Type-Based Verification of Assembly Language for Compiler Debugging

Bor-Yuh Evan Chang
George C. Necula
Adam Chlipala
Robert R. Schneck

University of California, Berkeley

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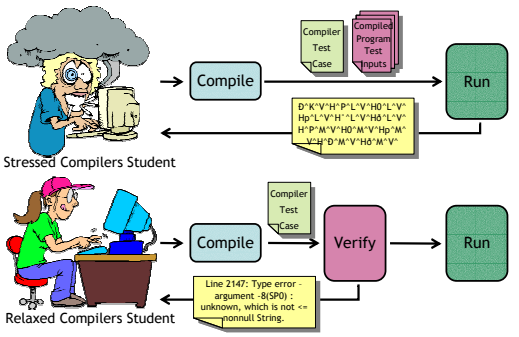
Problem and Motivation

- Type check **assembly code** produced by **existing** compilers for a Java-like language
- Validate that certifying compilation aids compiler debugging
  - using undergraduate compilers course as a test bed
- Introduce undergraduates to using compiler technology for software quality

Problem and Motivation

- Starting Point: Bytecode verification
  - Effective, simple, and very accessible
  - But does not work for assembly code
- Why assembly code?
  - Native code compilers are more complex
  - Also debug JITs
- Why existing compilers?
  - Force to make the verifier flexible
  - Better accessibility to students (i.e., require little or no annotations)
  - More test cases to validate "certified compilation for debugging"

Debugging Compilers with Verification



Challenges

```
class P {
   int f;
   int m() { … }
}
class C extends P {
   int m() { … }
}

…
P p = new P();
P c = new C();
c.m();
…
```

invokevirtual *P.m()*

```
branch (= r_c 0) L_abort
r_tmp := m[r_c + 8]
r_tmp := m[r_tmp + 12]
r_arg0 := r_c
r_ra := &L_ret
jump [r_tmp]
L_ret:
```


Challenges

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jump [r_tmp]
L_ret:
```

⟨r_c : P, … ⟩
⟨r_c : nonnull P, …⟩
⟨r_{tmp} : disp(P), …⟩
⟨r_{tmp} : meth(P,12), …⟩
⟨r_{arg0} : P, …⟩
⟨r_{rv} : int, …⟩

Challenges

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class P {
   int f;
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class C extends P {
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…
P p = new P();
P c = new C();
c.m();
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```
invokevirtual P.m()

branch (= r_c 0) L_abort
r_tmp := m[r_c + 8]
r_tmp := m[r_tmp + 12]
r_arg0 := r_p
r_ra := &L_ret
jump [r_tmp]
L_ret:
```

unsound

⟨r_c : P, …⟩
⟨r_c : nonnull P, …⟩
⟨r_tmp : disp(P), …⟩
⟨r_tmp : meth(P,12), …⟩
⟨r_arg0 : P, …⟩
⟨r_rv : int, …⟩

Challenges

```
class P {
   int f;
   int m() { … }
}
class C extends P {
   int m() { … }
}

…
P p = new P();
P c = new C();
int f = p.f;
p.m();
x = f + 1;
```

```
branch (= r_p 0) L_abort
r_tmp := r_p + 12
r_f := m[r_tmp]
branch (= r_p 0) L_abort
~~r_tmp := m[r_p + 8]~~
r_tmp := m[r_tmp + 12]
r_arg0 := r_p
r_ra := &L_ret
jump [r_tmp]
L_ret:
r_x := r_f + 1
```

reordering and optimization

Challenges

```
class P {
   int f;
   int m() { … }
}
class C extends P {
   int m() { … }
}

…
P p = new P();
P c = new C();
int f = p.f;
p.m();
x = f + 1;
```

```
branch (= r_p 0) L_abort
r_tmp := r_p + 12
r_f := m[r_tmp]
r_x := r_f + 1
~~branch (= r_p 0) L_abort~~
r_tmp := m[r_tmp - 4]
r_tmp := m[r_tmp + 12]
r_arg0 := r_p
r_ra := &L_ret
jump [r_tmp]
L_ret:
```

⟨r_tmp : int ptr, … ⟩

"funny" pointer arithmetic

Outline

- Overview
- Abstract State
  - Types
  - Join algorithm
- Verification Procedure
- Educational Experience
- Concluding Remarks

Overview

- To maximize accessibility (i.e., minimize annotations)
  - infer types at intermediate program points using abstract interpretation
  - willingness to have a limited amount of specialization to a compilation strategy
- To handle assembly code
  - use (simple) dependent types
- To be less sensitive to the compilation strategy
  - assign types to intermediate values lazily

Abstract State

abstract state	$\langle \Sigma \S \Gamma \rangle$
value state	$\Sigma \quad ::= \mathbf{r}_0 = e_0, \mathbf{r}_1 = e_1, \ldots, \mathbf{r}_{n-1} = e_{n-1}$
type state	$\Gamma \quad ::= \cdot \mid \Gamma, \alpha : \tau$
symbolic values	α, β
expressions	$e \quad ::= n \mid \alpha \mid \&L \mid e_0 + e_1 \mid e_0 \cdot e_1 \mid \cdots$

- Keep intermediate expressions in symbolic form
- *Symbolic values* abstract irrelevant expressions keeping only type information
- Intermediate expressions track many dependencies between registers

Why Symbolic Values?

- Used to track dependencies between registers

$r_1 = r_2 \ \wedge \ r_1 = r_3 + 4$

$\downarrow$

$r_1 = \alpha + 4,\ r_2 = \alpha + 4,\ r_3 = \alpha$

- Value state form convenient for abstract interpretation

$$\Sigma$$
$$r_1 := r_2$$
$$\Sigma[r_1 \rightarrow \Sigma(r_2)]$$

Values

values $v ::= n_0 \cdot \&L + n_1 \cdot \alpha + n_2 \mid \alpha = n \mid \alpha \neq n \mid \alpha < n \mid \cdots$

- Define a normalization of expressions to values
  $\Gamma \vdash e \Downarrow v \triangleright \Gamma'$
- Values give the expressions of interest
  - For our case, address computation and comparisons with constants
  - Would vary depending on the source language or compiler of interest
  - Not all equal expressions normalize to the same value, so value forms must be chosen carefully
- Registers are equal if they map to the same values (after normalization)

Types

- Primitive Types and Object References

types $\tau ::= \top \mid$ word $\mid \bot \mid$ [nonnull] $b \mid \tau$ ptr $\mid \ldots$

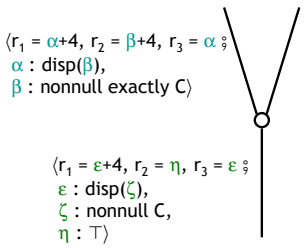
bounds $b ::= C$ bounded above by C
$\mid$ exactly C bounded above and below by C
$\mid$ classof(α) same class as α

- Types for Run-time Structures

types $\tau ::= \ldots$
$\mid$ disp(α) dispatch table of α
$\mid$ meth(α, n) t n
$\mid \ldots$

Tracks that the value is the dispatch table of object α

Join



Join

- Joining of type state basically given by subtyping
  - subtyping lattice still fairly simple - dictated mostly by the class inheritance hierachy
- Values are (fancy) labels for equivalence classes of registers
  - lattice of conjunctions of equalities on registers
  - first normalize expressions to values for join
  - each distinct pair of values in the input state gives an equivalence class in the result state

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Verification Example

```
class P {
   int f;
   int m() { … }
}
class C extends P
{ … }
```

Typing Rule

$$\frac{\Gamma \vdash e \Downarrow \alpha + n \triangleright \Gamma' \quad \Gamma' \vdash \alpha : \text{nonnull } C \triangleright \Gamma'' \quad (\text{field at offset } n \text{ of class } C \text{ has type } \tau)}{\Gamma \vdash e : \tau \text{ ptr} \triangleright \Gamma'}$$

```
branch (= r_p 0) L_abort
r_tmp := r_p + 12
r_f := m[r_tmp]
r_x := r_f + 1
r_tmp := m[r_tmp - 4]
r_tmp := m[r_tmp + 12]
r_arg0 := r_p
r_ra := &L_ret
jump [r_tmp]
L_ret:
```

⟨r_p = ρ ; ρ : P⟩
⟨… ; ρ : nonnull P⟩
⟨r_tmp = ρ + 12 ; …⟩
⟨r_f = ϕ ; ϕ : int⟩
⟨r_x = ϕ + 1 ; ϕ : int⟩

Verification Example

```
class P {
   int f;
   int m() { … }
}
class C extends P
{ … }
```

Typing Rule

$$\frac{\Gamma \vdash e \Downarrow \alpha + 8 \triangleright \Gamma' \quad \Gamma' \vdash \alpha : \text{nonnull } C \triangleright \Gamma''}{\Gamma \vdash e : \text{disp}(\alpha) \text{ ptr} \triangleright \Gamma''}$$

```
branch (= r_p 0) L_abort
r_tmp := r_p + 12
r_f := m[r_tmp]
r_x := r_f + 1
r_tmp := m[r_tmp - 4]
r_tmp := m[r_tmp + 12]
r_arg0 := r_p
r_ra := &L_ret
jump [r_tmp]
L_ret:
```

ρ + 12 - 4 ⇓ ρ + 8

Calling meth(ρ,12) checks r_arg0 = ρ

⟨r_p = ρ ; ρ : P⟩
⟨… ; ρ : nonnull P⟩
⟨r_tmp = ρ + 12 ; …⟩
⟨r_f = ϕ ; ϕ : int⟩
⟨r_x = ϕ + 1 ; ϕ : int⟩
⟨r_tmp = θ ; θ : disp(ρ)⟩
⟨r_tmp = σ ; σ : meth(ρ,12)⟩
⟨r_arg0 = ρ ; …⟩
⟨r_rv = μ ; μ : int⟩

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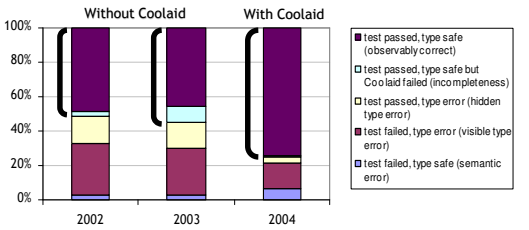
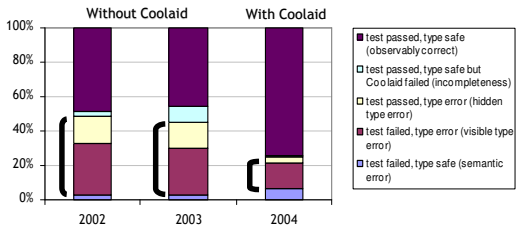
Comparing Compiler Development



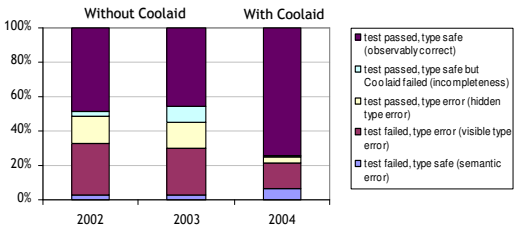
- Good compilations increase: 53% to 75%

Comparing Compiler Development



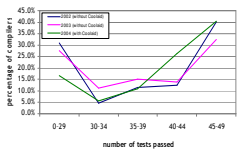
- Type errors decrease: 44% to 19%
  - even 29% to 15% if only consider those that are visible in testing

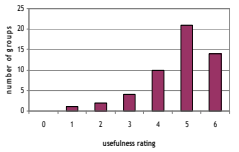
Comparing Compiler Development



- False alarms: 6% to 1%
  - price for ease of use

Student Perspective





- Traditional testing procedure
  - 49 test cases / inputs
- Mean scores:
  - 33 (67%) in 2002
  - 34 (69%) in 2003
  - 39 (79%) in 2004

- 0: "counter-productive"
  6: "can't imagine being without it"
- A favorite comment:
  "I would be totally lost without Coolaid. I learn best when I am using it hands-on …. I was able to really understand stack conventions and optimizations and to appreciate them."

Conclusion

- Extended data-flow based type inference of intermediate languages to assembly code
  - Able to retrofit existing compilers
  - Minimal annotations for accessibility
- Provided experimental confirmation that certifying compilation helps early compiler debugging
- Introduced undergraduates to the idea of improving software quality with program analysis