Verifying Recursive Programs using Verifiers for Non-recursive Programs

Project Progress Report

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Outline

- Introduction
- Overview
- Experiment Result
- Discussion

Introduction

From WAVAS

Background & Our Goal

- Established Tools
  - Predator, UFO, CPAChecker, Blast, etc.
  - Handle non-recursive programs efficiently
  - Limited support on recursion for most verifiers
- Light-weight extensions to handle recursion
  - Based on established verifiers
  - Minimize efforts on implementation

Overview

From WAVAS

Sample

```
/* Original */
int main()
{
 if(y<0)
    y = rec(x);
 assert(y >= 0);
 return 0;
}
```

How to verify?

Sample

```
/* Original */
int main()
{
 if(y<0)
    y = rec(x);
 assert(y >= 0);
 return 0;
}
```

How to verify?
Find assertion violation that
rec() is not involved

Under-approximation

```
/* Original */
int main()
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   y = rec(x);
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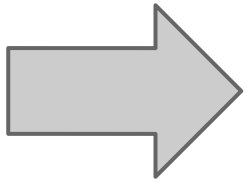
How to verify?
Find assertion violation that rec() is not involved



```
/* Under-approx. */
int main()
{
 if(y<0)
   /*y = rec(x);*/
   assume(false);
 assert(y >= 0);
 return 0;
}
```

Consider executions without calling rec() only

Replace all function calls with assume(false)

Under-approximation~

```
/* Original */
int main()
{
 if(y<0)
   y = rec(x);
 assert(y >= 0);
 return 0;
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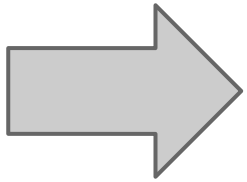
How to verify?
Find assertion violation that rec() is not involved



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int main()
{
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   /*y = rec(x);*/
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 assert(y >= 0);
 return 0;
}
```

Consider executions without calling rec() only
What if all such executions are safe?

Sample ~ with assumption

```
/* Original */
int main()
{
 if(y<0)
    y = rec(x);
 assert(y >= 0);
 return 0;
}
```

How to verify?

Assume we have

{true} y=rec(x) {y >= 0}

Over-approximation

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/* Original */
int main()
{
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   y = rec(x);
 assert(y >= 0);
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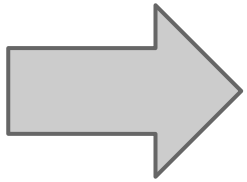

```
/* Over-approx. */
int main()
{
 if(y<0)
   /*y = rec(x);*/
   assume(y>=0);
 assert(y >= 0);
 return 0;
} SAFE
```

How to verify?

Assume we have

{true} y=rec(x) {y >= 0}

Replace all function calls with assume(summary)

Over-approximation~

```
/* Original */
int main()
{
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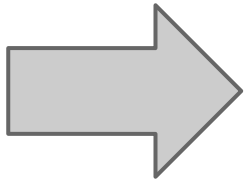
 assert(y >= 0);
 return 0;
}
```

How to verify?

Assume we have

{true} y=rec(x) {y >= 0}



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int main()
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How to find reasonable function summaries?

Over-approximation~~

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/* Original */
int main()
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How to verify?

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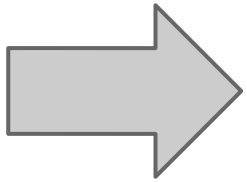

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int main()
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} SAFE
```

How to find reasonable function summaries?

We guess

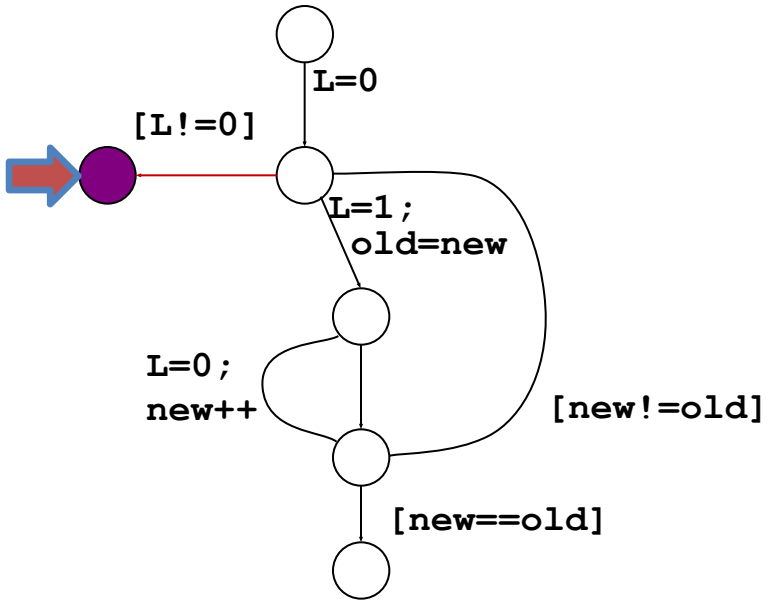
Guess Summary

Preliminary

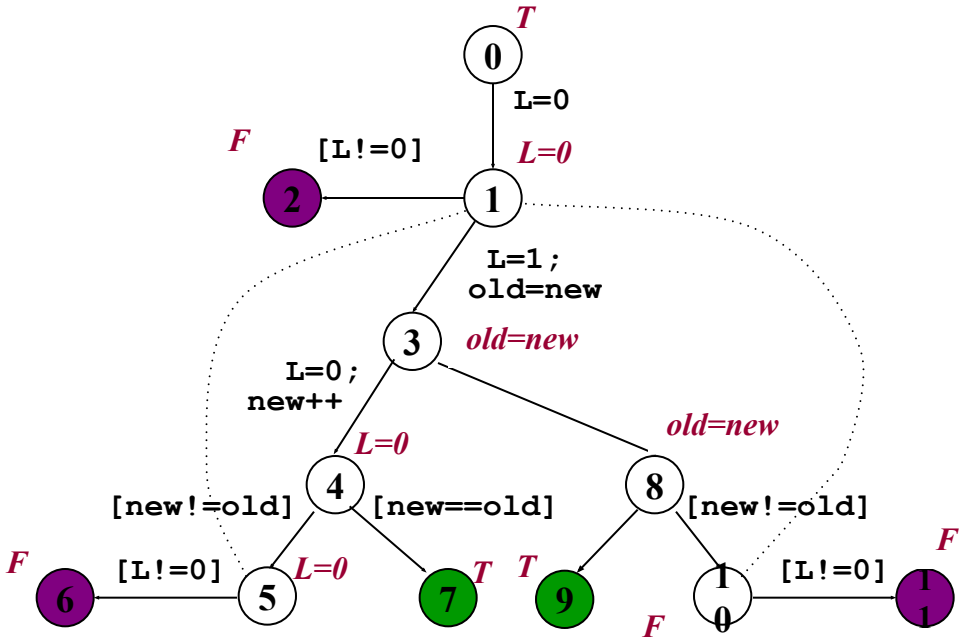
- Lazy Abstraction
  - Abstract Reachable Tree/Graph

- Handle Function Call
  - Unwind all function calls
  - Not work for recursive function
    - Recursive call remains
- Handle Recursive Function Call
  - Use aforementioned Under-approximations of recursive functions

Unwinding the CFG



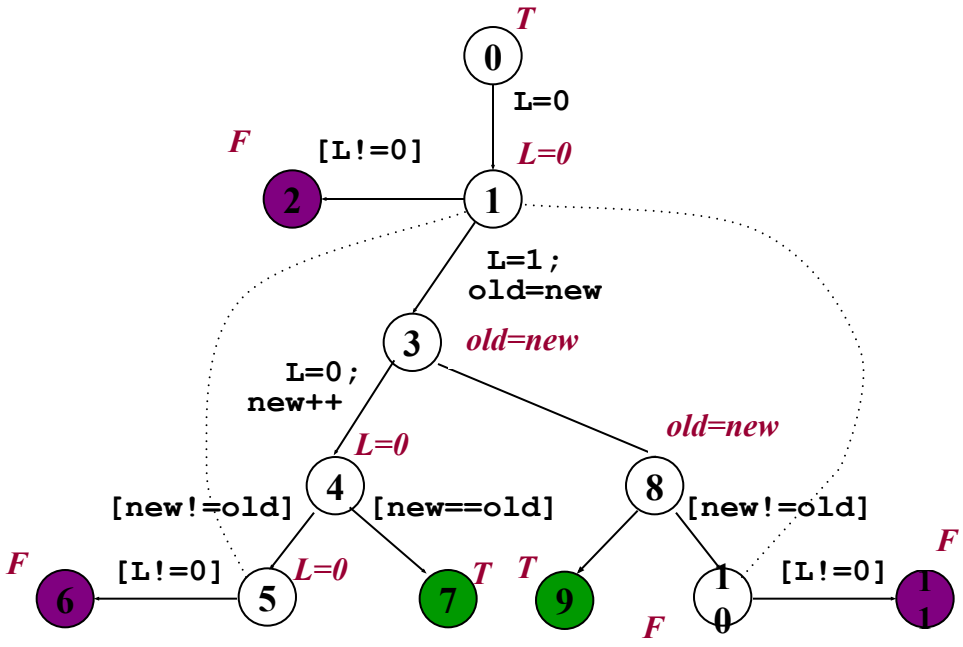
control-flow graph



Error Node Unreachable
SAFE and complete ARG

Unwinding the CFG

- Label on Node
  - Approximation of reachable states at that location
- Approxiamte a Function Call
  - Select labels at begin and end of a function call

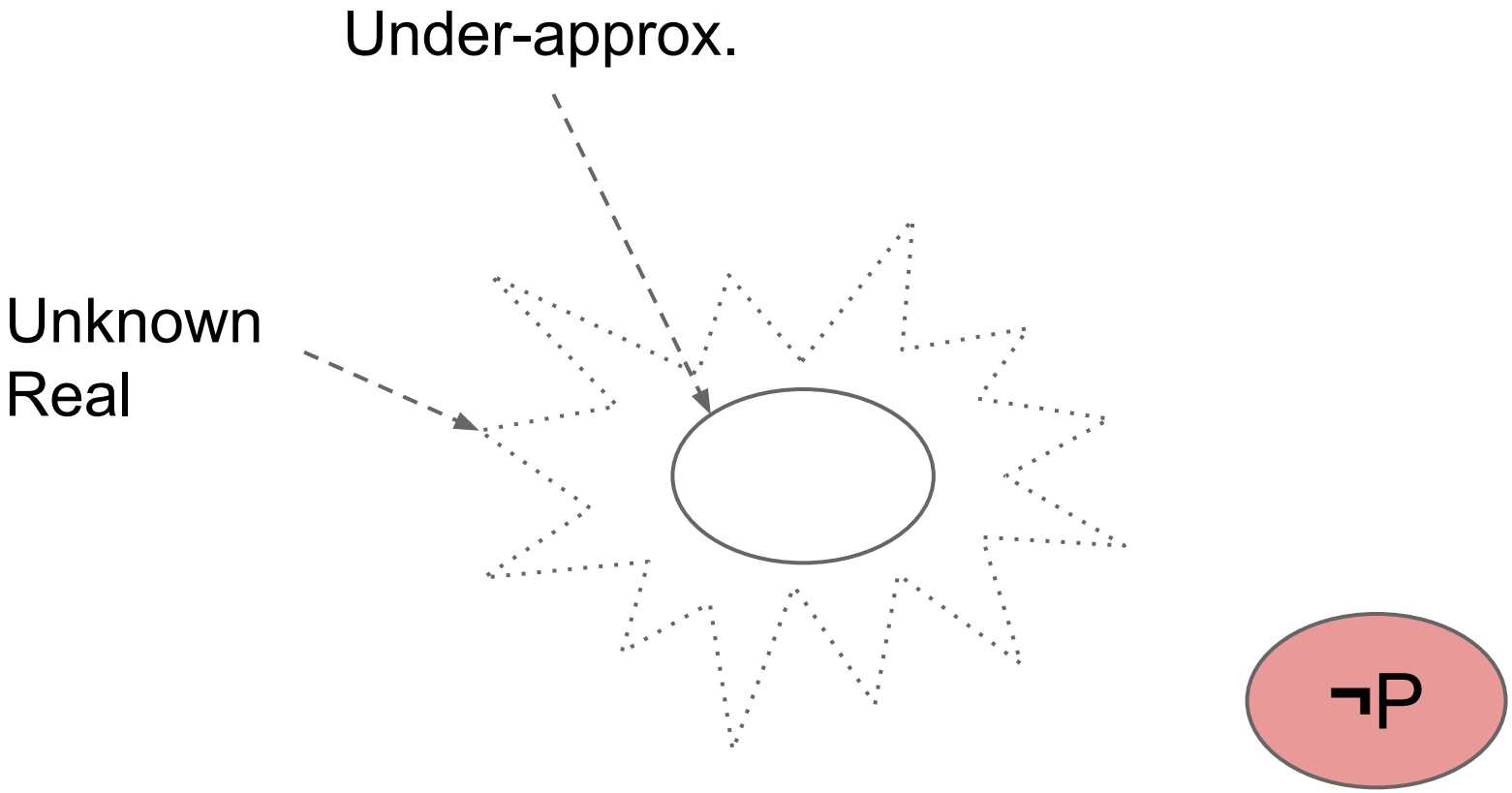


Error Node Unreachable
SAFE and complete ARG

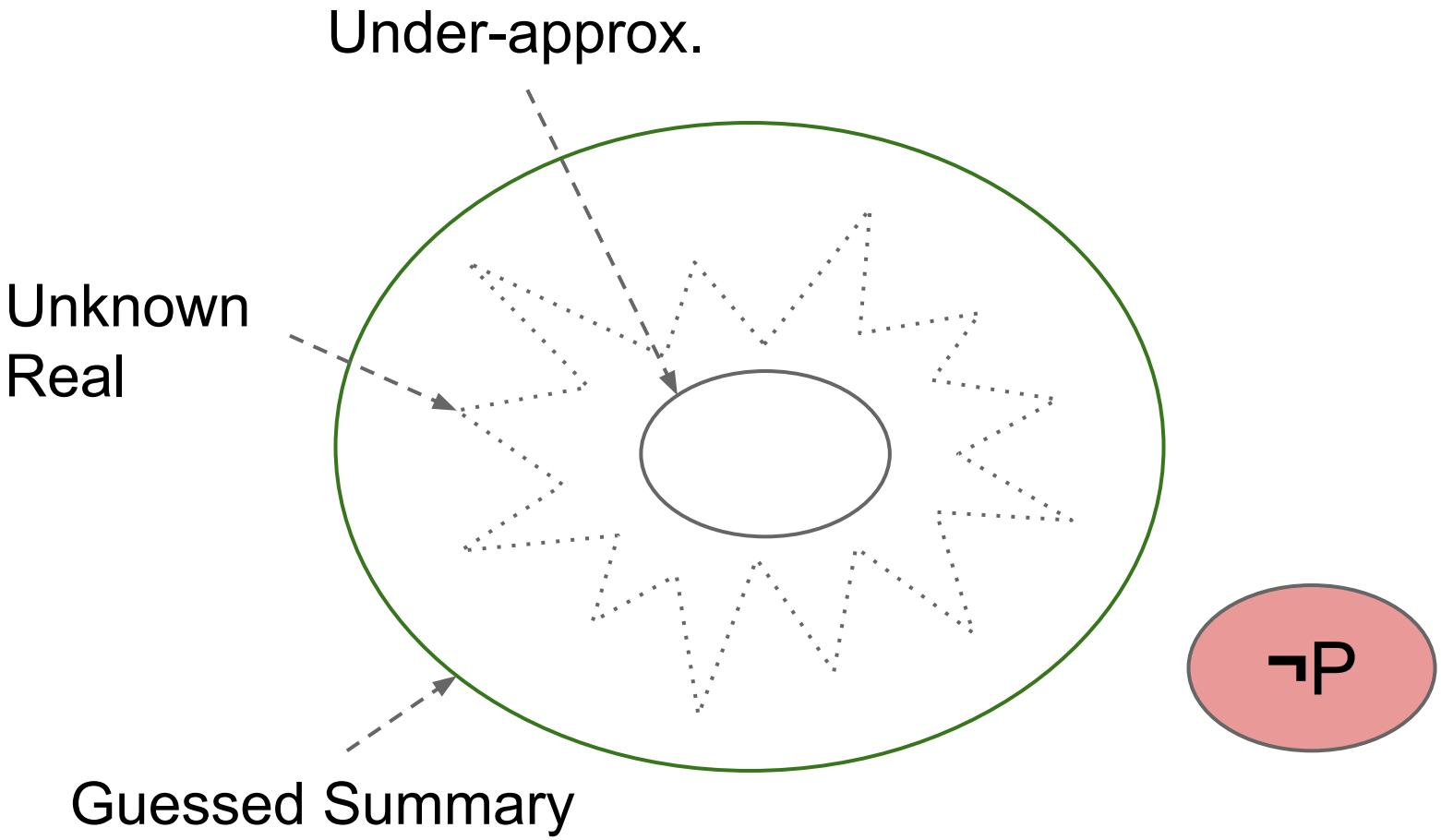
Generate Summary for function

- Pre-Condition *Pre-CON*
  - Given some labels mapped to begin of an unwinded function call, pre_1, …, pre_k
  - *Pre-CON* = $pre_1 \vee \ldots \vee pre_k$
- Post-Condition *Post-CON*
  - Given some labels mapped to end of the function call
    , $post_1$, …, $post_n$
  - *Post-CON* = $post_1 \vee \ldots \vee post_n$
- Summary *SUM*
  - *SUM* = (*Pre-CON* => *Post-CON*)
    = (¬*Pre-CON* ∨ *Post-CON*)

A SAFE design



Valid Guess



Question

- Summary is an over-approximation of ?
  - Overapproximate the unwinded function call
  - But we use under-approximation of recursive call.
  - What does it over-approximate?
    - Under-approximation
- Generated summary is a guess
  - How to validate?

Check
Guessed Summary

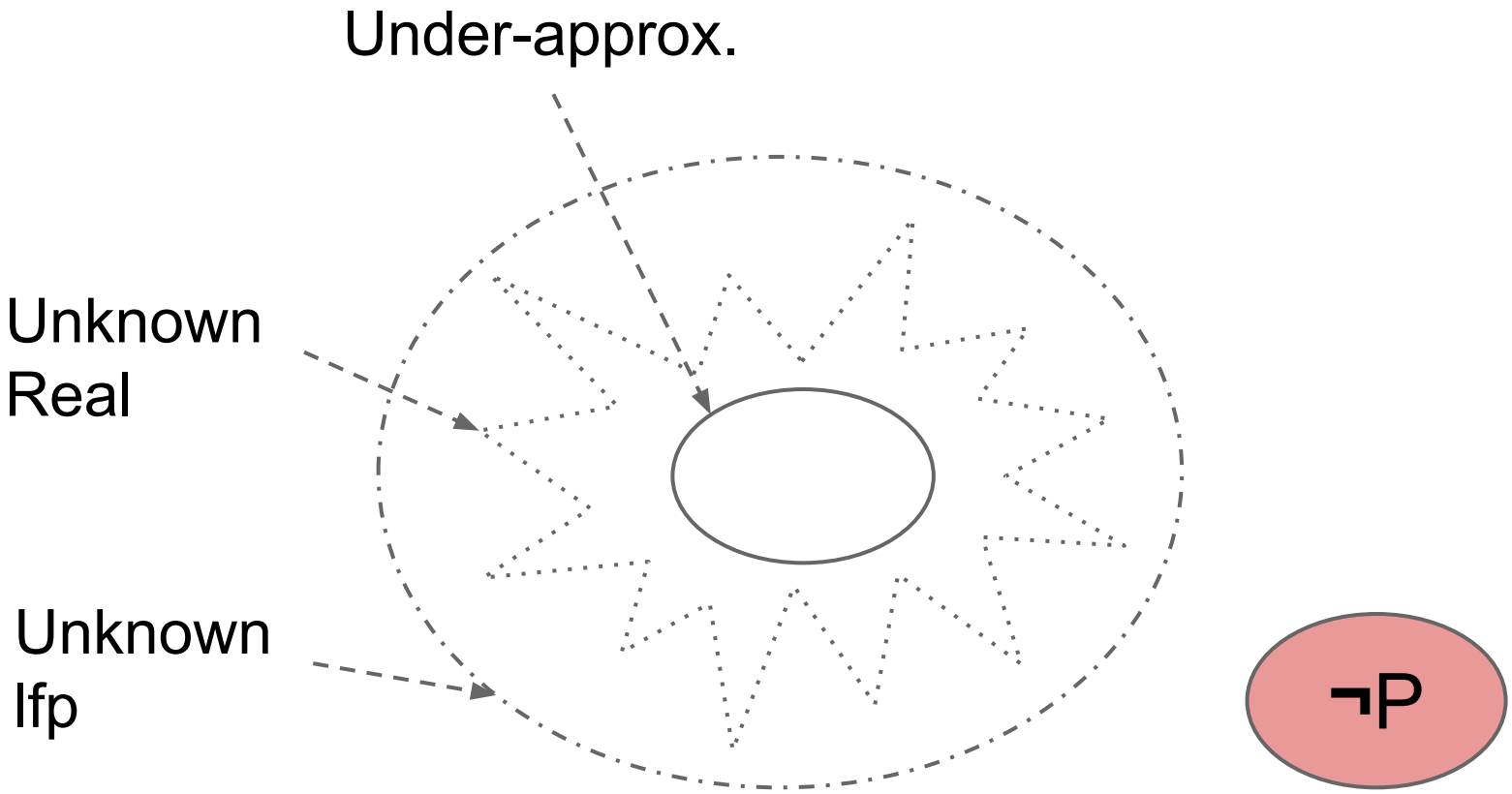
Preliminary

- Least Fixedpoint (lfp)
  - Tarski's fixed point theorem

$$\bigwedge P = \bigwedge \{x \in L \mid x \geq f(x)\}$$

- Result
  - f as recursive function, x as guessed summary
  - If x contains f(x)
    - We develop a method to check this
  - x must contain least fixedpoint

Least Fixedpoint for SAFE design



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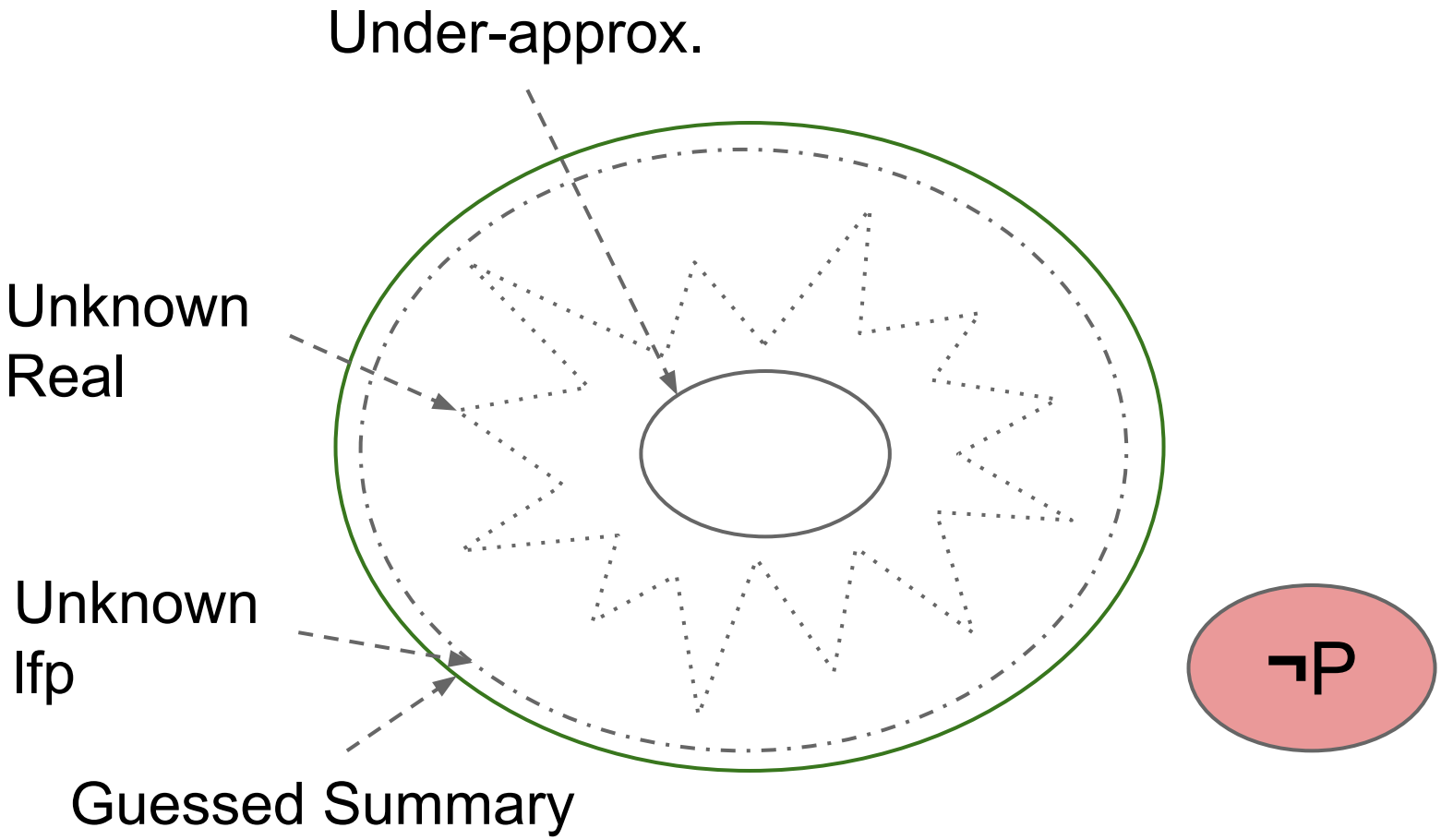
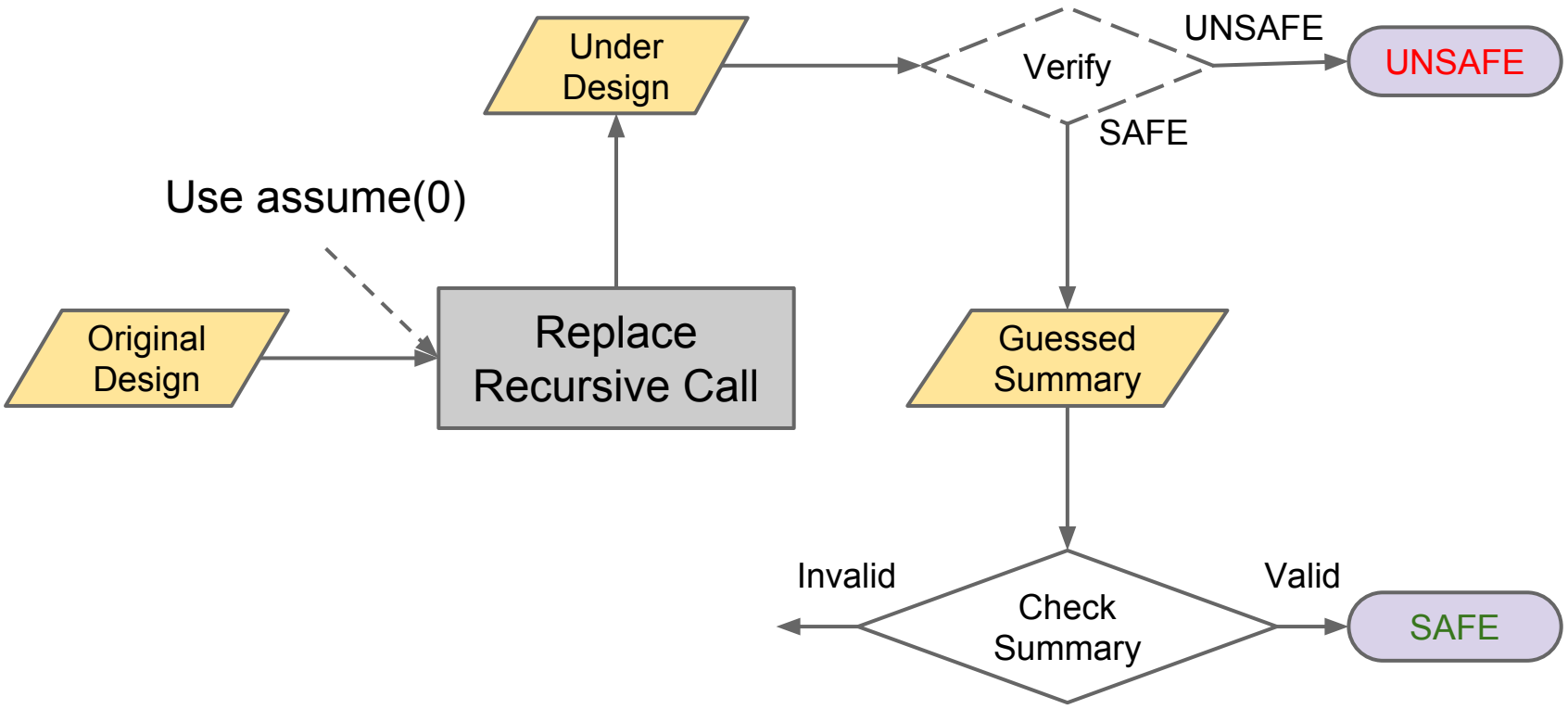


Flow

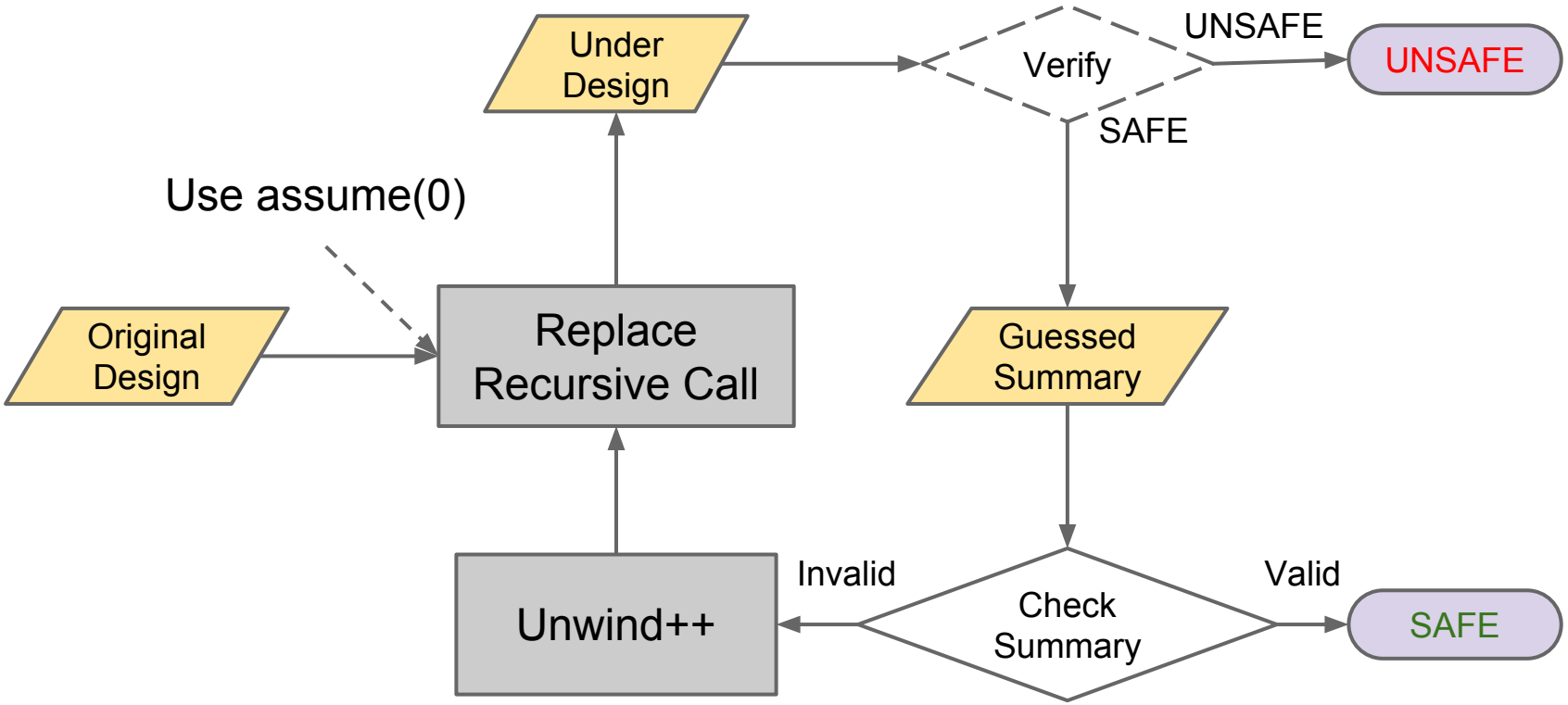

Under Design
Verify
UNSAFE
UNSAFE
SAFE
Use assume(0)
Original Design
Replace Recursive Call
Guessed Summary
Invalid
Check Summary
Valid
SAFE

Invalid Guessed Summary

- What if this guess is invalid?
- Guess another summary
  - From another under-approximation
  - Produced new under-approximation by further unwinding recursive call

- Refine current guess
  - Currently working on this

Flow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Experiment Result

- Benchmarks from SVCOMP 14
  - Category “recursive”
  - 23 cases in total with each case an assertion
  - Timeout: 900 sec. for a case
- Second Place Winner, Ultimate
  - Because 1st place winner is a little controversial
  - Solved: 8 cases
- Our Result
  - Solved: 10 cases
  - Solved after timeout: 2

Discussion

- Correctness
  - For UNSAFE design
    - A bug must be found after enough unwinding.
  - For SAFE design
    - Find a summary for recursive function
    - Provide a check method to validate its correctness
- Effectiveness on SAFE design
  - Assertion is usually an over-approximation of the recursive function being verified.
  - Our approach will frequently choose the assertion as our guessed summary.

Discussion~

- Inefficiency on UNSAFE design
  - Depend on unwinding enough times
  - Cause exponential growth of verified design size

- Case Study on unsolved cases
  - Assertion is a nonlinear property
    - Limited by the capability of chosen verifier

Thank you.