C for Yourself:
Comparison of Front-End Techniques for Formal Verification

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Department of Measurement and Information Systems

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ftsrg **Critical Systems Research Group**

Motivation

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- We are the developers of Θtheta

https://github.com/ftsrg/theta/

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ANTLR

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  - **Why?**

ANTLR

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Contributions

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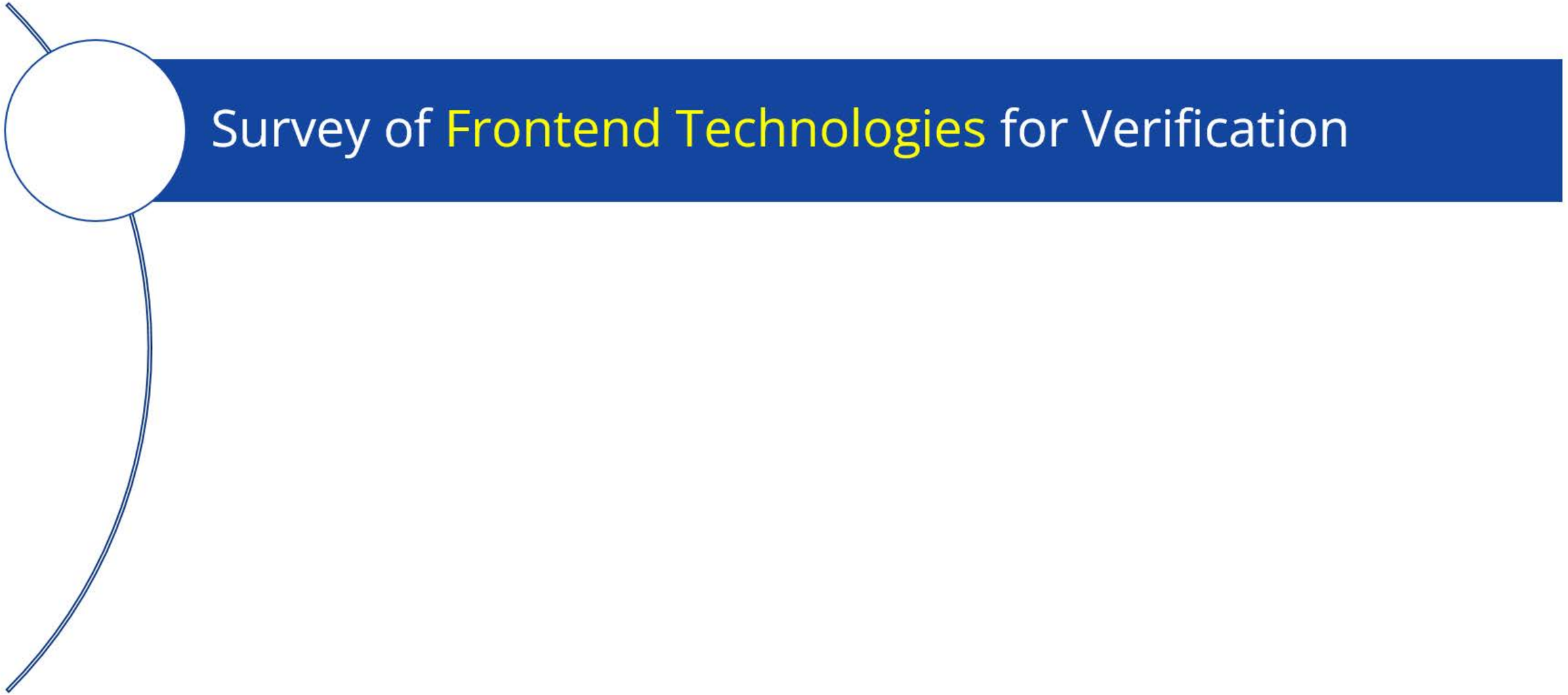


Contributions

Contributions

- Survey of Frontend Technologies for Verification
- Theoretical Justification of Observed Patterns
- Proposal of a Verification-First Frontend Project

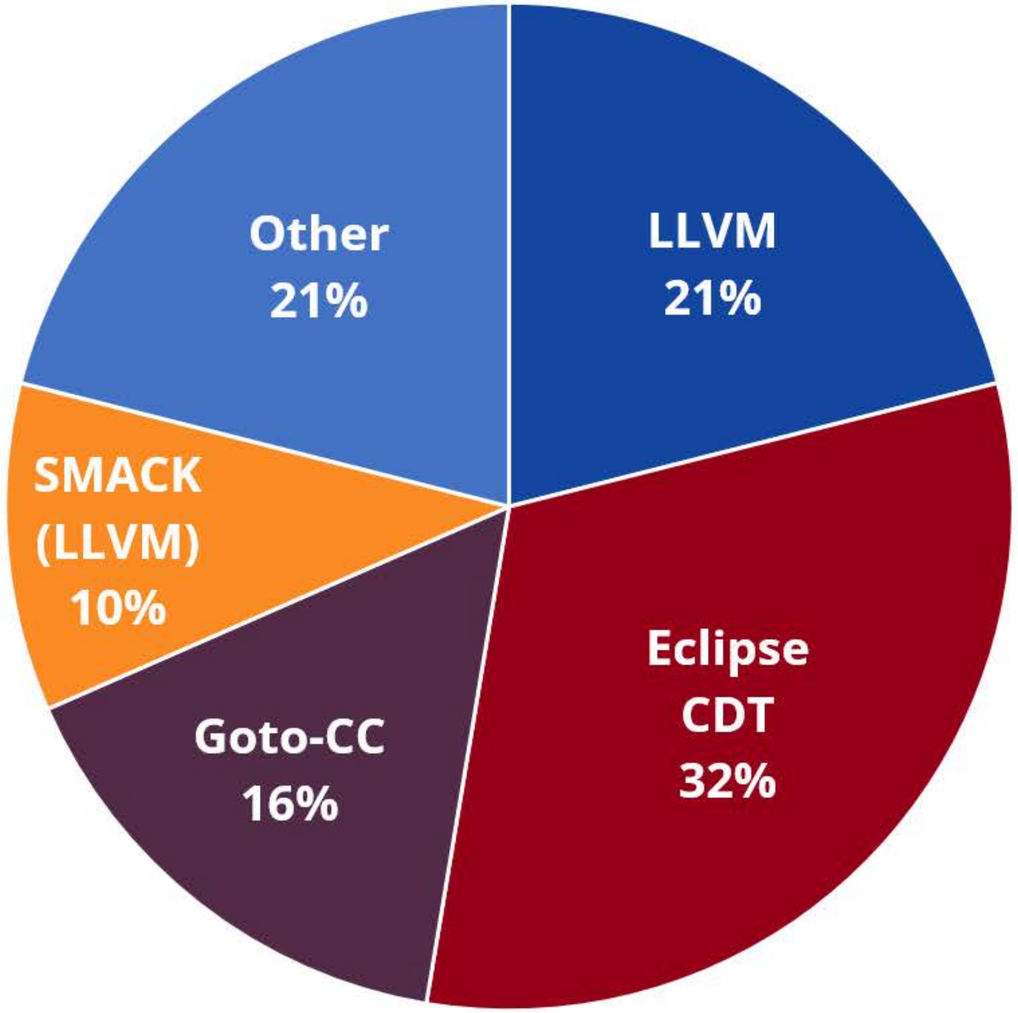
Frontend Technologies

Survey

What Frontends do Tools Use?

Source: SV-COMP 2021

What Frontends do Tools Use?



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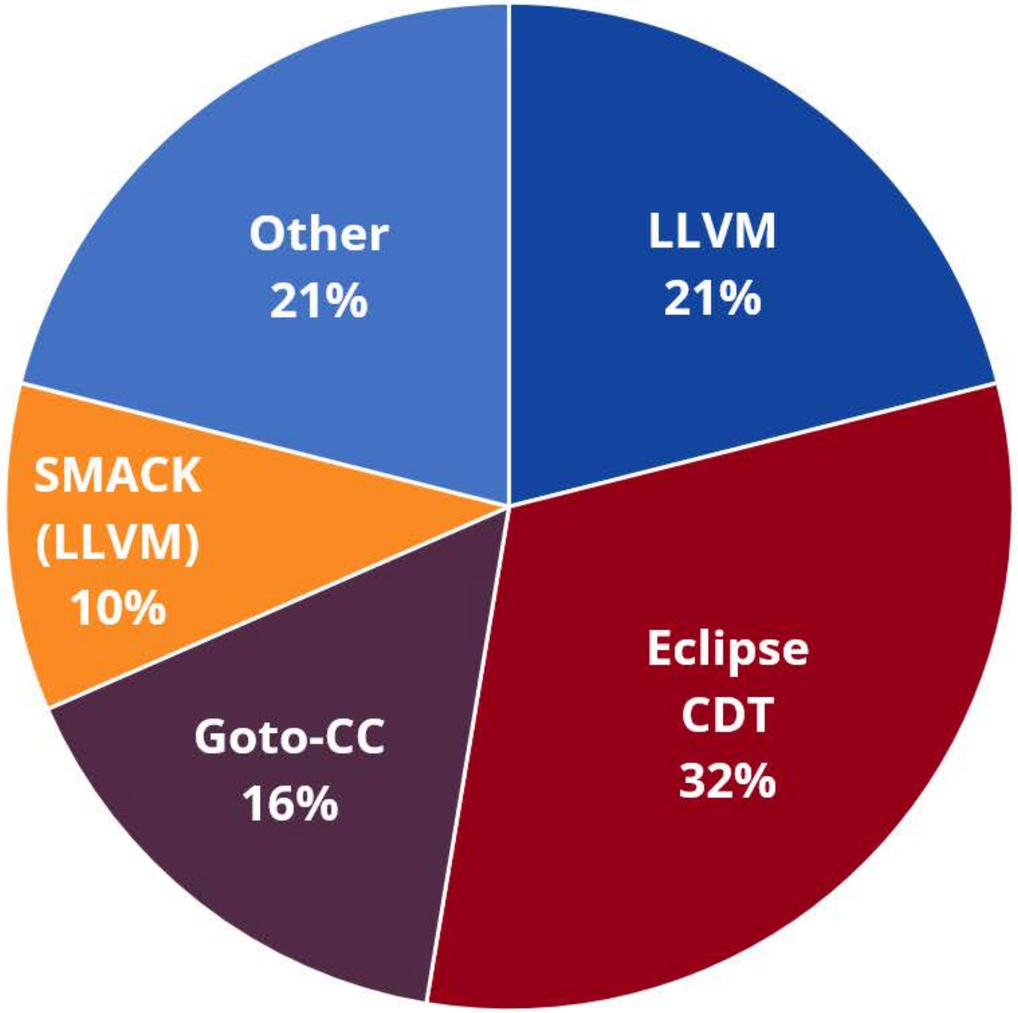

No best framework?

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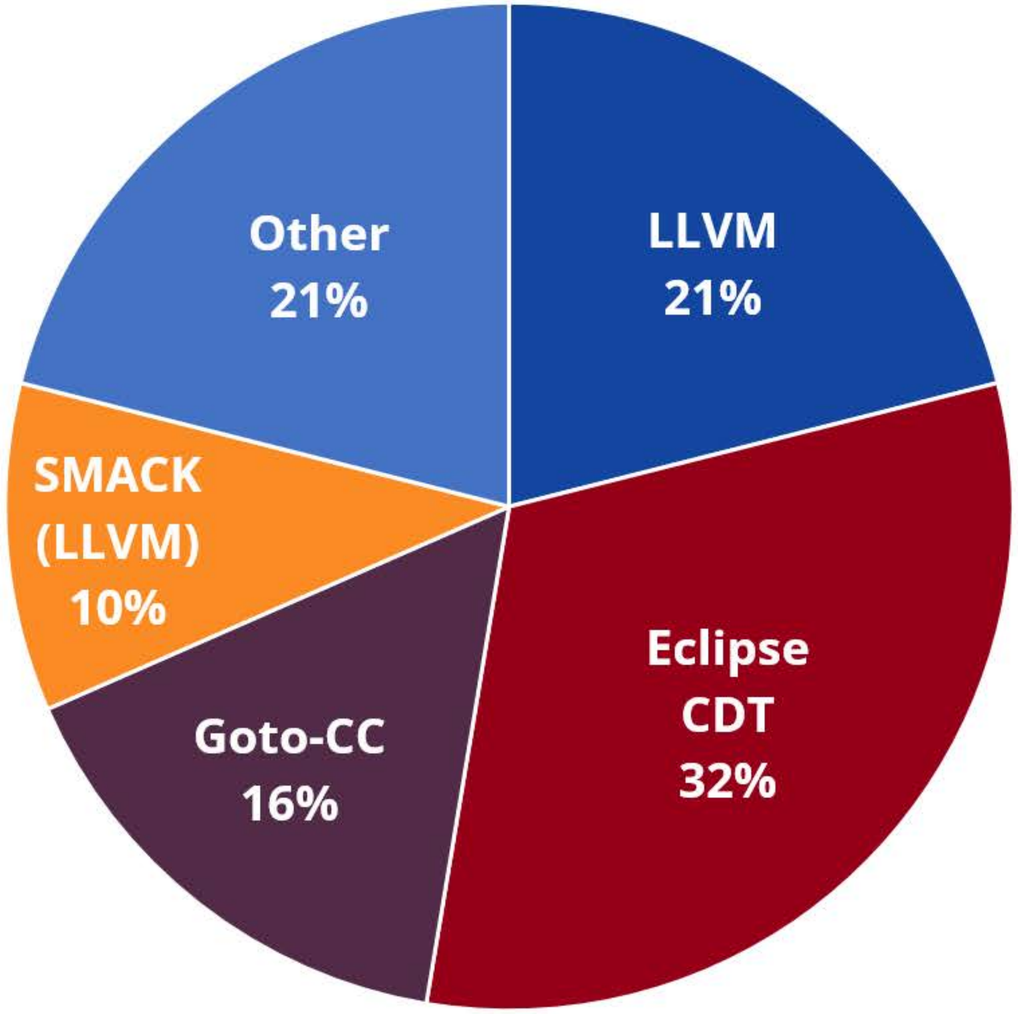

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LLVM (+SMACK)

- ✓ Easy to integrate
- ✓ Decades of development

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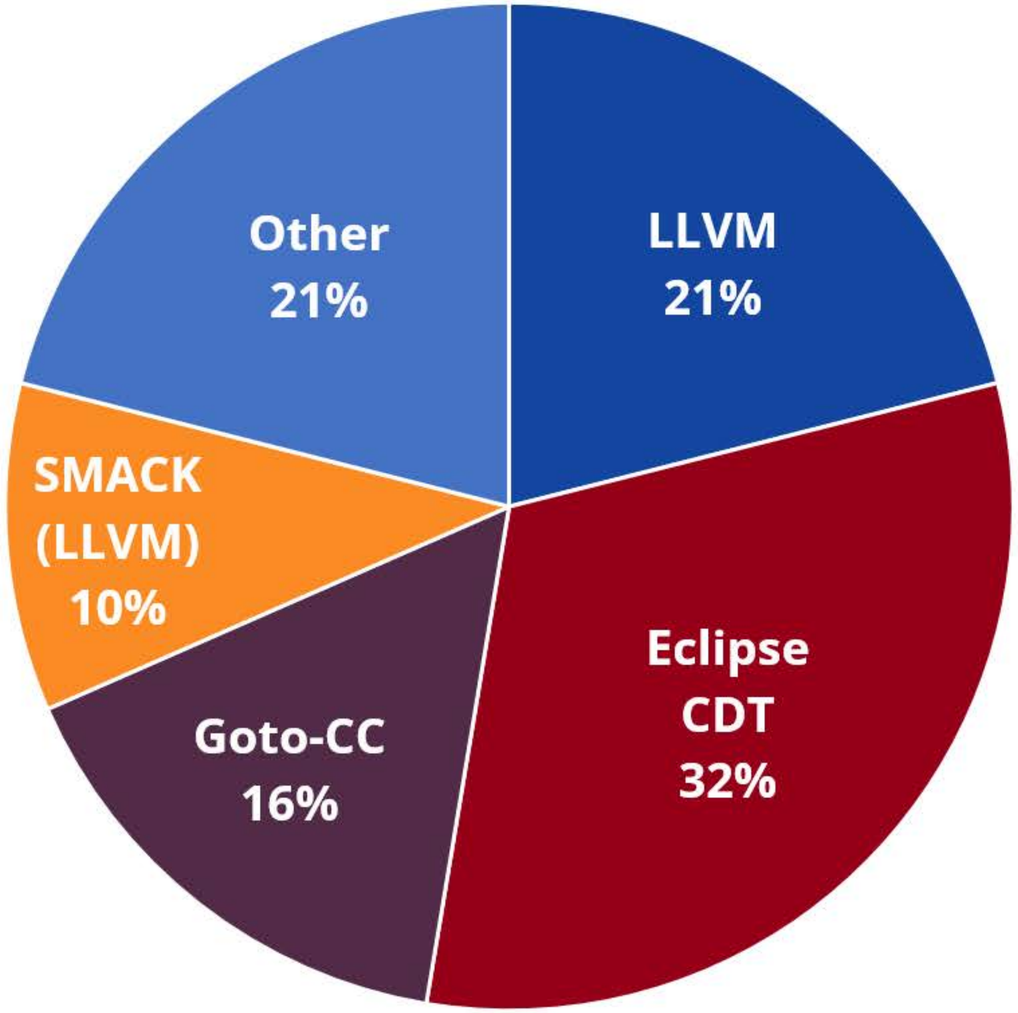

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✓Easy to integrate ✓Decades of development	✓Low-level access to syntax ✓Widely used

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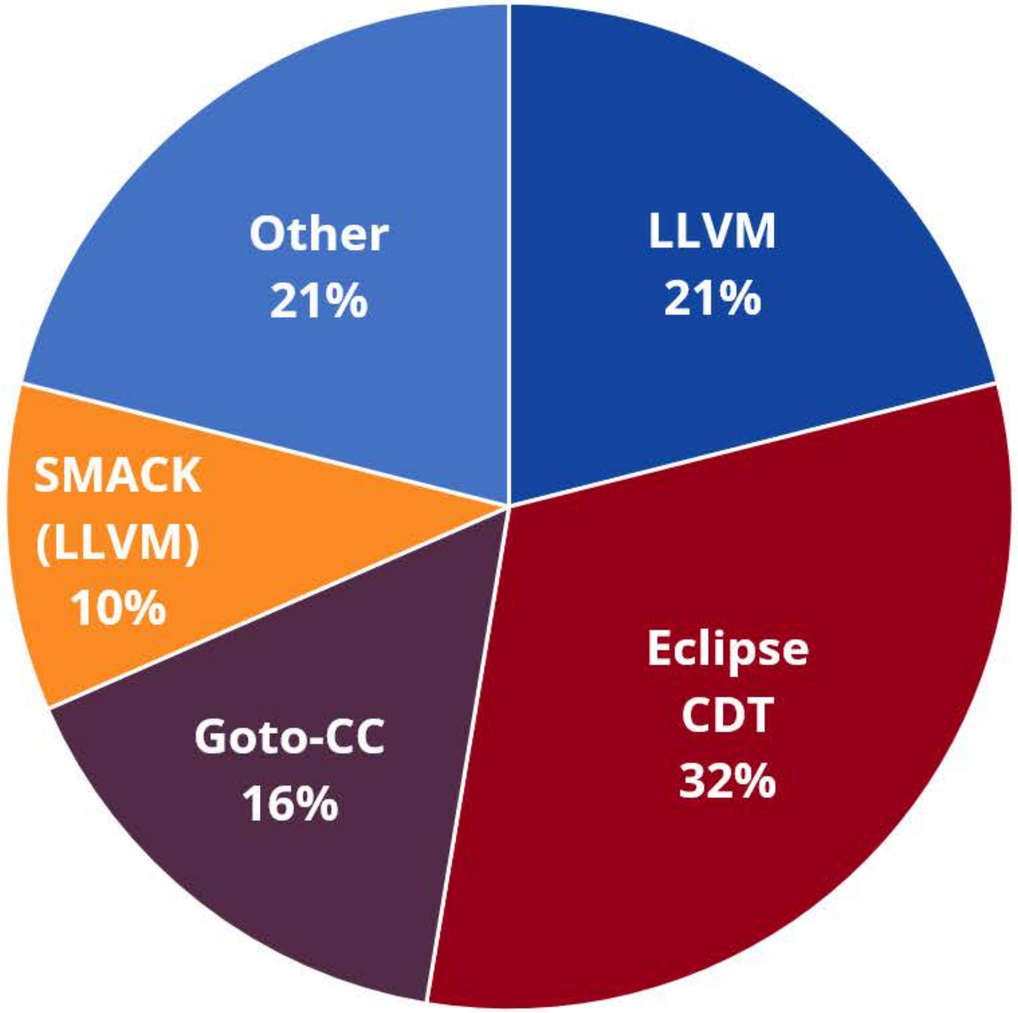

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✓Easy to integrate ✓Decades of development	✓Low-level access to syntax ✓Widely used	✓Verification-centric ✓Proven to work well (CBMC)

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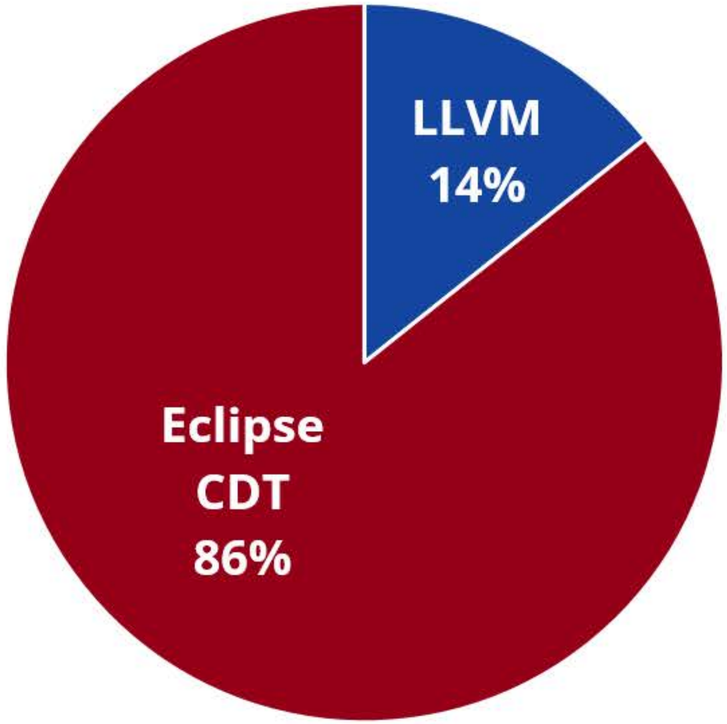

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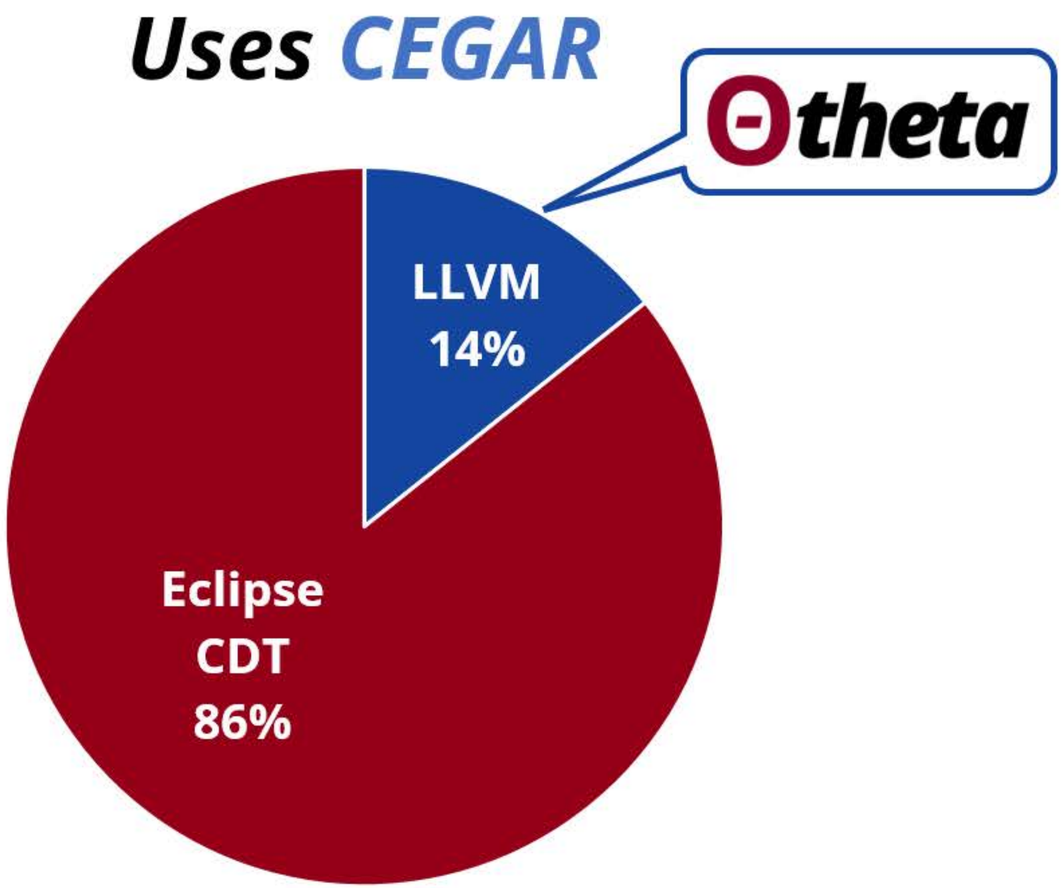

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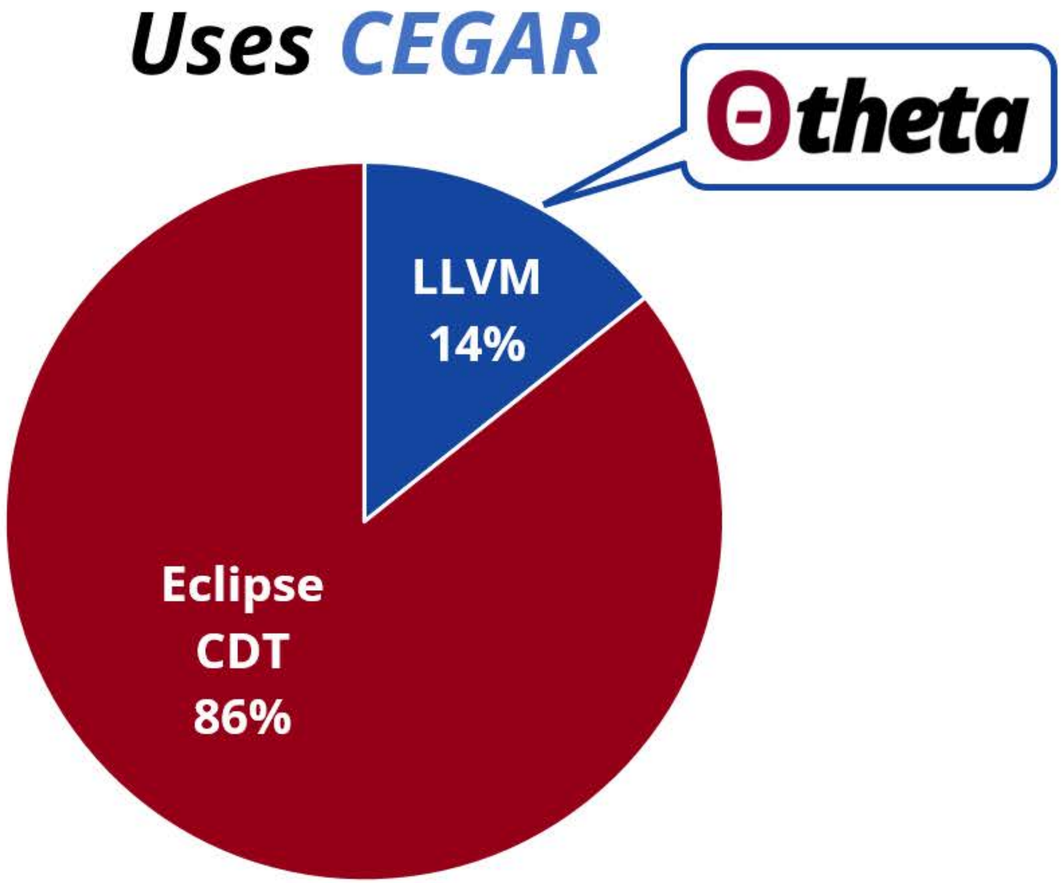

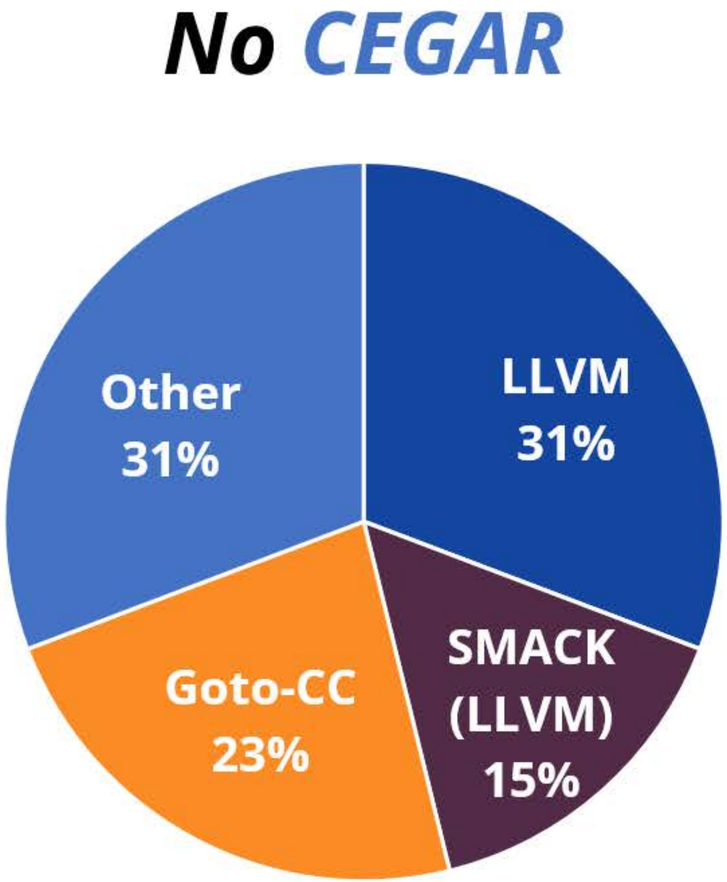

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Software Model Checking Overview

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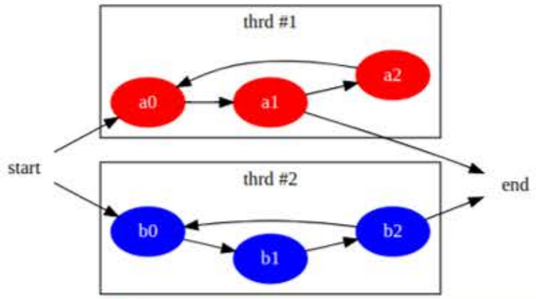

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- Low-level
- Precise

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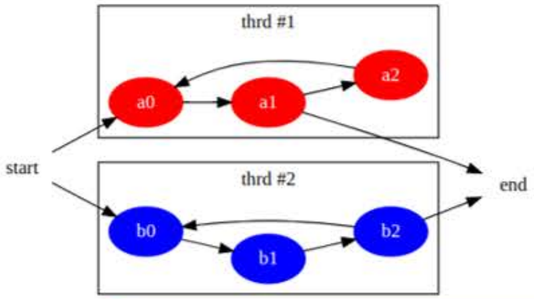

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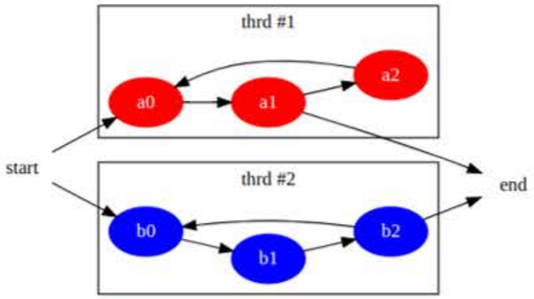

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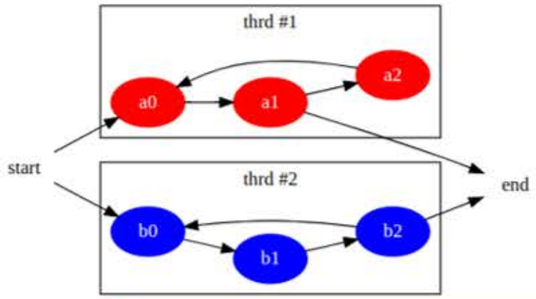
Analysis



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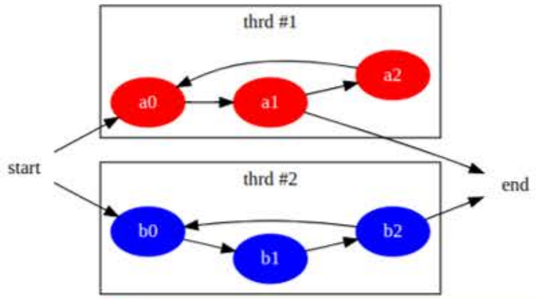

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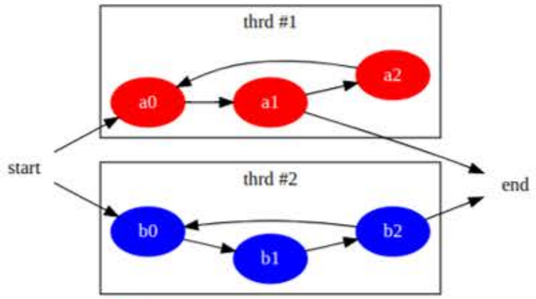

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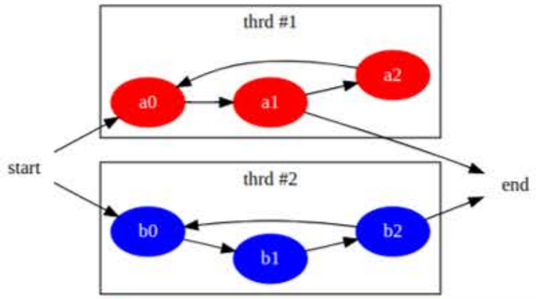

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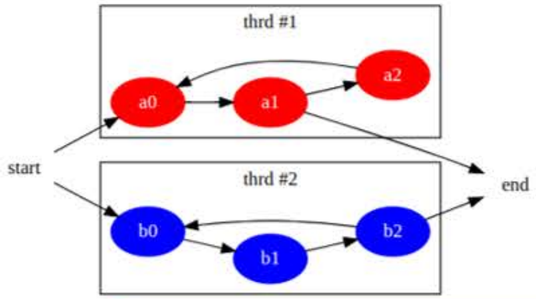

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Bounded Model Checking (**BMC**)

Counterexample-Guided Abstraction Refinement (**CEGAR**)

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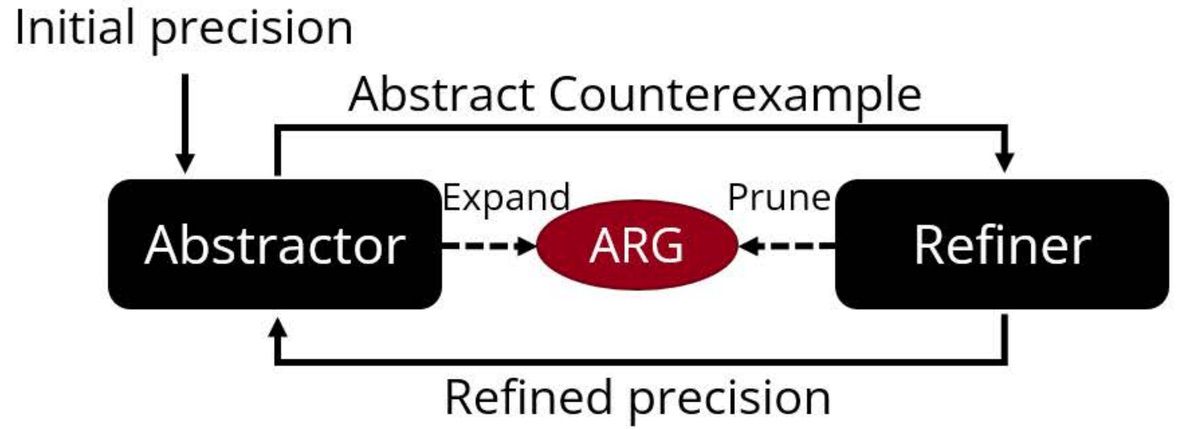

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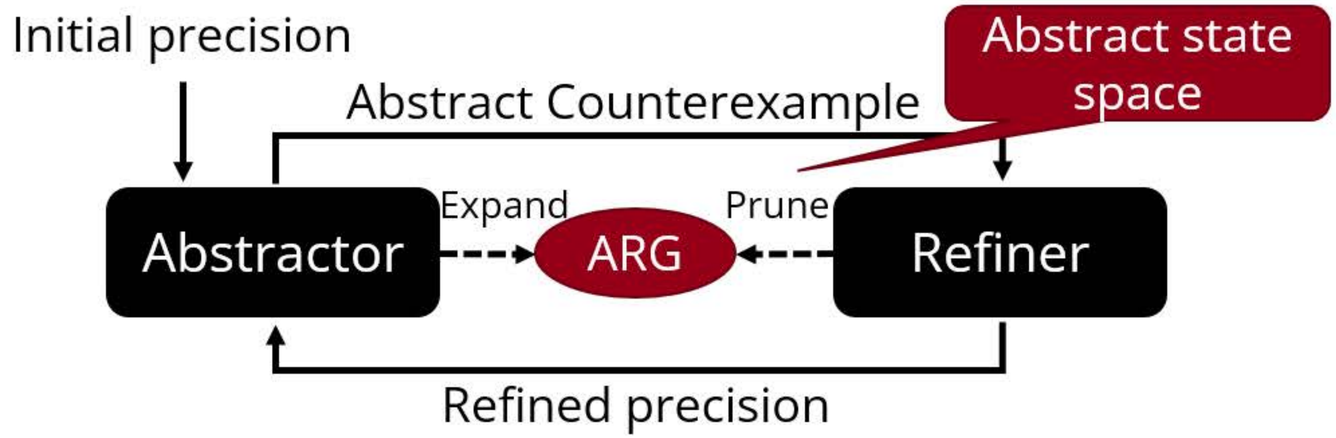

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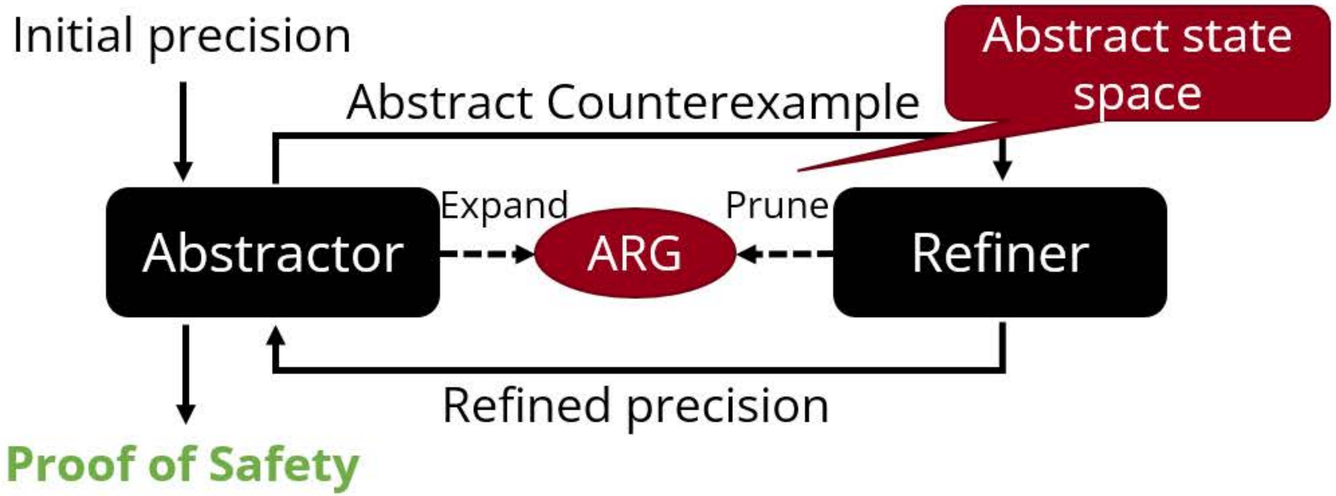

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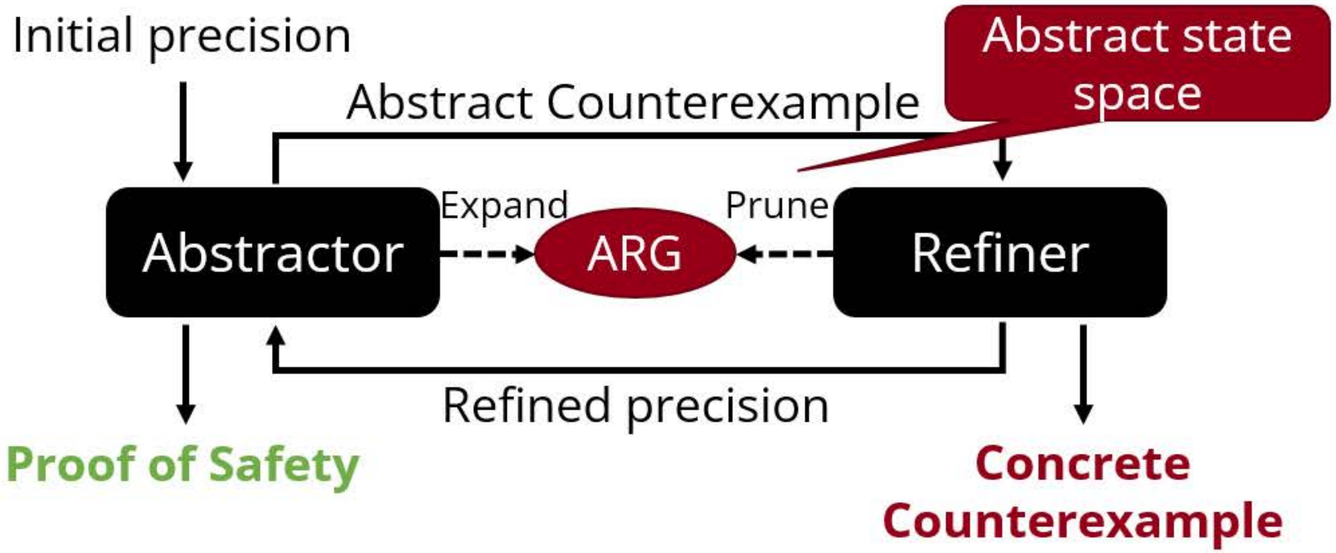

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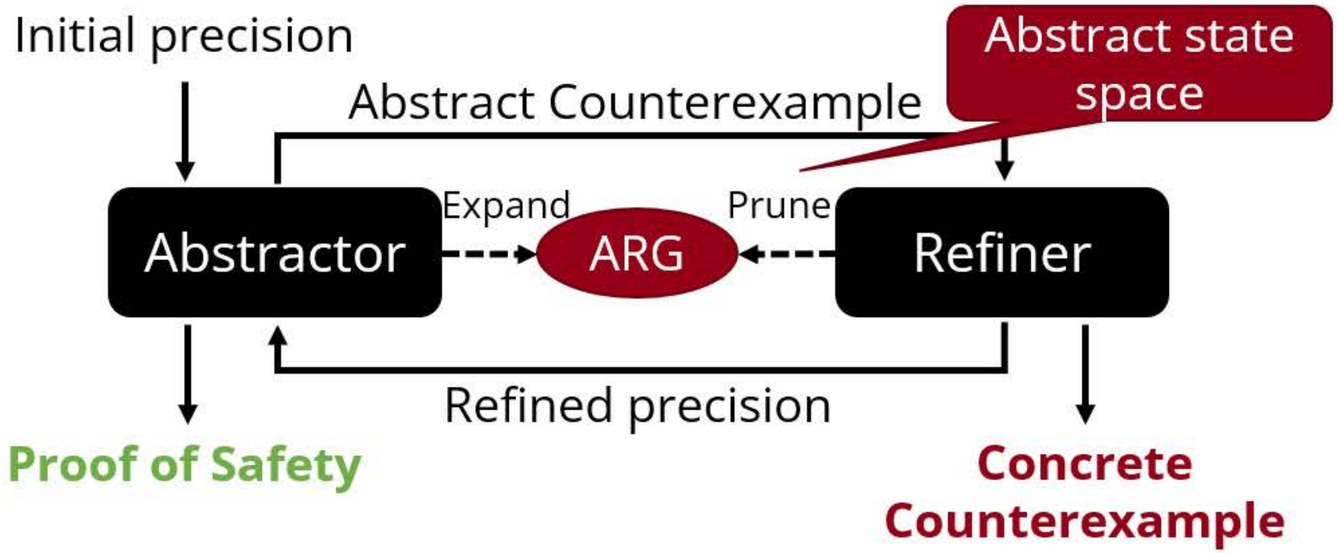

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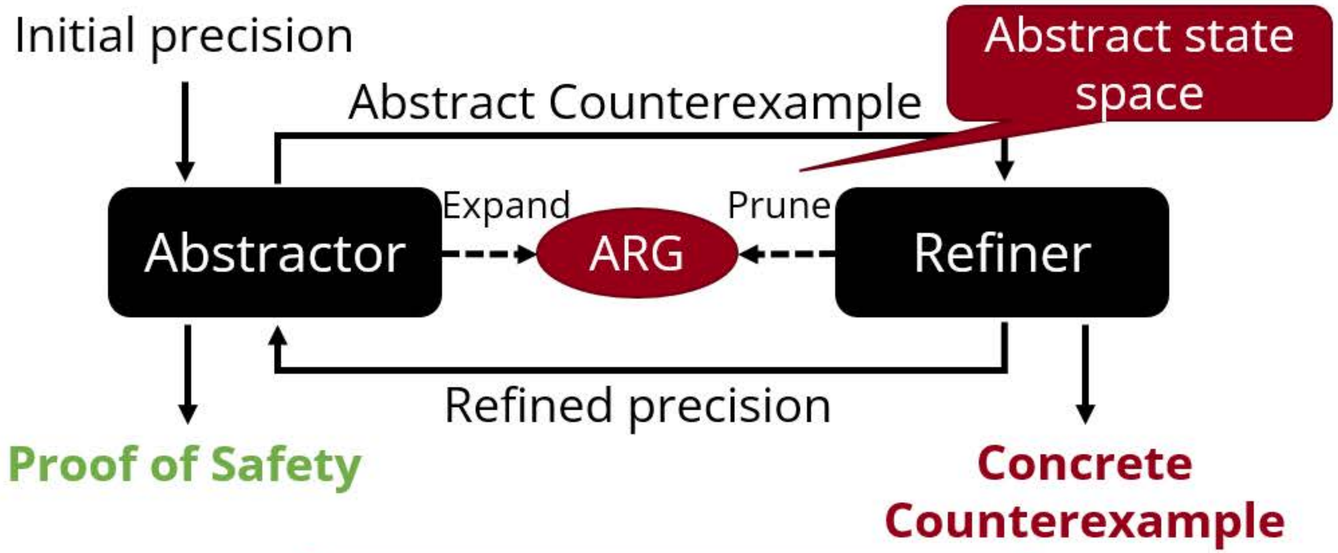

Encodes an abstract trace

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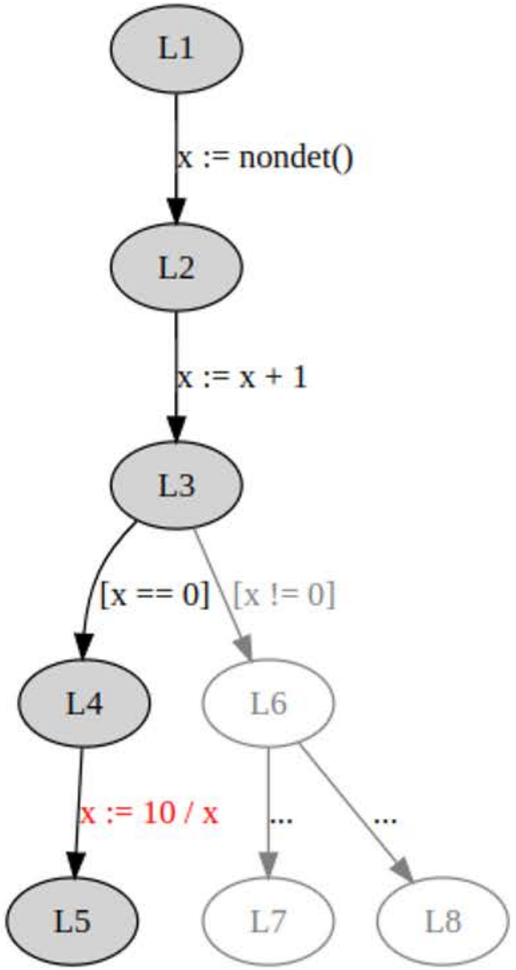
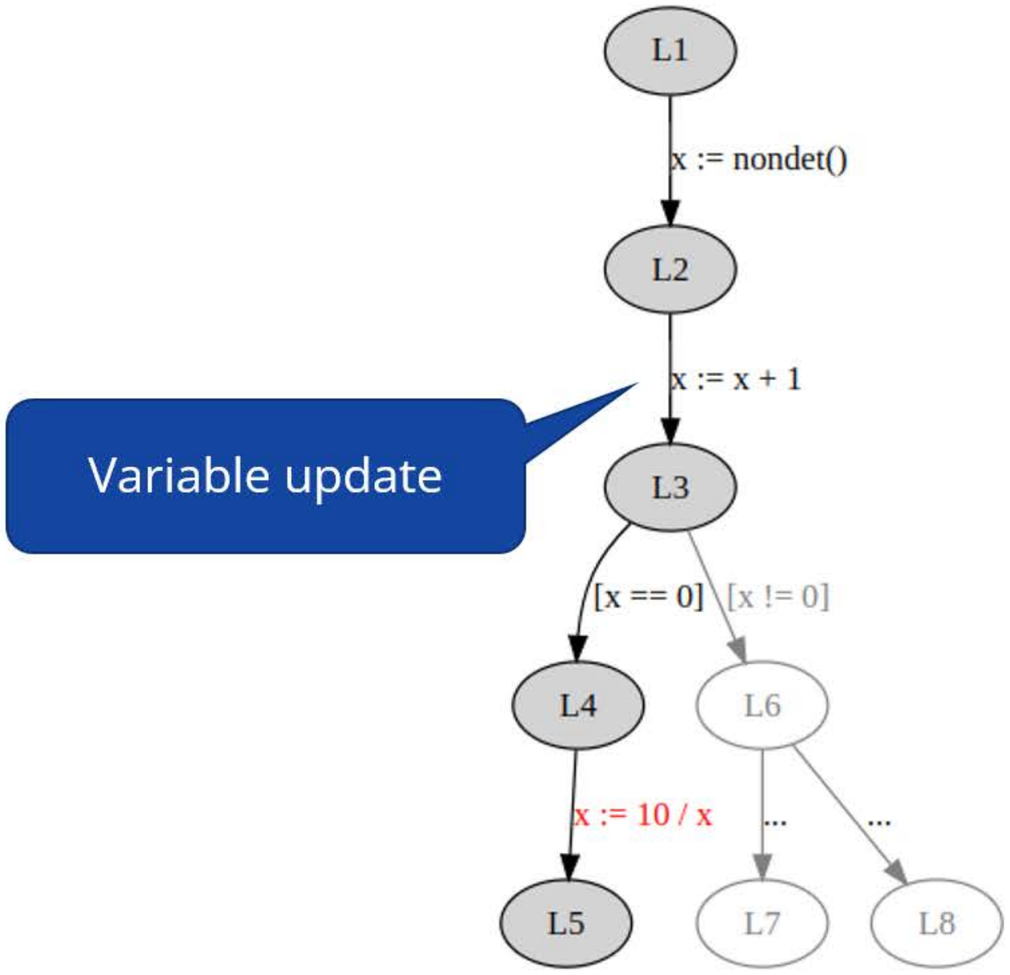


Encoding Traces as SMT-formulae



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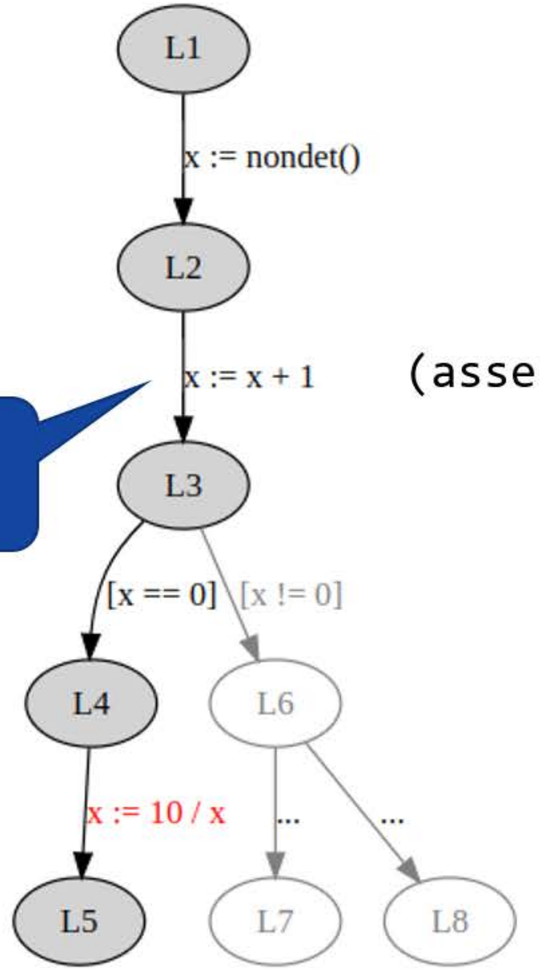
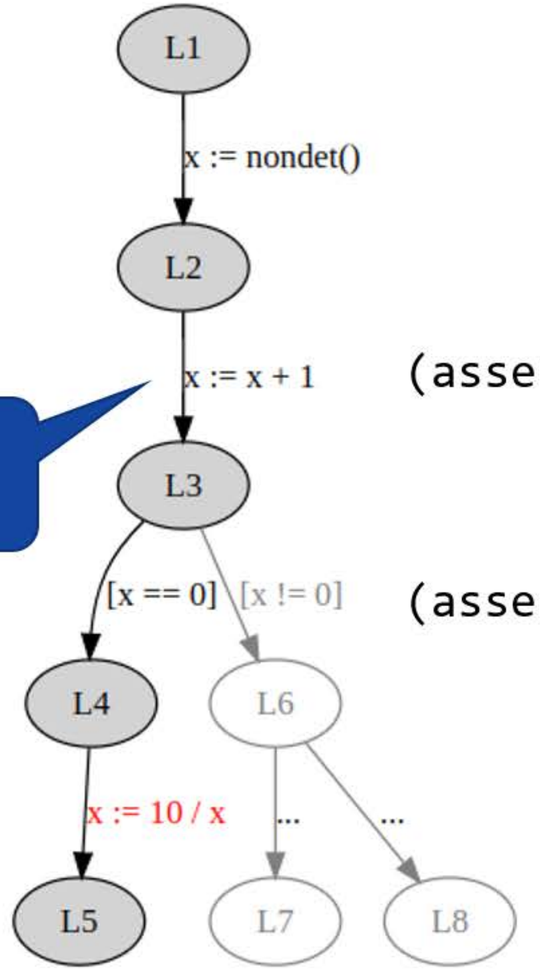


Variable update

```
(assert (= x1 (+ x0 1)))
```

Encoding Traces as SMT-formulae



Variable update

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(assert (= x1 (+ x0 1)))
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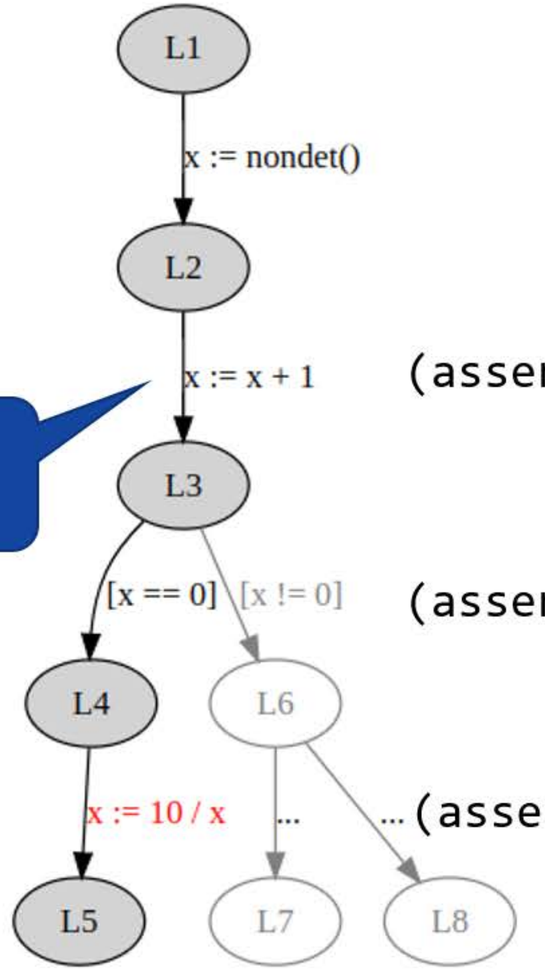
```
(assert (= x1 10))
```

Encoding Traces as SMT-formulae



Variable update

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(assert (= x1 (+ x0 1)))
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(assert (= x1 10))
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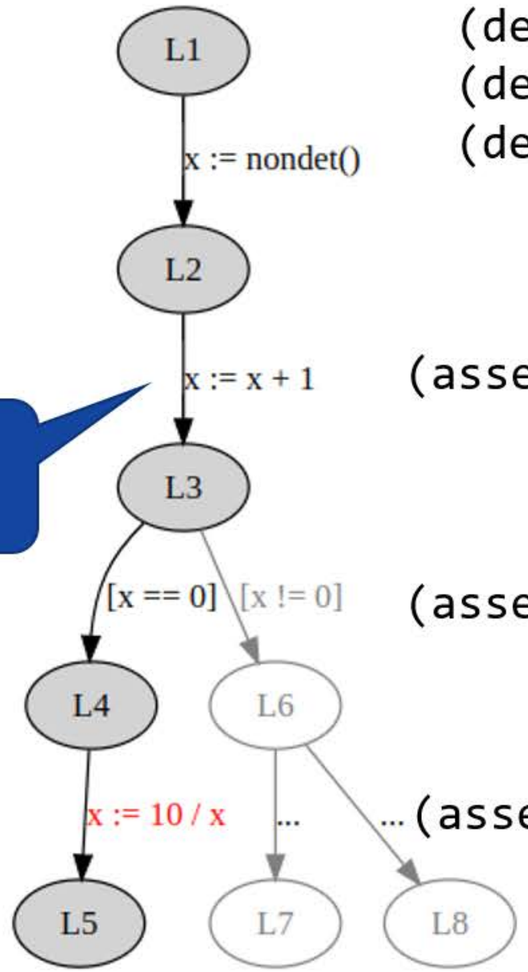
```
(assert (= x2 (/ 10 x1)))
```

Encoding Traces as SMT-formulae



Variable update

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(declare-fun x0 () Int)
(declare-fun x1 () Int)
(declare-fun x2 () Int)
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(assert (= x1 (+ x0 1)))
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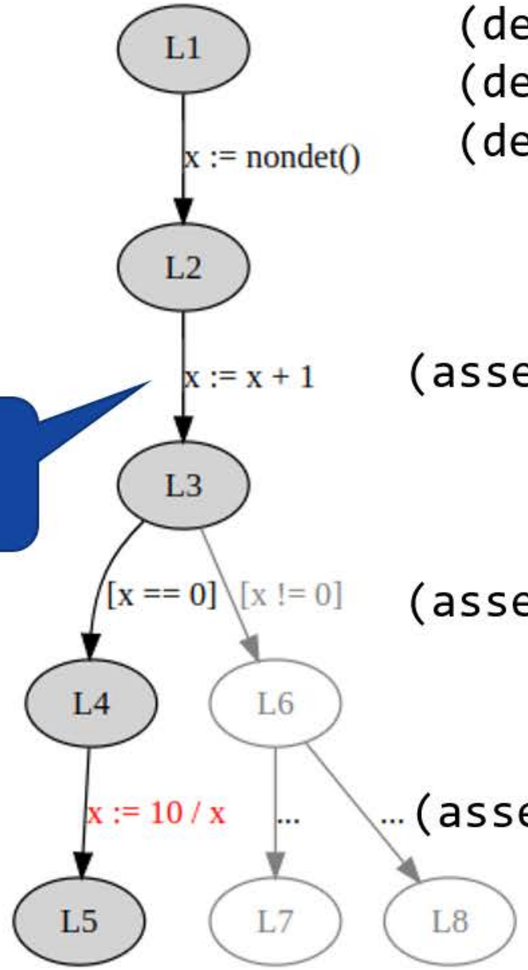


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Multiple constants

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Variable update

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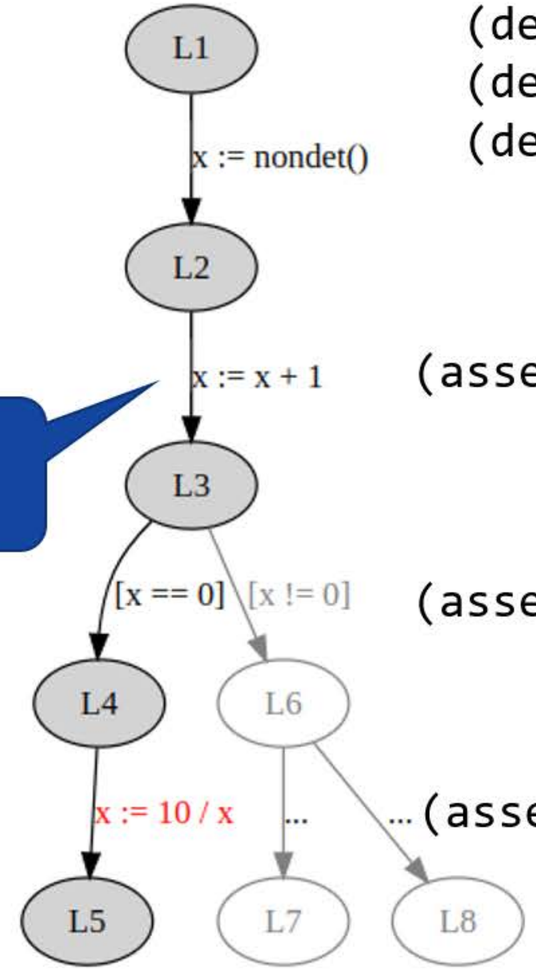


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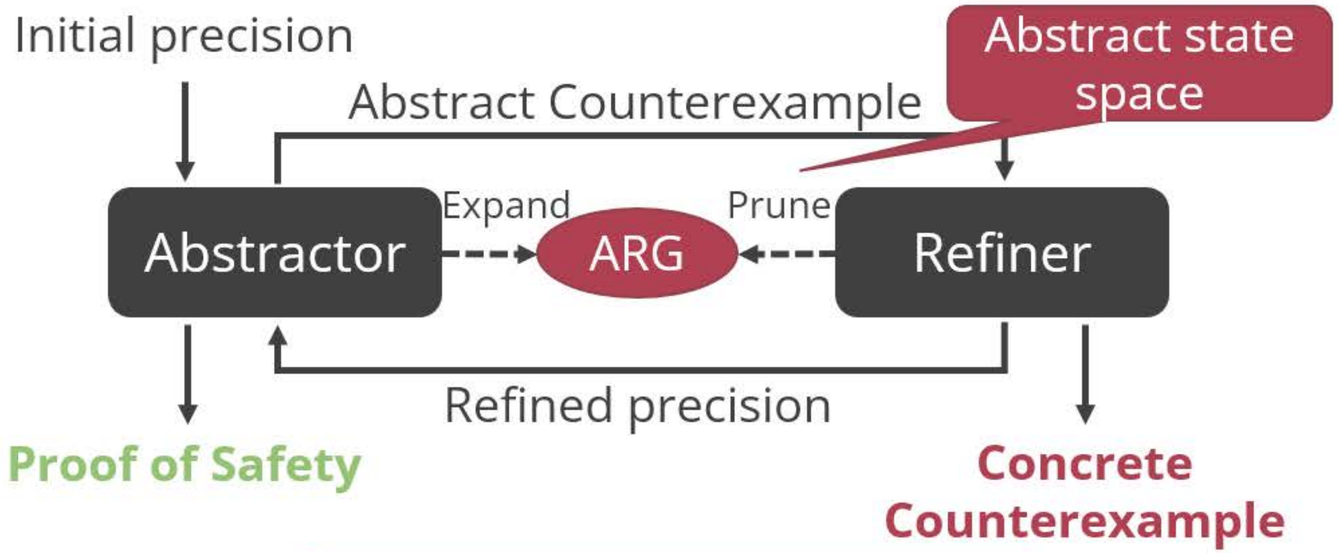
Static Single Assignment (SSA) form

SMT-Based Model Checking

Bounded Model Checking (**BMC**)

- Up to a bound **k**:
  - Traverse all paths
  - Encode into an SMT query φ_P
  - Encode error property: φ_{Err}
  - $SAT(\varphi_P \wedge \varphi_{ERR}) \Rightarrow UNSAFE$

Counterexample-Guided Abstraction Refinement (**CEGAR**)



Encodes the program directly

SMT

Encodes an abstract trace

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SSA

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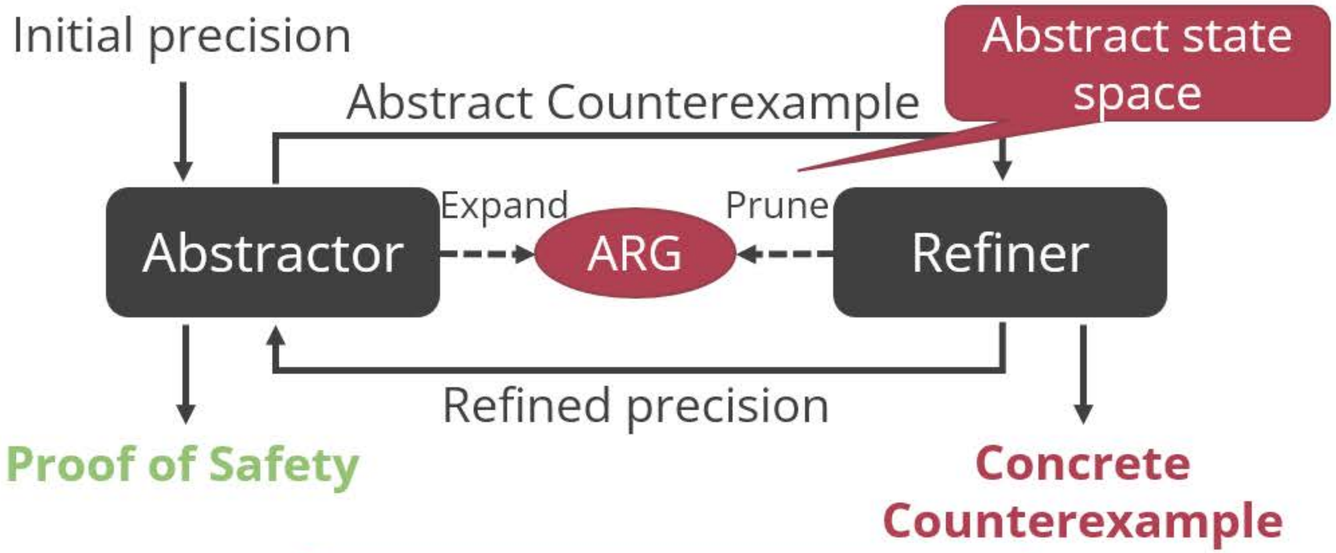

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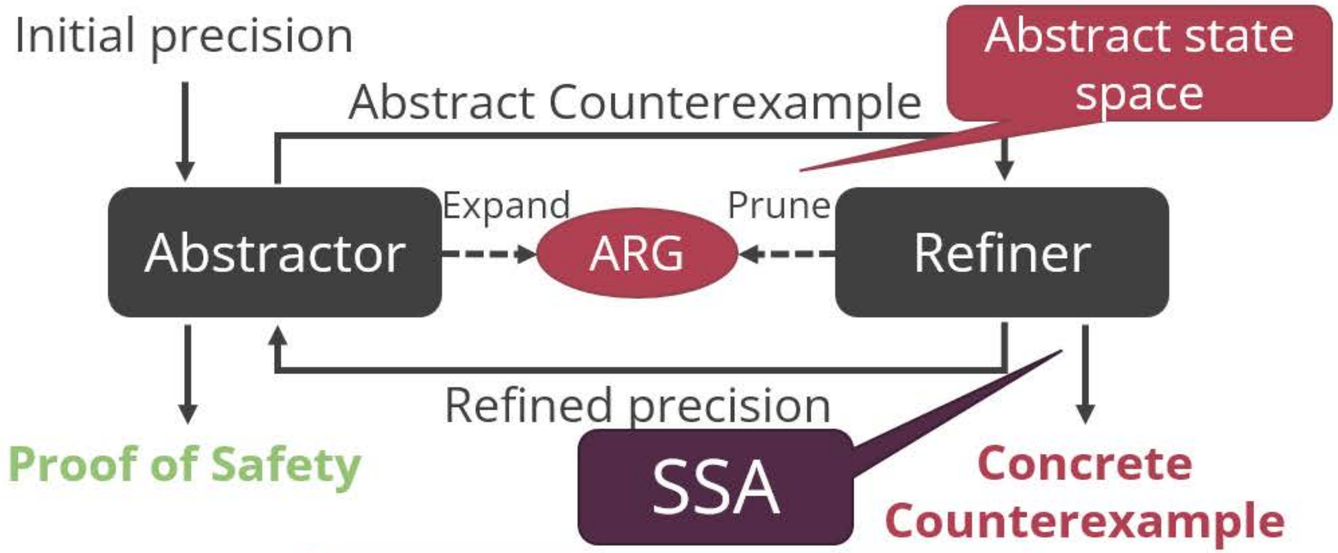

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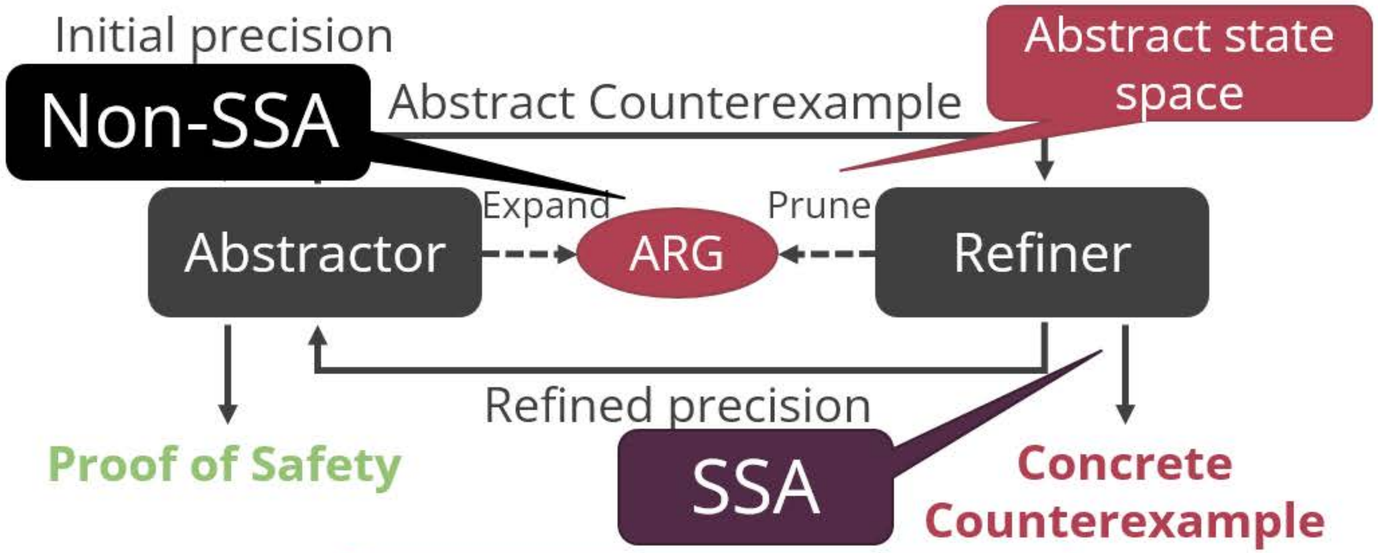

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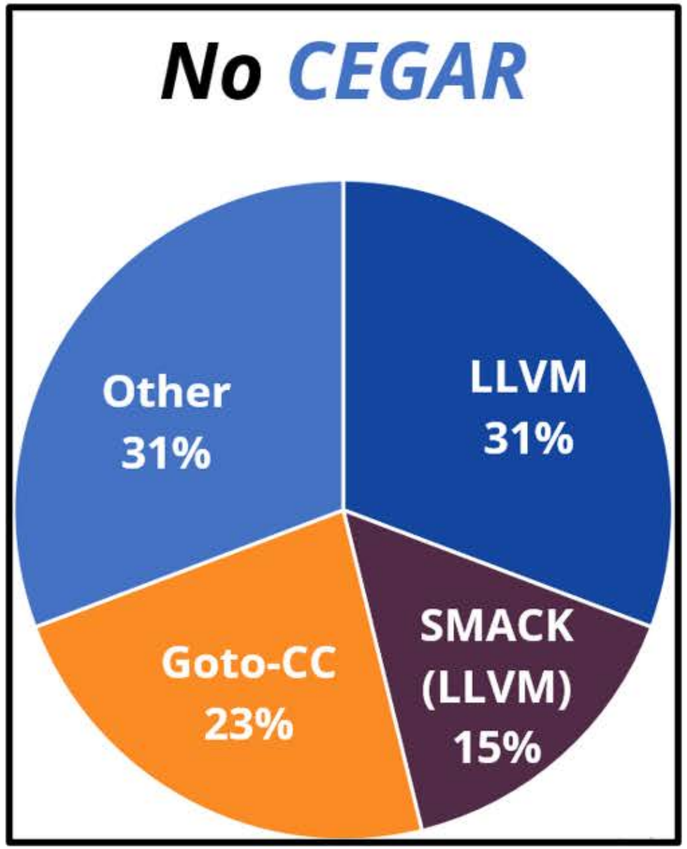
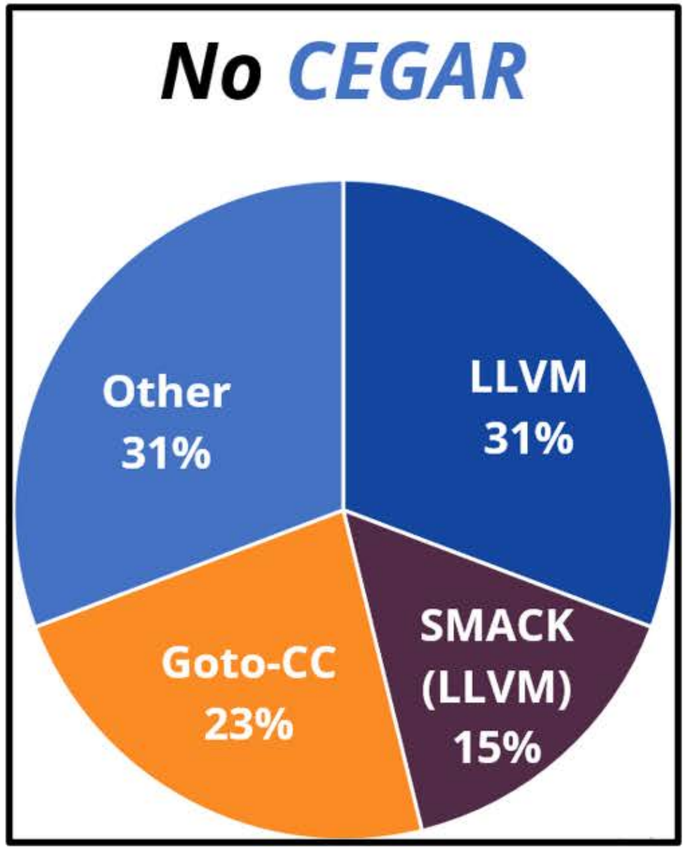
LLVM

LLVM



LLVM



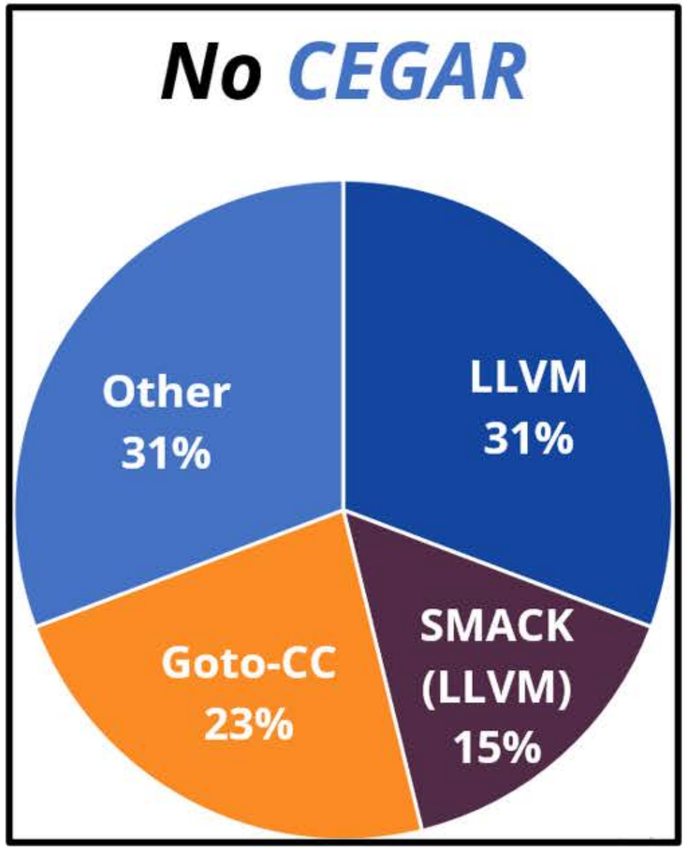
LLVM Overview

The LLVM Project is a collection of modular and reusable compiler and toolchain technologies. Despite its name, LLVM has little to do with traditional virtual machines. The name "LLVM" itself is not an acronym; it is the full name of the project.

LLVM began as a research project at the University of Illinois, with the goal of providing a modern, SSA-based compilation strategy capable of supporting both static and dynamic compilation of arbitrary programming languages. Since then,

https://llvm.org/

LLVM



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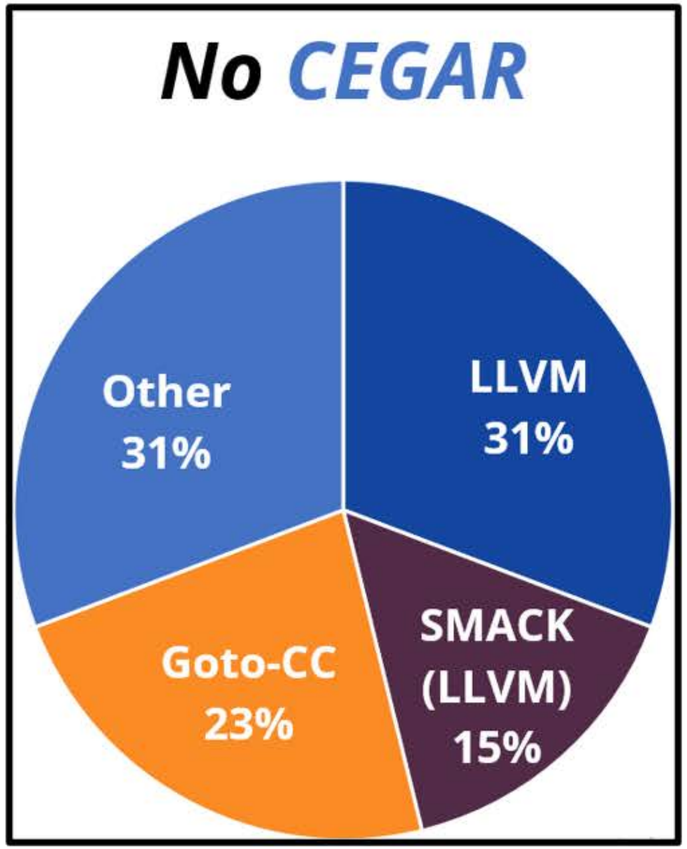
LLVM



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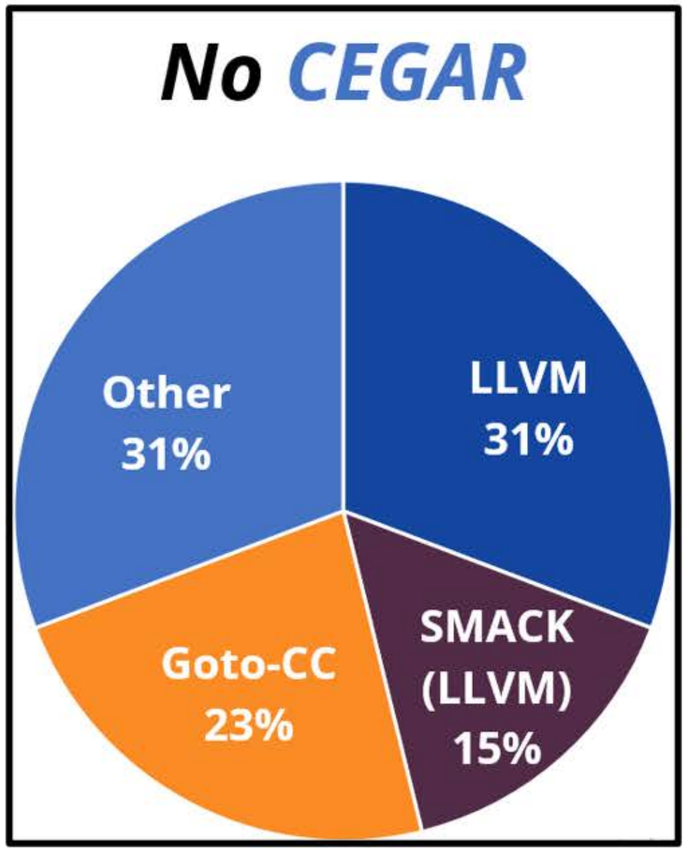

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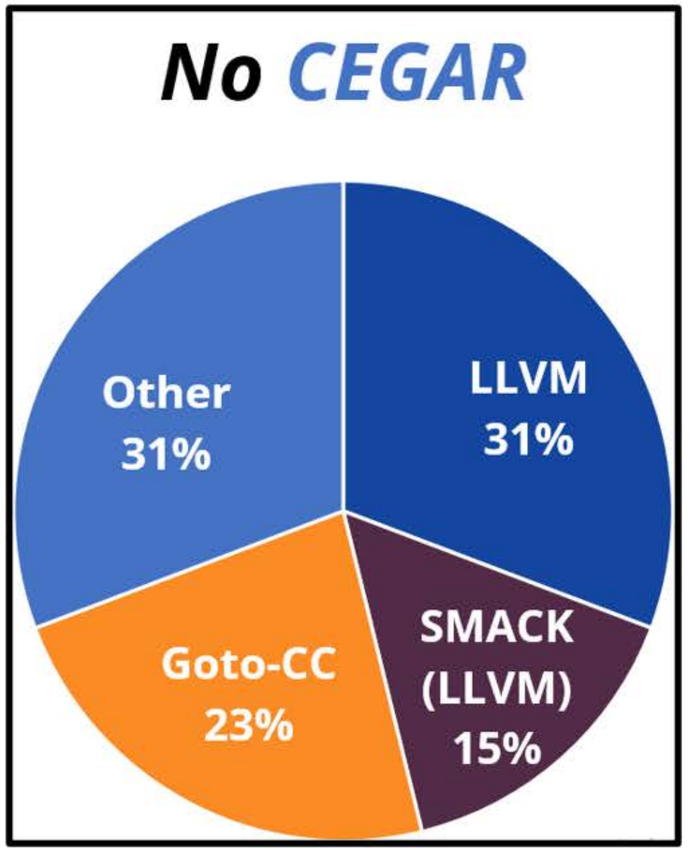
SSA-form

Optimizations

→ Works well for **BMC**

LLVM



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SSA-based

SSA-form

Optimizations

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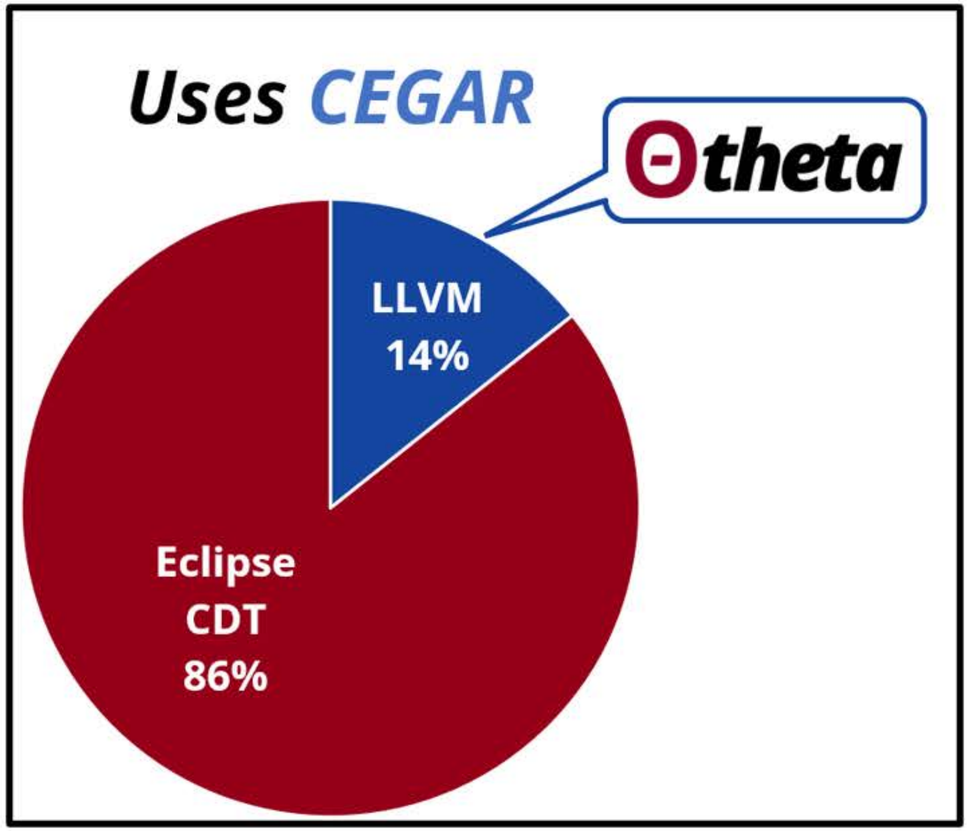
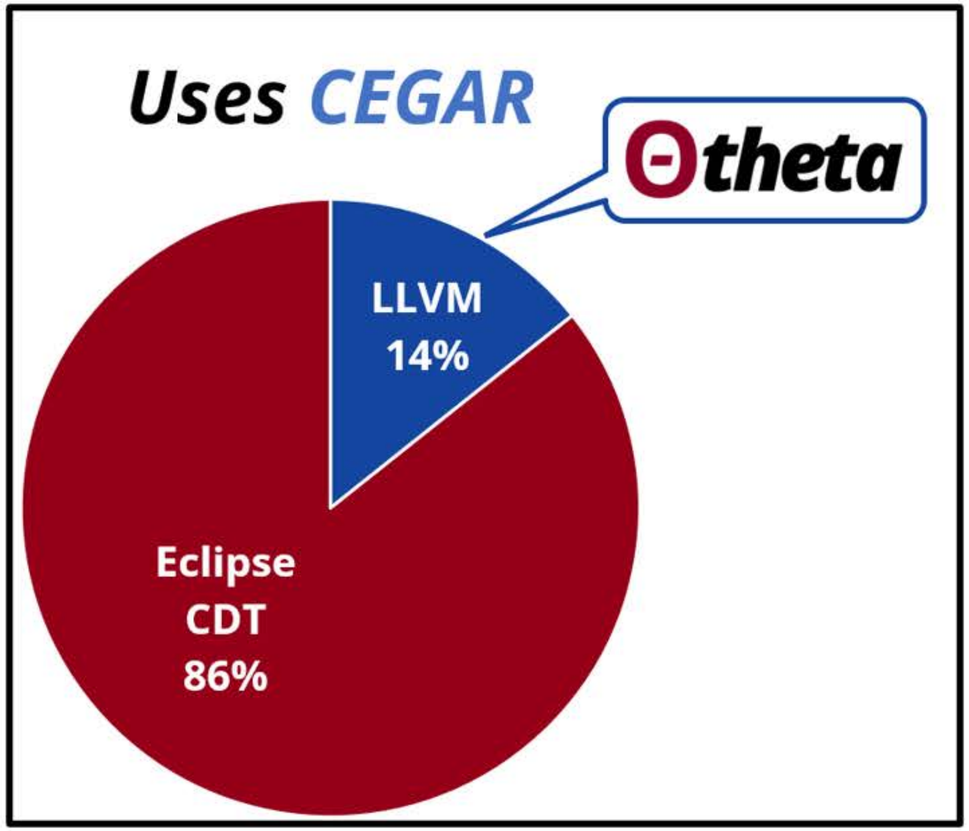
Caveat: Optimizations work **over SSA**

LLVM

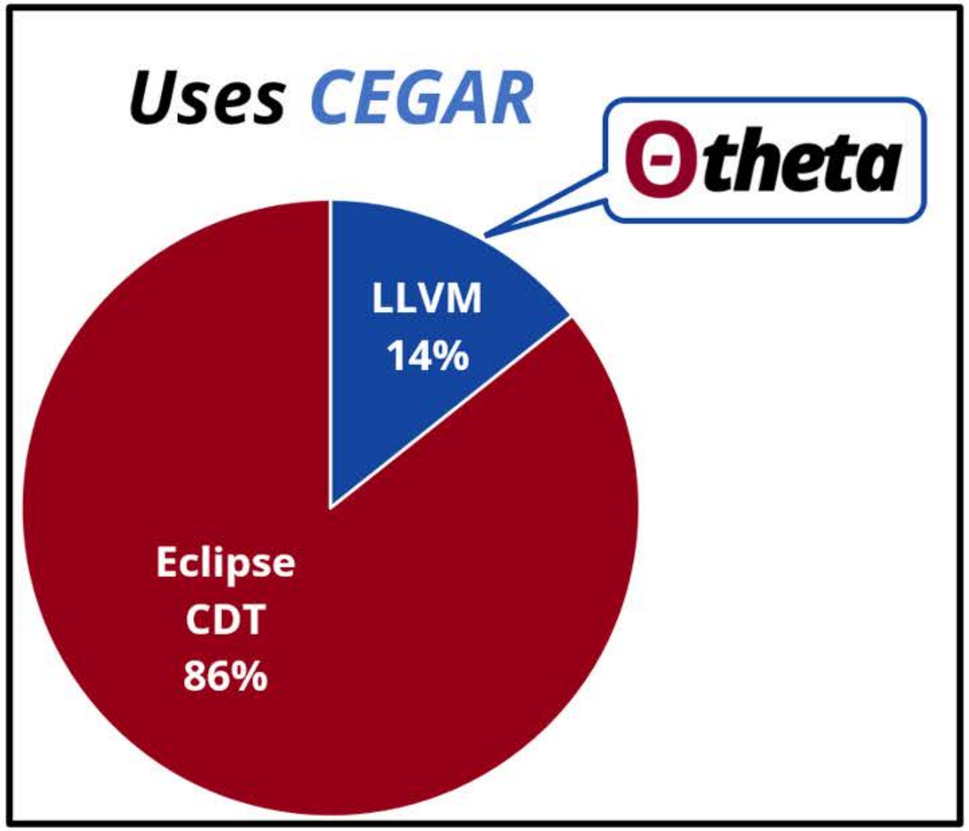


LLVM



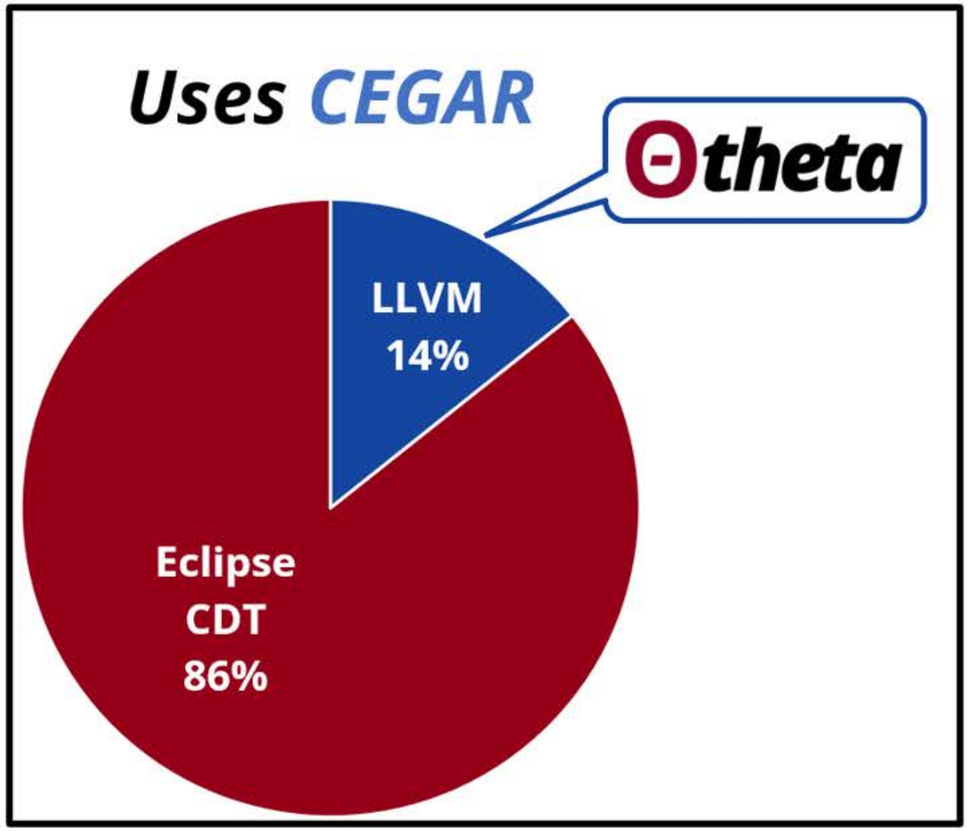
- Works well for BMC: ✓

LLVM



- Works well for BMC: ✓
- Works poorly for CEGAR: ?

LLVM



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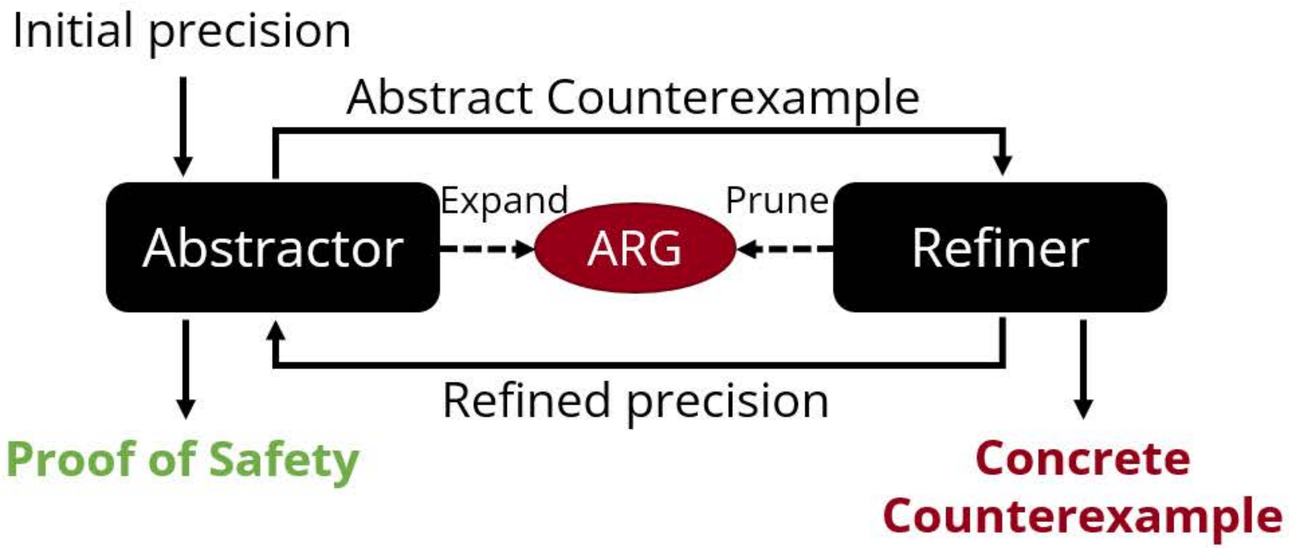
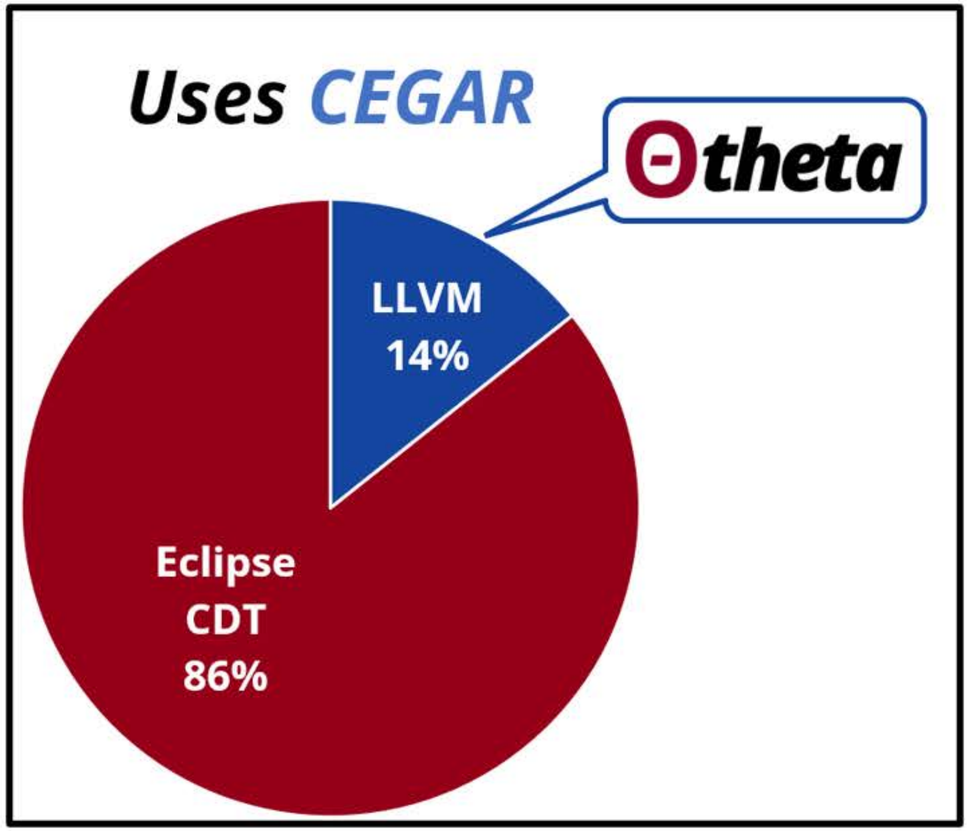


LLVM



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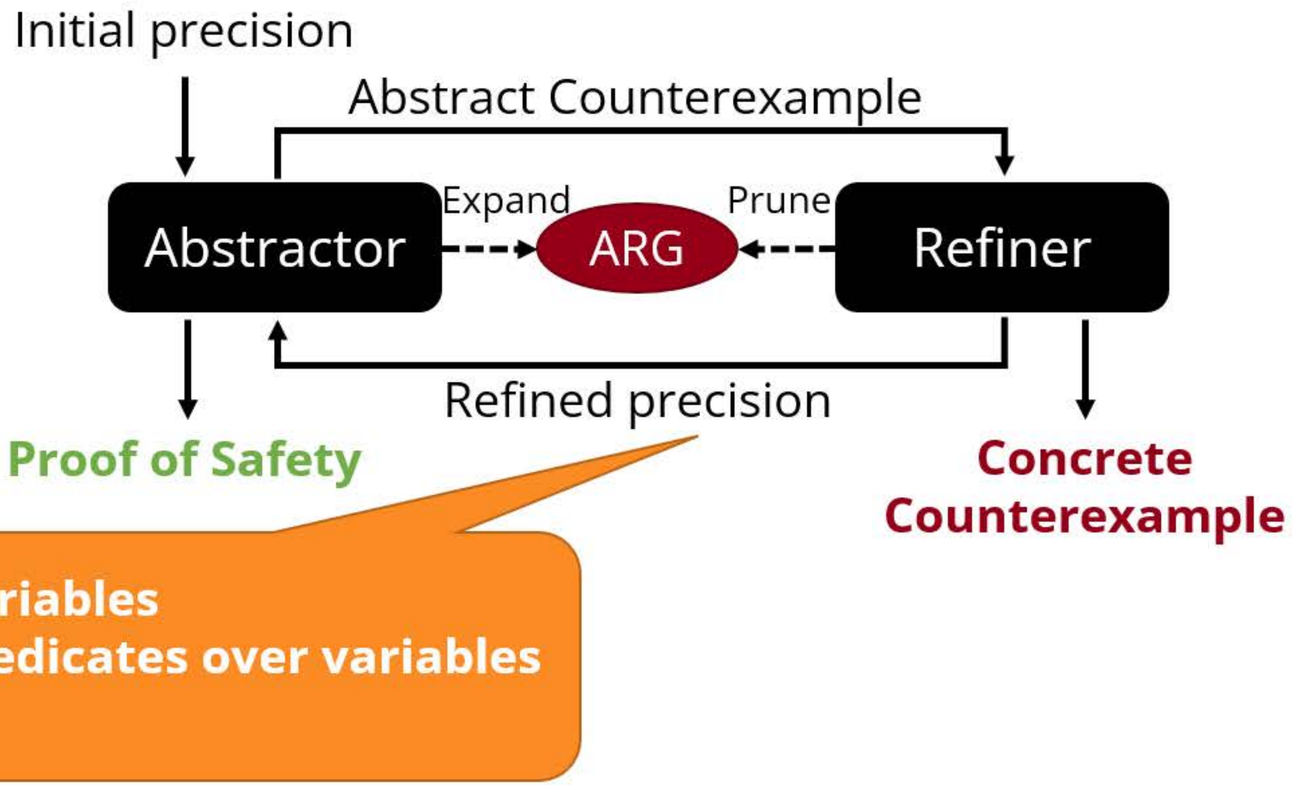
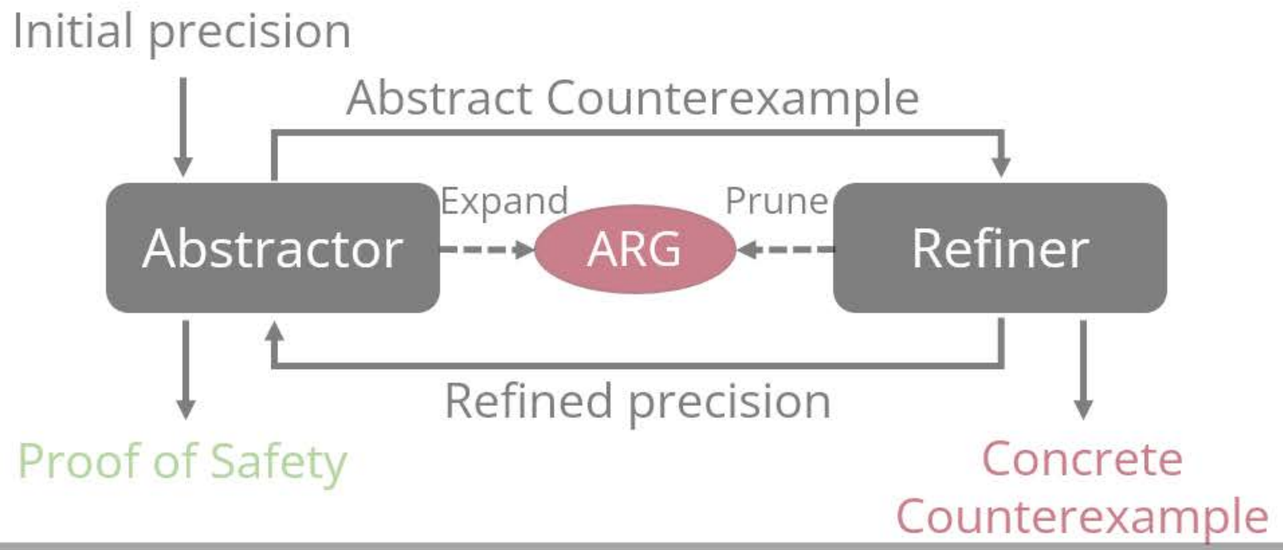


Use of the Precision in CEGAR



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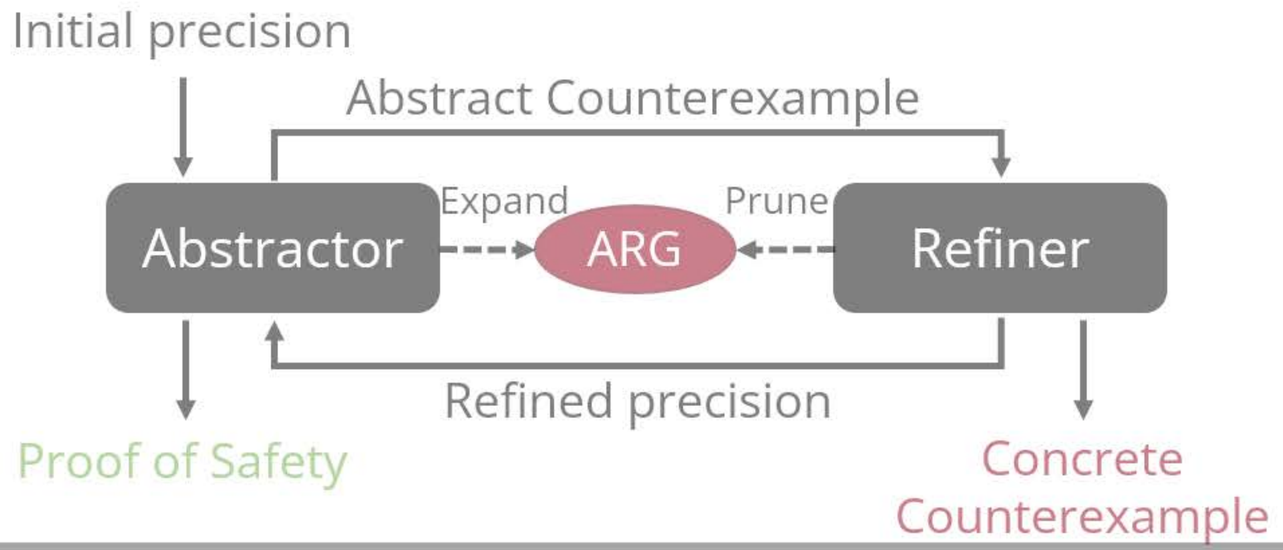

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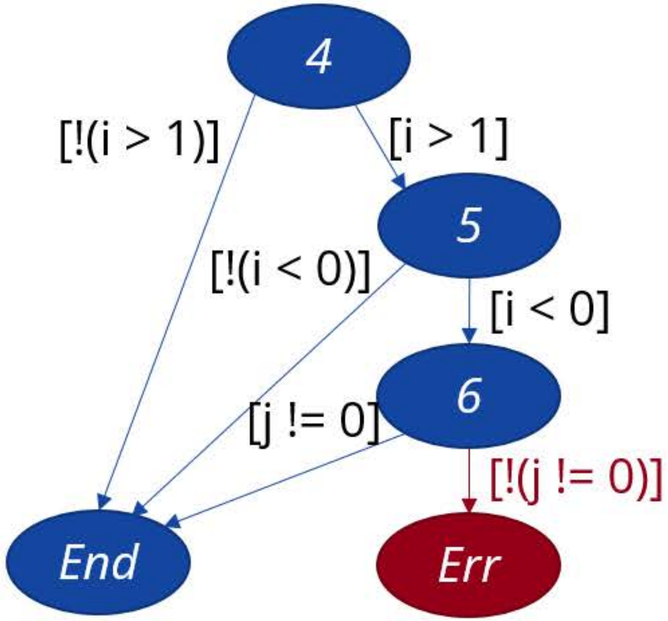

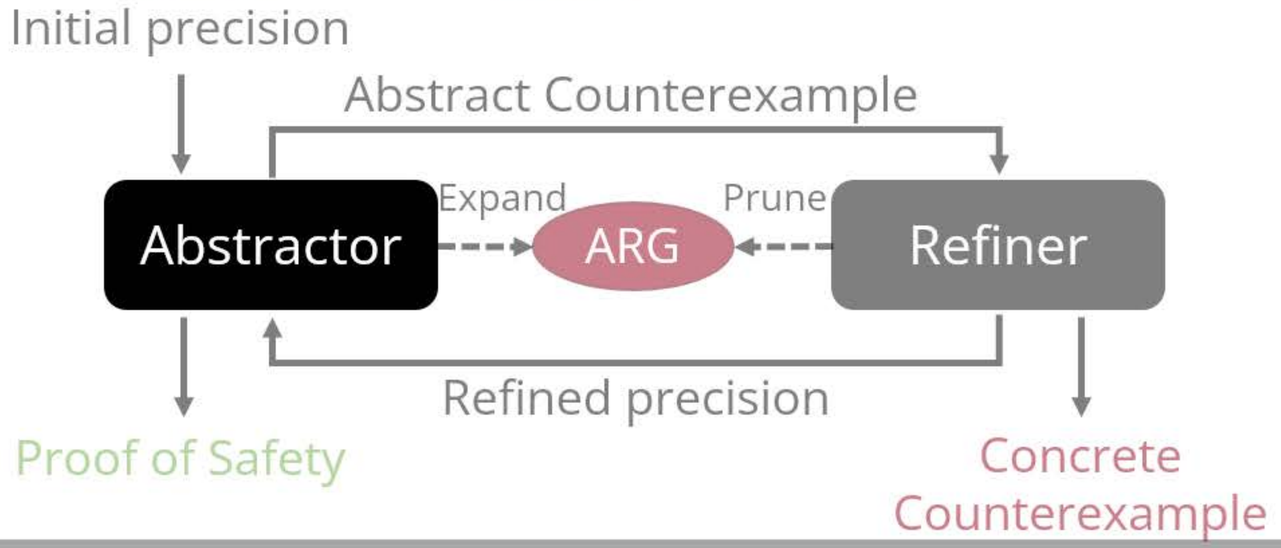

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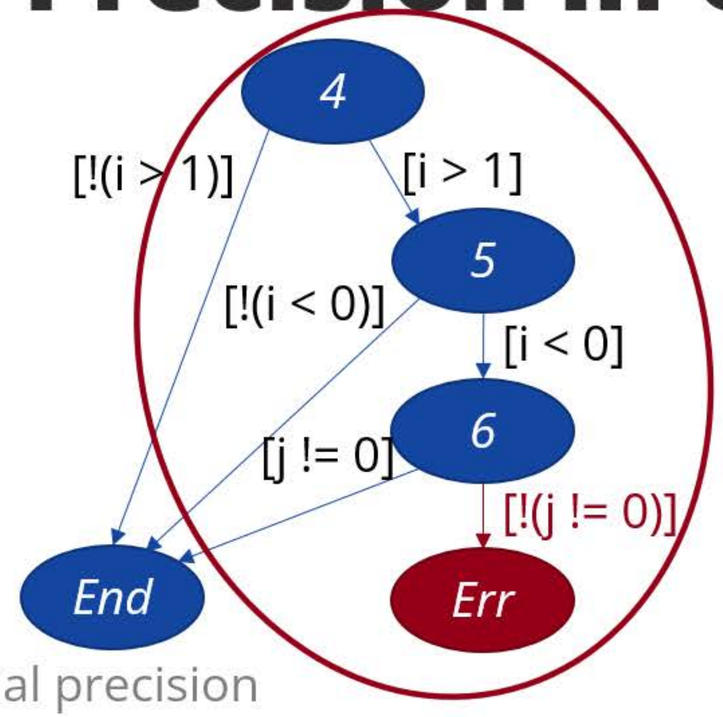

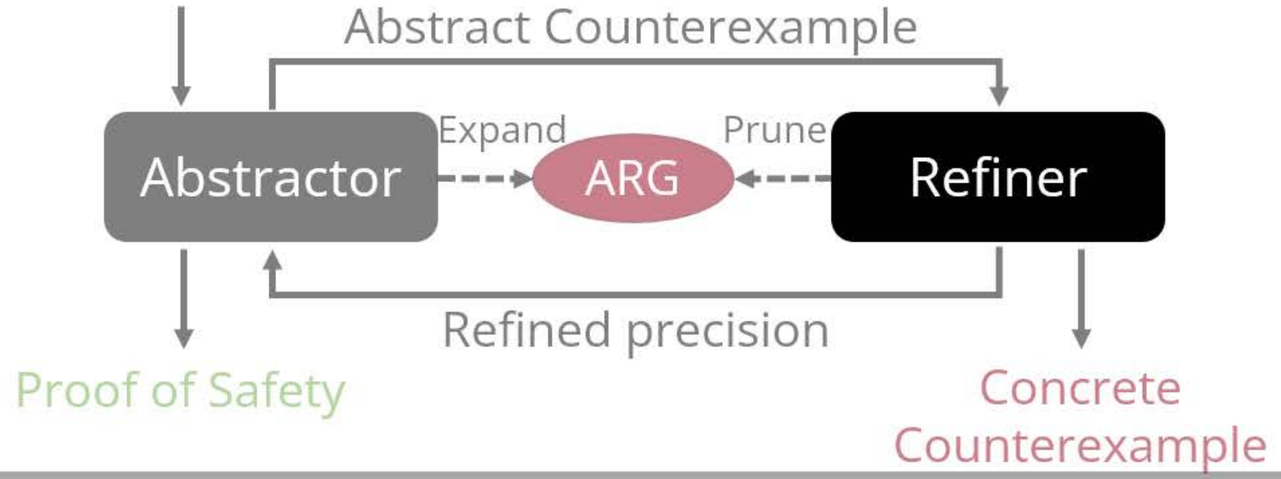

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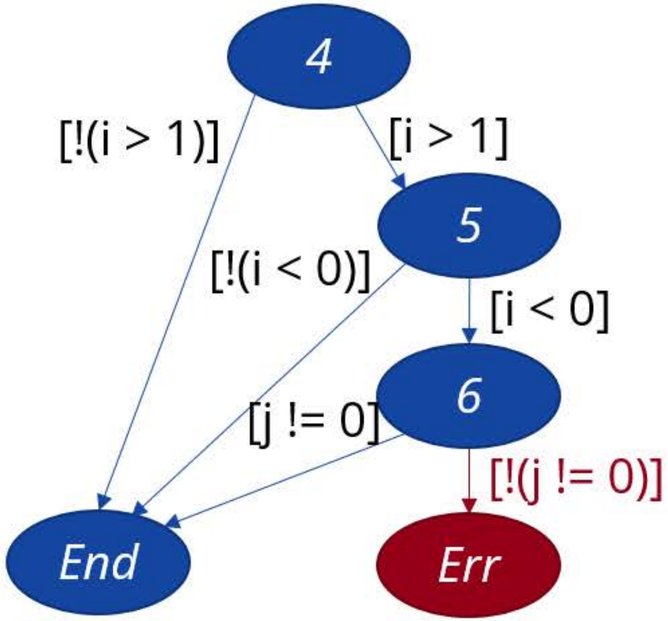

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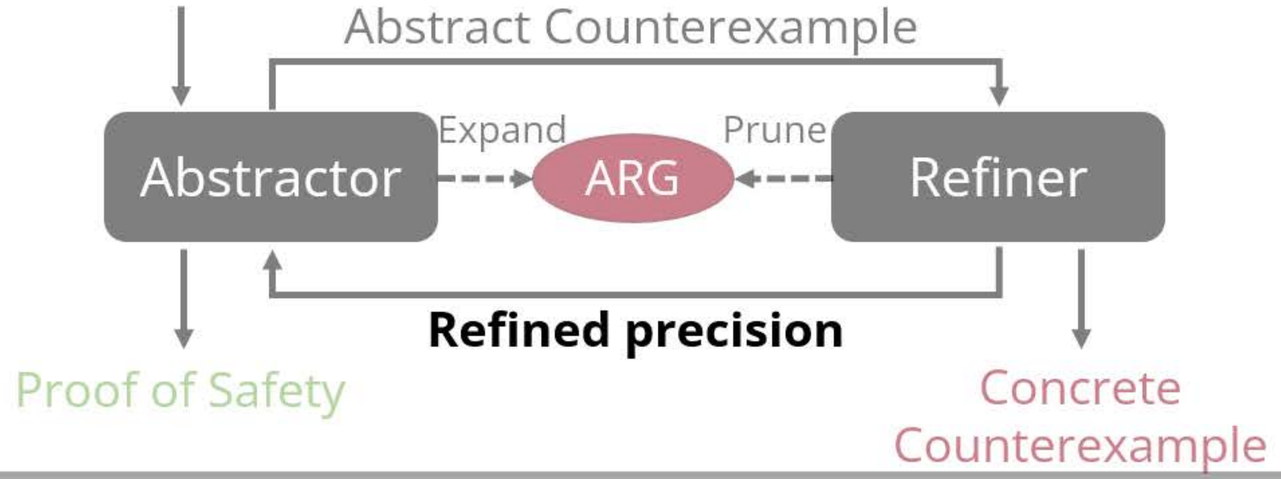

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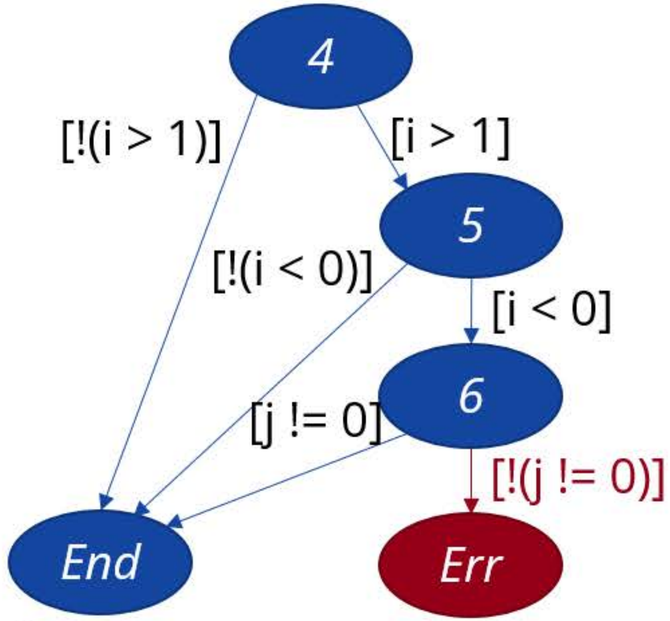

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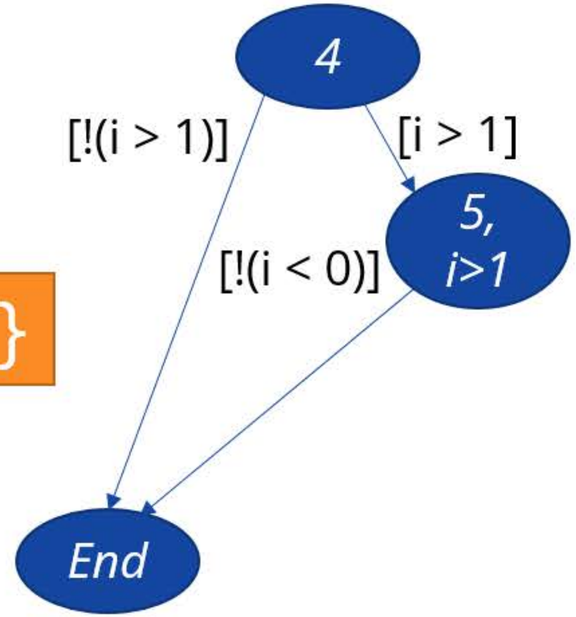

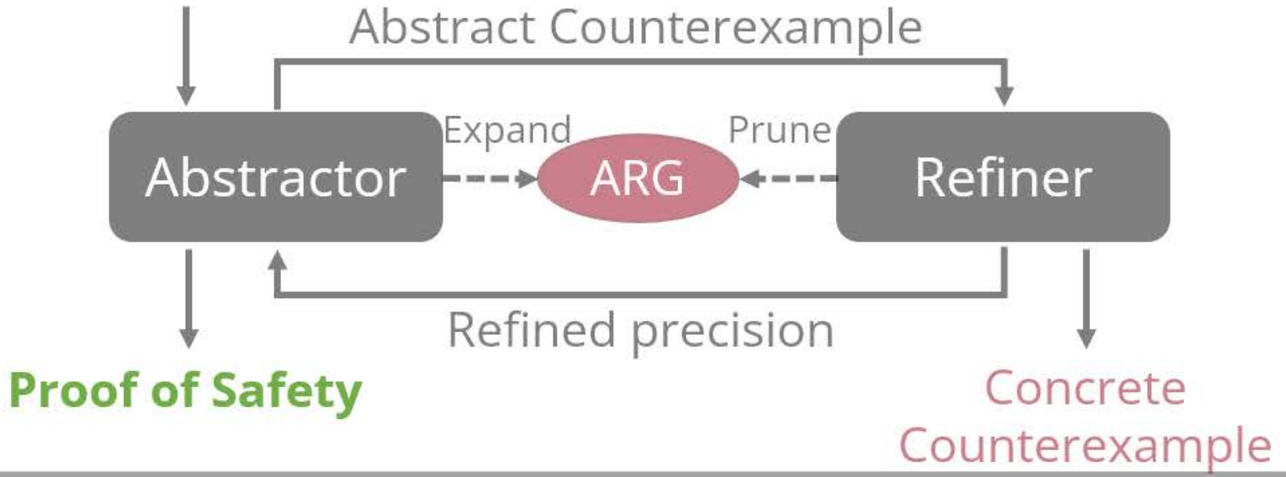

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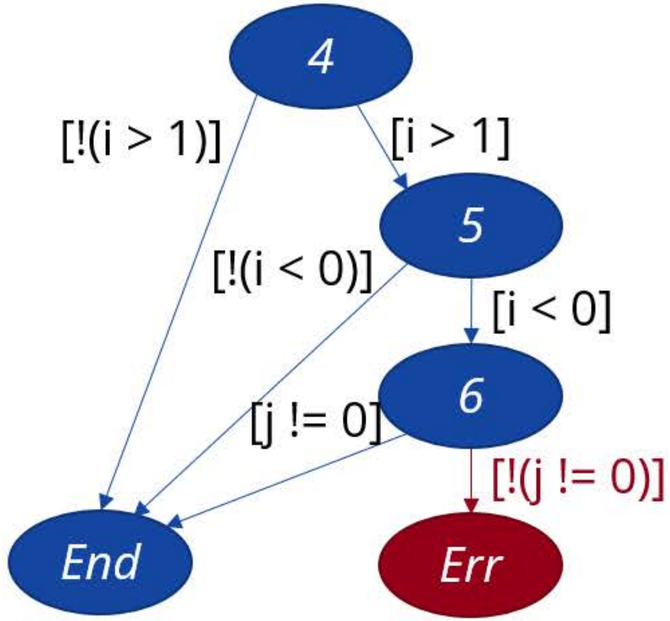

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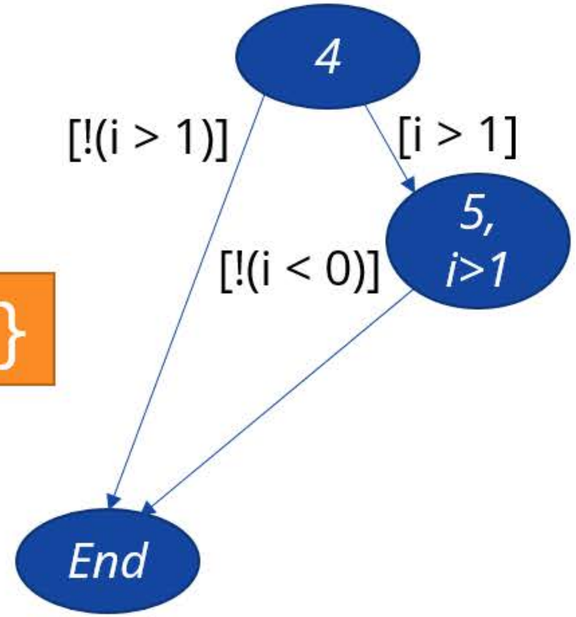

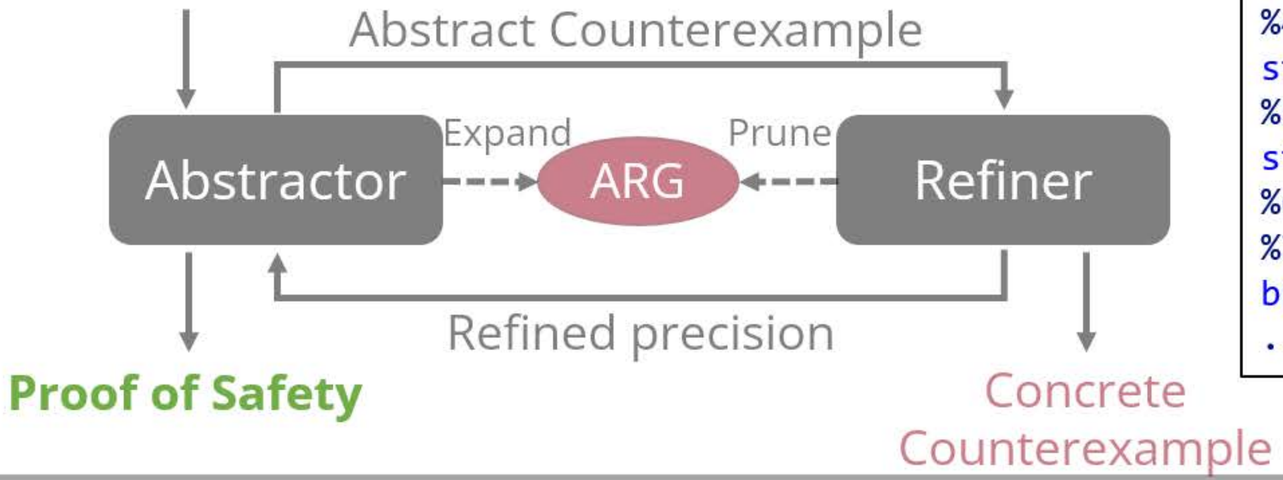


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%4 = call i32 (...) @nondet()
store i32 %4, i32* %2, align 4
%5 = call i32 (...) @nondet()
store i32 %5, i32* %3, align 4
%6 = load i32, i32* %2, align 4
%7 = icmp eq i32 %6, 1
br i1 %7, label %8, label %17
...
```

LLVM IR

Use of the Precision in CEGAR

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1: int main() {
2:   int i = nondet();
3:   int j = nondet();
4:   if(i > 1) {
5:     if (i < 0) {
6:       assert(j != 0);
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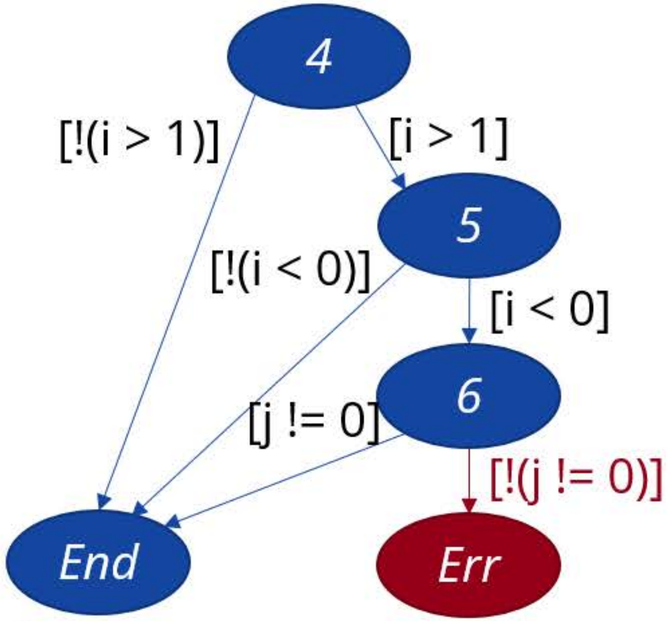
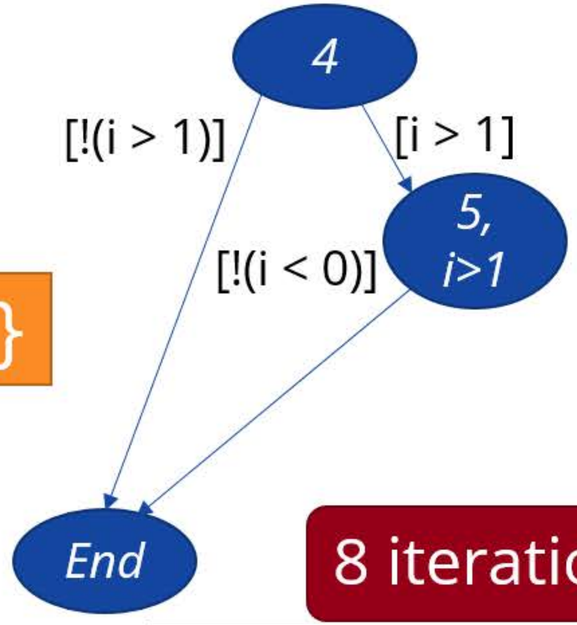
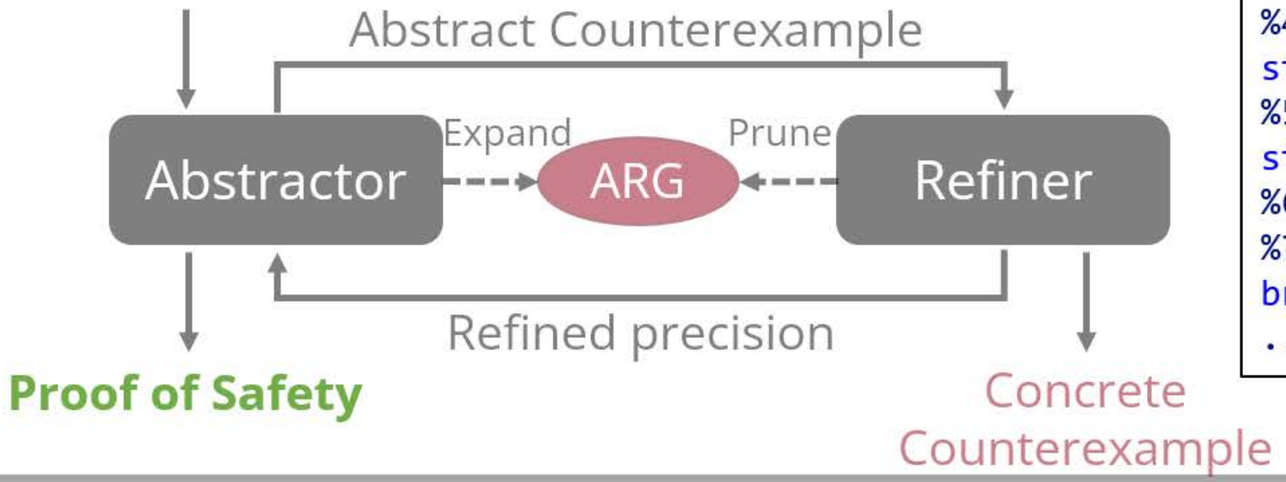


{i > 1}



8 iterations

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LLVM IR

LLVM

C code

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- 2 variables

LLVM IR

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- 18 “variables”

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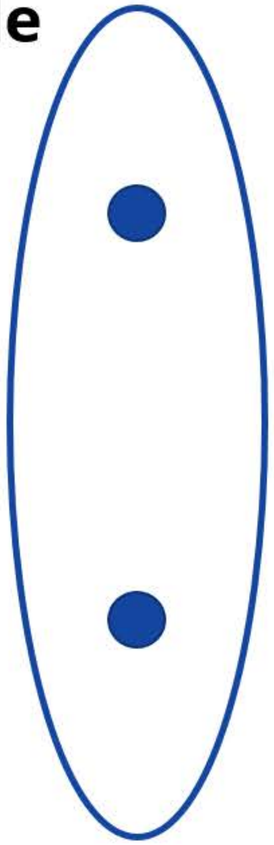

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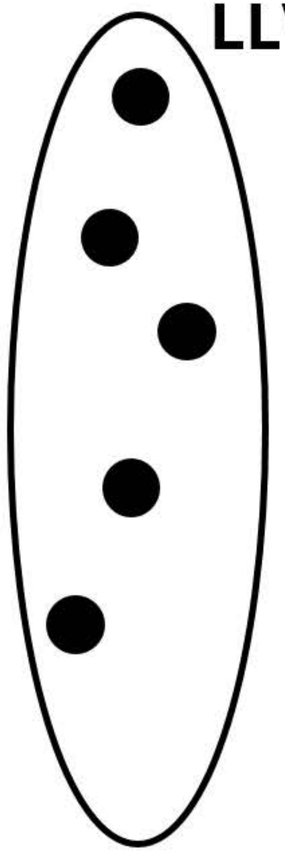
LLVM IR



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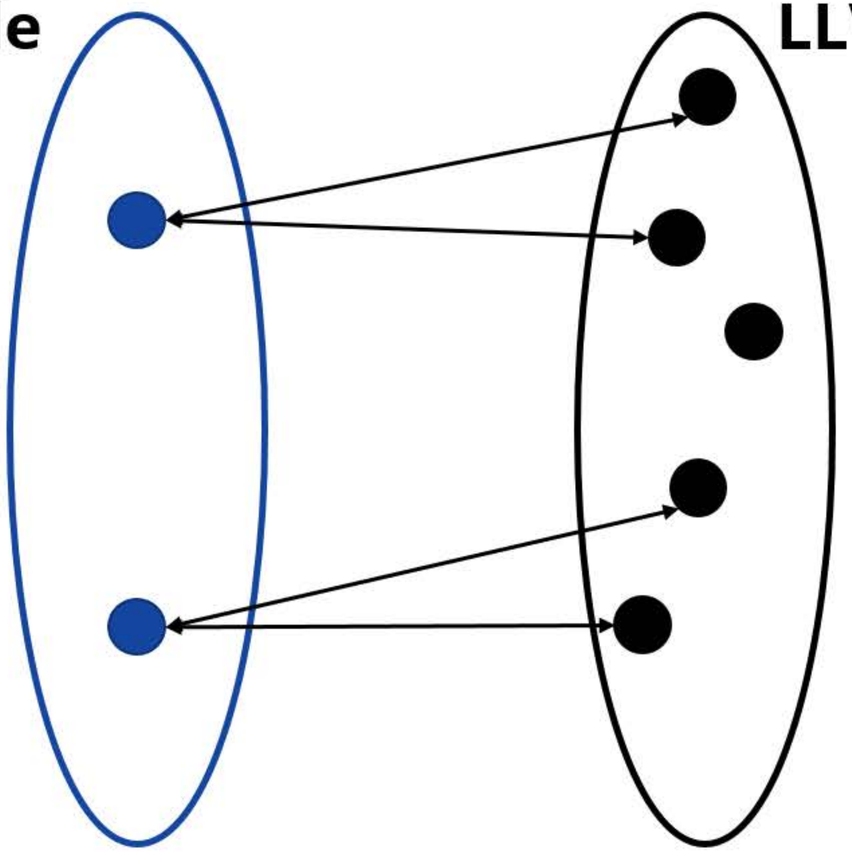

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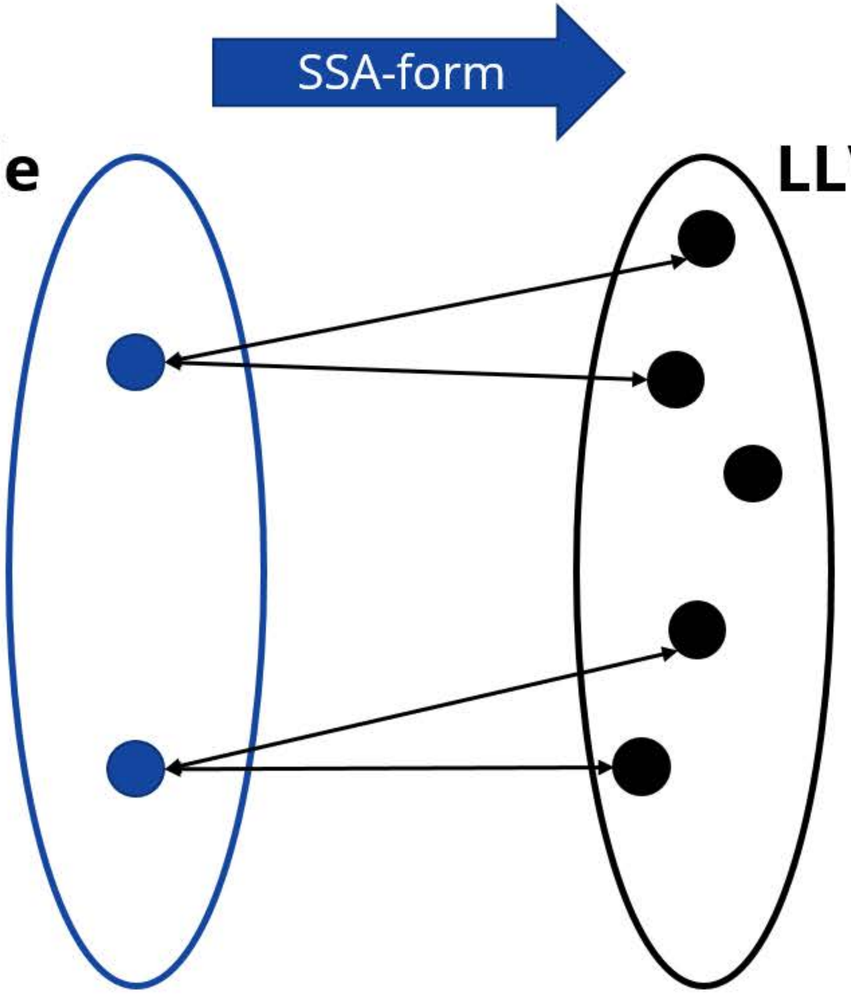

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LLVM

SSA-form

C code

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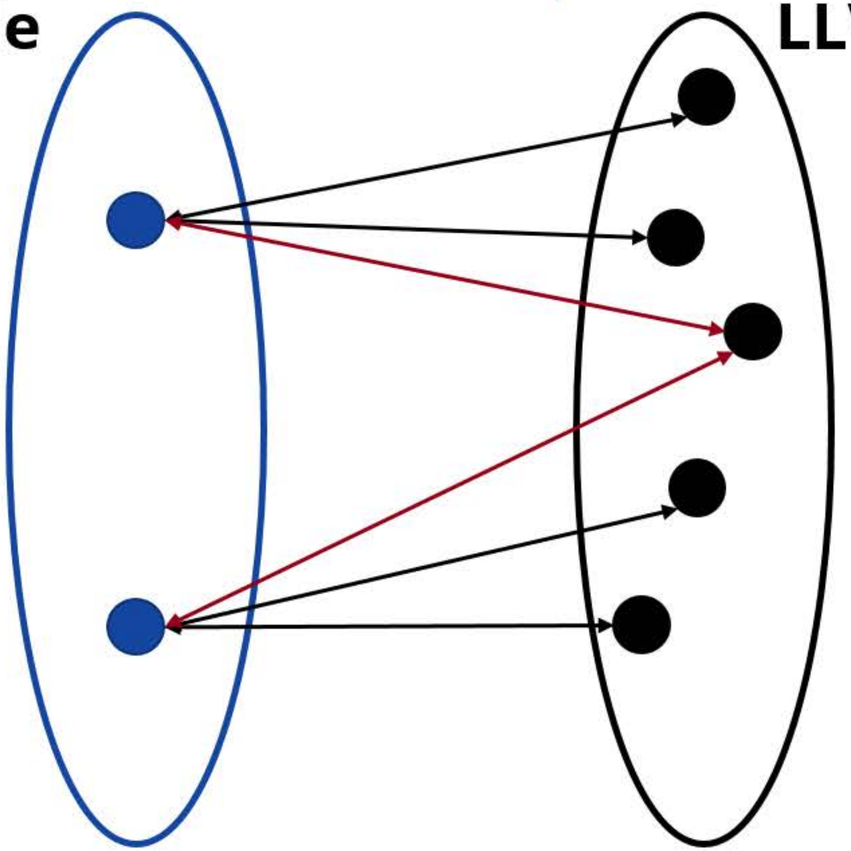

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ftsrg

LLVM

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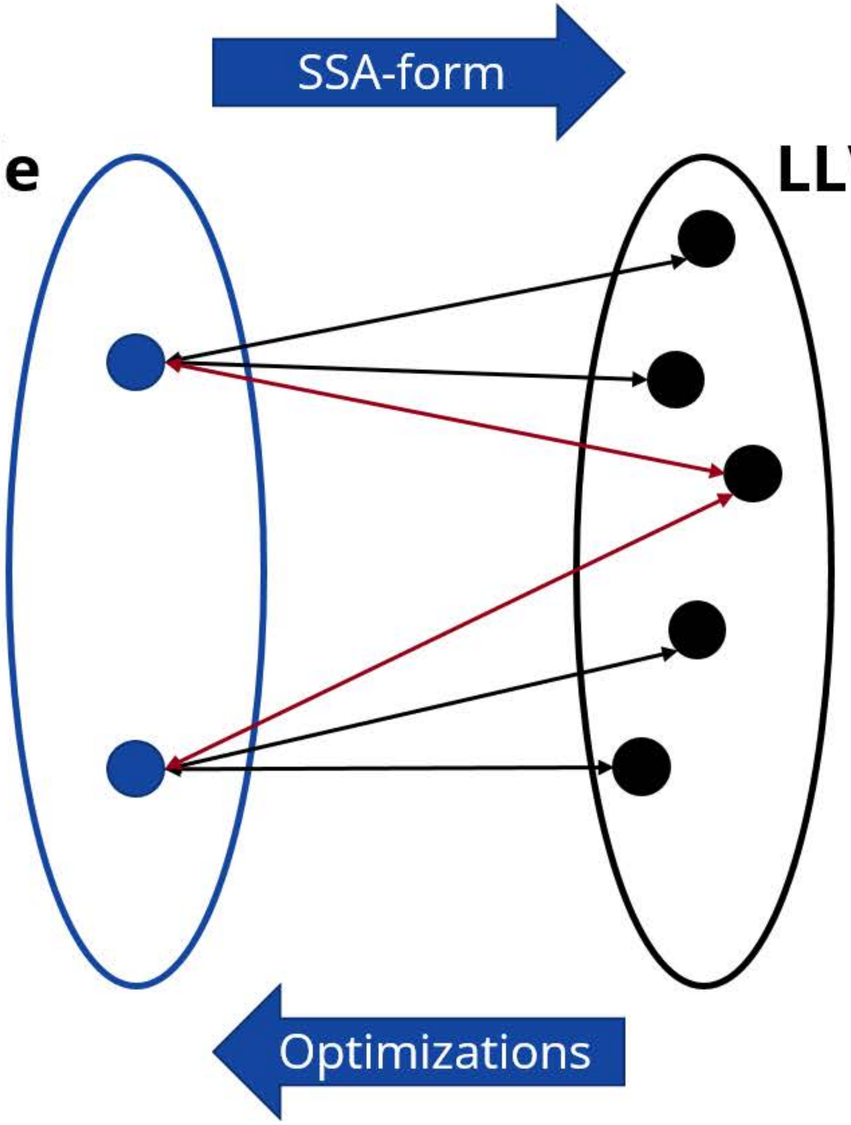

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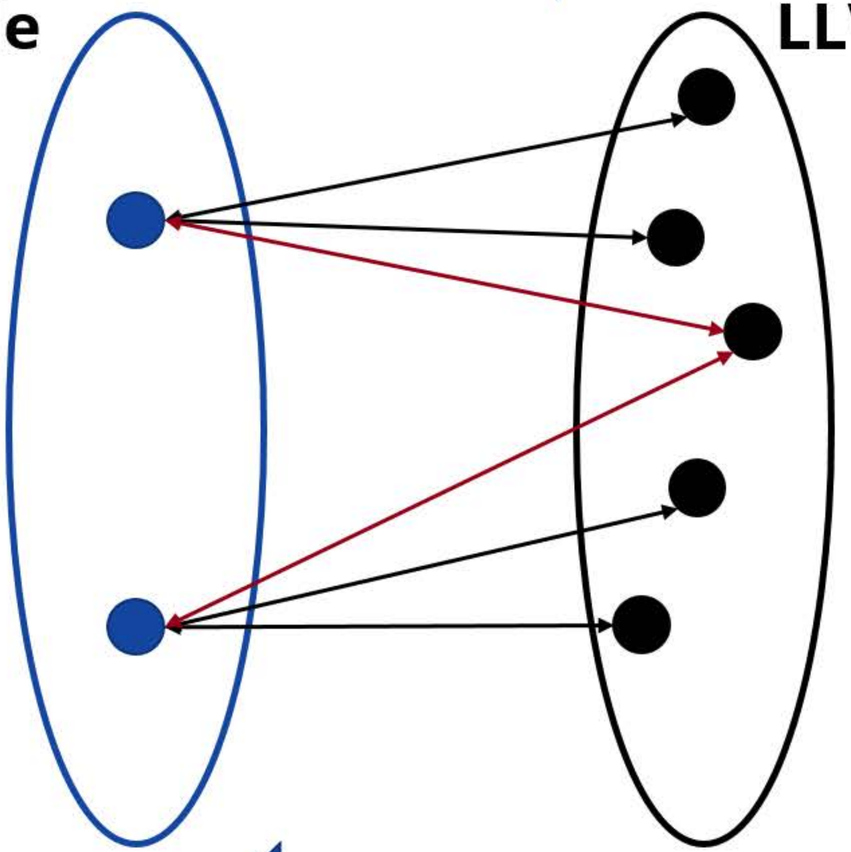

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Optimizations

- 2 variables
- Well-defined roles

- 18 “variables”

LLVM

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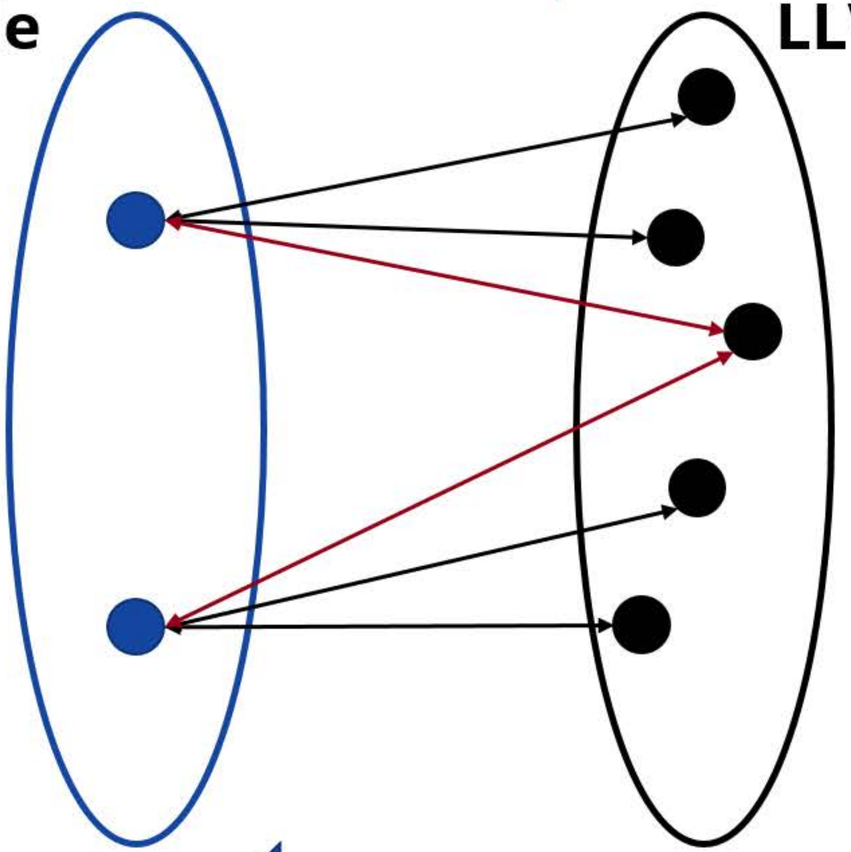

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Optimizations

- 2 variables
- Well-defined roles

- 18 “variables”
- N:N mapping

Summary of the Survey

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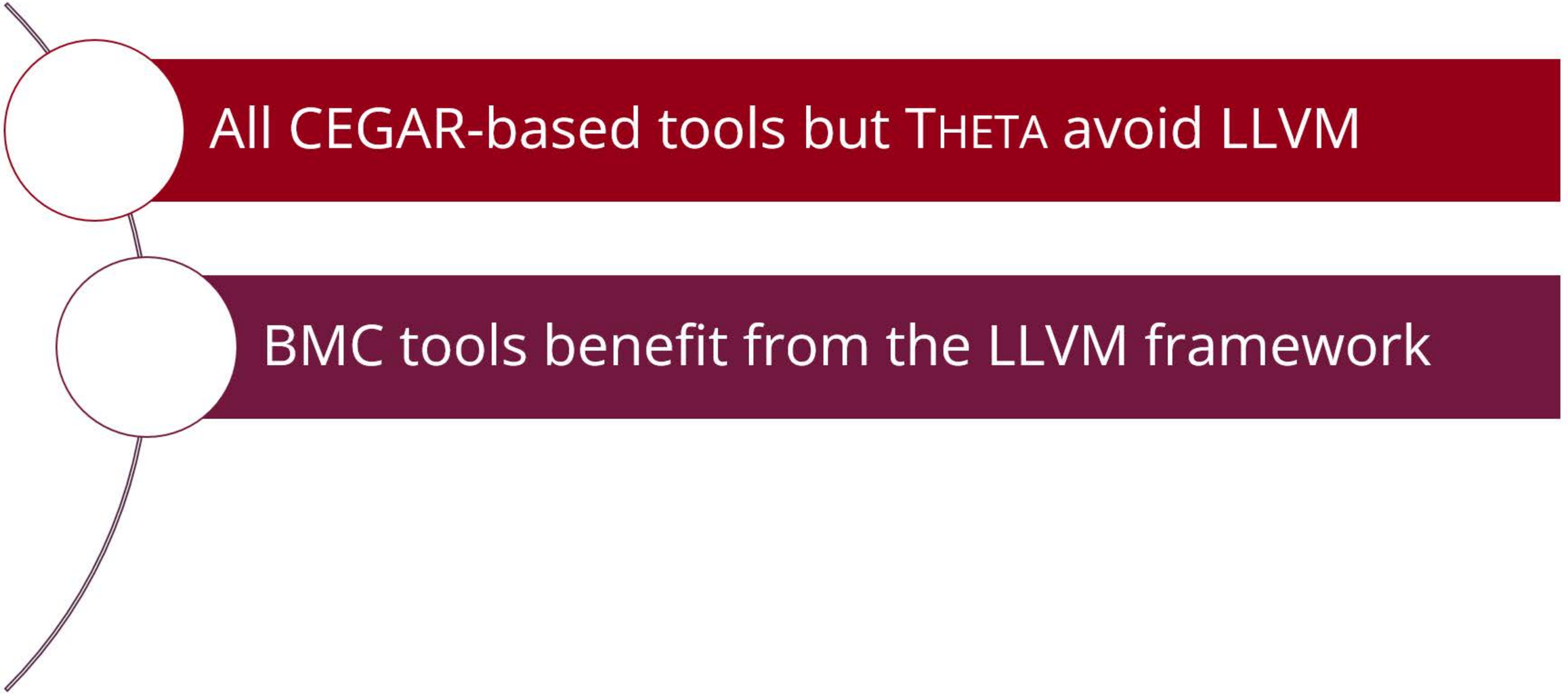

Summary of the Survey

All CEGAR-based tools but THETA avoid LLVM

BMC tools benefit from the LLVM framework

LLVM's SSA form hurts the performance of CEGAR

Verification-first frontend

Proposal

Requirements

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R4 *Verifier-Centric*	The resulting model should be **optimized for verification**, not for executable generation
R5 *Metadata Access*	The verification tools must have access to **metadata** from the source file
R6 *Unhandled Patterns*	The transformation must **raise an exception** if an unhandled pattern is found, lest an erroneous model be created

Proposed Workflow - „The LLVM of verification”

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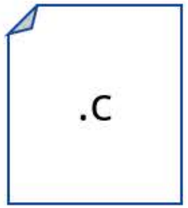
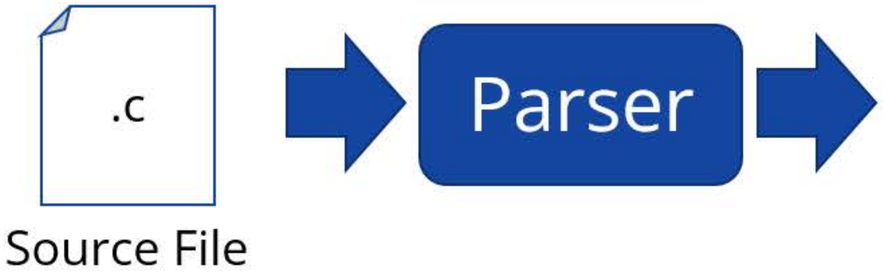


Source File

Proposed Workflow - „The LLVM of verification”



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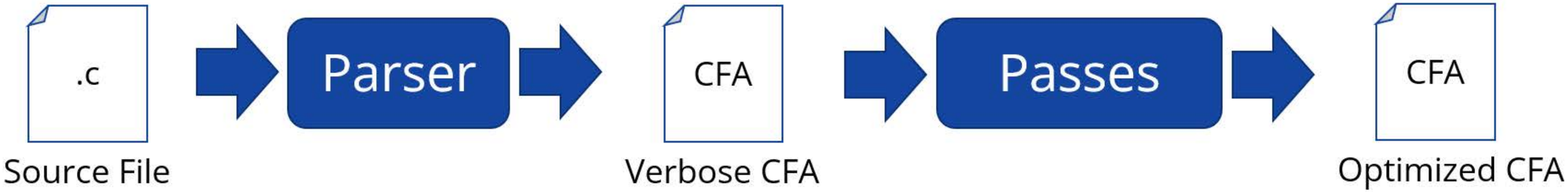

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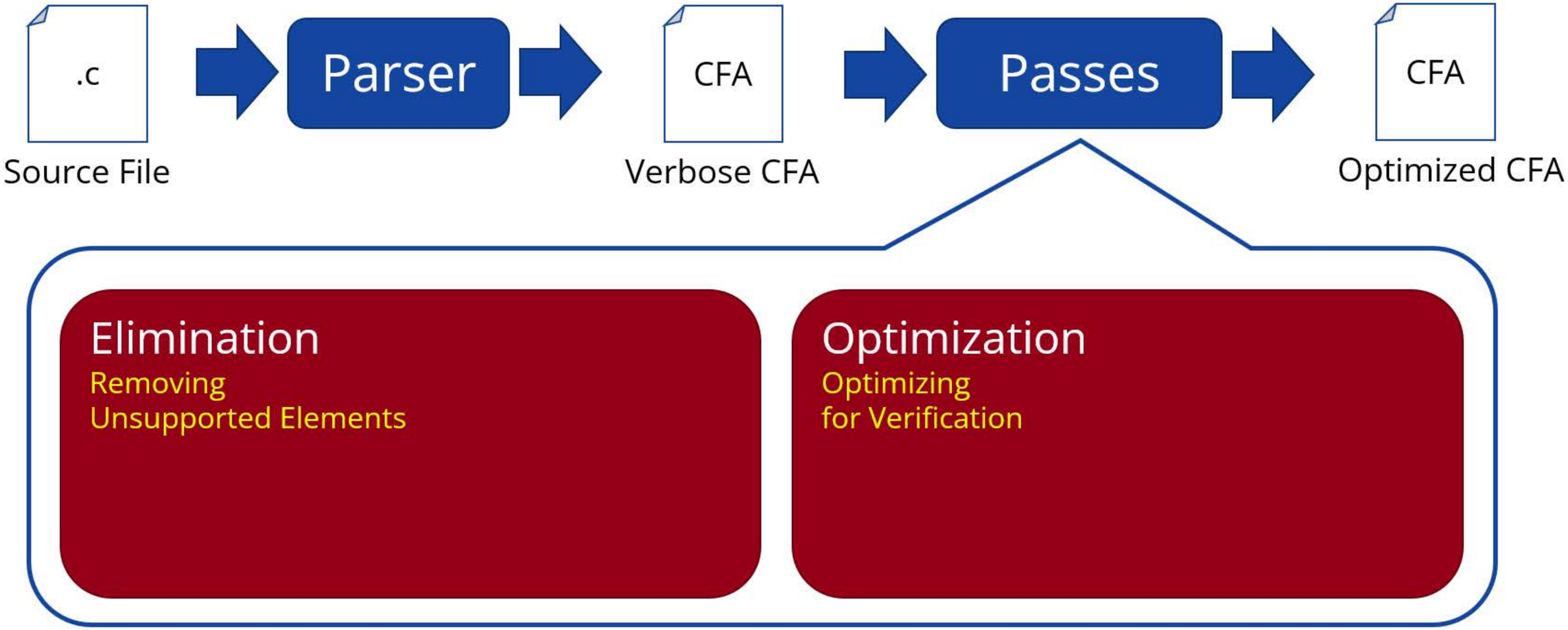

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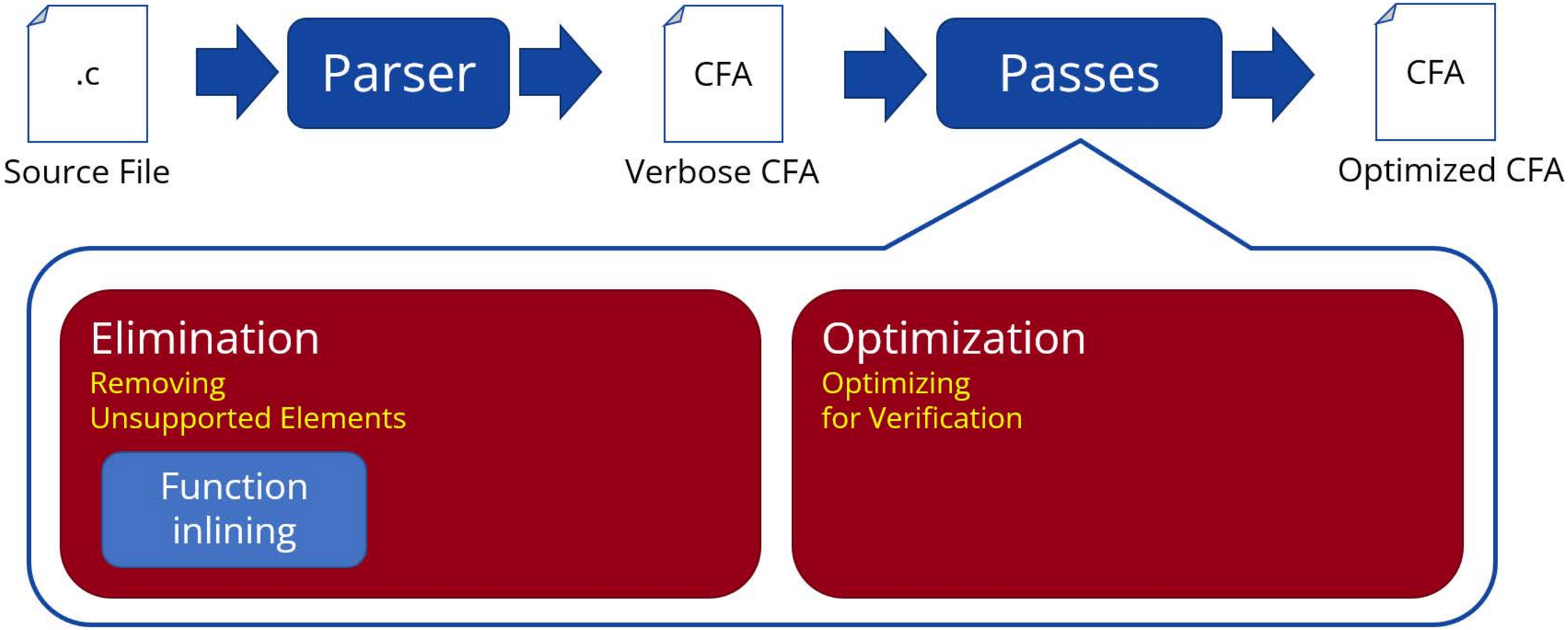

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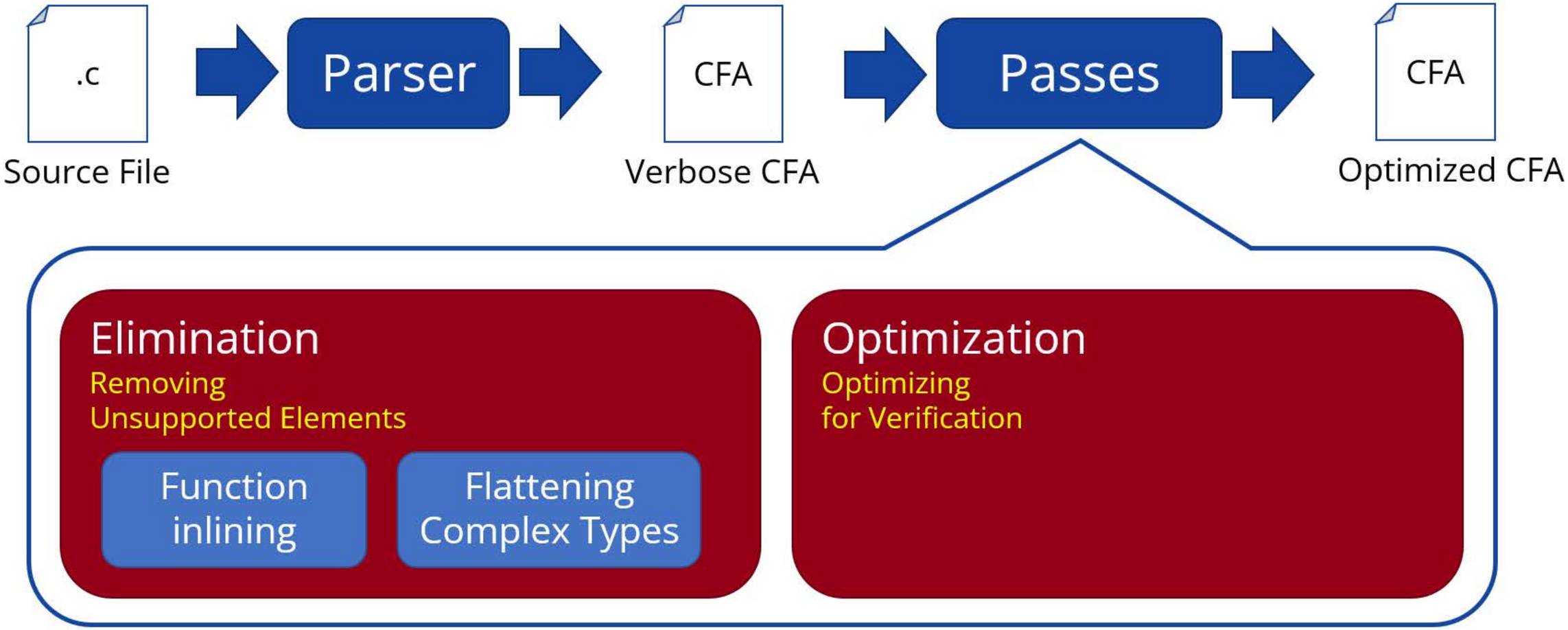

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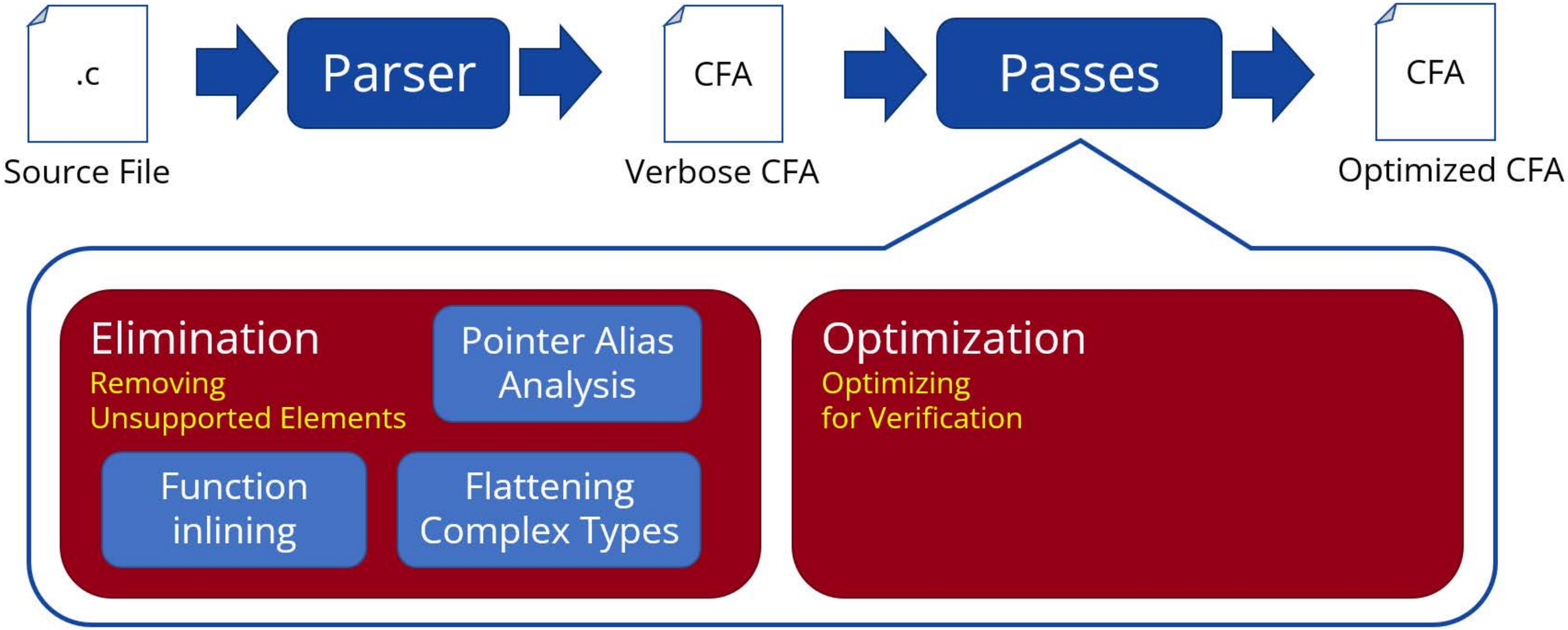

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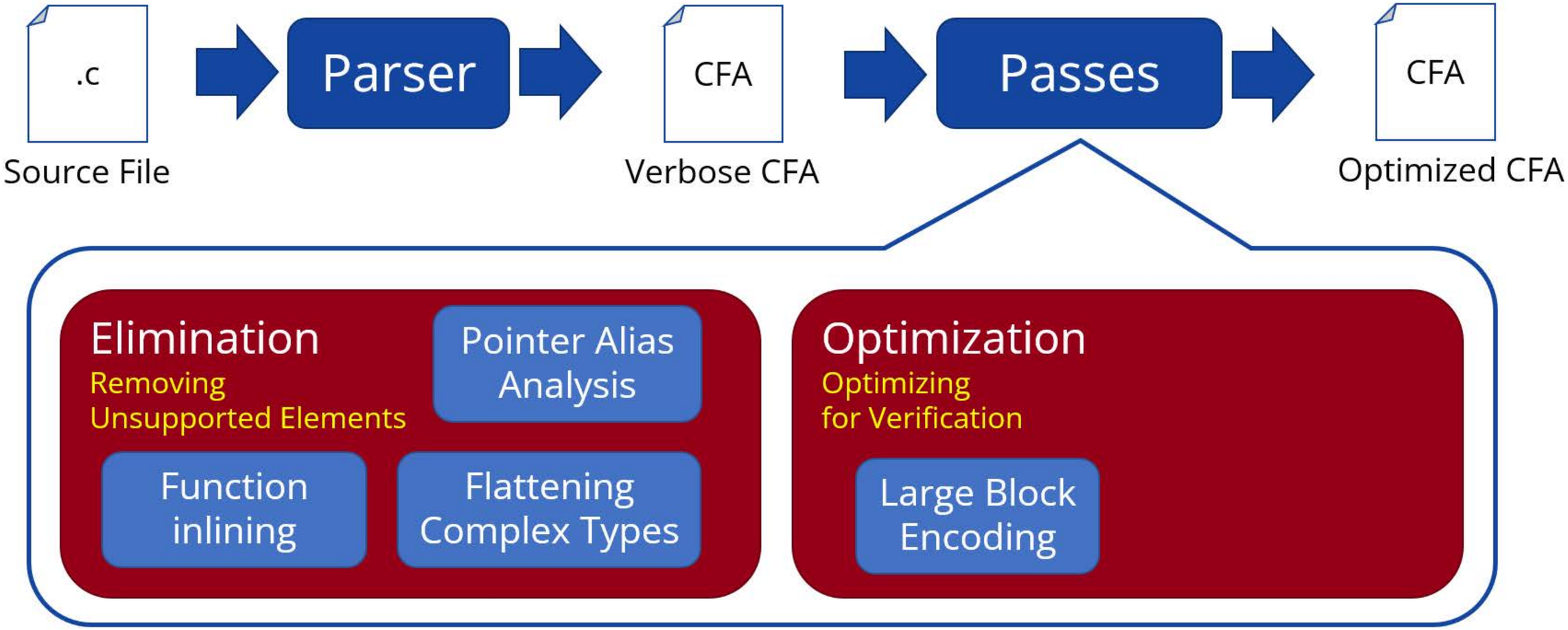

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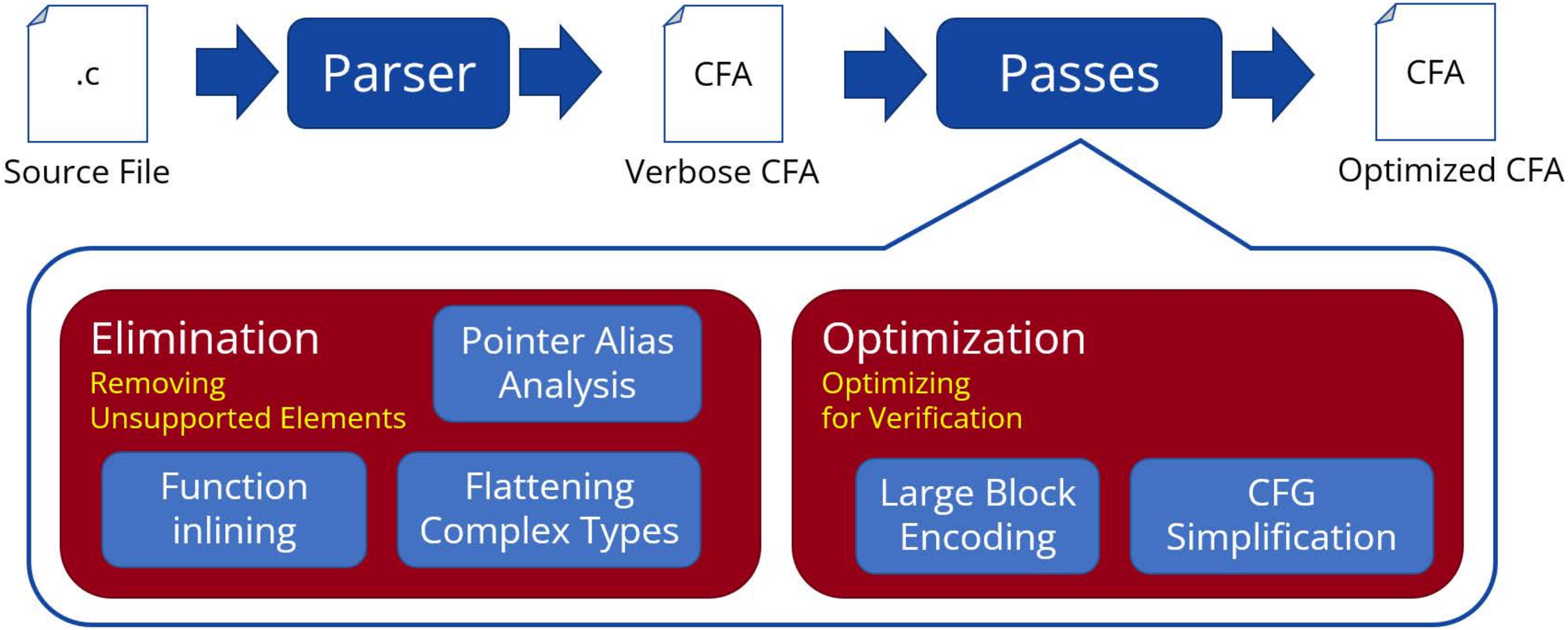

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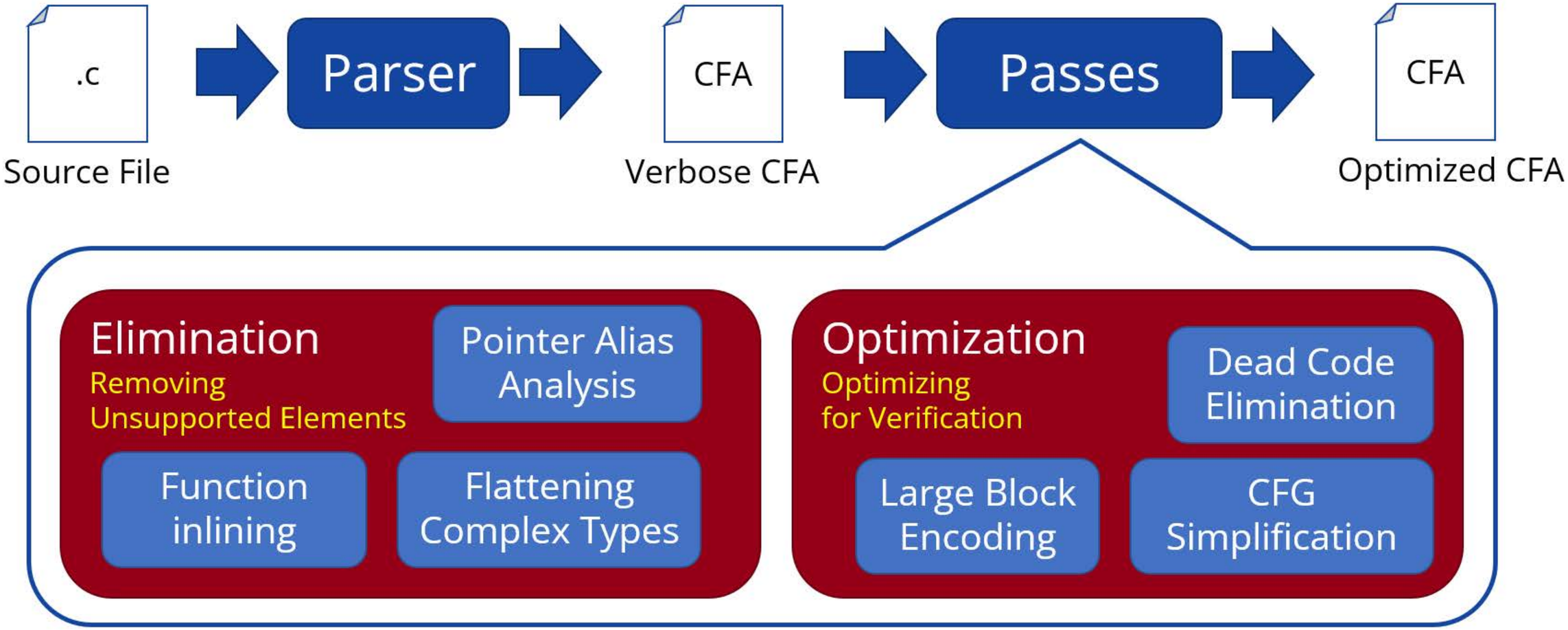

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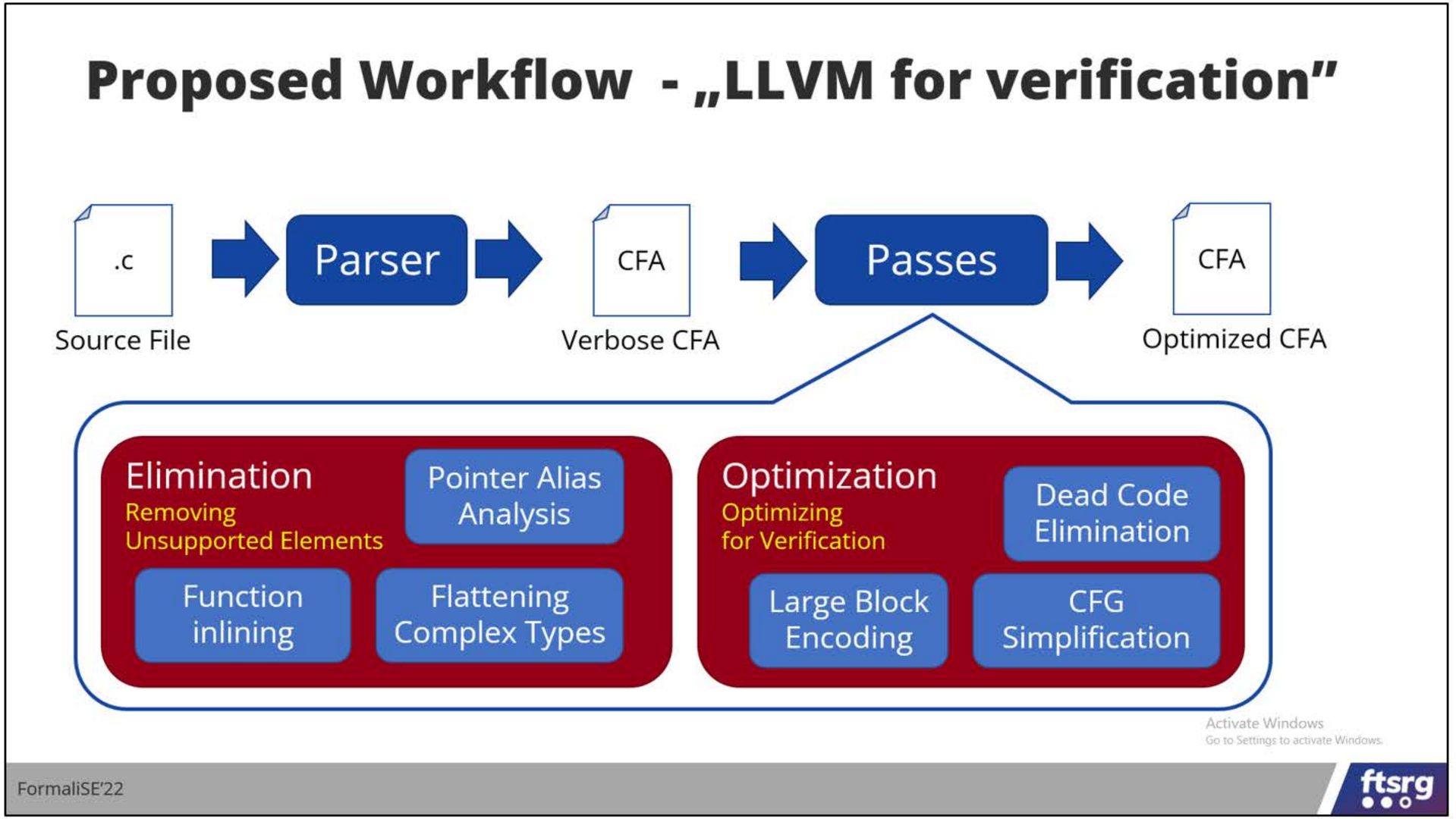

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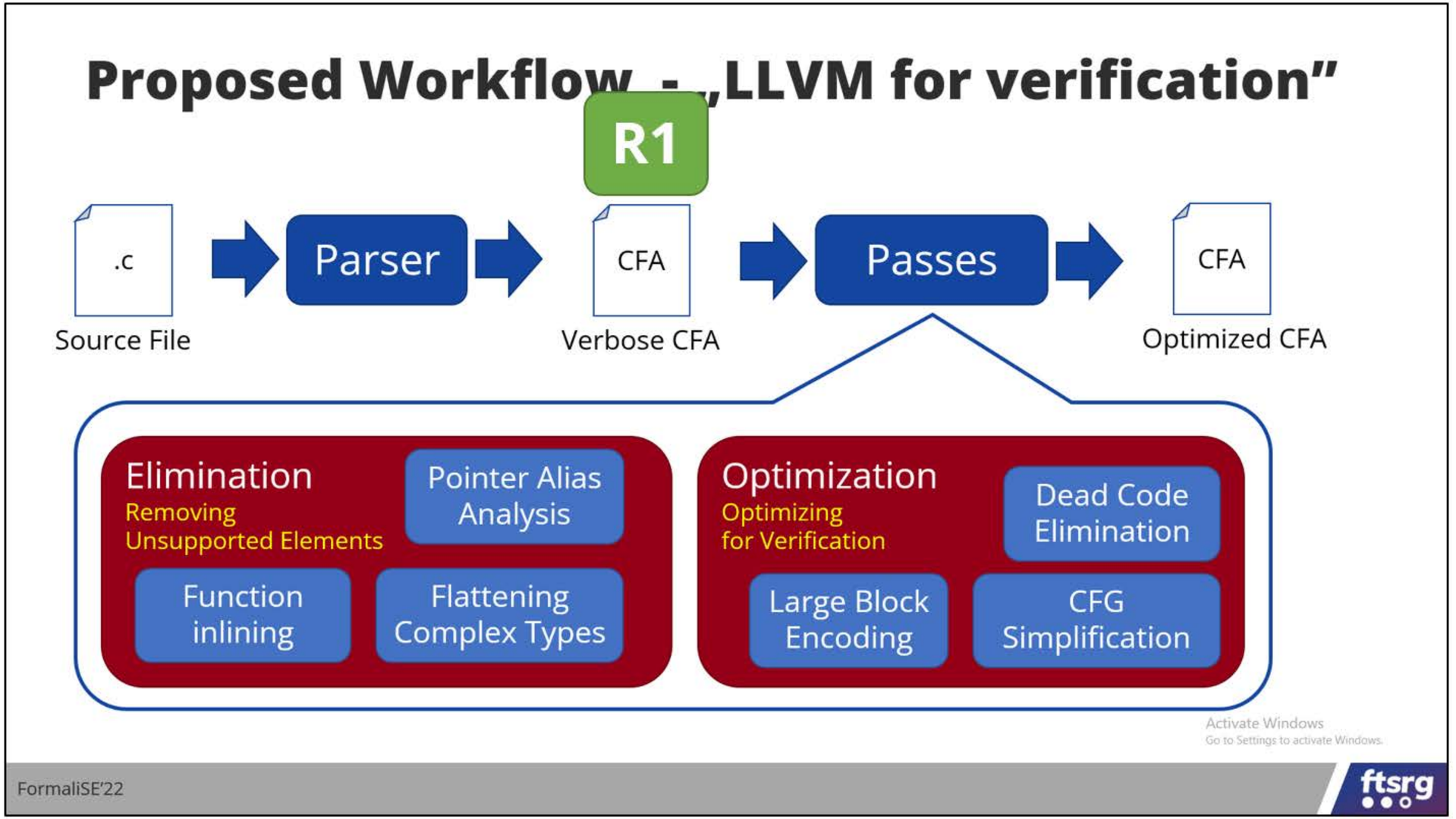

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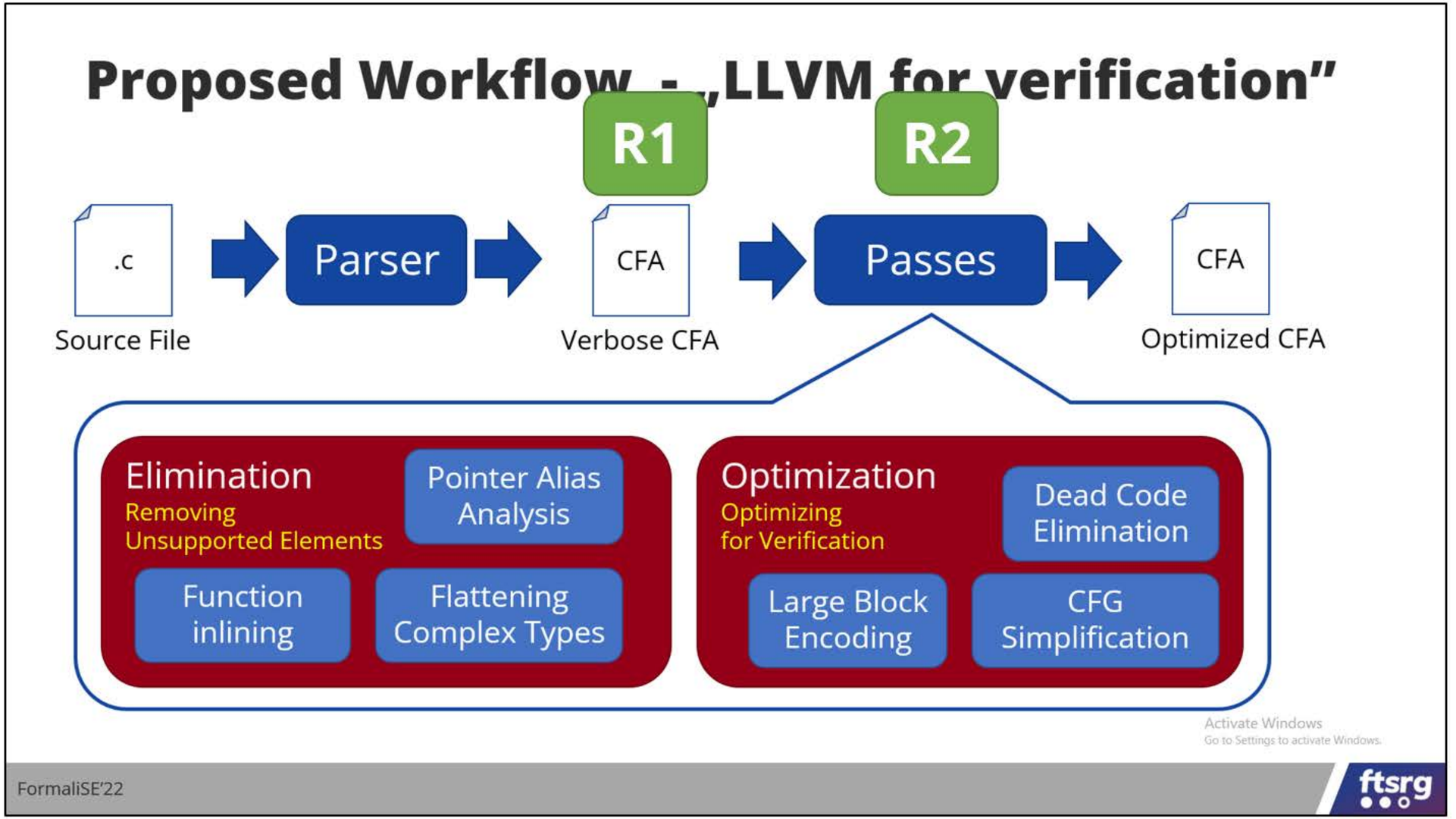

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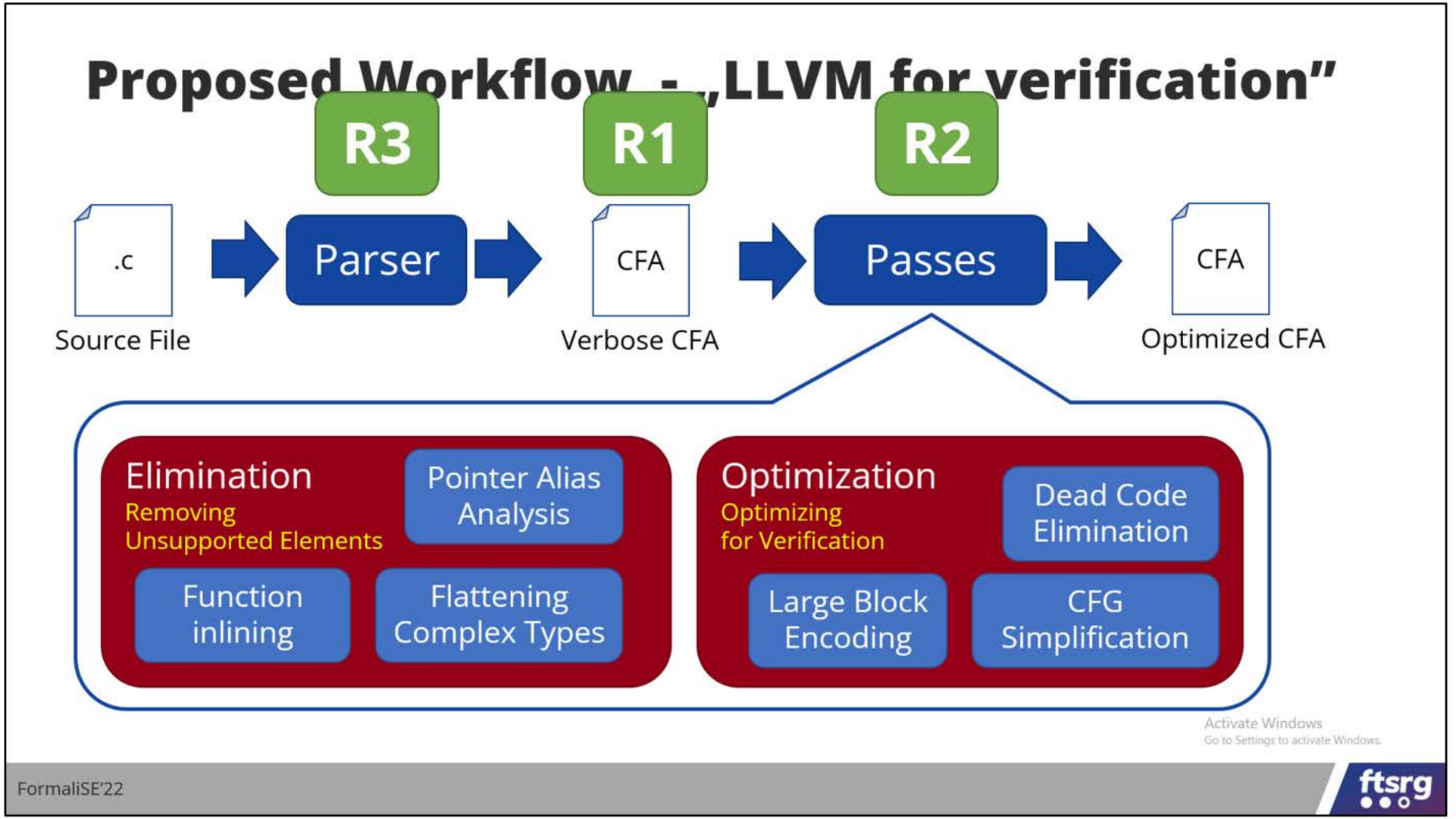

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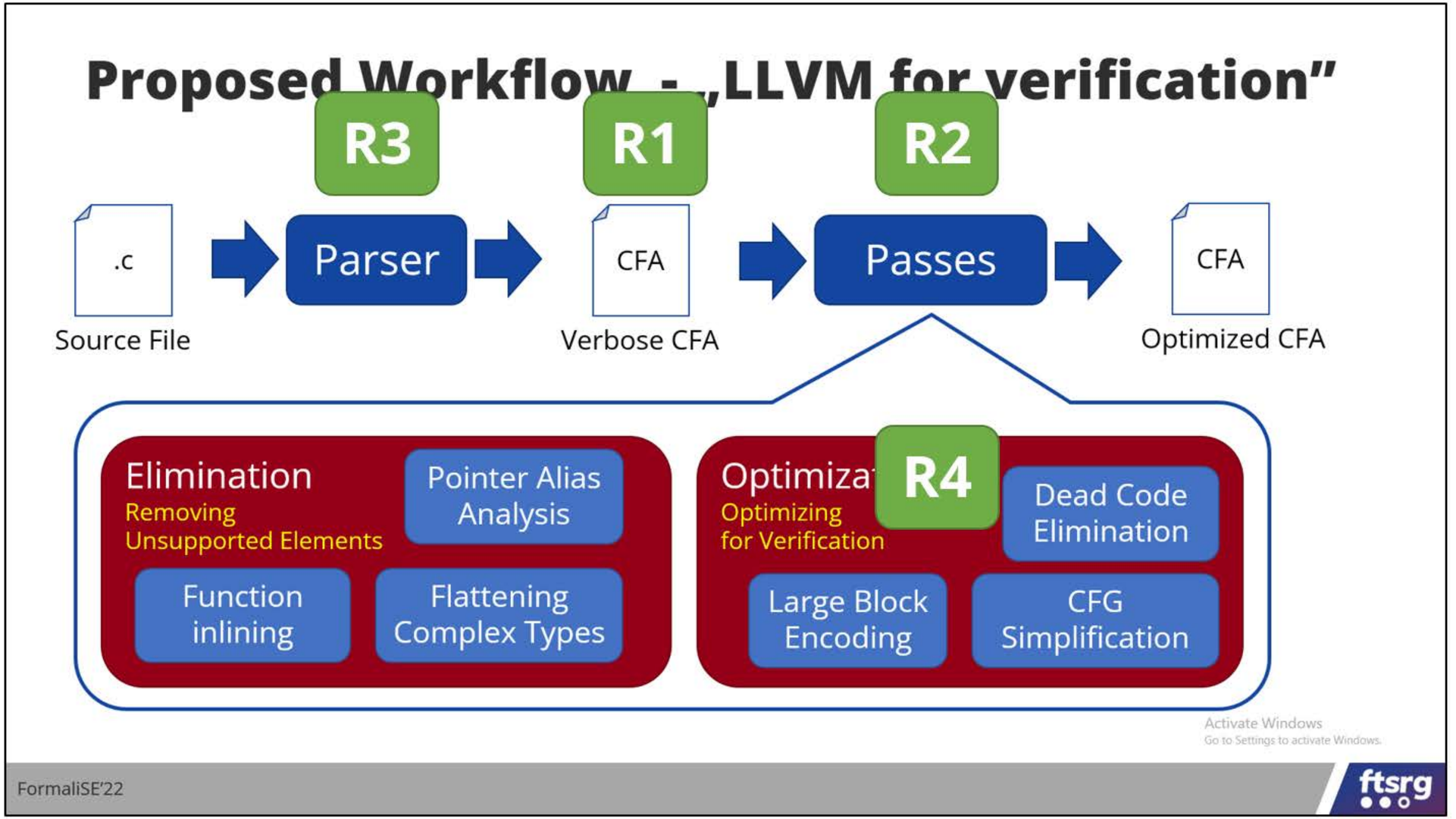
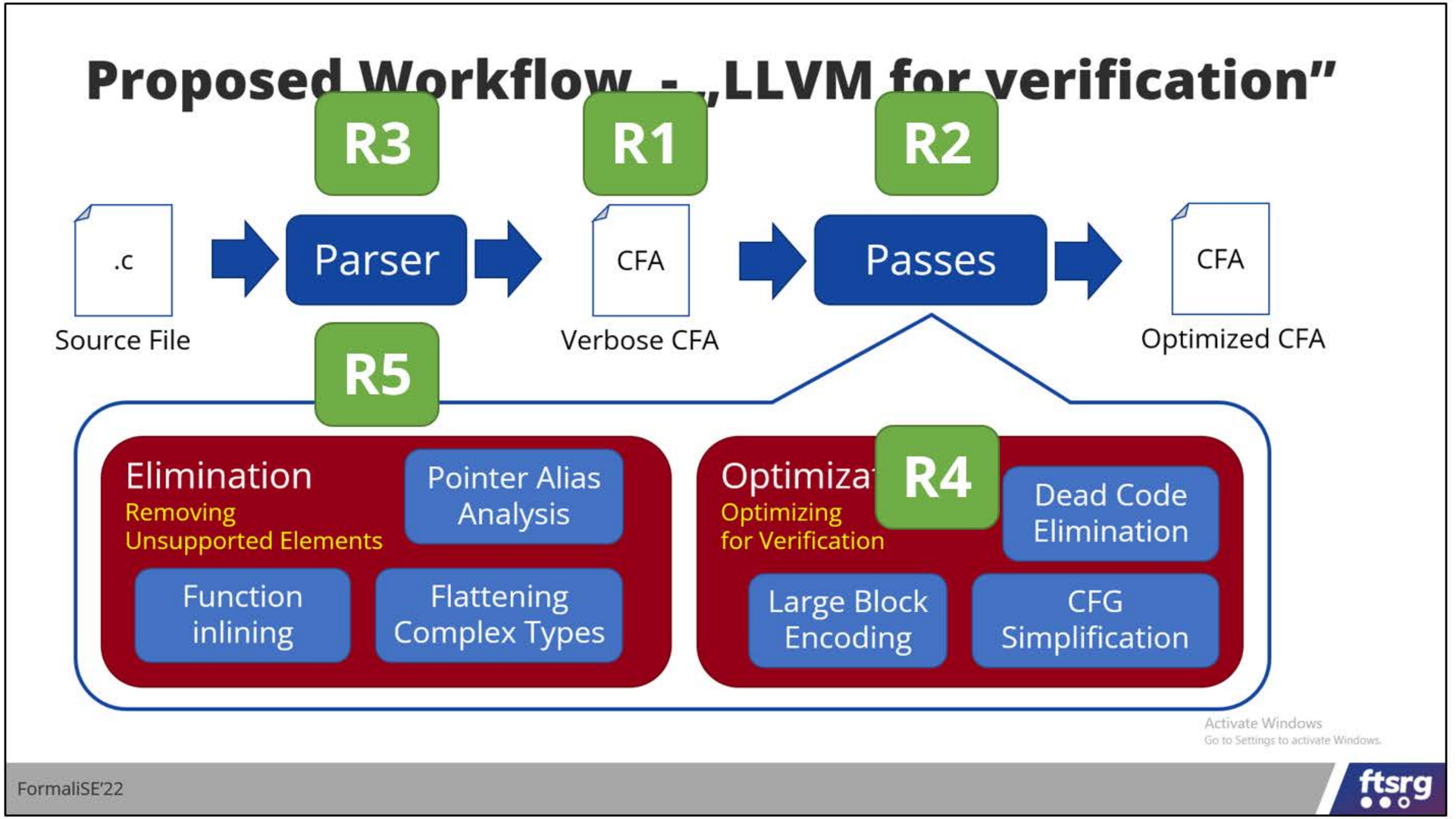
- R5 *Metadata Access*
- R6 *Unhandled Patterns*



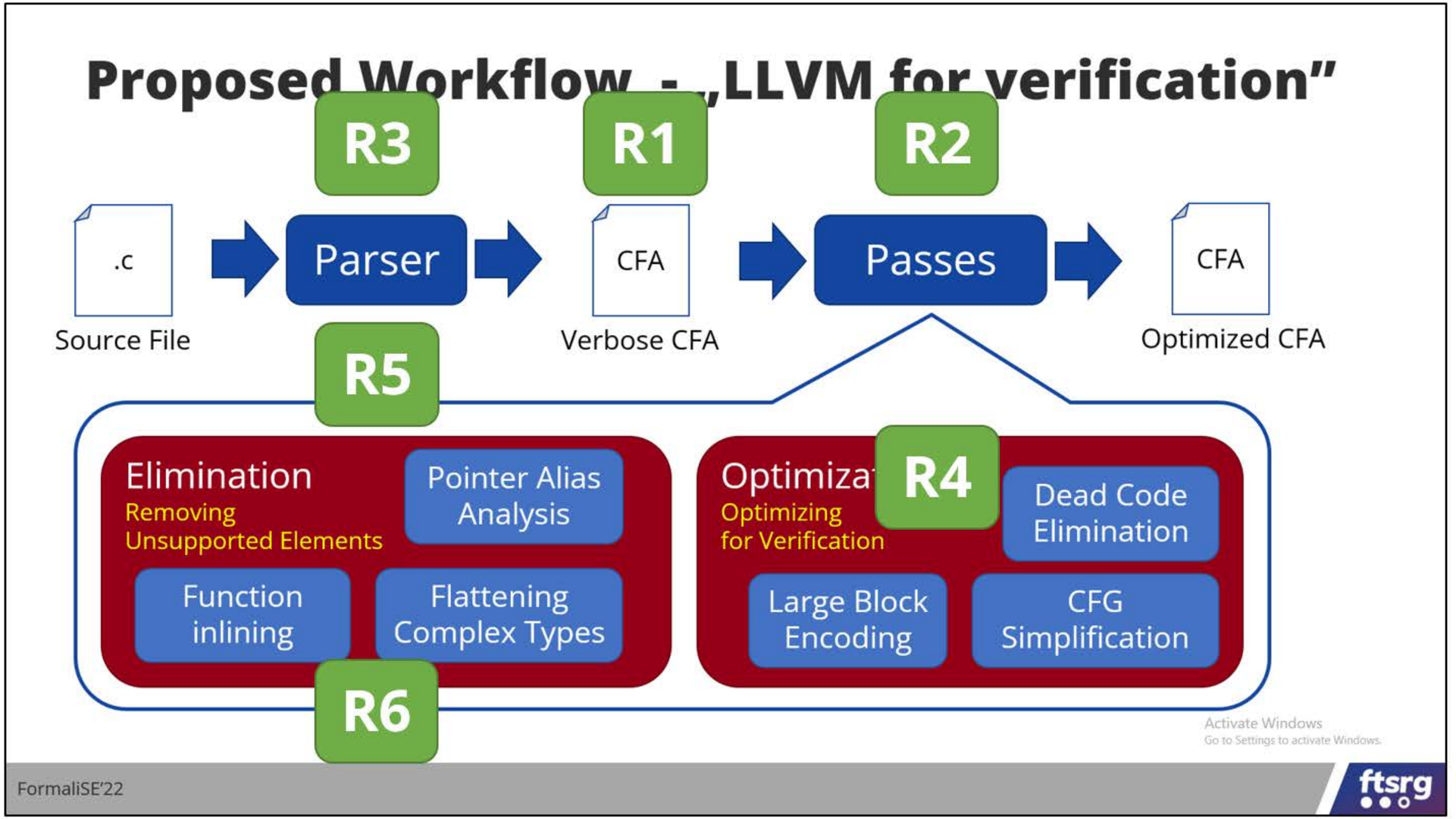
Requirements

- R1 *Formal*
- R2 *Configurable*
- R3 *Direct Access*
- R4 *Verifier-Centric*
- R5 *Metadata Access*
- R6 *Unhandled Patterns*



Requirements

- R1 *Formal*
- R2 *Configurable*
- R3 *Direct Access*
- R4 *Verifier-Centric*
- R5 *Metadata Access*
- R6 *Unhandled Patterns*



Requirements

R1
Formal

R2
Configurable

R3
Direct Access

R4
Verifier-Centric

R5
Metadata Access

R6
Unhandled Patterns

Requirements

	LLVM
R1 *Formal*	✓
R2 *Configurable*	✓
R3 *Direct Access*	✗
R4 *Verifier-Centric*	✗
R5 *Metadata Access*	✓/?
R6 *Unhandled Patterns*	✗

Requirements

	LLVM
R1 *Formal*	✓
R2 *Configurable*	✓
R3 *Direct Access*	✗
R4 *Verifier-Centric*	✗
R5 *Metadata Access*	✓/?
R6 *Unhandled Patterns*	✗

SSA

Requirements

	LLVM
R1 *Formal*	✓
R2 *Configurable*	✓
R3 *Direct Access*	✗
R4 *Verifier-Centric*	✗
R5 *Metadata Access*	✓/?
R6 *Unhandled Patterns*	✗

SSA

Best Effort

Requirements

	LLVM	Grammar-Based (Eclipse CDT, etc)
R1 *Formal*	✓	✗
R2 *Configurable*	✓	✗
R3 *Direct Access*	✗	✓
R4 *Verifier-Centric*	✗	✗
R5 *Metadata Access*	✓/?	✓
R6 *Unhandled Patterns*	✗	✗

SSA

Best Effort

Requirements

	LLVM	Grammar-Based (Eclipse CDT, etc)
R1 *Formal*	✗	✗
R2 *Configurable*	✓	✗
R3 *Direct Access*	✗	✓
R4 *Verifier-Centric*	✗	✗
R5 *Metadata Access*	✓/?	✓
R6 *Unhandled Patterns*	✗	✗

Implementation dependent

SSA

Best Effort

Requirements

	LLVM	Grammar-Based (Eclipse CDT, etc)	Goto-CC
R1 *Formal*	✓/✗	✗	✓
R2 *Configurable*	✓	✗	✗
R3 *Direct Access*	✗	✓	✓
R4 *Verifier-Centric*	✗	✗	✗
R5 *Metadata Access*	✓/?	✓	✓
R6 *Unhandled Patterns*	✗	✗	✓

Implementation dependent

SSA

Best Effort

Requirements

	LLVM	Grammar-Based (Eclipse CDT, etc)	Goto-CC
R1 *Formal*		✗	✓
R2 *Configurable*	✓	✗	✗
R3 *Direct Access*	✗	✓	✓
R4 *Verifier-Centric*	✗	✗	✗
R5 *Metadata Access*	✓/?		✓
R6 *Unhandled Patterns*	✗	✗	✓

Implementation dependent

SSA

Best Effort

No optimization, only verbose CFA

Experimental Evaluation

Is LLVM really that bad?

ANTLR

Goals of the Experiment

Goals of the Experiment

Given a mature frontend project (LLVM),

Goals of the Experiment

Given a mature frontend project (LLVM),

and a proof-of-concept prototype of the proposed workflow…

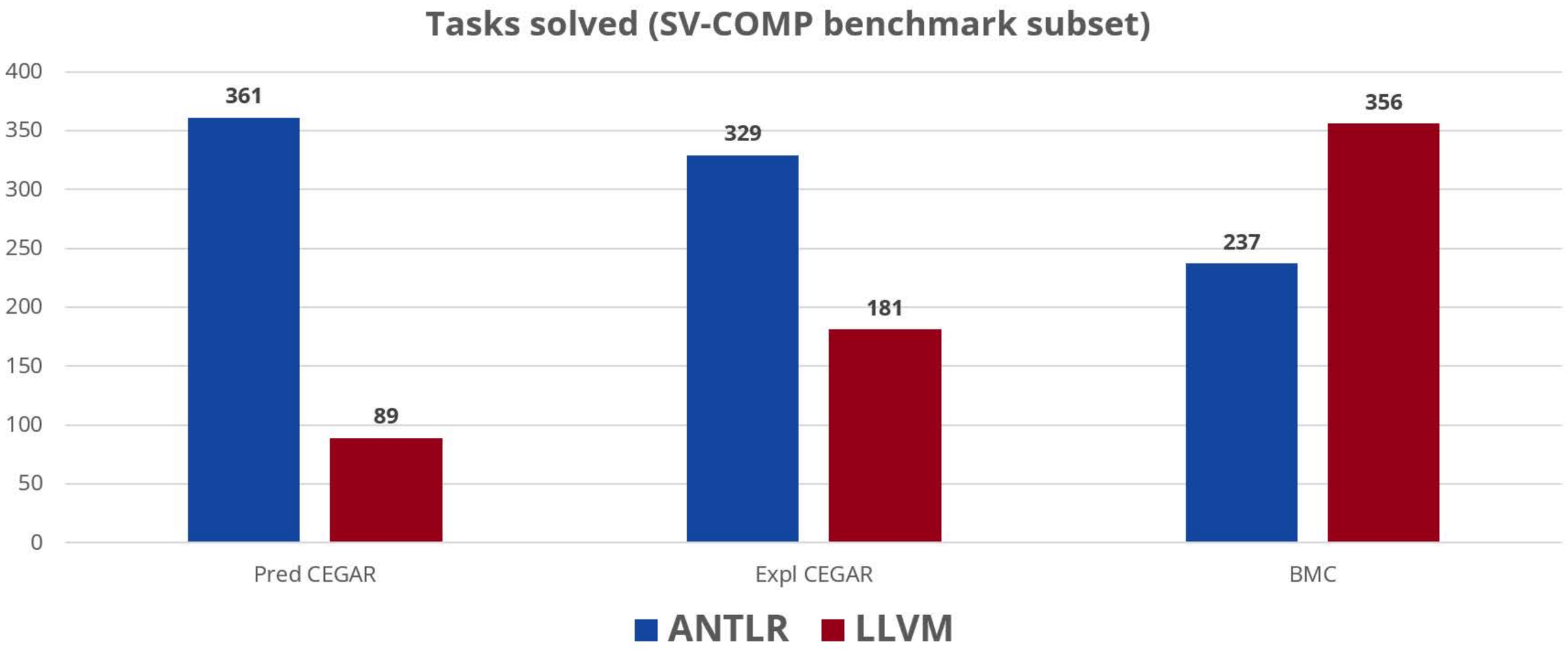
Goals of the Experiment

Given a mature frontend project (LLVM),

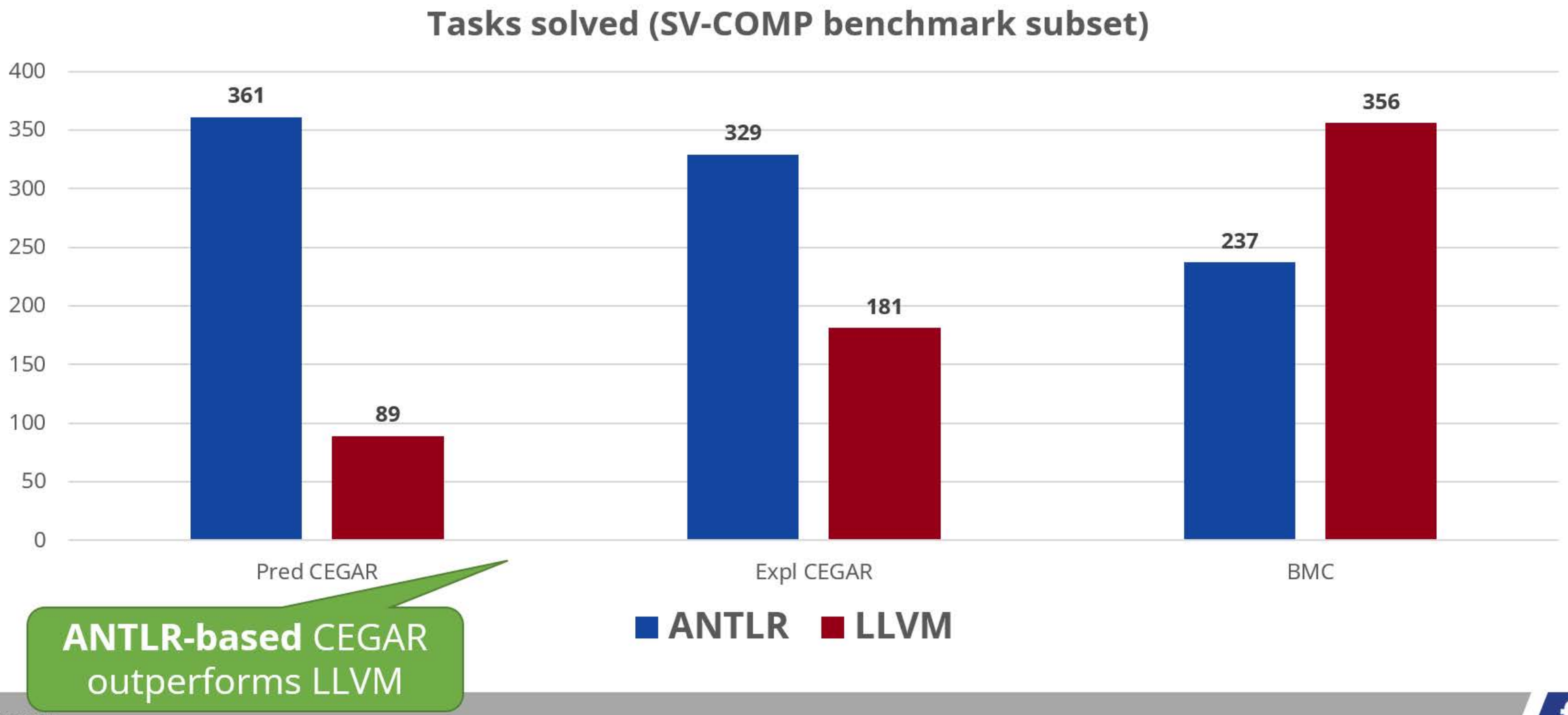
and a proof-of-concept prototype of the proposed workflow…

Can the latter outperform the former over CEGAR?

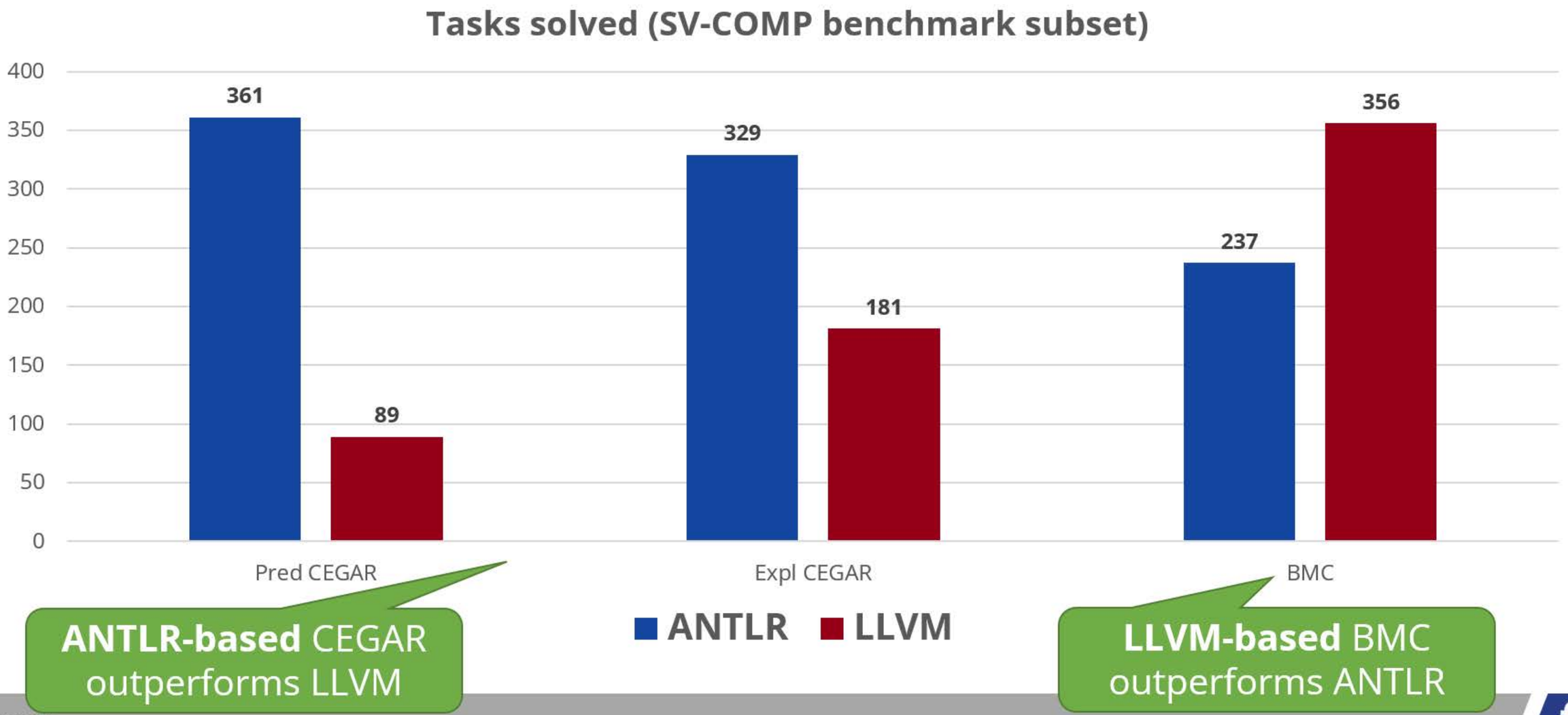
Results


Tasks solved (SV-COMP benchmark subset)
400
350
300
250
200
150
100
50
0
361
89
329
181
237
356
Pred CEGAR
Expl CEGAR
BMC
ANTLR
LLVM

Results


Tasks solved (SV-COMP benchmark subset)
400
350
300
250
200
150
100
50
0
361
89
329
181
237
356
Pred CEGAR
Expl CEGAR
BMC
ANTLR
LLVM
ANTLR-based CEGAR outperforms LLVM

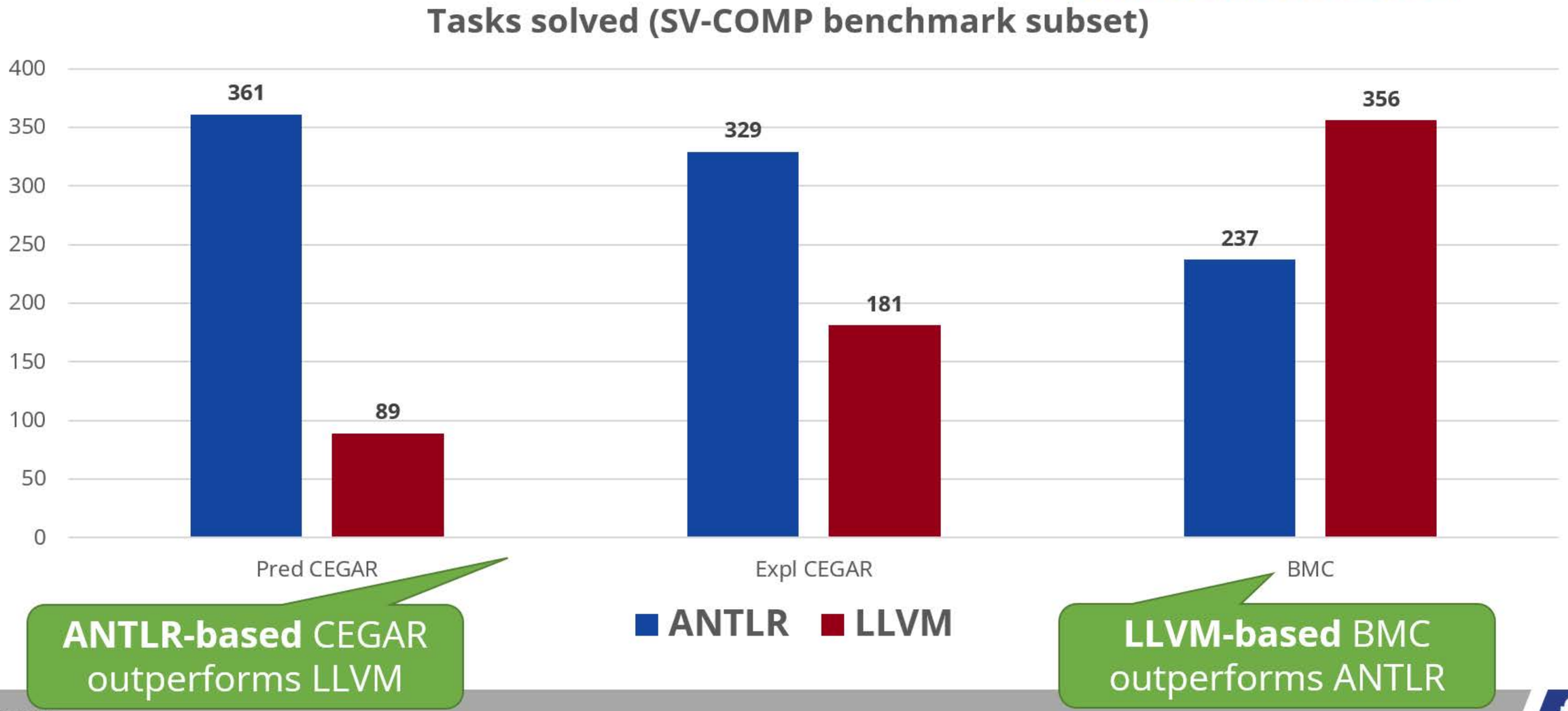
Results


Tasks solved (SV-COMP benchmark subset)
400
350
300
250
200
150
100
50
0
361
89
329
181
237
356
Pred CEGAR
Expl CEGAR
BMC
ANTLR
LLVM
ANTLR-based CEGAR outperforms LLVM
LLVM-based BMC outperforms ANTLR

Results

10.5281/zenodo.5920382

FormaliSE Artifact Evaluation 2022 Accepted



ftsrg