Automatic inference of necessary preconditions

P. Cousot, R. Cousot

M. Fahndrich, F. Logozzo

The paper in one slide

Problem: Automatic inference of preconditions

Define: What is a precondition?

- Sufficient precondition: if it holds, the function is correct
- Necessary precondition: if it does not hold, the function is definitely wrong

When automatic inference is considered, only necessary preconditions make sense

- Sufficient preconditions impose too large a burden to callers
- Necessary preconditions are easy to explain to users

Implementation in Clousot

- Precision improvements 9% to 21%
- Extremely low false positive ratio

Example

```
int Example1(int x, object[] a)
{
  if (x >= 0)
  {
    return a.Length;
  }
  return -1;
}
```

Sufficient precondition: `a != null`

- Too strong for the caller
- No runtime errors when x < 0 and a == null

Clousot users complained about it

- "wrong preconditions"

Example

```
void Example2(object[] a)
{
  Contract.Requires(a != null);

  for (var i = 0; i <= a.Length; i++)
  {
    a[i] = F(a[i]);
    if (NonDet())
      return;
  }
}
```

Sufficient precondition: `false`

- It may fail, so eliminate all runs

Necessary precondition: `0 < a.Length`

- If `a.Length == 0` it will always fail

Necessary precondition is weaker than the weakest precondition!!!

Semantics

Program semantics

Program traces: T = G ∪ B ∪ I

- G = good traces, terminating in a good state
- B = bad traces, terminating in an assertion violation
  - Assertions:
    - Language-induced: division by zero, null pointers, buffer overrun …
    - User-supplied annotations: assertions, preconditions, postconditions, object invariants
- I = infinite traces, non-termination

Notation: X(*s*) are the traces starting with *s*

Necessary and sufficient

In $S \Longrightarrow N$ we say that

- S in a sufficient condition for N
- N is a necessary condition for S

For a program P

- A condition S is sufficient if its truth ensures that P is correct
- A condition N is necessary if its falsehood ensures P is incorrect

Sufficient Preconditions

Weakest (liberal) preconditions

Provide sufficient preconditions guaranteeing partial correctness:

$$wlp(P, true)(s_0) \stackrel{def}{=} (B(s_0) = \emptyset)$$

Drawbacks of wlp for the automatic inference of preconditions:

1. With loops, there is no algorithm to compute wlp(**P**, true)
   Solution in deductive verification: Use loop invariant
2. Inferred preconditions are sufficient but not the weakest anymore
   Under-approximation of loops
3. Sufficient preconditions rule out good runs
   Callers should satisfy a too strong condition

Example

```
int Sum(int[] xs)
{
  Contract.Requires(xs != null);

  int sum = 0;
  for (var i = 0; i < xs.Length; i++)
     sum += xs[i];

  Contract.Assert(sum >=0);

  return sum;
}
```

Overflows are not an error

Ex. Sum([*-2147483639, 2147483638, -10*]) = *19*

In deductive verification, provide loop invariant

Which is the weakest precondition?

The method itself

Sufficient preconditions:

$\forall i \in$ [0, xs.Length], 0 ≤ xs[*i*] < MaxInt/ xs.Length

or

xs.Length == 3 ∧ xs[0] + xs[1] == 0 ∧ xs[2] >= 0

or

....

Under-approximation of wlp

Formally, with loop invariants, we compute a sufficient condition S:

$$S(s_0) \Longrightarrow wlp(P, true)(s_0)$$

Which is equivalent to

$$[I(s_0) = \emptyset] \Longrightarrow [S(s_0) \Longrightarrow G(s_0) \neq \emptyset]$$

So that it may exists some initial state s such that

$$\neg S(s) \land G(s) \neq \emptyset$$

i.e., s does not satisfy S, but it does not lead to a bad state

Consequences

Sufficient preconditions impose too large a burden to the caller

They just ensure the correctness of the callee

Not practical in a realistic setting

Users complained about “wrong” preconditions

“wrong preconditions” = sufficient preconditions

Necessary preconditions

Strongest necessary preconditions

If the program terminates in a good state for s_0 then $N(s_0)$ should hold:

$$[I(s_0) = \varnothing] \Longrightarrow [G(s_0) \neq \varnothing \Longrightarrow N(s_0)]$$

Equivalently

$$[I(s_0) = \varnothing] \Longrightarrow [\neg N(s_0) \Longrightarrow (G(s_0) = \varnothing \wedge B(s_0) \neq \varnothing)]$$

i.e., if N does not hold, either

- The program diverges, or
- The program reaches a bad state

Strongest (liberal) necessary precondition:

$$\text{snp}(\mathbf{P}, \text{true})(s_0) \stackrel{\text{def}}{=} \neg[G(s_0) = \varnothing \wedge B(s_0) \neq \varnothing] = [G(s_0) \neq \varnothing \vee B(s_0) = \varnothing]$$

Comparison, ignoring non-termination

Weakest sufficient preconditions

	S(s_0)	G(s_0): ∅	G(s_0): ≠ ∅
B(s_0)	∅	true	true
	≠ ∅	false	false

Strongest necessary preconditions

	N(s_0)	G(s_0): ∅	G(s_0): ≠ ∅
B(s_0)	∅	true	true
	≠ ∅	false	true

Approximation of necessary conditions

Static analyses to infer an error condition <u>E</u> such that

$$\underline{E}(s_0) \Longrightarrow [G(s_0) = \varnothing \wedge B(s_0) \neq \varnothing]$$

i.e., <u>E</u> is sufficient to guarantee the presence of definite errors or non-termination

<u>E</u> is an under-approximation of the error semantics

The negation, $\underline{\neg E}$ = N is weaker than the strongest (liberal) necessary precondition:

$$G(s_0) \neq \varnothing \vee B(s_0) = \varnothing \Longrightarrow \neg\underline{E}(s_0)$$

Inference

Main Algorithm

Iterate until stabilization
  For each method m
    Analyze m using the underlying static analysis
    Collect proof obligations $\mathbb{A}$
    Use the analysis to prove the assertions in $\mathbb{A}$
    Let $\mathbb{W} \subseteq \mathbb{A}$ be the set of warnings
    If $\mathbb{W} \neq \emptyset$ then
      Infer necessary preconditions for assertions in $\mathbb{W}$
      Simplify the inferred preconditions
      Propagate the necessary preconditions to the callers of m

Static analyses for the inference

All-Paths precondition analysis
  Hoists unmodified assertions to the code entry

Conditional-path precondition analysis
  Hoist assertions by taking into account assignments and tests
  Use dual-widening for loops
    Dual-widening under-approximates its arguments

Quantified precondition analysis
  Deal with unbounded data structures

Examples

```
int FirstOccurence(int[] a)
{
  int i = 0;

  while (a[i] != 3)
    i++;

  return i;
}
```

All-paths infers
  a != null

Conditional-paths also infers
  $a.Length > 0 \land (a[0] != 3 \Longrightarrow a.Length > 1)$

Quantified infers
  $\exists\ j \in [0, a.Length).\ a[j] == 3$

Details in the paper

Simplification

We can infer many preconditions for a given method

Simplification allows reducing them

- Key to scalability
- Pretty print preconditions for the user

Simplification is a set of rewriting rules to iterate to fixpoint

Examples

- P, [b⇒ a], [¬b ⇒ a] → P, [true ⇒ a]
- P, [true ⇒ a] → P, a

Implementation

Code Contracts static checker

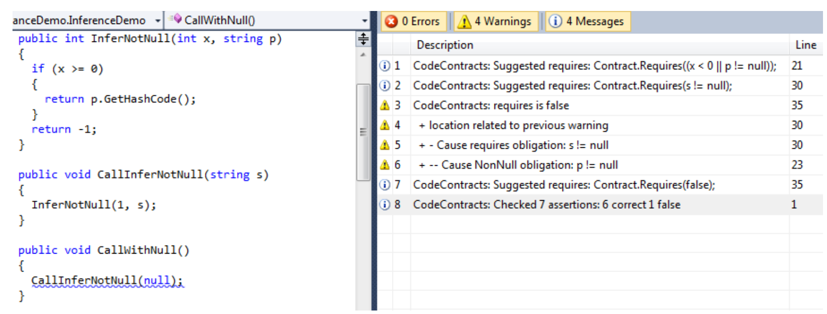
Clousot/cccheck static analyzer for .NET

- Downloaded more than 80,000 times
- Use preconditions/postconditions to reason on method calls
- Suggest and propagates inferred preconditions and postconditions

Users complained about sufficient preconditions

Starting point for this work

User experience



Experimental results

- Un-annotated code (.net base libraries)
  - All paths analysis
    - *Infer 18,643 preconditions*
    - *Simplification removes >32%*
  - Conditional path analysis
    - *Infers 28,623 preconditions*
    - *Simplification removes >24%*
- Similar results for partially annotated code (Facebook C# SDK)
- Conditional path analysis is more precise but up to 4x slower than all-paths analysis
  - Because of inferred disjunctions

Precision

- Number of inferred preconditions is not a good measure
- We are interested in the precision, i.e., fewer methods with warnings
  - Precision gain is between 9% (framework libraries) and 21% (facebook C# SDK)
- Missing preconditions public surface are errors
  - The library does not defend against "bad inputs"
- On mscorlib, the core library of .Net, we found 129 new bugs
  - Only **one** false positive
    - *Because of exception handling in clousot*

Conclusions

Sic transit gloria mundi

- The violation of a necessary precondition guarantee a definite error
- When automatically inferring preconditions, only necessary preconditions make sense
  - Sufficient preconditions are too strict for callers
- Advantages
  - Easy to explain to the users
  - Provide chain leading to errors
  - No false positives
- Implemented, and used in a widely downloaded tool (Clousot/cccheck)