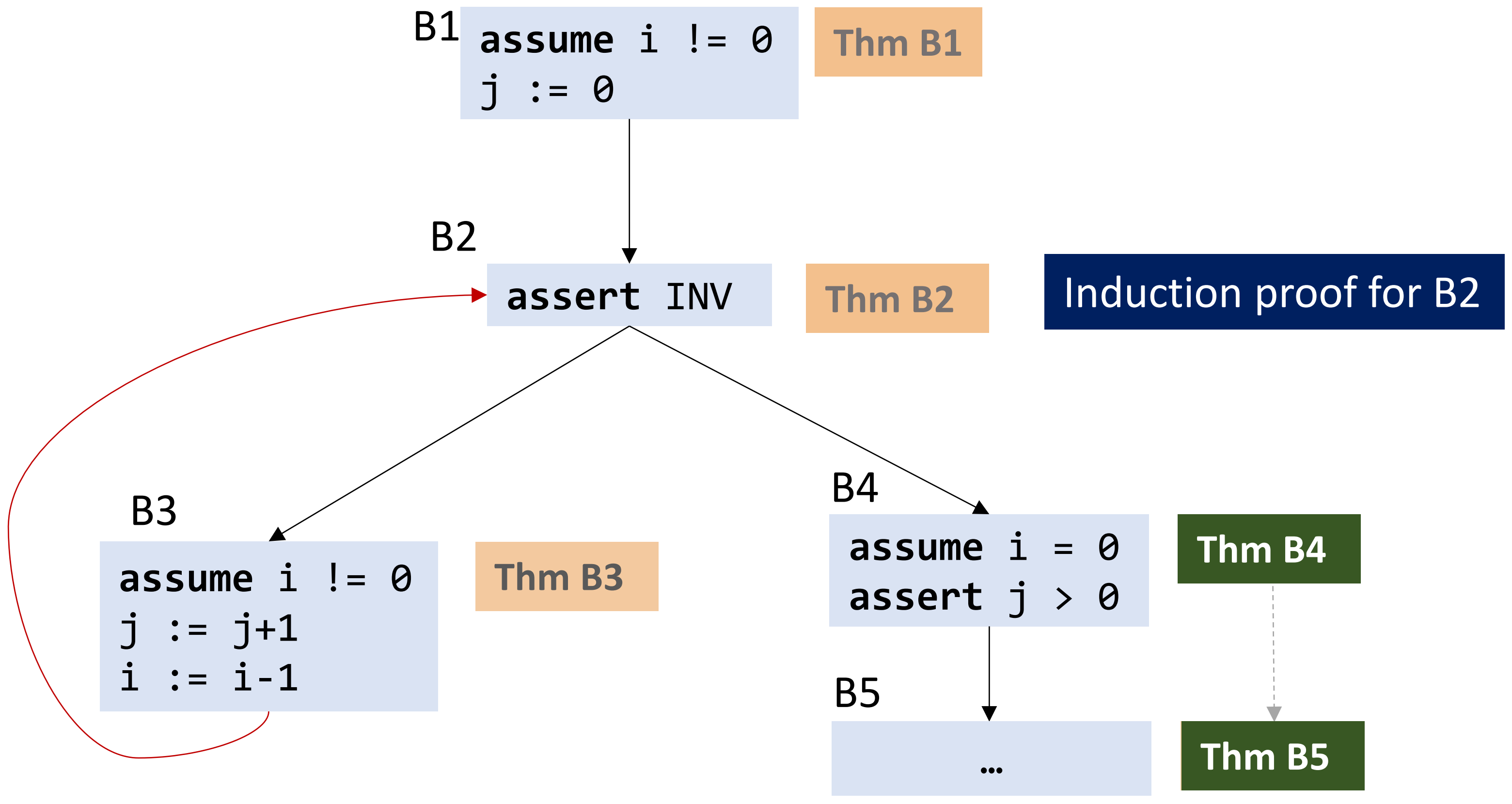
CFG-to-DAG validation: global proof strategy



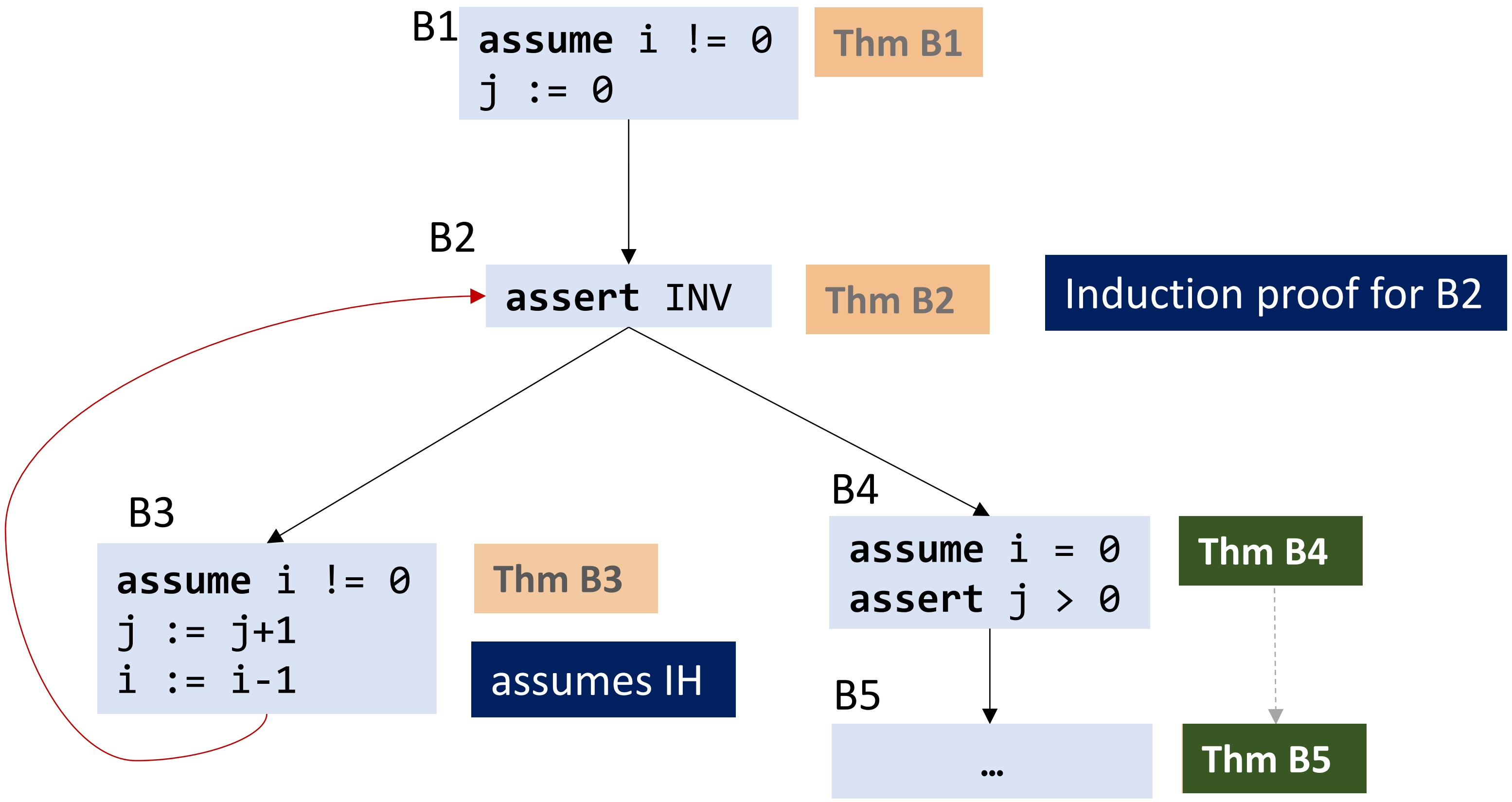
CFG-to-DAG validation: global proof strategy



CFG-to-DAG validation: global proof strategy



CFG-to-DAG validation: global proof strategy



```
B1:
assume i != 0
j := 0

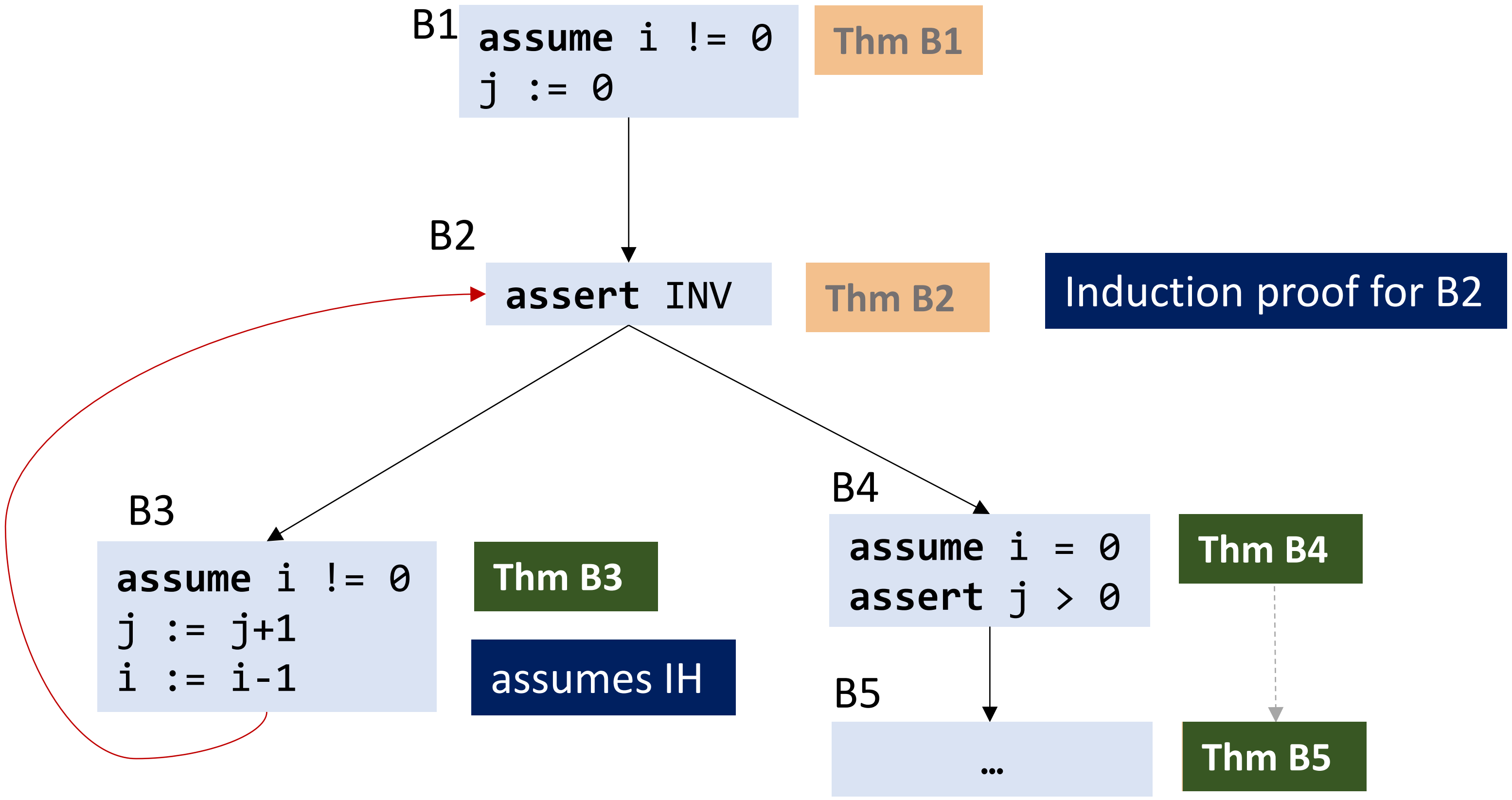
B2:
assert INV

B3:
assume i != 0
j := j+1
i := i-1

B4:
assume i = 0
assert j > 0

B5:
…
```

CFG-to-DAG validation: global proof strategy



B1
```
assume i != 0
j := 0
```
Thm B1

B2
```
assert INV
```
Thm B2

Induction proof for B2

B3
```
assume i != 0
j := j+1
i := i-1
```
Thm B3

assumes IH

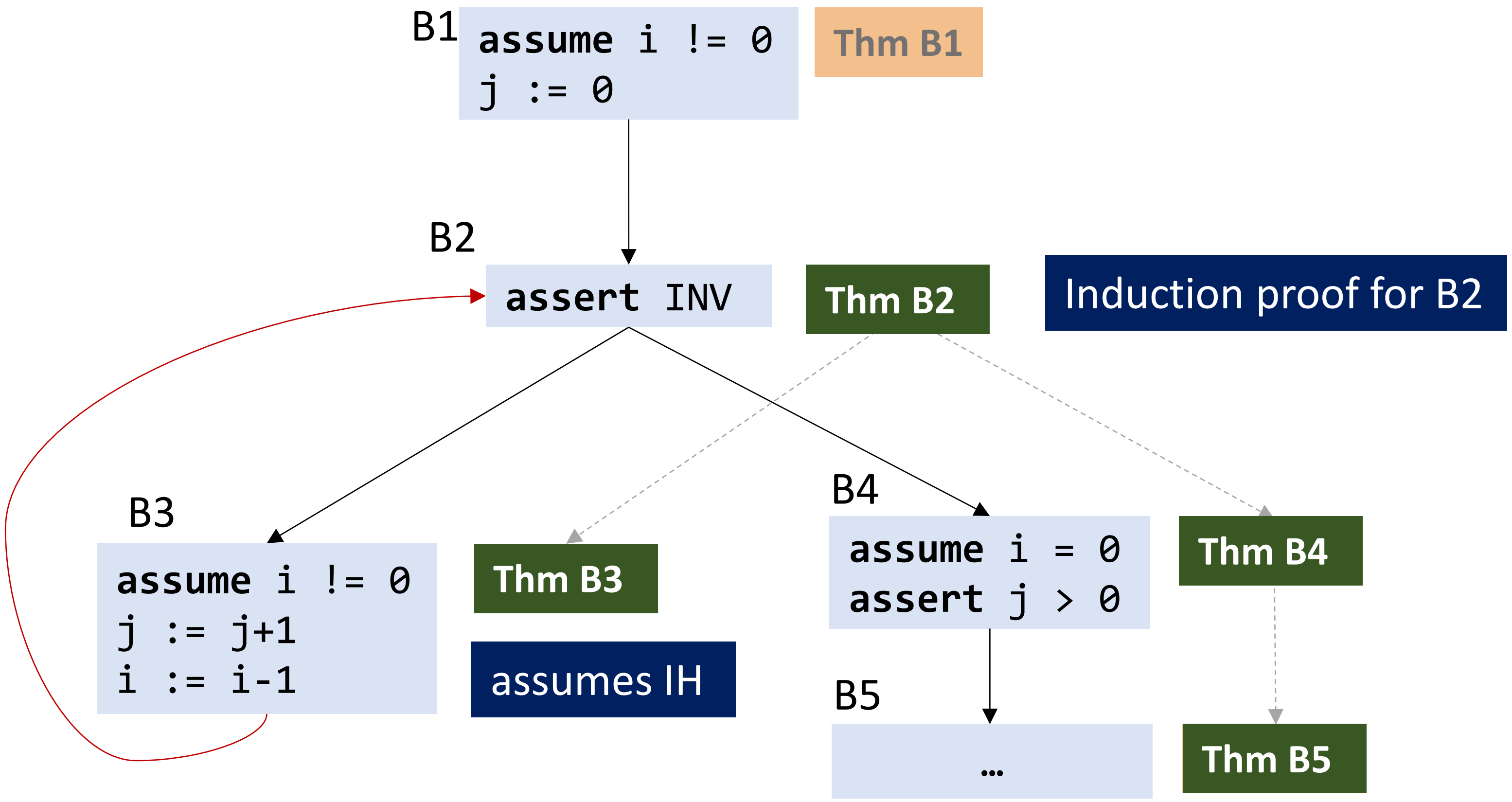
B4
```
assume i = 0
assert j > 0
```
Thm B4

B5

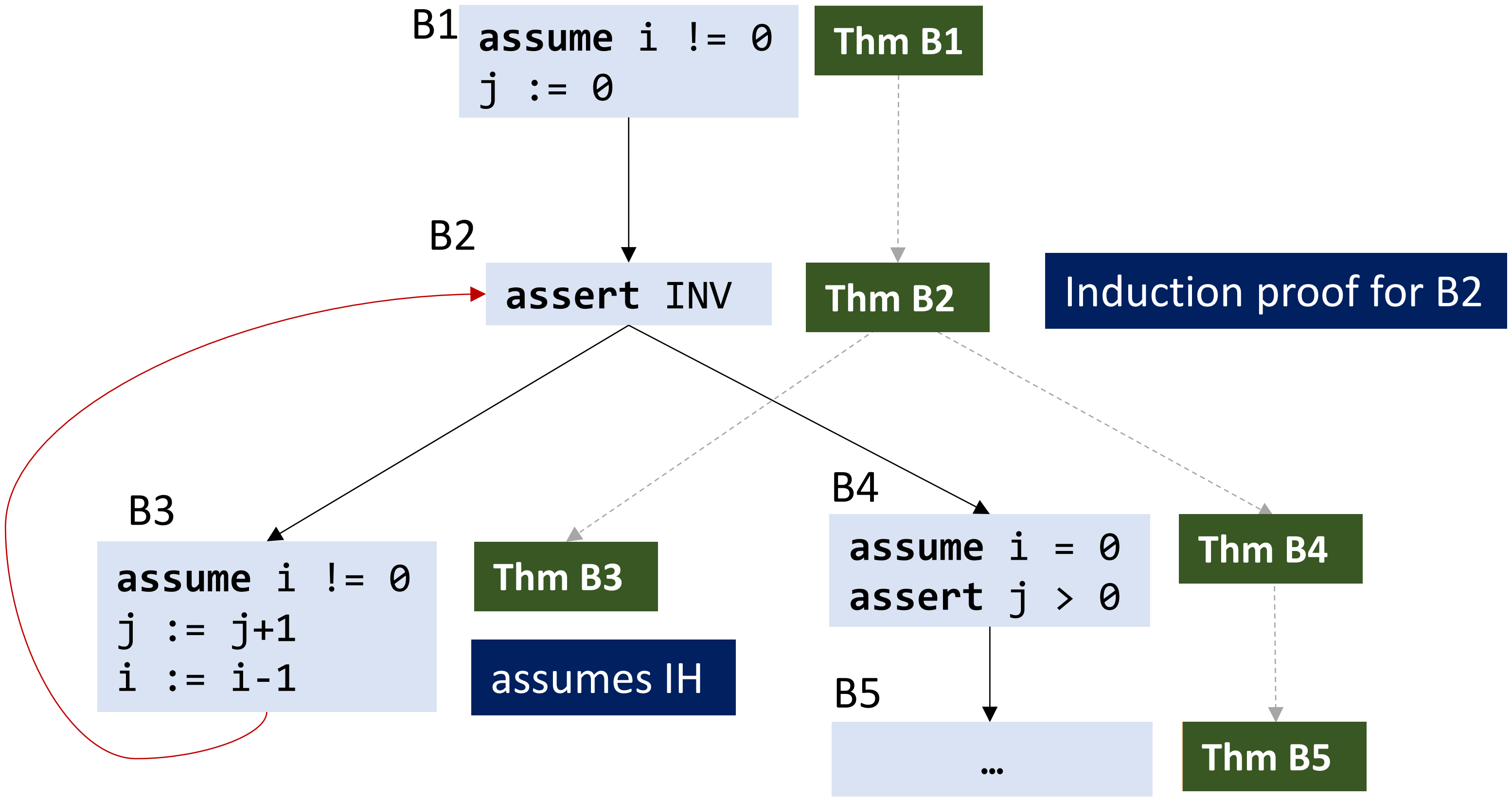
…

Thm B5

CFG-to-DAG validation: global proof strategy



CFG-to-DAG validation: global proof strategy



VC Phase

VC Phase

∀ VC quant . VC assumptions ⟹ CFG WP

VC Phase

$$\forall \underbrace{\text{VC quant}}_{\substack{\text{type encoding parameters,} \\ \text{Boogie variables,} \\ \ldots}} \,.\, \text{VC assumptions} \Longrightarrow \text{CFG WP}$$

VC Phase

$$\forall\ \underbrace{\text{VC quant}}_{\begin{array}{l}\text{type encoding parameters,}\\ \text{Boogie variables,}\\ \text{...}\end{array}}\ .\ \underbrace{\text{VC assumptions}}_{\begin{array}{l}\text{type encoding axiomatisation,}\\ \text{Boogie axioms,}\\ \text{...}\end{array}} \Longrightarrow \text{CFG WP}$$

VC Phase

$$\forall\ \underbrace{\text{VC quant}}_{\substack{\text{type encoding parameters,}\\ \text{Boogie variables,}\\ \text{…}}}\ .\ \underbrace{\text{VC assumptions}}_{\substack{\text{type encoding axiomatisation,}\\ \text{Boogie axioms,}\\ \text{…}}}\ \Longrightarrow\ \underbrace{\text{CFG WP}}_{\text{weakest precondition}}$$

Evaluation

functional
Artifact
CAV AEC
Evaluated
available reusable

Validated 96/100 examples from Boogie’s test suite (that verify and are in our subset)

Evaluation

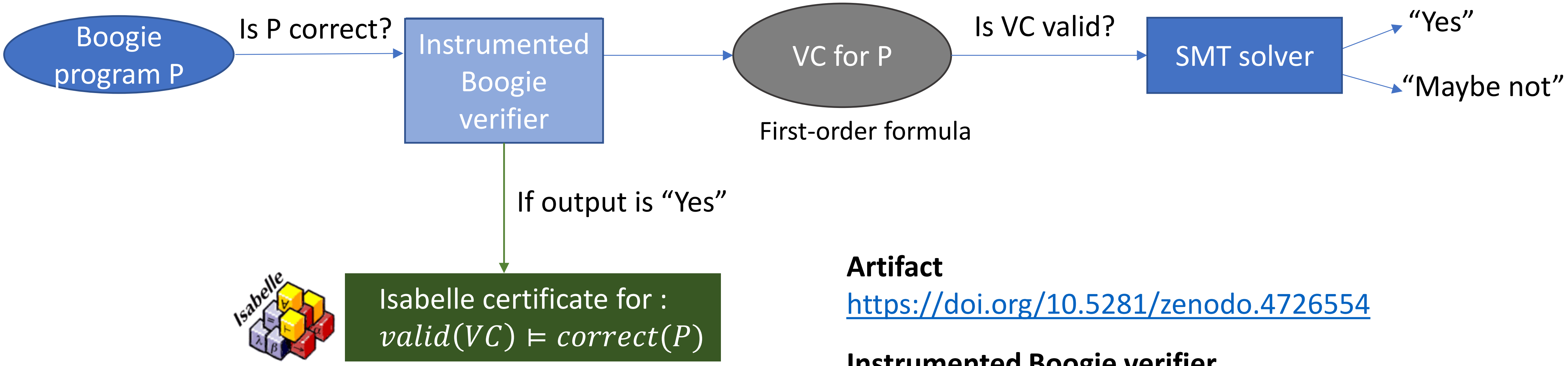
functional Artifact CAV AEC Evaluated available reusable

Validated 96/100 examples from Boogie’s test suite (that verify and are in our subset)

Validated 10 algorithmic examples

Program	LOC	# Procedures	Time [seconds]	Isabelle LOC
MaxOfArray	22	1	19.9	1944
Plateau	50	1	22.9	2019
DutchFlag	76	2	52.8	3994
…	…	…	…	…

Summary



Boogie program P

Is P correct?

Instrumented Boogie verifier

VC for P

First-order formula

Is VC valid?

SMT solver

“Yes”

“Maybe not”

If output is “Yes”

Isabelle certificate for :

$valid(VC) \vDash correct(P)$

Artifact
https://doi.org/10.5281/zenodo.4726554

Instrumented Boogie verifier
https://github.com/gauravpartha/boogie_proofgen/

Boogie formalisation
https://github.com/gauravpartha/foundational_boogie/