Explicit-State Software Model Checking Based on CEGAR and Interpolation

Dirk Beyer – Stefan Löwe

UNIVERSITÄT PASSAU

Fakultät für Informatik und Mathematik

Software Verification

```
int a, b, c;
a := 0;
b := a;
c := a;
if(a == 0) {
    a := 1;
}
if(a == -1) {
   assert(0);
}
```

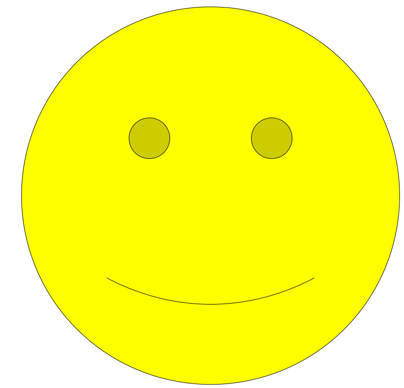
The goal is to find an answer to the question:

← *Is the “error” reachable?*

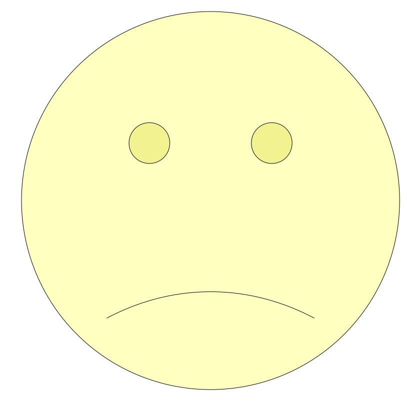
Software Model Checking

```
int a, b, c;
a := 0;
b := a;
c := a;
if(a == 0) {
    a := 1;
}
if(a == -1) {
  assert(0);
}
```

SAFE ?

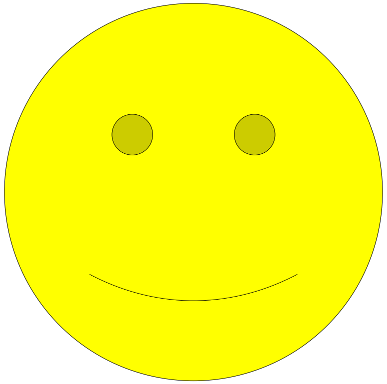


UNSAFE ?



Is the error reachable?

Explicit-State Software Model Checking



```
int a, b, c;
a := 0;
b := a;
c := a;
if(a == 0) {
    a := 1;
}
if(a == -1) {
  assert(0);
}
```

{a → T, b → T, c → T}

{**a → 0**, b → T, c → T}

{a → 0, **b → 0**, c → T}

{a → 0, b → 0, **c → 0**}

{**a → 1**, b → 0, c → 0}

{**a → 1**, b → 0, c → 0}

SAFE !

The error is unreachable!

il buono, il brutto, il cattivo

[the Good, the Bad, the Ugly]

Very efficient successor computation

Independent of expensive solver techniques

Imprecise when joining

State-space explosion

especially when not joining

Explicit-State Software Model Checking

```
extern int system_call();
int main() {
  int result;
  int flag = 0;
  while(1) {
     result = system_call();
     if(result == 0) {
        break;
     }
  }
  if(flag > 0) {
     assert(0);
  }
}
```

Explicit-State Software Model Checking

Existing approach: simple value assignments

- ? Abstraction
- ? Counterexample-Guided Abstraction Refinement
- ? Interpolation

All known in the predicate domain for years

Explicit-State Software Model Checking

New approach: **integrate CEGAR and Interpolation**

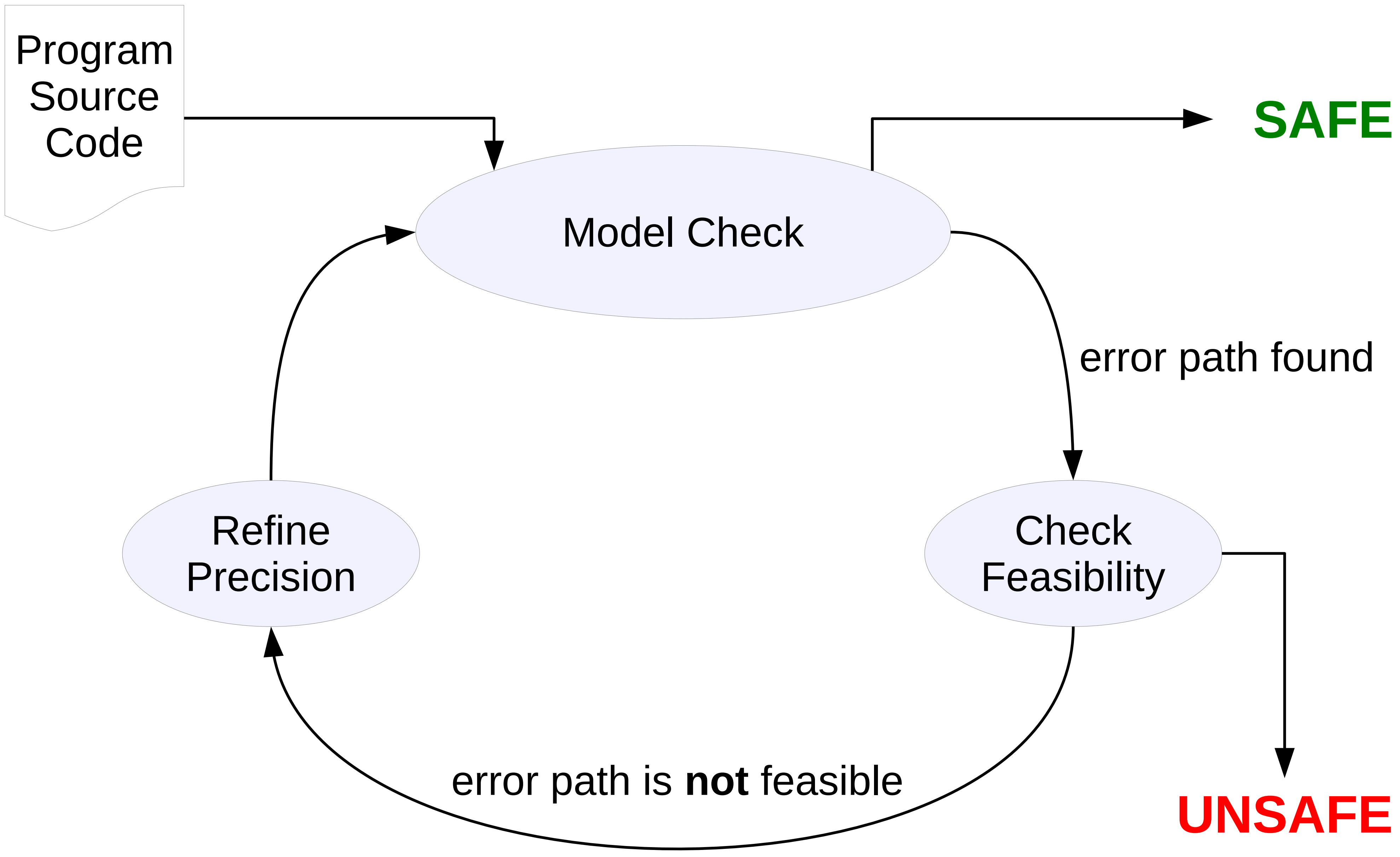
- ! Abstraction
- ! Counterexample-Guided Abstraction Refinement
- ! Interpolation

✔ *Explicit-State Software Model Checking*

based on ***CEGAR***

and ***Interpolation***

CEGAR Loop


Program
Source
Code
Model Check
SAFE
error path found
Refine
Precision
Check
Feasibility
error path is **not** feasible
UNSAFE

Abstraction

```
int a, b, c;
a := 0;
b := a;
c := a;
if(a == 0) {
   a := 1;
}
if(a == -1) {
   assert(0);
}
```

{ }

{ }

{ }

{ }

{ }

{ }

if the abstraction is too coarse,
spurious counterexamples will be reported

Counterexamples

counterexample as

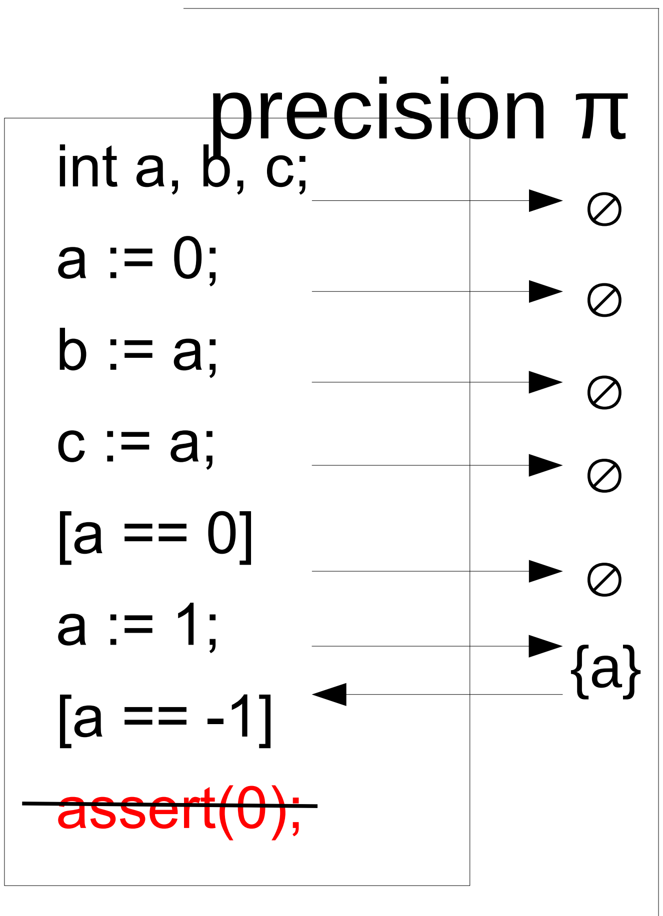
constraint sequence

```
int a, b, c;
a := 0;
b := a;
c := a;
[a == 0]
a := 1;
[a == -1]
assert(0);
```

We extract variable identifiers from spurious counterexamples in order to avoid repeated explorations of the same spurious counterexamples

Therefore, we introduce the notion of a precision

Precision



a set of variable identifiers to track at a program location

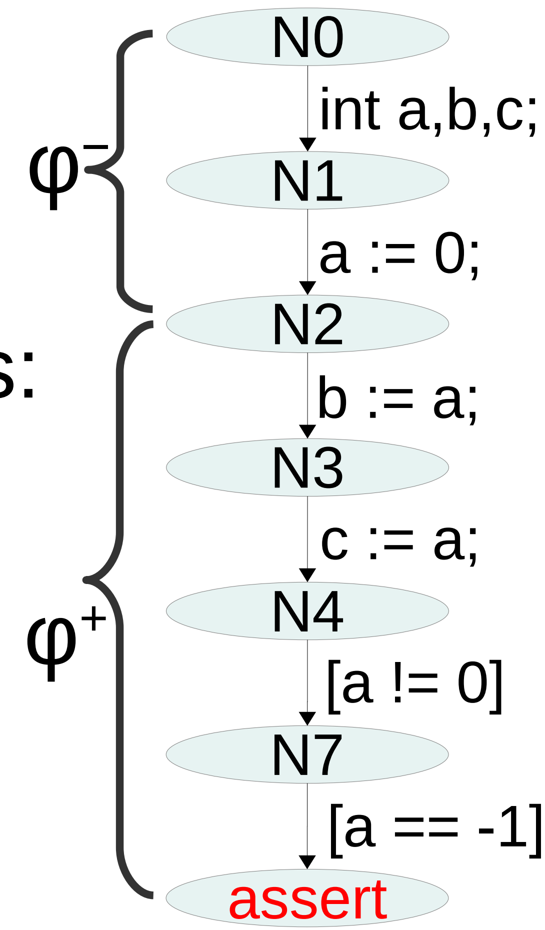
- be precise enough to avoid spurious counterexamples
- be abstract enough to allow an efficient analysis

How to obtain such a parsimonious precisions?

Craig Interpolation

For a pair of ***formulas*** $\boldsymbol{\varphi^-}$ and $\boldsymbol{\varphi^+}$,
such that $\boldsymbol{\varphi^- \wedge \varphi^+}$ is ***unsatisfiable***,
a Craig ***interpolant*** $\boldsymbol{\psi}$ is a ***formula***
that fulfills the following requirements:

1) φ^- implies ψ
2) $\psi \wedge \varphi^+$ is unsatisfiable
3) ψ only contains symbols that are common to both φ^- and φ^+



[Abstractions from Proofs, 2004, Henzinger, Jhala, Majumdar, McMillan]

Craig Interpolation

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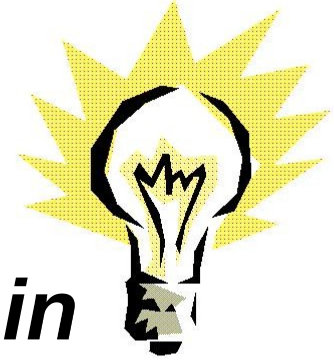
→ ***apply this to the Explicit-Value Domain***



Our Main Contribution

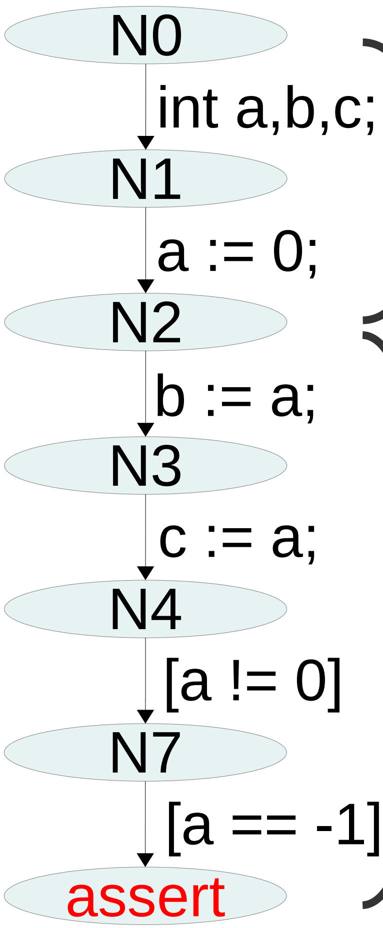
→ apply interpolation to constraint sequences

For a pair of ***constraint sequences*** $\boldsymbol{\gamma^-}$ and $\boldsymbol{\gamma^+}$,
such that $\boldsymbol{\gamma^- \wedge \gamma^+}$ is ***contradicting***,
an ***interpolant*** $\boldsymbol{\psi}$ is a ***constraint sequence***
that fulfills the following requirements:

1) γ^- implies ψ
2) $\psi \wedge \gamma^+$ is contradicting
3) ψ only contains symbols that are common to both γ^- and γ^+

→ ***Explicit-Value Interpolation***

Explicit-Value Interpolation



- ✔ path is infeasible, i.e., $\gamma^- \wedge \gamma^+$ is contradicting

γ^- : a := 0;

γ^+ : b := a;
c := a;
[a != 0]
[a == -1]

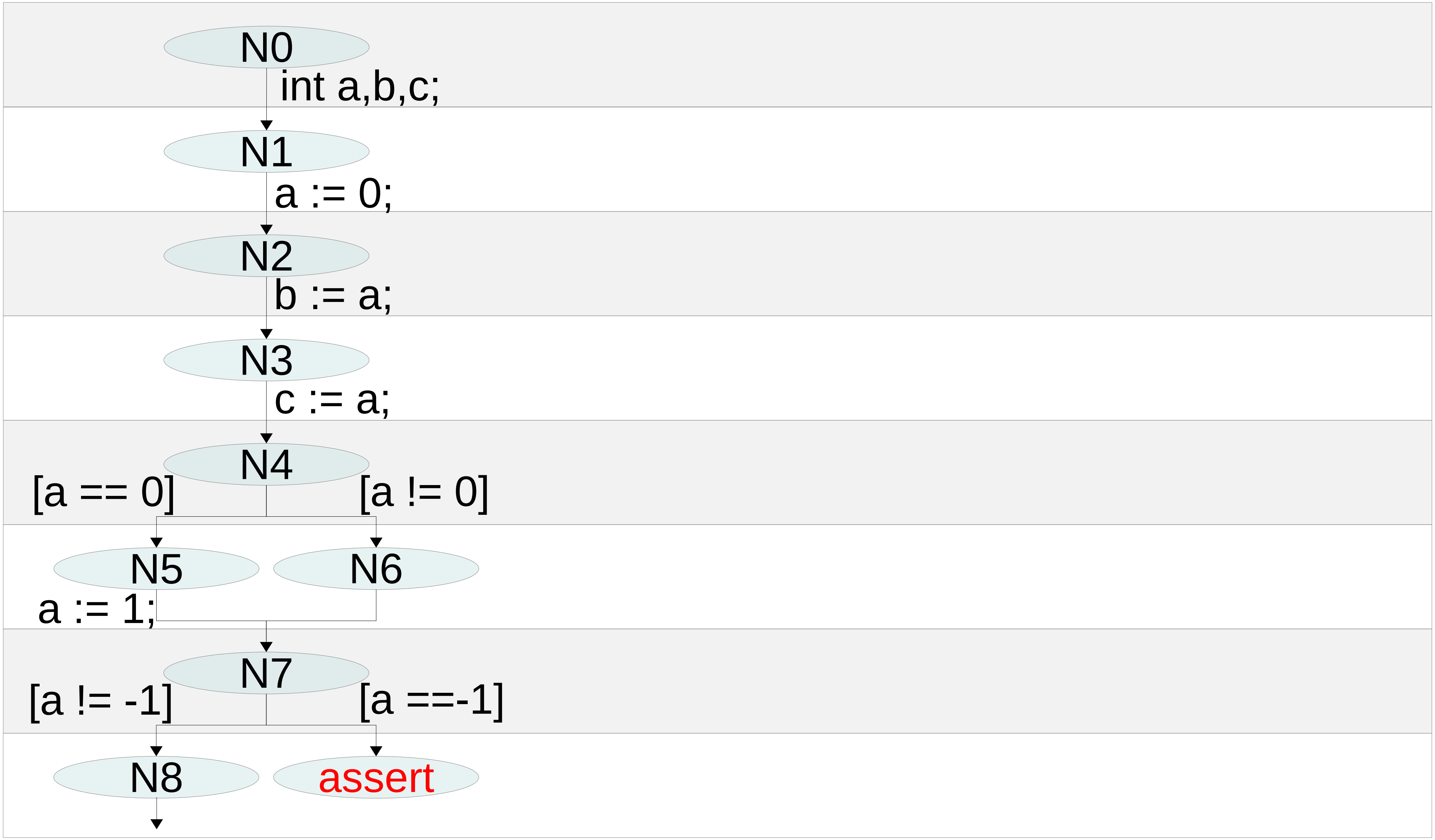
ψ : {a := 0;}

- ✔ γ^- implies ψ
- ✔ $\psi \wedge \gamma^+$ is contradicting
- ✔ common symbols

➢ ***Add "a" to the precision of location N2***

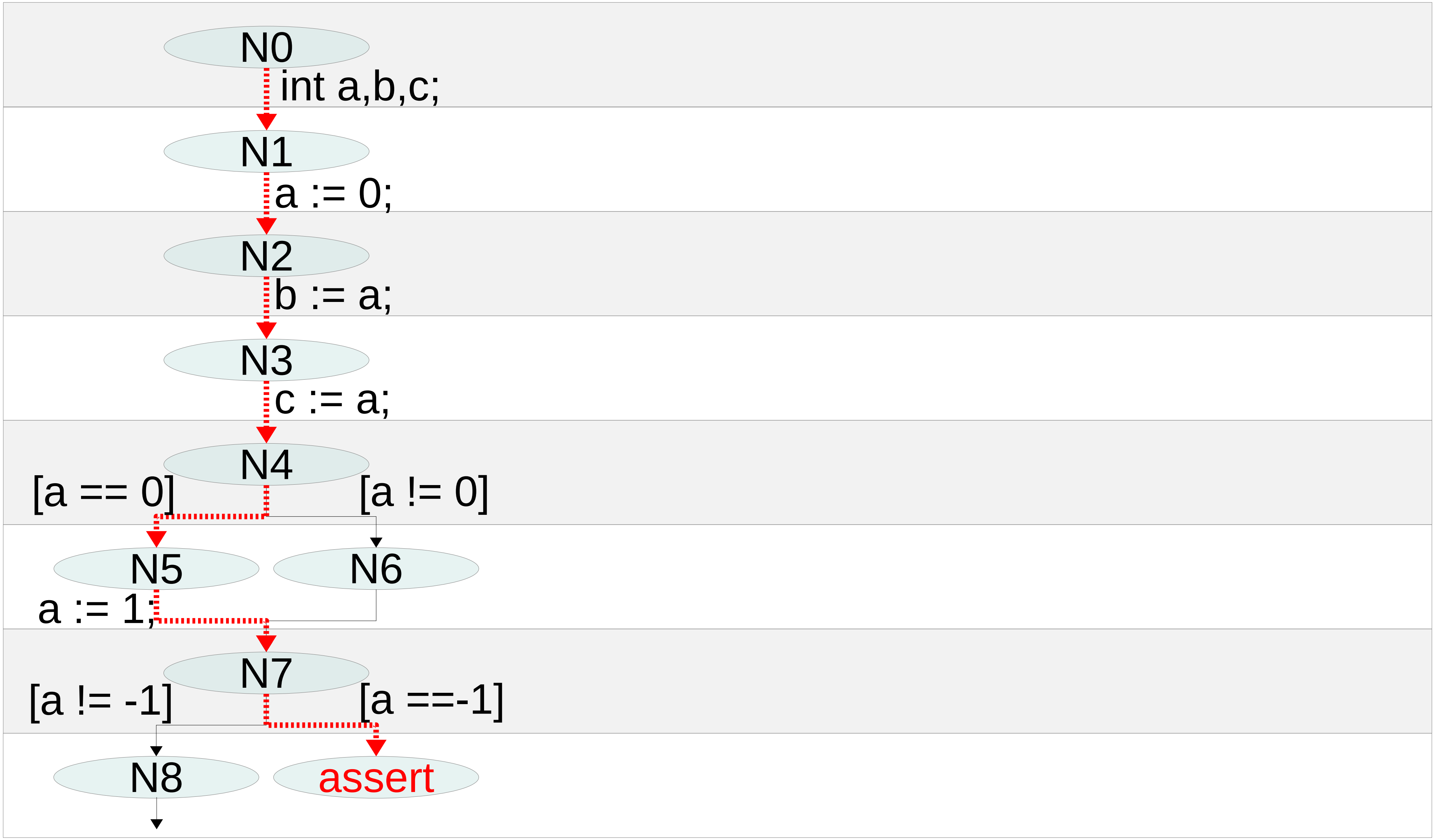
Interpolation-Based Refinement

Control-Flow Automaton

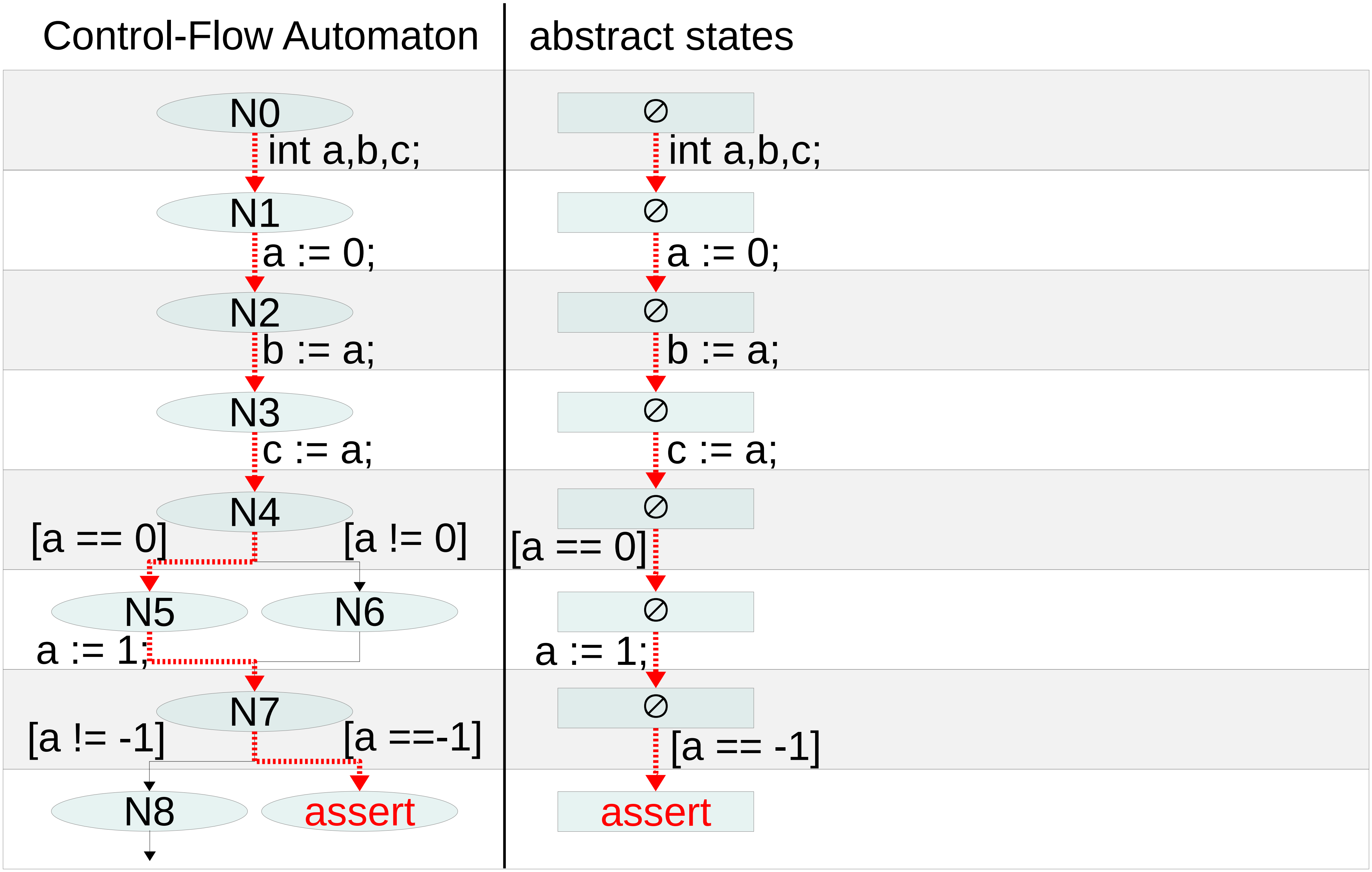


Interpolation-Based Refinement

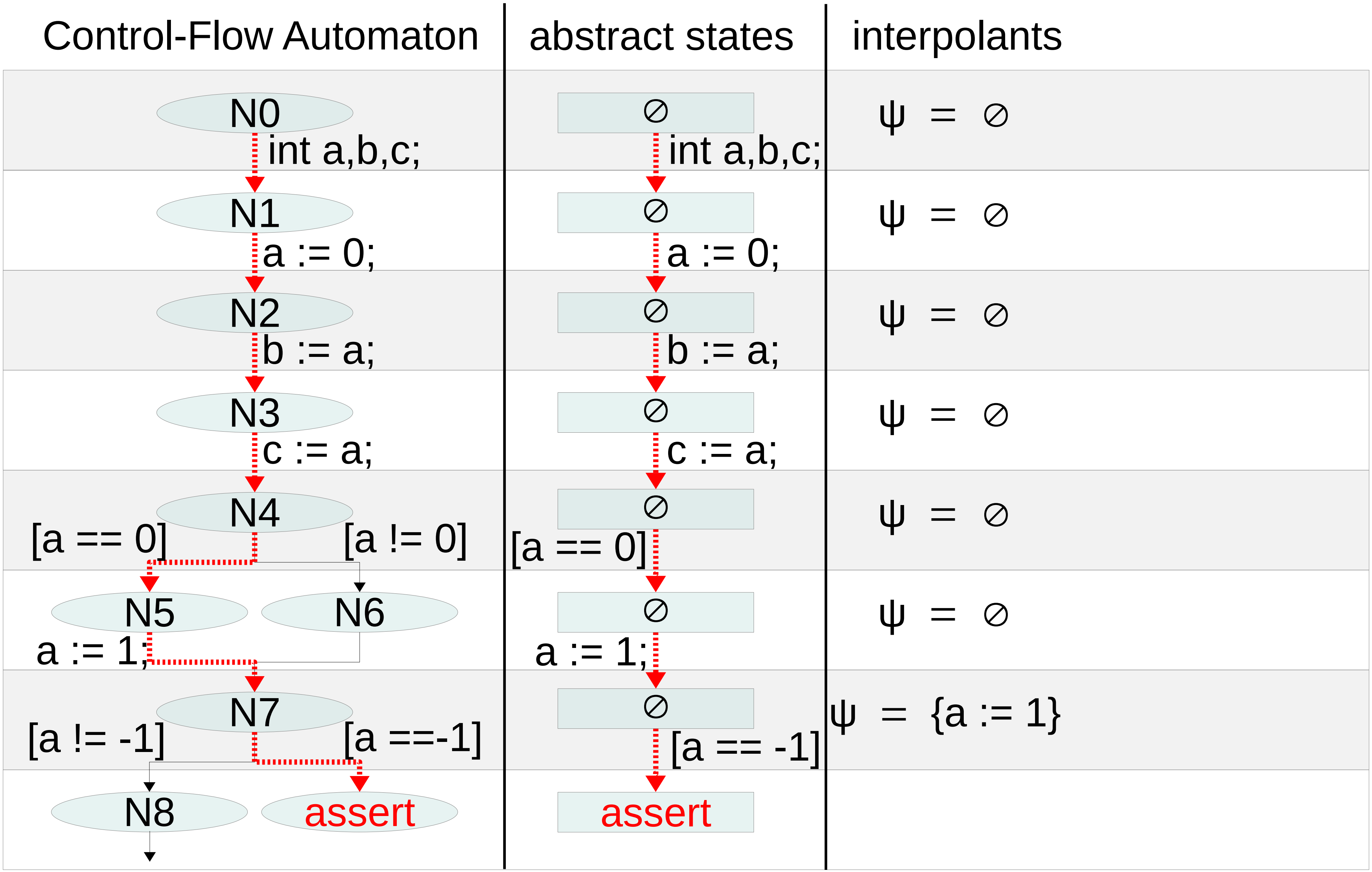
Control-Flow Automaton



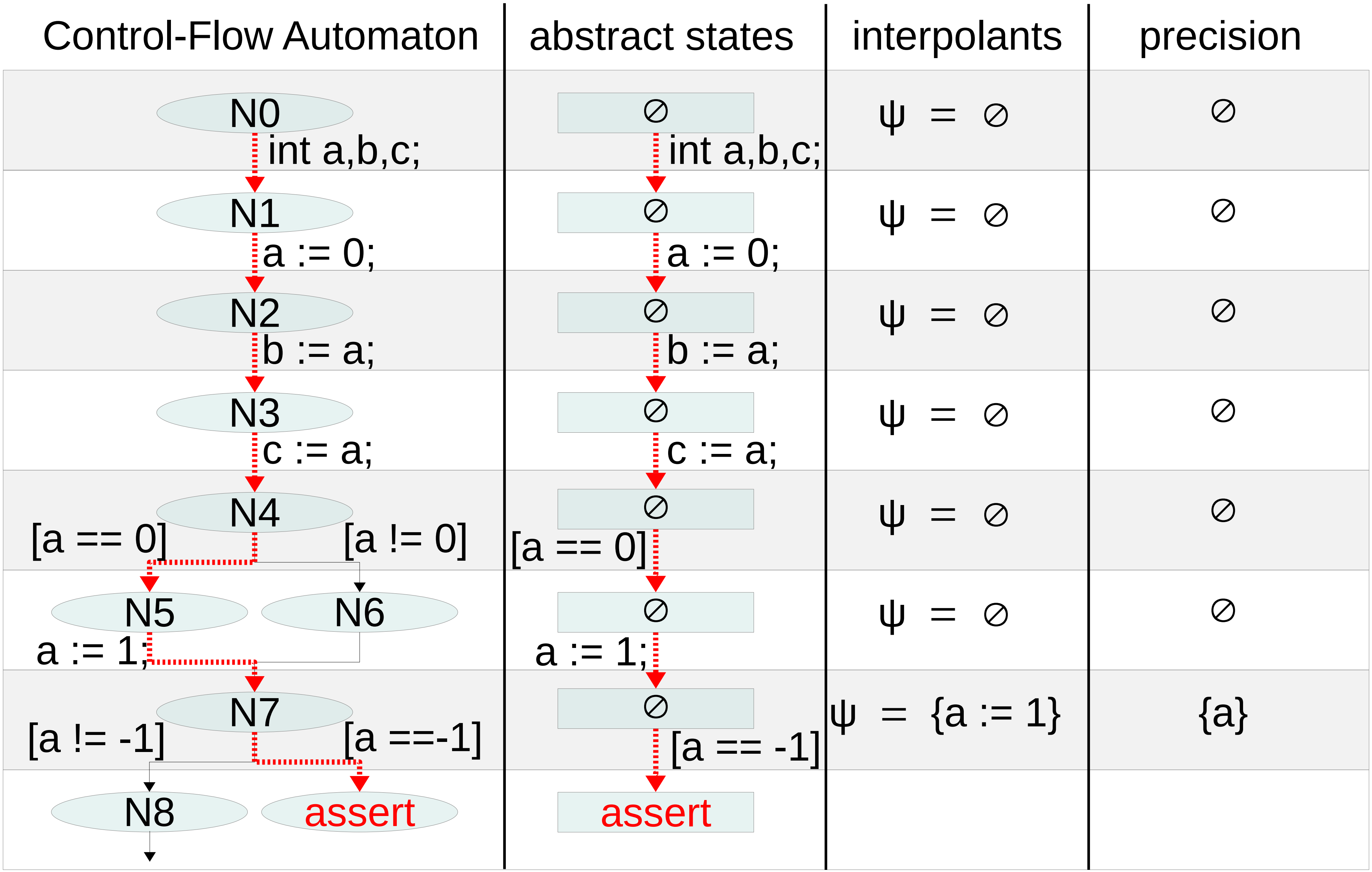
Interpolation-Based Refinement



Interpolation-Based Refinement



Interpolation-Based Refinement

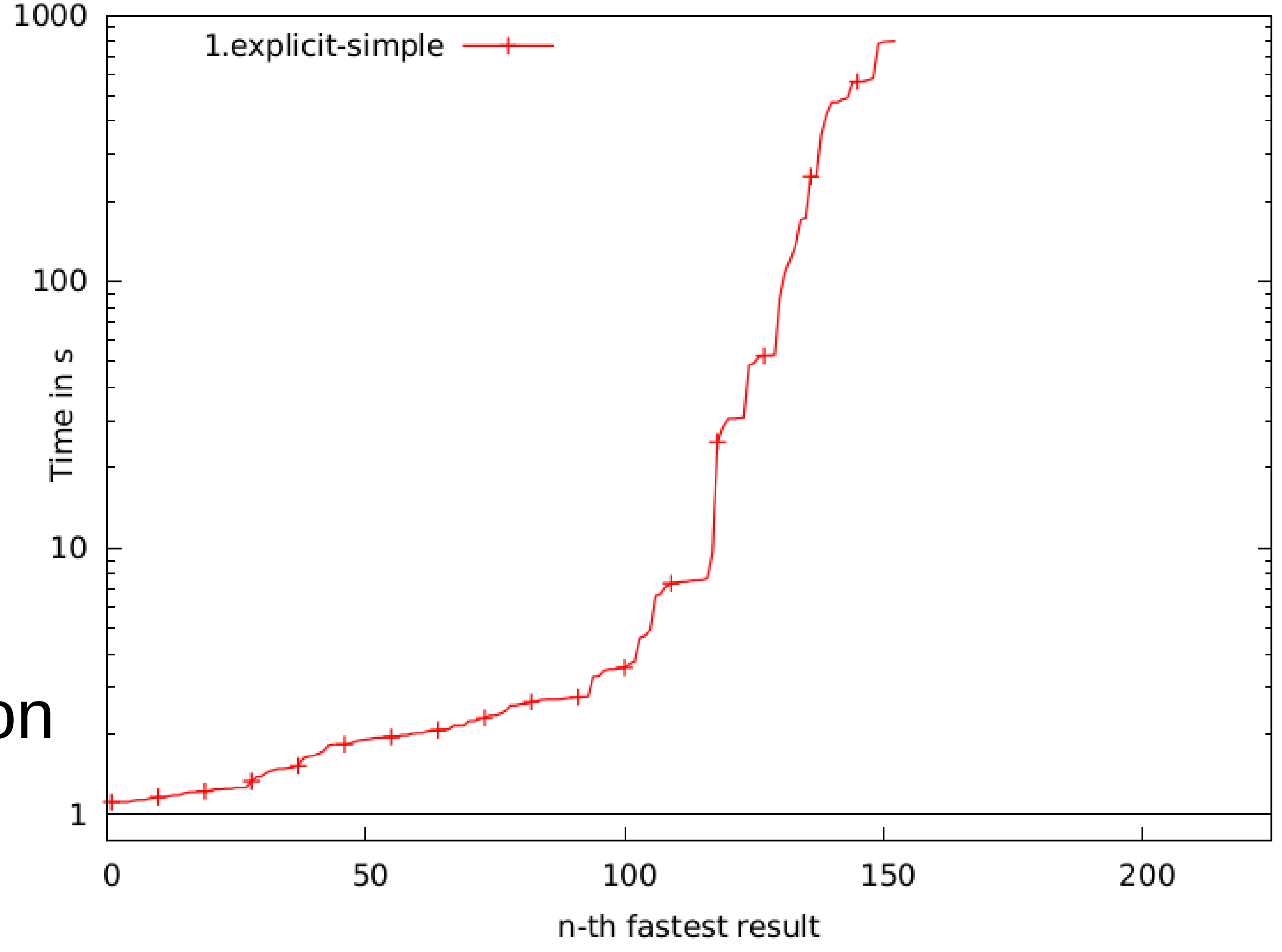


Interpolation-Based Refinement

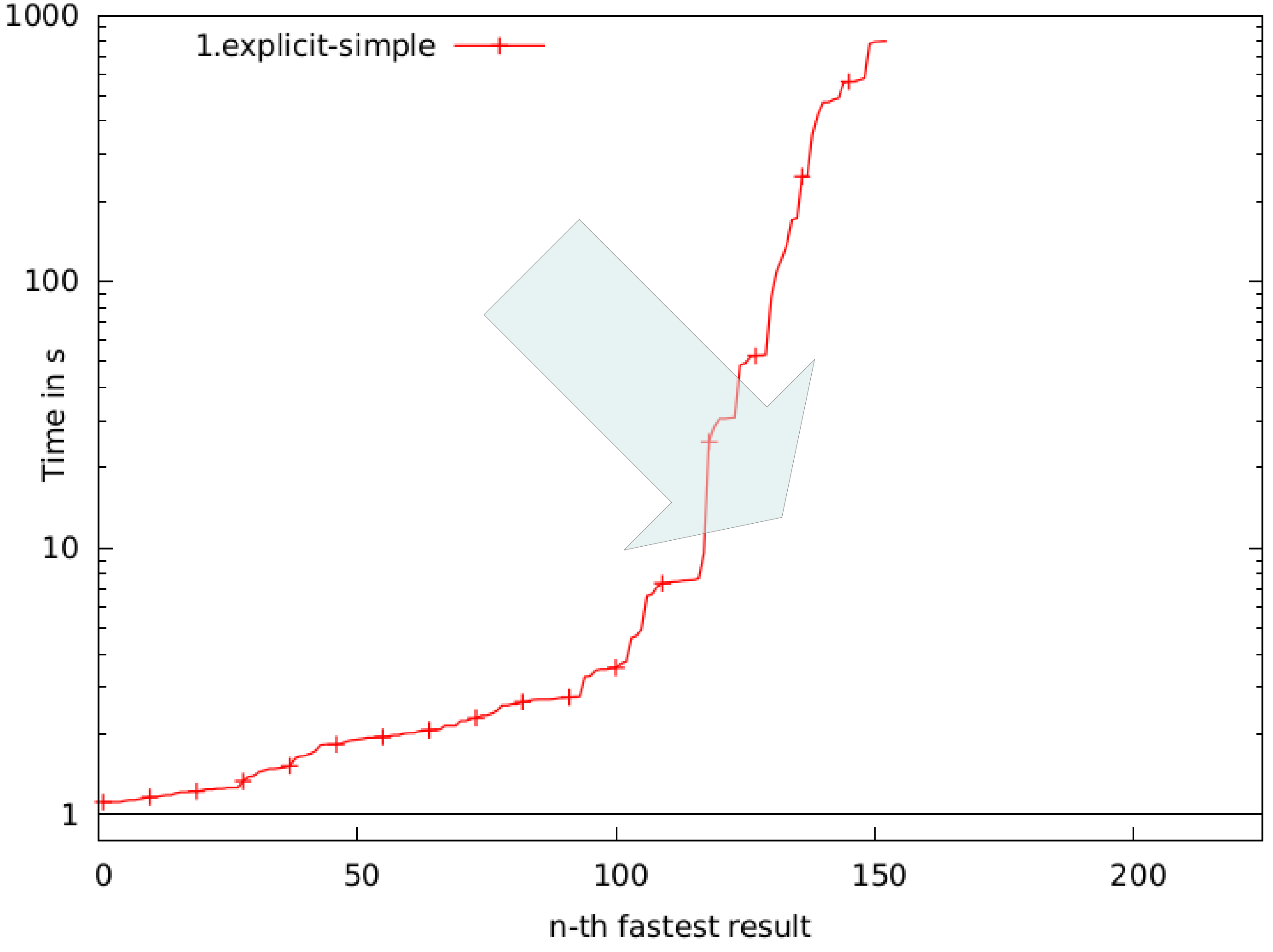
abstract states	interpolants	precision	error path refuted
$\emptyset$ int a,b,c;	$\psi = \emptyset$	$\emptyset$	N0 int a,b,c;
$\emptyset$ a := 0;	$\psi = \emptyset$	$\emptyset$	N1 a := 0;
$\emptyset$ b := a;	$\psi = \emptyset$	$\emptyset$	N2 b := a;
$\emptyset$ c := a;	$\psi = \emptyset$	$\emptyset$	N3 c := a;
$\emptyset$ [a == 0]	$\psi = \emptyset$	$\emptyset$	N4 [a == 0] [a != 0]
$\emptyset$ a := 1;	$\psi = \emptyset$	$\emptyset$	N5 N6 a := 1;
$\emptyset$ [a == -1]	$\psi = \{a := 1\}$	{a}	N7 [a != -1] [a ==-1]
assert			N8 ~~assert~~

Experimental Evaluation

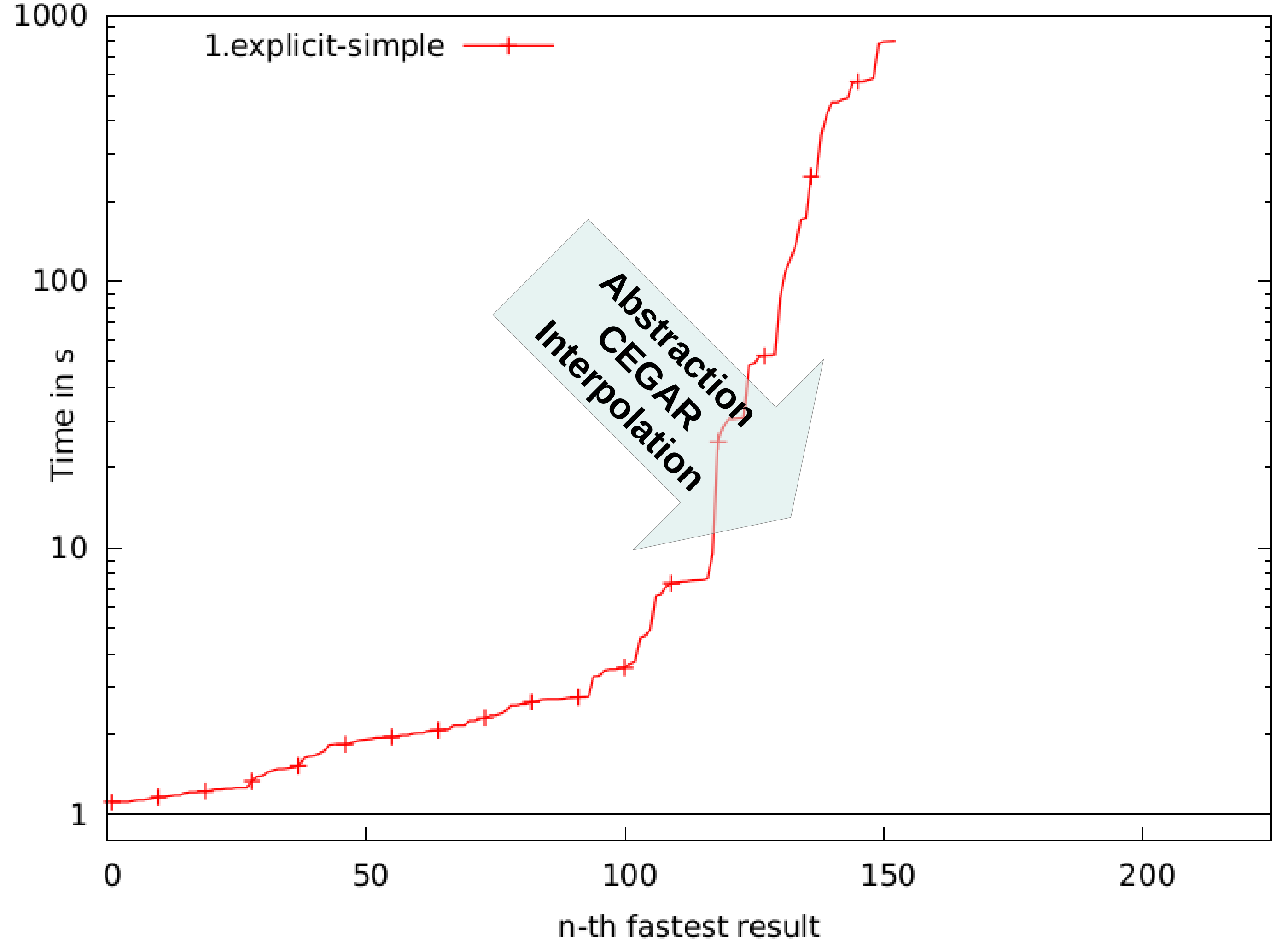
benchmarks from
1st International
Competition on
Software Verification
(SV-Comp'12)



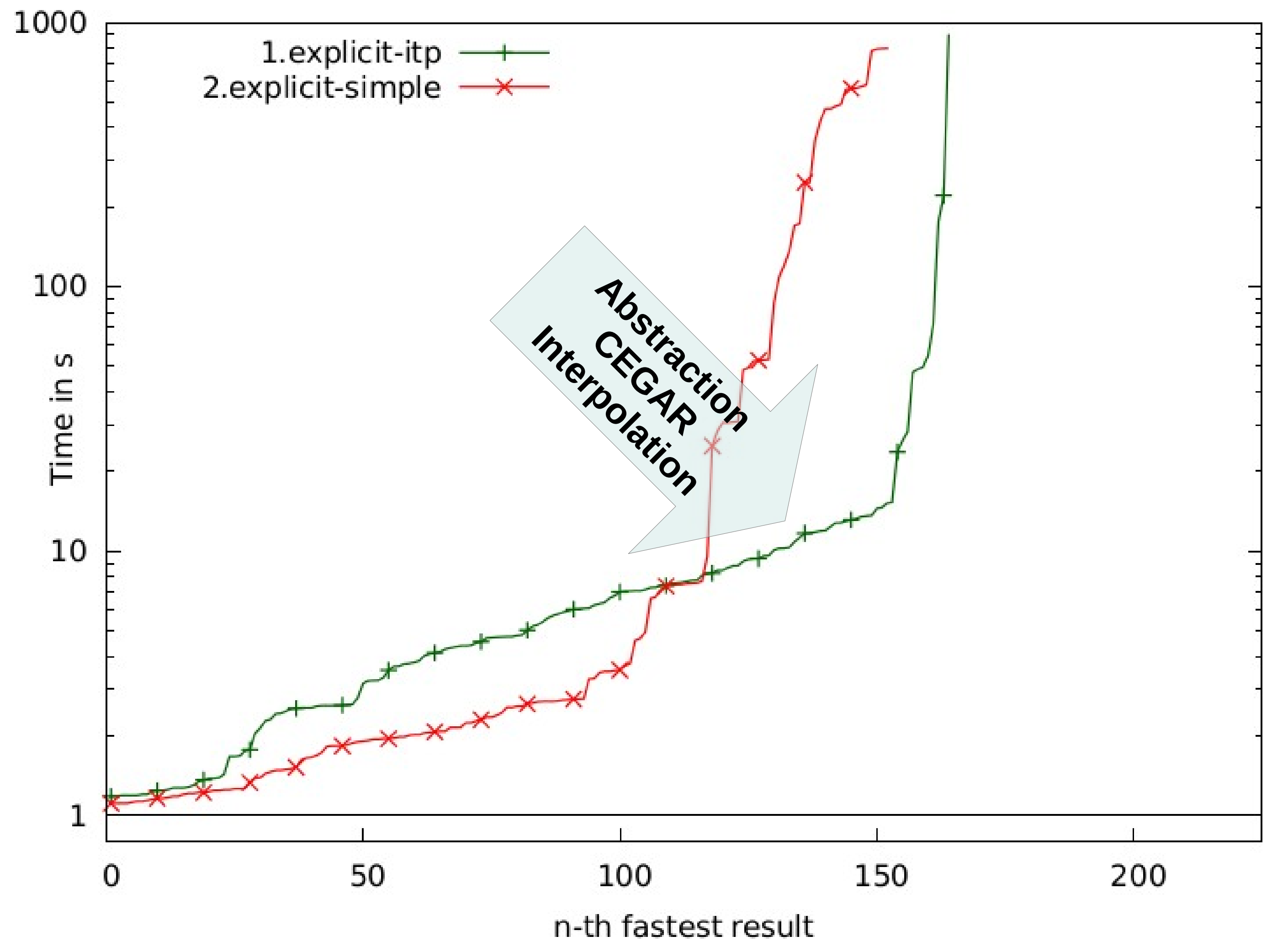
Experimental Evaluation



Experimental Evaluation



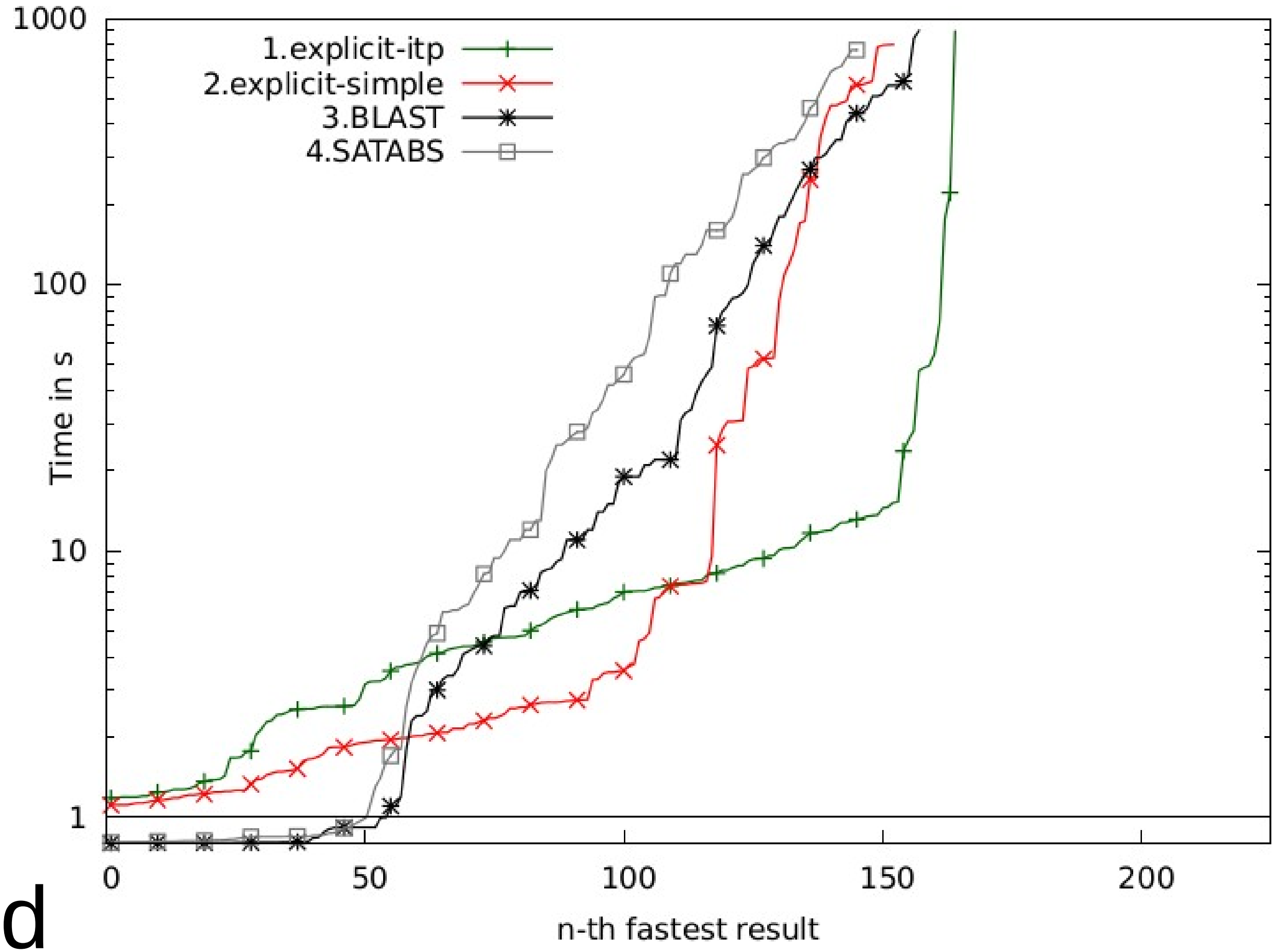
Performance Improvement



- ✔ Faster
- ✔ Better

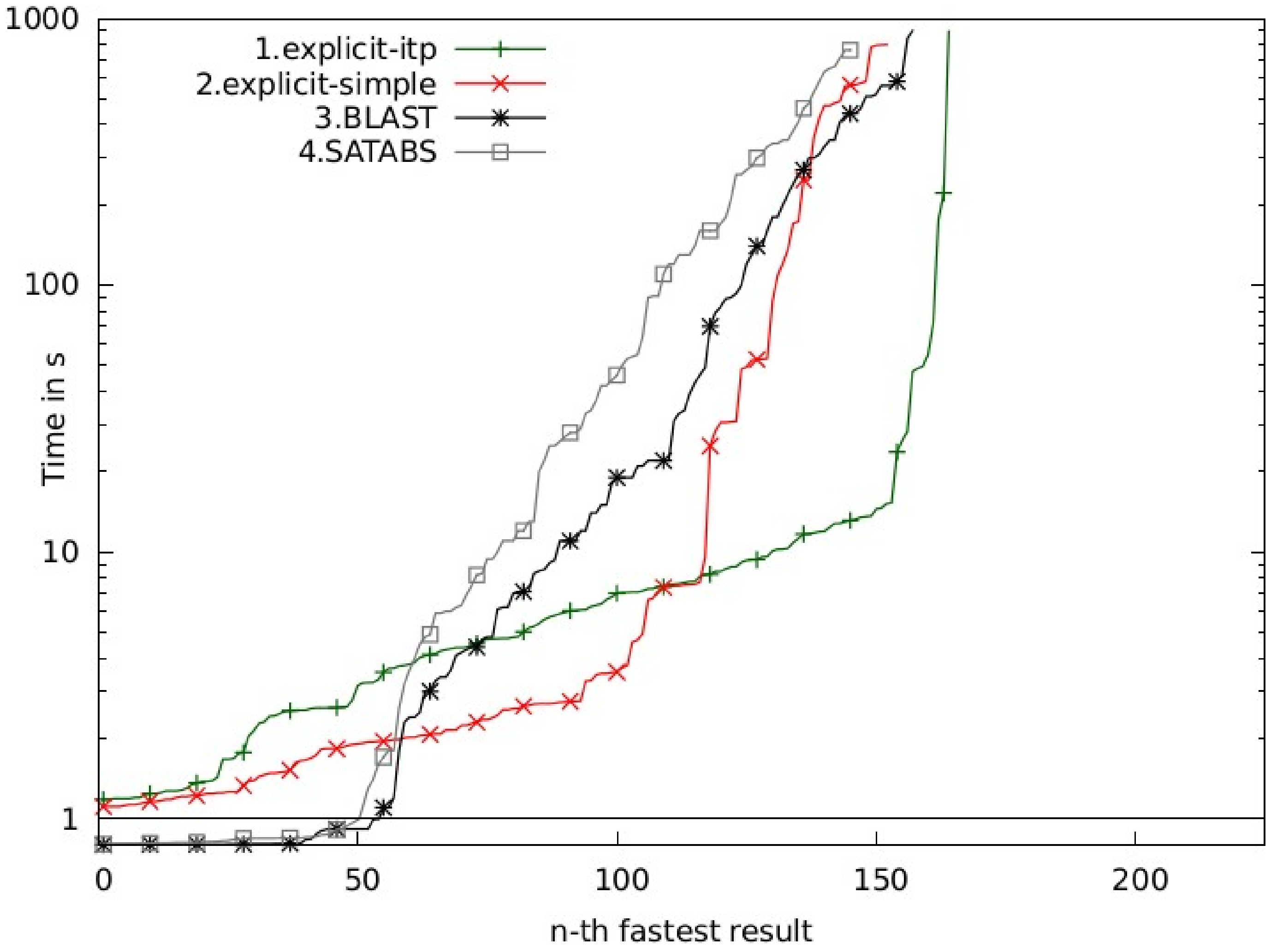
✔ Abstraction ✔ CEGAR ✔ Interpolation

Comparison with Well-Established Tools



Out-performs
well-established
predicate-based tools like BLAST or SATABS

Comparison with Well-Established Tools



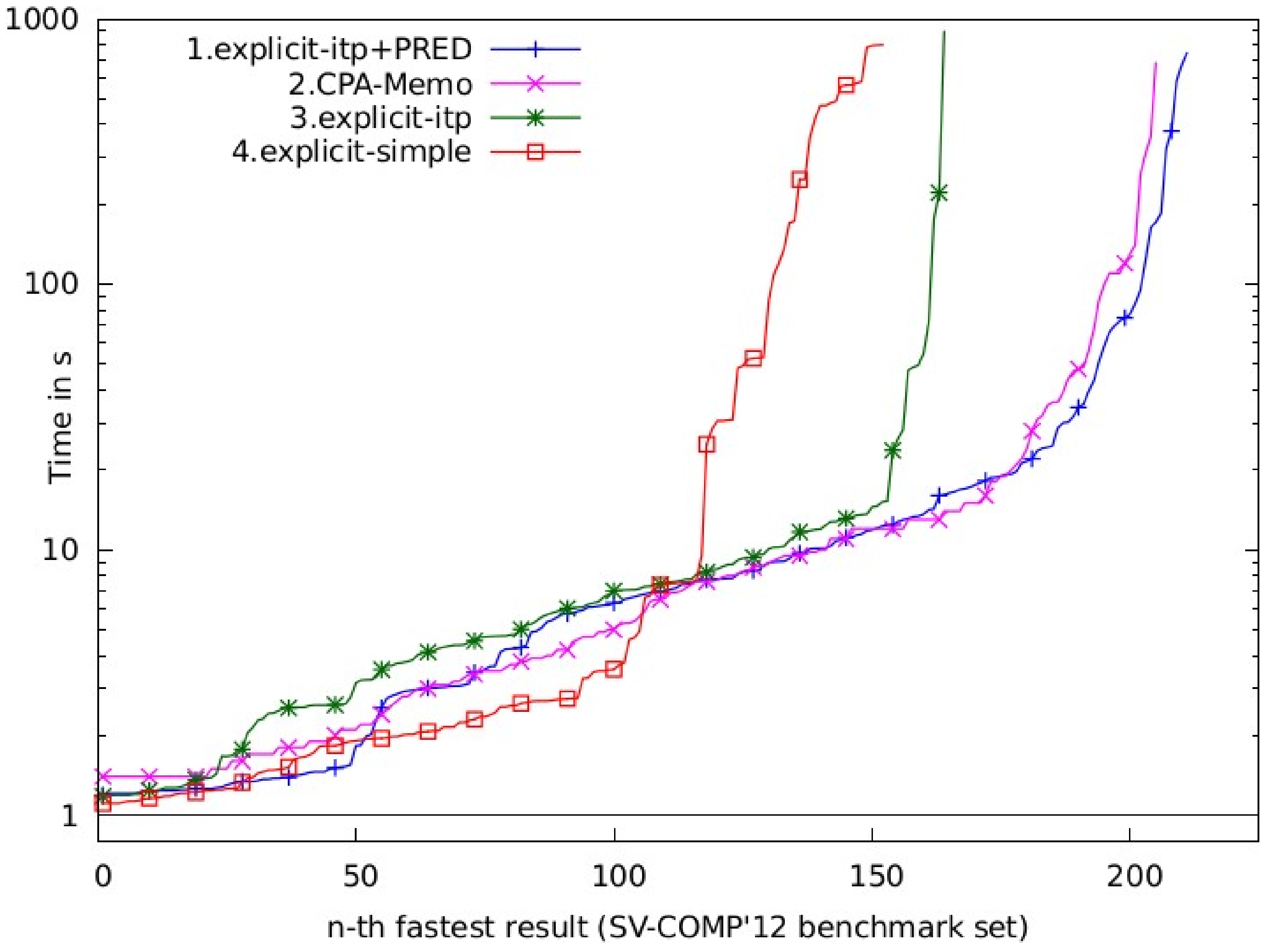
Can we further improve on this?

Have best of both worlds

Add auxiliary predicate analysis:

- Refinement of both domains based on their expressiveness
- Explicit analysis tracks most information efficiently
- Predicate analysis tracks only what is beyond that

Combined with Predicate Analysis



out-performs SV-COMP'12 Winner CPA-Memo

Results of SV-COMP'13

Our tool implementation
CPAchecker-Explicit 1.1.10
participated in SV-COMP'13, and won ...

Silver Medal in category **ControlFlowInteger**
Silver Medal in category **DeviceDrivers64**
Silver Medal in category **SystemC**

Silver Medal in category **Overall**

Award ceremony tomorrow, 10:30 in room A1

Conclusion

- Defined and implemented
  - Abstraction
  - CEGAR
  - Interpolation

  for the explicit domain
- Compelling Results
  - Effective method to reduce reached set
  - Avoid state-space explosion

CPAchecker

http://cpachecker.sosy-lab.org