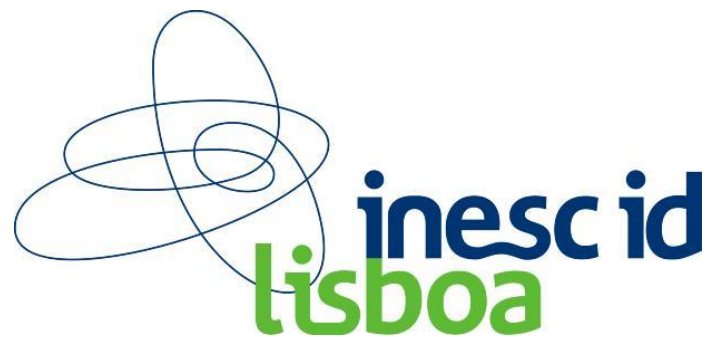


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# Weakest Precondition Synthesis for Compiler Optimizations

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# Why WP Synthesis for Compiler Optimizations?



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- Deriving preconditions by hand is hard; WPs are often non-trivial
- WPs derived by hand are often wrong!
- Weaker preconditions expose more optimization opportunities

- Yang, Chen, Eide, Regehr. Finding and Understanding Bugs in C Compilers, PLDI'12:
  - 79 bugs in GCC (25 P1)
  - 202 bugs in LLVM
  - 2 wrong-code bugs in CompCert
- 32 open P1 bug reports in GCC (as of last week)
- 403 open wrong-code bug reports in GCC
- 16 open wrong-code bug reports in LLVM

# Verification to the Rescue: LLVM PR17827



lib/Transforms/InstCombine/InstCombineCompares.cpp

```
// For a logical right shift, we can fold if the comparison is not
// signed. We can also fold a signed comparison if the shifted mask
// value and the shifted comparison value are not negative.
// These constraints are not obvious, but we can prove that they are
// correct using an SMT solver such as "Z3" :
// http://rise4fun.com/Z3/Tslfh
```

```
if (ShiftOpcode == Instruction::AShr) {
    // There may be some constraints that make this possible,
    // but nothing simple has been discovered yet.
    CanFold = false;
}
```

- Preliminaries
- Language of Preconditions
- Example
- Algorithm
- Evaluation: PSyCO

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- Compiler optimization
  - Transformation function
  - Precondition
  - Profitability heuristic

```
while I < N do  
  if B then  
    S1  
  else  
    S2  
  I := I + 1
```

→

```
if B then  
  while I < N do  
    S1  
    I := I + 1  
else  
  while I < N do  
    S2  
    I := I + 1
```

S<sub>1</sub>, S<sub>2</sub> are template statements  
B is a template Boolean expression



# Loop Unswitching: Example Instantiation

```
...  
while I < N do  
  if B then  
    S1 := A + N  
  else  
    S2 := A + 1  
  I := I + 1  
...
```

→

```
if N > 5 then  
  while I < N do  
    A := A + N  
    I := I + 1  
else  
  while I < N do  
    A := A + 1  
    I := I + 1
```

## Instantiation:

$B \mapsto N > 5$

$S_1 \mapsto A := A + N$

$S_2 \mapsto A := A + 1$

# Loop Unswitching: Weakest Precondition

```
while I < N do
  if B then
    S1
  else
    S2
  I := I + 1
```

→

```
if B then
  while I < N do
    S1
    I := I + 1
else
  while I < N do
    S2
    I := I + 1
```

## Precondition:

$$I \notin R(B) \wedge$$
$$W(S_1) \cap R(B) = \emptyset \wedge$$
$$W(S_2) \cap R(B) = \emptyset$$

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- Read and Write sets for each template statement/expression
- Arbitrary constraints over read/write sets
- In practice constraints are only over R/W and W/W intersection
  - $v \notin R(B)$
  - $W(S_1) \cap R(B) = \emptyset$
  - $W(S_1) \cap W(S_2) = \emptyset$

- Books and developers already informally speak about read and write sets
- Can be efficiently discharged using current compiler technology:
  - Memory dependence analysis
  - Alias/pointer analysis
  - Loop analysis
  - Range analysis
  - ...

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# Synthesizing WP for Loop Unswitching

```
while I < N do
  if B then
    S1
  else
    S2
  I := I + 1
```

→

```
if B then
  while I < N do
    S1
    I := I + 1
else
  while I < N do
    S2
    I := I + 1
```

# 1) Find counterexample

```
while I < N do
  if B then
    S1
  else
    S2
  I := I + 1
```

→

```
if B then
  while I < N do
    S1
    I := I + 1
else
  while I < N do
    S2
    I := I + 1
```

Pre = true

I < N

**B**

**S<sub>1</sub>**

I := I + 1

I < N

**¬B**

**S<sub>2</sub>**

I := I + 1

I ≥ N

**B**

I < N

**S<sub>1</sub>**

I := I + 1

I < N

**S<sub>1</sub>**

I := I + 1

I ≥ N



## 2) Synthesize WP for counterexample: VC Gen

$I < N$

**B**

**S<sub>1</sub>**

$I := I + 1$

$I < N$

$\neg B$

**S<sub>2</sub>**

$I := I + 1$

$I \geq N$

$I_0 < N_0 \wedge$

$B_0 \wedge$

$I_1 = \text{ite}(wS_1I, S_1I0, I_0) \wedge$

$N_1 = \text{ite}(wS_1N, S_1N0, N_0) \wedge$

$I_2 = I_1 + 1 \wedge$

$I_2 < N_1 \wedge$

$\neg B_1 \wedge$

$I_3 = \text{ite}(wS_1I, S_1I1, I_2) \wedge$

$N_2 = \text{ite}(wS_1N, S_1N1, N_1) \wedge$

$I_4 = I_3 + 1 \wedge$

$I_4 \geq N_2$

## 2) Synthesize WP for counterexample: Conditional Ackermannization

$$I_0 < N_0 \wedge$$

$$B_0 \wedge$$

$$I_1 = \text{ite}(wS_1I, S_1I0, I_0) \wedge$$

$$N_1 = \text{ite}(wS_1N, S_1N0, N_0) \wedge$$

$$I_2 = I_1 + 1 \wedge$$

$$I_2 < N_1 \wedge$$

$$\neg B_1 \wedge$$

$$I_3 = \text{ite}(wS_1I, S_1I1, I_2) \wedge$$

$$N_2 = \text{ite}(wS_1N, S_1N1, N_1) \wedge$$

$$I_4 = I_3 + 1 \wedge$$

$$I_4 \geq N_2$$

$B_0$  and  $B_1$  are equal if the values of the variables in  $R(B)$  are equal

$$\left( (I \in R(B) \rightarrow I_0 = I_2) \wedge \right. \\ \left. (N \in R(B) \rightarrow N_0 = N_1) \right) \\ \rightarrow B_0 = B_1$$

## 2) Synthesize WP for counterexample: Must-write vs may-write

$$\begin{aligned} I_0 &< N_0 \wedge \\ B_0 &\wedge \\ I_1 &= \text{ite}(wS_1I, S_1I0, I_0) \wedge \\ N_1 &= \text{ite}(wS_1N, S_1N0, N_0) \wedge \\ I_2 &= I_1 + 1 \wedge \\ I_2 &< N_1 \wedge \\ \neg B_1 &\wedge \\ I_3 &= \text{ite}(wS_1I, S_1I1, I_2) \wedge \\ N_2 &= \text{ite}(wS_1N, S_1N1, N_1) \wedge \\ I_4 &= I_3 + 1 \wedge \\ I_4 &\geq N_2 \end{aligned}$$

If a variable is in the write set of a statement, it may or may not be written.

$$\begin{aligned} wS_1I &\rightarrow I \in W(S_1) \\ wS_1N &\rightarrow N \in W(S_1) \end{aligned}$$

## 2) Synthesize WP for counterexample: Final constraint

$I < N$ <b>B</b> <b>S<sub>1</sub></b> $I := I + 1$	<b>B</b> $I < N$ <b>S<sub>1</sub></b> $I := I + 1$
$I < N$ $\neg \mathbf{B}$ <b>S<sub>2</sub></b> $I := I + 1$ $I \geq N$	$I < N$ <b>S<sub>1</sub></b> $I := I + 1$ $I \geq N$

$\exists S \forall V Path \wedge Ackermann \wedge MustWrite \wedge \dots \rightarrow PathIsCorrect$

**S** = Read/Write sets

**V** = Vars from VCGen, Must-write vars

A possible model:

$$W(S_1) = \emptyset$$

$$R(S_1) = \emptyset$$

$$R(B) = \emptyset$$

## 2) Synthesize WP for counterexample: Disjunction of all models

$I < N$

**B**

**S<sub>1</sub>**

$I := I + 1$

$I < N$

$\neg$ **B**

**S<sub>2</sub>**

$I := I + 1$

$I \geq N$

**B**

$I < N$

**S<sub>1</sub>**

$I := I + 1$

$I < N$

**S<sub>1</sub>**

$I := I + 1$

$I \geq N$

Precondition:

$I \notin R(B) \wedge$

$W(S_1) \cap R(B) = \emptyset$

### 3) Iterate until no more counterexamples can be found

```
while I < N do  
  if B then  
    S1  
  else  
    S2  
  I := I + 1
```

→

```
if B then  
  while I < N do  
    S1  
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else  
  while I < N do  
    S2  
    I := I + 1
```

Precondition:

$$I \notin R(B) \wedge$$
$$W(S_1) \cap R(B) = \emptyset \wedge$$
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- 1) Find counterexample
- 2) Generate WP that rules out the counterexample
- 3) Iterate until no more counterexamples can be found



- Model generalization
- Exploit UNSAT cores
- Bias towards R/W and W/W intersections

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# PSyCO: Precondition Synthesizer for Compiler Optimizations



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- About 1,400 lines of Python
- Uses Z3 for constraint solving
- Source code and benchmarks available from <http://goo.gl/7K02H9>

Optimization	# Counterexamples	# Models	WP Time	Total Time
Code hoisting	1	1	0.07s	0.23s
Constant propagation	1	1	0.04s	0.16s
Copy propagation	0	0	0s	0.11s
If-conversion	0	0	0s	0.11s
Partial redundancy elimin.	1	1	0.10s	0.30s
Loop fission	6	36	1.28s	2.18s
Loop flattening	1	1	0.07s	3.31s
Loop fusion	6	36	1.26s	2.19s
Loop interchange	11	25	1.42s	23.8s
Loop invariant code motion	3	3	0.22s	0.55s
Loop peeling	0	0	0s	0.27s
Loop reversal	4	7	0.25s	0.54s
Loop skewing	1	1	0.06s	163s
Loop strength reduction	1	2	1.14s	1.41s
Loop tiling	1	1	0.07s	4.60s
Loop unrolling	2	4	0.13s	0.50s
Loop unswitching	2	2	0.15s	0.77s
Software pipelining	1	2	0.13s	0.58s

# Example of Synthesized WP: Software Pipelining

<b>while</b> $V_1 < V_2$ <b>do</b>		<b>if</b> $V_1 < V_2$ <b>then</b>
$S_1$		$S_1$
$S_2$	$\Rightarrow$	<b>while</b> $V_1 < (V_2 - 1)$ <b>do</b>
$V_1 := V_1 + 1$		$S_2$
		$V_1 := V_1 + 1$
		$S_1$
		$S_2$
		$V_1 := V_1 + 1$

Precondition:

$$\begin{aligned} &V_2 \notin W(S_2) \wedge \\ &((R(S_1) \cap W(S_2) = \emptyset \wedge \\ &R(S_1) \cap W(S_1) = \emptyset \wedge \\ &R(S_2) \cap W(S_2) = \emptyset) \vee \\ &V_1 \notin W(S_2)) \end{aligned}$$

(Weaker than  
PEC's [PLDI'09])

- Deriving WPs by hand is hard and error-prone
- Weaker preconditions enable more optimization opportunities
- Presented the first algorithm for the automatic synthesis of WPs for compiler optimizations



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