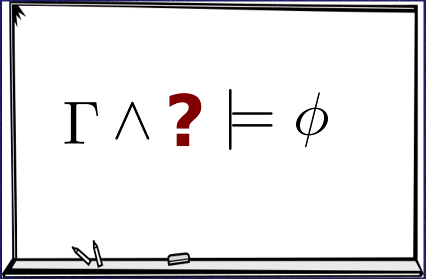
Abductive Inference and its Applications in Program Analysis, Verification, and Synthesis



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- i.e., given invalid formula $\Gamma \Rightarrow \phi$, find a "simple" formula ψ such that $\Gamma \wedge \psi \Rightarrow \phi$ is valid and ψ does not contradict Γ.

Simple Example

- Premises: “If it rains, then it is wet and cloudy”, “If it is wet, then it is slippery”: $(R \Rightarrow W \wedge C) \wedge (W \Rightarrow S)$

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- Conclusion: "It is cloudy and slippery", i.e., $C \land S$
- Conclusion doesn't follow from premises; use abduction to find missing hypothesis
- Possible solution: R, i.e., "It is rainy"

Arithmetic Example

- Suppose we know $x \geq -2$

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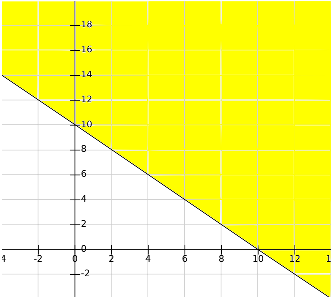

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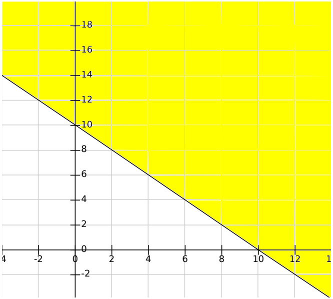

- Suppose we know $x \geq -2$
- Want to prove: $x + y > 10$
- Abductive explanation: $y > 12$

Outline of Talk

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5. Use of abduction in program synthesis
6. Conclusion and future directions

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- So, what kind of solutions do want to compute?

Which Abductive Explanations Are Good?

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Occam's Razor

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- If there are multiple competing hypotheses, select the one that makes fewest assumptions
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- Succinctness: Minimize number of variables

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- First talk about how to compute solutions with fewest variables
- Then talk about how to obtain most general solution containing these variables

Minimum Satisfying Assignments

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Minimum satisfying assignment (MSA):

- ✓ assigns values to a subset of variables in formula
- ✓ sufficient to make formula true
- ✓ Among all other partial satisfying assignments, contains fewest variables

Example

- Consider the following formula in linear integer arithmetic:

$$x + y + w > 0 \lor x + y + z + w < 5$$

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- Note: Algorithm for computing MSAs given in our CAV'12 paper, "Minimum Satisfying Assignments for SMT"

Why Are MSAs Useful for Abduction?

- Given facts Γ and conclusion ϕ, MSA σ of $\Gamma \Rightarrow \phi$ consistent with Γ is a solution to abduction problem:

$$\sigma \models \Gamma \Rightarrow \phi \quad \text{hence} \quad \sigma \wedge \Gamma \models \phi$$

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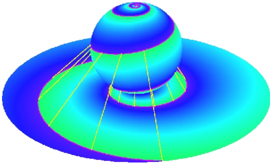
- Furthermore, it uses a fewest number of variables
- But it is not the most general solution

Finding Most General Solutions



Key idea:
Quantifier elimination

- To find most general solution containing variables in the MSA, universally quantify all other variables $\overline{V}$ and apply quantifier elimination to $\forall \overline{V}.\ \Gamma \Rightarrow \phi$

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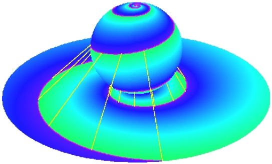

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- This yields most general solution with fewest variables

Abduction Algorithm

- abduce yields formula ψ such that

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and ψ is consistent with Γ and θ

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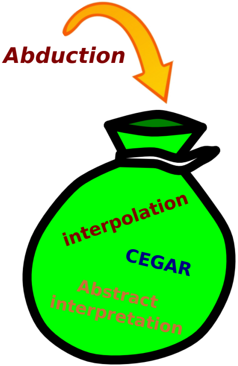
Applications



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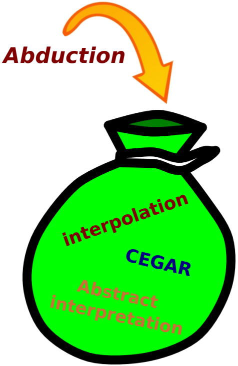

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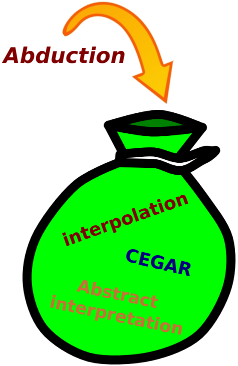

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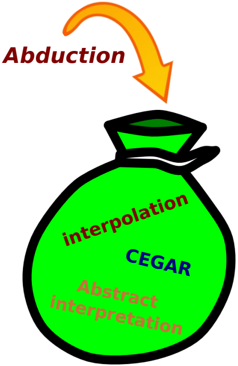

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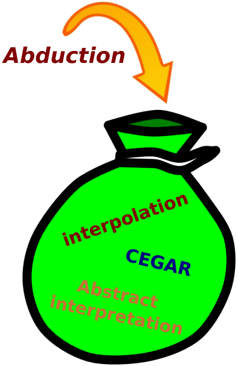

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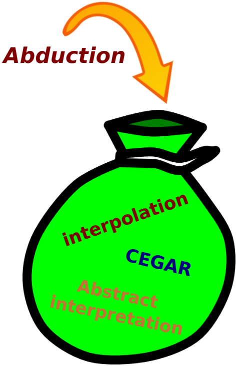

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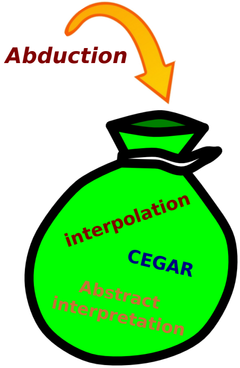

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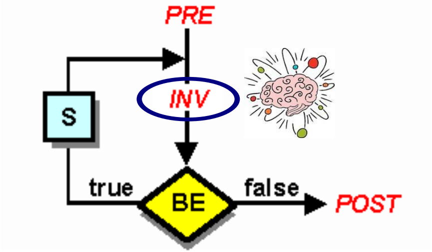

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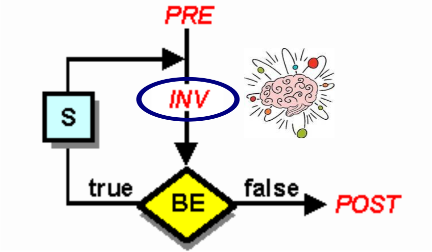

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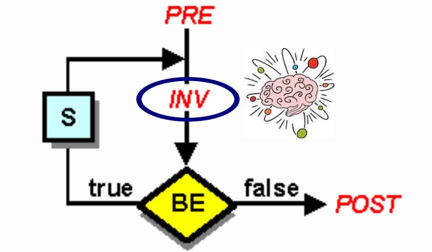

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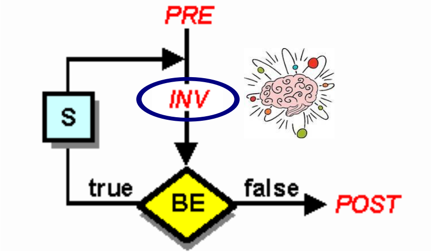

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- Inductive loop invariant **Inv** is implied by **Pre** and preserved in each iteration assuming only **Inv**
- But **Inv** is only useful if it is sufficient to prove **Post**

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- Use abduction to speculate an invariant I that implies post-condition Q:

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- Now, check if $I \land I'$ is inductive, if not, keep strengthening using (i) proof goes through, or (ii) get contradiction

Simple Example

- Start by solving abduction problem:

$$i > n \wedge ?? \Rightarrow i \geq 1$$

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{i=1, j = 0, n<5}

while(i <= n) {
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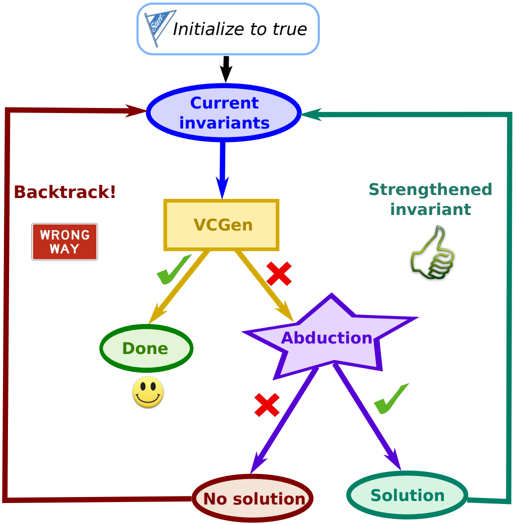
- This is inductive, so algorithm terminates

Overall Algorithm



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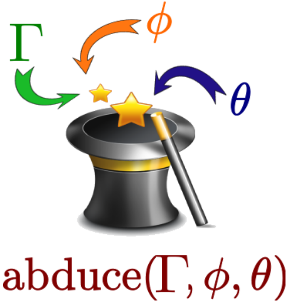

Algorithm lazily generates abductive explanations

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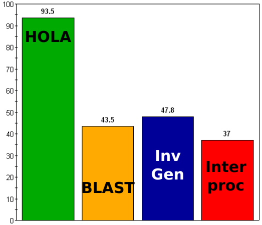

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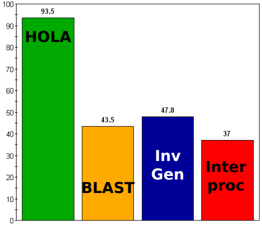

- Can verify 13 benchmarks that no other tool can verify, but cannot prove two benchmarks at least one tool can show

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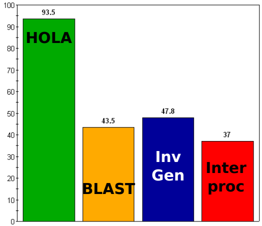
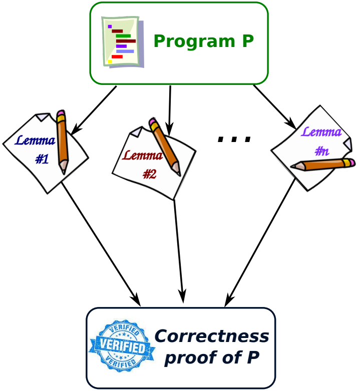
- Evaluated this technique on 46 loop invariant benchmarks
- Compared our results against BLAST, InvGen, and Interproc:

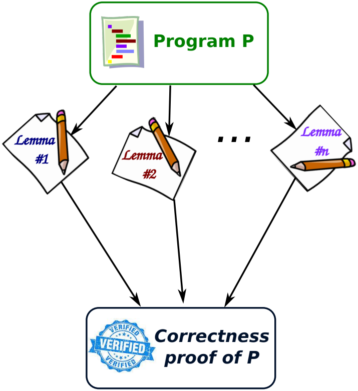


- Can verify 13 benchmarks that no other tool can verify, but cannot prove two benchmarks at least one tool can show
- No termination guarantees

Application #2: Compositional Verification



Application #2: Compositional Verification



- Compositional approaches decompose proof into lemmas

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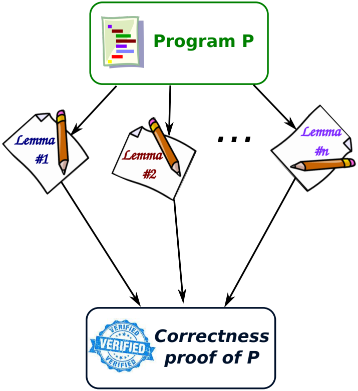

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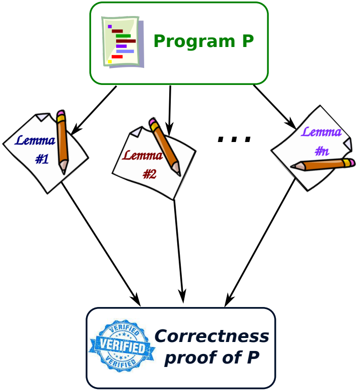

- Compositional approaches decompose proof into lemmas
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  1. **Scalability:** Each lemma concerns small syntactic part $\Rightarrow$ reason about program fragments in isolation

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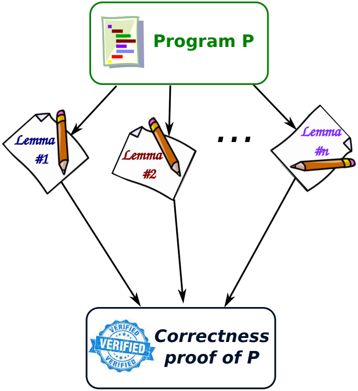
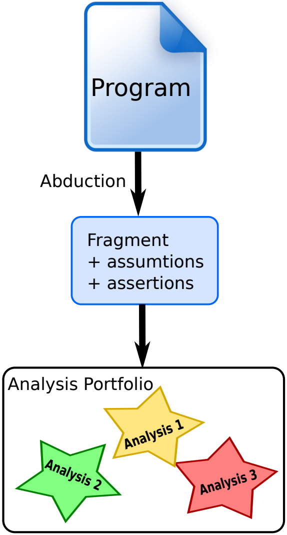


- Compositional approaches decompose proof into lemmas
- Two key advantages:
  1. **Scalability:** Each lemma concerns small syntactic part $\Rightarrow$ reason about program fragments in isolation
  2. **Abstraction:** Each lemma can be proven using a different abstraction $\Rightarrow$ combine strengths of different techniques

Overview of Compositional Verification Approach

- **Key idea:** Use **abduction** to decompose proof into auxiliary lemmas



Overview of Compositional Verification Approach

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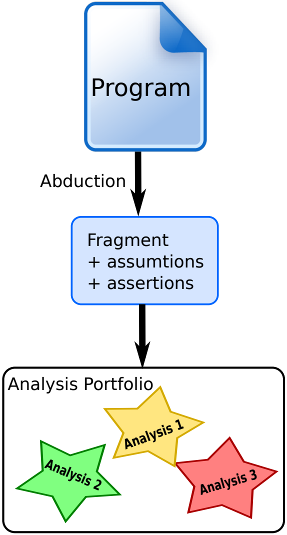
  - Lemmas are snippets annotated with assertions and assumptions



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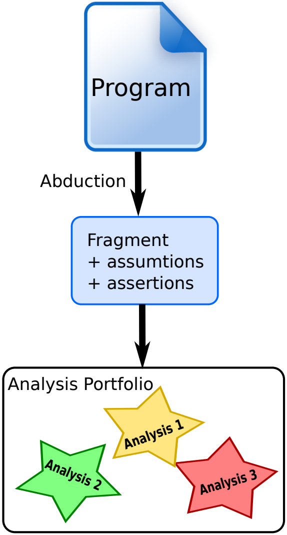

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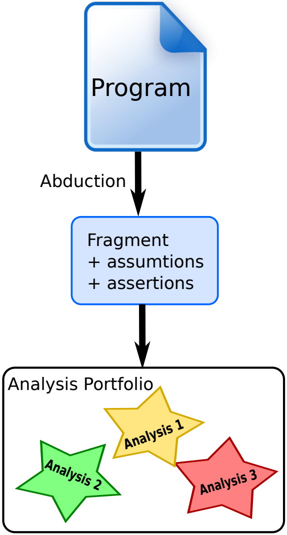

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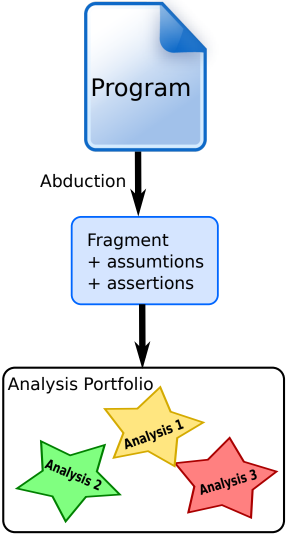
  - Each lemma can assume correctness of all other lemmas



Example

- Consider this code snippet

```
int i=1, j=0;
while(*) {j++; i+=3;}
int z = i-j;
int x=0, y=0, w=0;
while(*) {
  assert(x==y);

  z+=x+y+w;
  y++;
  x+=z%2;
  w+=2;
}
```

Example

- Consider this code snippet
- Want to reason about two fragments in isolation

Fragment 1

```
int i=1, j=0;
while(*) {j++; i+=3;}
int z = i-j;
```

```
int x=0, y=0, w=0;
while(*) {
  assert(x==y);

  z+=x+y+w;
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}
```

Fragment 2

Example

- Consider this code snippet
- Want to reason about two fragments in isolation
- Focus on fragment containing assertion

```
int i=1, j=0;
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Example

- Consider this code snippet
- Want to reason about two fragments in isolation
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- Cannot verify it yet because need precondition "z is odd"

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Example

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- Want to reason about two fragments in isolation
- Focus on fragment containing assertion
- Cannot verify it yet because need precondition "z is odd"
- Want to automatically infer such missing assumptions!

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Example cont.

Program Decoration and VC Generation

```
int i=1, j=0;
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- **Idea:** Decorate program with assume statements containing placeholders (e.g., ϕ_1, ϕ_2)

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$$(x = 0 \wedge y = 0 \\ \wedge w = 0 \wedge \phi_1) \Rightarrow x = y$$

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- Generate VCs over unknowns ϕ_1 and ϕ_2
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$$(x = 0 \land y = 0 \land w = 0 \land \phi_1) \Rightarrow x = y$$

- VC 2:

$$(\phi_2 \land x = y) \Rightarrow wp(\sigma, x = y)$$

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int i=1, j=0;
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σ

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- Generate VCs over unknowns ϕ_1 and ϕ_2
- VC 1: VALID

$$(x = 0 \land y = 0 \land w = 0 \land \phi_1) \Rightarrow x = y$$

- VC 2: NOT VALID

$$(\phi_2 \land x = y) \Rightarrow wp(\sigma, x = y)$$

- Fix VC2 using abduction:

$$\phi_2 : (w + z)\%2 = 1$$

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int i=1, j=0;
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- Now use **circular compositional reasoning**

```
int i=1, j=0;
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Example, cont.
Lemma Inference using Abduction

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$$\phi_2 : (w + z)\%2 = 1$$

- Now use **circular compositional reasoning**

- **Subgoal 1:** Prove $x = y$ using $(w + z)\%2 = 1$

```
int i=1, j=0;
while(*) {j++; i+=3;}
int z = i-j;
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while(*) {
   assert(x==y);
   assume((w+z)%2=1);
   z+=x+y+w;
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}
```

Example, cont.
Lemma Inference using Abduction

- Fix VC2 using abduction:

$$\phi_2 : (w + z)\%2 = 1$$

- Now use **circular compositional reasoning**

- **Subgoal 1:** Prove $x = y$ using $(w + z)\%2 = 1$

- **Subgoal 2:** Prove ϕ_2 assuming $x = y$

```
int i=1, j=0;
while(*) {j++; i+=3;}
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Example, cont.

Lemma Inference using Abduction

- Fix VC2 using abduction:

$$\phi_2 : (w + z)\%2 = 1$$

- Now use **circular compositional reasoning**
- **Subgoal 1:** Prove $x = y$ using $(w + z)\%2 = 1$
- **Subgoal 2:** Prove ϕ_2 assuming $x = y$
- Subgoal 1 is immediately discharged; focus on subgoal 2

```
int i=1, j=0;
while(*) {j++; i+=3;}
int z = i-j;
int x=0, y=0, w=0;

while(*) {
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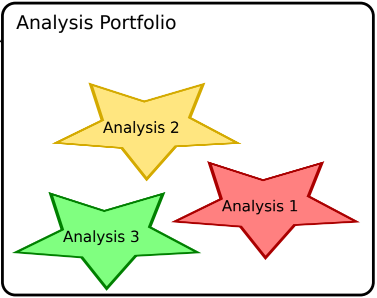
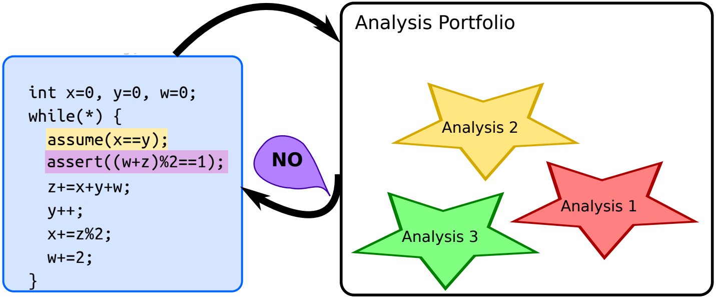


- Invoke client analyses to discharge proof subgoal

Example, cont.



- Invoke client analyses to discharge proof subgoal
- No client can prove it because initial value of z unconstrained

Example, cont.

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- Go back to lemma inference and annotate program with unknown precondition

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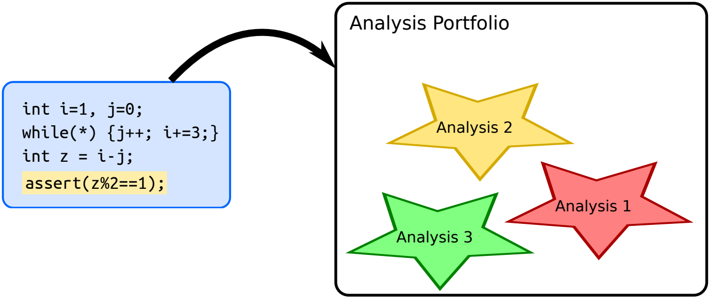
$$\phi_1 : z\%2 = 1$$

- Now, ϕ_1 becomes a lemma (assertion) to be proven

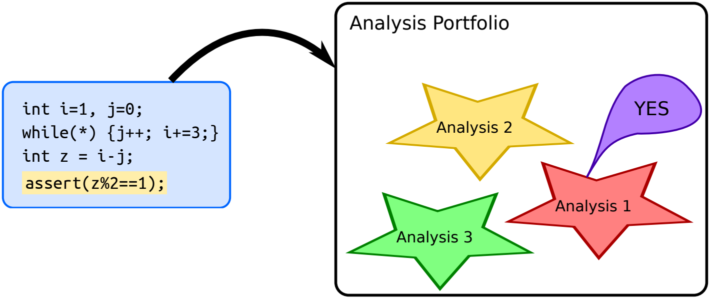
Example, cont.
Invoking Client Analyses



- Now, annotate first fragment with assertion and invoke clients

Example, cont.

Invoking Client Analyses



- Now, annotate first fragment with assertion and invoke clients
- Can be shown by any client analysis that can establish $i = 3j + 1$

Example, cont.

Final Piece

```
int x=0, y=0, w=0;
assume(z%2==1);
while(*) {
  assume(x==y);
  assert((w+z)%2==1);
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- Now, add this as assumption to second fragment

Example, cont.

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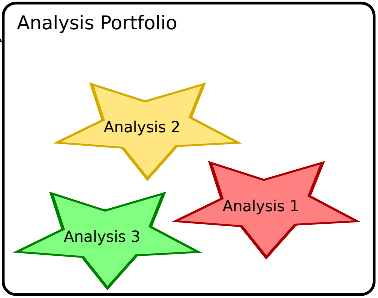

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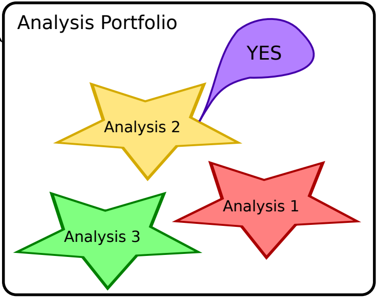

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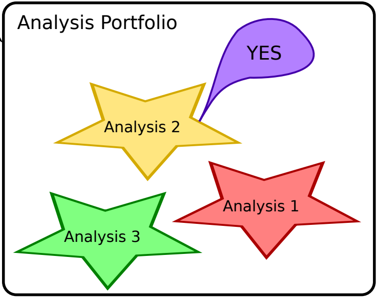

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We have now proven the original assertion!

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- Approach involves two key ingredients: **assertion elimination** and **assertion introduction**

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- Approach involves two key ingredients: **assertion elimination** and **assertion introduction**
- Assertions introduced using abductive inference
- Assertions eliminated using client analyses and circular compositional reasoning
- Similar to SMT solver – core part performs VC gen + abduction

- Client analyses similar to theory solvers

Experiments

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Wizardpen Linux Driver	1242	3.8	5	1.5	29
OpenSSH clientloop	1987	2.8	3	2.3	5
Coreutils su	1057	3.0	5	1.7	6
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Property can be proven using our technique, but not using individual clients

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Verification time reasonable (0.6-16.9s)

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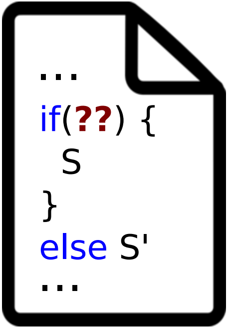
Fragments extracted for queries small in practice

Application #3: Automated Guard Synthesis



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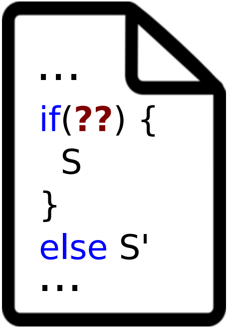
Application #3: Automated Guard Synthesis



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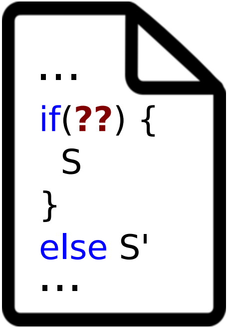

- In **program sketching**, programmer writes a draft program with "holes"
- Program synthesizer completes the holes in a way that satisfies specification
- Abduction is useful for synthesizing unknown guards in program sketches

Concrete Use Case: Memory Safety

- Programmers often write checks to prevent memory safety errors (buffer overruns, null dereferences, ...)

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if(C) {R} else { /* handle error */}
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if(C) {R} else { /* handle error */}
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- Such checks are tedious to write and error-prone (e.g, off-by-one errors common cause of buffer overflows)

Guard Synthesis for Memory Safety

Key Idea: Program synthesis to guarantee memory safety

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if(???)  {R} else { /* handle error */}
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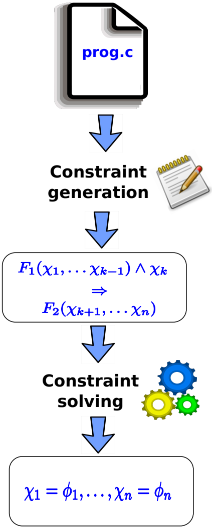
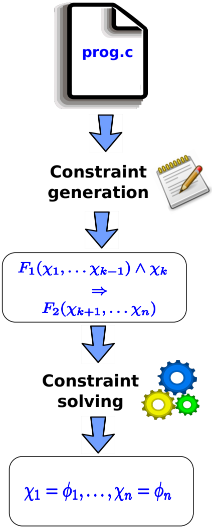
1. Programmer specifies which parts of the program should be protected and how to handle error
2. Technique synthesizes guards that guarantee memory safety
   - Guards should be as permissive and concise as possible
   - Key ingredient of synthesis algorithm is abduction

Solution Overview



1. Constraint Generation:

Solution Overview



1. Constraint Generation:
   - Represent unknown guards using placeholders

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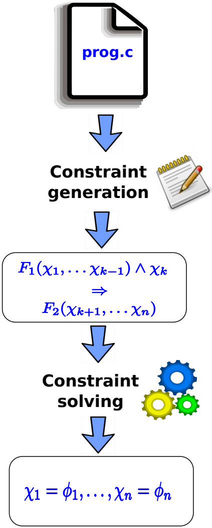

1. Constraint Generation:
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   - Perform dual forward and backward analysis to generate constraint for each unknown

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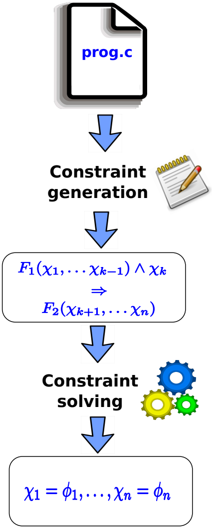

1. Constraint Generation:
   - Represent unknown guards using placeholders
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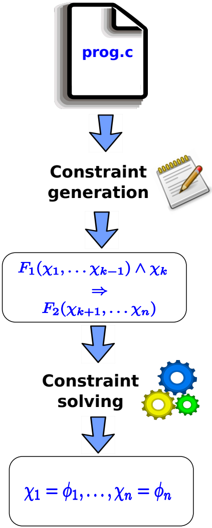
2. Constraint Solving:

Solution Overview



1. Constraint Generation:
    - Represent unknown guards using placeholders
    - Perform dual forward and backward analysis to generate constraint for each unknown
2. Constraint Solving:
    - An extended abduction algorithm for solving constraint system with multiple unknowns

In More Detail

- Generate one constraint per unknown

ϕ
```
{
    ...
}
```

ψ
```
if(??)
{
    ...
}
```

In More Detail

ϕ
```
{
    ...
}
```

```
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{
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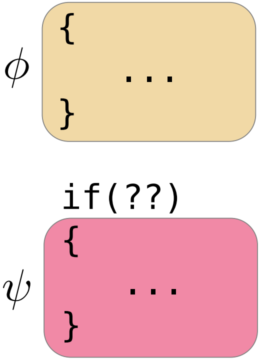
- Generate one constraint per unknown
- Compute postcondition ϕ of code before unknown

In More Detail



- Generate one constraint per unknown
- Compute postcondition ϕ of code before unknown
- Compute safety precondition ψ of code nested inside unknown

In More Detail

```
φ  {
       ...
   }

   if(??)
ψ  {
       ...
   }
```

- Generate one constraint per unknown
- Compute postcondition ϕ of code before unknown
- Compute safety precondition ψ of code nested inside unknown
- To guarantee memory safery, find ?? such that $\phi \wedge\ ?? \models \psi$

In More Detail

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    ...
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    ...
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- To guarantee memory safery, find $??$ such that $\phi \land\ ?? \models \psi$
- This is almost an abduction problem, but ϕ, ψ can have other unknowns
- Impose ordering on constraints and reduce to standard abduction

Example

- Code snippet from Unix Coreutils with protected memory access

```
int main(int argc,
    char** argv)
{
  if(argc<=1) return -1;
  argv++; argc--;

  optind=0;
  while(...) {
    optind++;
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           argc--;}
  }
  if(??) {
    argv[optind+1]=...;
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}
```

Example

- Code snippet from Unix Coreutils with protected memory access
- Convention: For pointer p:

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Example

- Code snippet from Unix Coreutils with protected memory access
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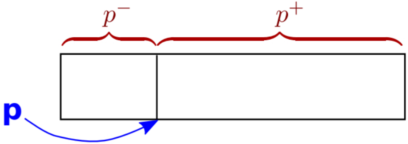
  - p^+ represents distance to end of memory block

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```
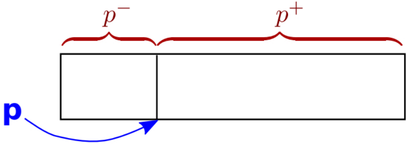

Example

- Code snippet from Unix Coreutils with protected memory access
- Convention: For pointer p:
  - p^+ represents distance to end of memory block
  - p^- represents distance from beginning of memory block

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Example Cont.

- First Step: Compute what is known at ?? $\Rightarrow$ postcondition ϕ

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Example Cont.

- First Step: Compute what is known at ?? $\Rightarrow$ postcondition ϕ
  - From language semantics:

$$argv^{+} = argc \wedge argv^{-} = 0$$

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Example Cont.

- First Step: Compute what is known at ?? $\Rightarrow$ postcondition ϕ
  - From language semantics:

    $$argv^{+} = argc \wedge argv^{-} = 0$$

  - From computing the strongest postcondition:

    $$argv^{+} = argc \wedge argv^{-} \geq 1 \;\wedge\; optind \geq 0$$

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   char** argv)
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Example Cont.

- Second Step: Compute what needs to hold at ?? to ensure memory safety
  $\Rightarrow$ precondition ψ

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Example Cont.

- Second Step: Compute what needs to hold at ?? to ensure memory safety
  $\Rightarrow$ precondition ψ

- Buffer access:

$$optind + 1 < argv^{+} \wedge$$
$$optind + 1 \geq -argv^{-}$$

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  $\phi \wedge ?? \models \psi$ where

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- Solution: $argc - optind > 1$

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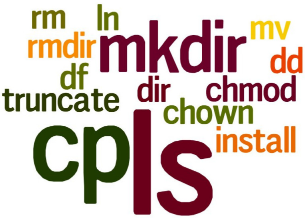
Experiments

- Evaluated technique on the Unix Coreutils and parts of OpenSSH



Experiments

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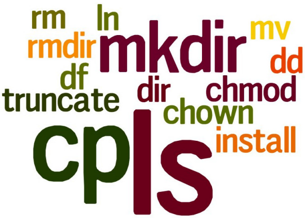
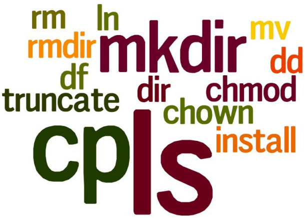
- Removed conditionals used to prevent memory safety errors



Experiments

- Evaluated technique on the Unix Coreutils and parts of OpenSSH
- Removed conditionals used to prevent memory safety errors
- Used our new technique to synthesize the missing guards



Experiments Cont.

Program	Lines	# holes	Time (s)	Memory	Synthesis successful?	Bug?
Coreutils hostname	160	1	0.15	10 MB	Yes	No
Coreutils tee	223	1	0.84	10 MB	Yes	Yes
Coreutils runcon	265	2	0.81	12 MB	Yes	No
Coreutils chroot	279	2	0.53	23 MB	Yes	No
Coreutils remove	710	2	1.38	66MB	Yes	No
Coreutils nl	758	3	2.07	80 MB	Yes	No
SSH - sshconnect	810	3	1.43	81 MB	Yes	No
Coreutils mv	929	4	2.03	42 MB	Yes	No
SSH - do_authentication	1,904	4	3.92	86 MB	Yes	Yes
SSH - ssh_session	2,260	5	4.35	81 MB	Yes	No

Used technique to synthesize 27 unknown guards in real C programs

Experiments Cont.

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In 21 out of 27 cases, tool inferred same predicate as programmer

Experiments Cont.

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In 4 cases, syntactically different, but semantically equivalent guards

Experiments Cont.

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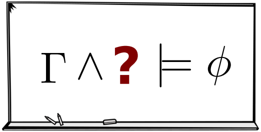
In 2 cases, guards did not match
$\Rightarrow$ bug in original program!

Summary



- Abduction $=$ logical formulation of “guessing”

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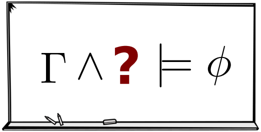

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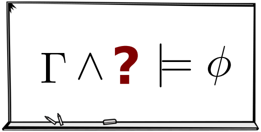

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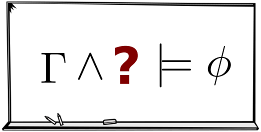

- Abduction = logical formulation of "guessing"
- Lots of uses in automated reasoning about programs, particularly when combined with backtracking search
- If you are interested in using abduction, check out:

  http://www.cs.utexas.edu/∼tdillig/mistral/explain.html
- Easy to use: `expl = conclusion.abduce(premises);`

Limitations and Future Work

- ⚠ Abduction algorithm uses quantifier elimination $\Rightarrow$ limited scalability and requires to theories that admit QE

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Limitations and Future Work

⚠ Abduction algorithm uses quantifier elimination $\Rightarrow$ limited scalability and requires to theories that admit QE

- **Future work:** Alternative algorithms that don't use QE

⚠ Abduction requires single unknown in LHS, but sometimes there are multiple unknowns

- **On-going work:** Multi-abduction algorithm to simultaneously infer multiple unknowns

Questions?