Automatically Checking the Correctness of Program Analyses and Transformations

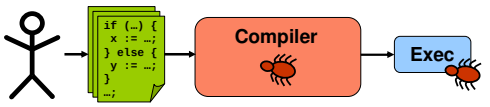
Compilers have many bugs

Searched for "incorrect" and "wrong" in the gcc-bugs mailing list. Some of the results:

- [Bug middle-end/19650] New: miscompilation of correct code
- [Bug c++/19731] arguments incorrectly named in static member specialization
- [Bug rtl-optimization/13300] Variable incorrectly identified as a biv
- [Bug rtl-optimization/16052] strength reduction produces wrong code
- [Bug tree-optimization/19633] local address incorrectly thought to escape
- [Bug target/19683] New: MIPS wrong-code for 64-bit multiply
- [Bug c++/19605] Wrong member offset in inherited classes
- Bug java/19295] [4.0 regression] Incorrect bytecode produced for bitwise AND
- …

Total of 545 matches…
And this is only for Janary 2005!
On a mature compiler!

Compiler bugs cause problems



- **They lead to buggy executables**
- **They rule out having strong guarantees about executables**

The focus: compiler optimizations

- A key part of any optimizing compiler

The focus: compiler optimizations

- A key part of any optimizing compiler
- Hard to get optimizations right
  - Lots of infrastructure-dependent details
  - There are many corner cases in each optimization
  - There are many optimizations and they interact in unexpected ways
  - It is hard to test all these corner cases and all these interactions

Goals

- Make it easier to write compiler optimizations
  - student in an undergrad compiler course should be able to write optimizations
- Provide strong guarantees about the correctness of optimizations
  - automatically (no user intervention at all)
  - statically (before the opts are even run once)
- Expressive enough for realistic optimizations

The Rhodium work

- A domain-specific language for writing optimizations: Rhodium
- A correctness checker for Rhodium optimizations
- An execution engine for Rhodium optimizations
- Implemented and checked the correctness of a variety of realistic optimizations

Broader implications

- Many other kinds of program manipulators: code refactoring tools, static checkers
  - My work is about program analyses and transformations, the core of any program manipulator
- Enables safe extensible program manipulators
  - Allow end programmers to easily and safely extend program manipulators
  - Improve programmer productivity

Outline

- Introduction
- Overview of the Rhodium system
- Writing Rhodium optimizations
- Checking Rhodium optimizations
- Evaluation

Rhodium system overview

Written by me

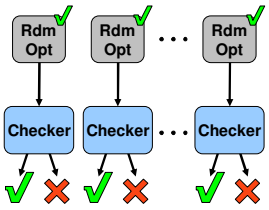
Written by programmer

Rhodium system overview

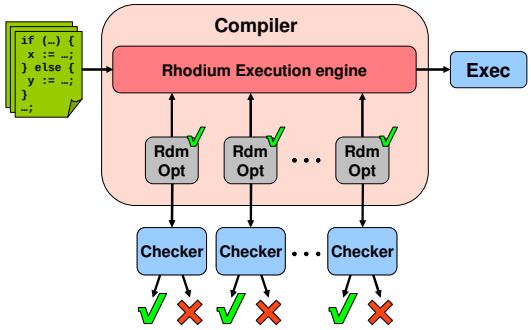
Written by me

Written by programmer

Rhodium system overview



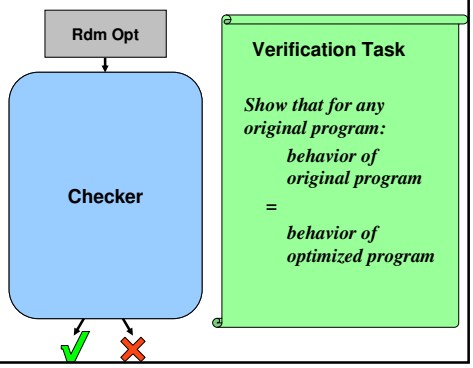
Rhodium system overview



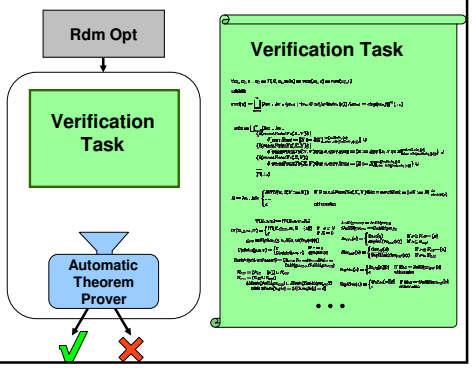
The technical problem

- Tension between:
  - Expressiveness
  - Automated correctness checking
- Challenge: develop techniques
  - that will go a long way in terms of expressiveness
  - that allow correctness to be checked

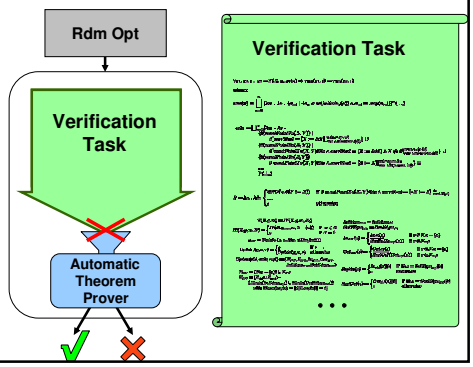
Contribution: three techniques



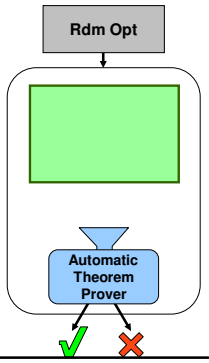
Contribution: three techniques



Contribution: three techniques

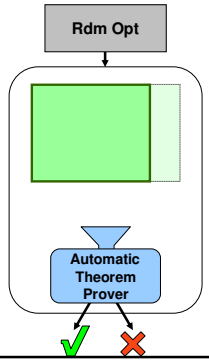


Contribution: three techniques



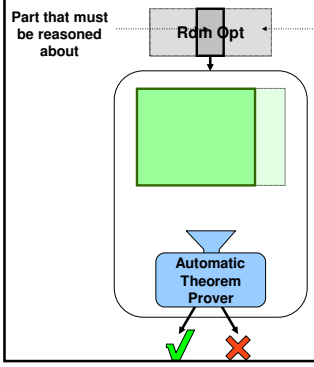
1. **Rhodium is declarative**
   - declare intent using rules
   - execution engine takes care of the rest

Contribution: three techniques



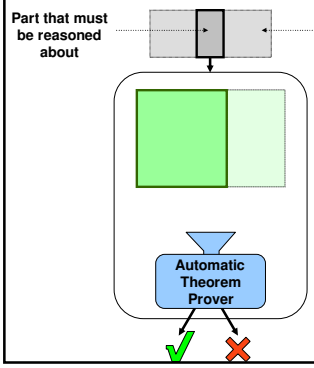
1. **Rhodium is declarative**
   - declare intent using rules
   - execution engine takes care of the rest

Contribution: three techniques



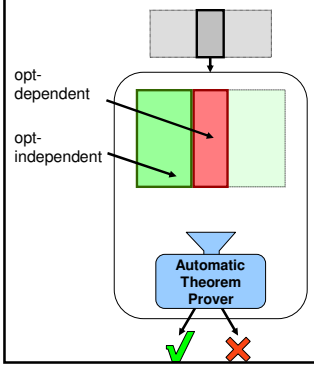
1. **Rhodium is declarative**
2. **Factor out heuristics**
   - legal transformations
   - vs. profitable transformations

Contribution: three techniques



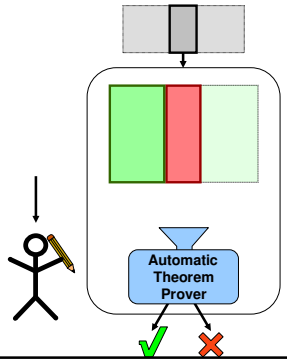
1. **Rhodium is declarative**
2. **Factor out heuristics**
   - legal transformations
   - vs. profitable transformations

Contribution: three techniques



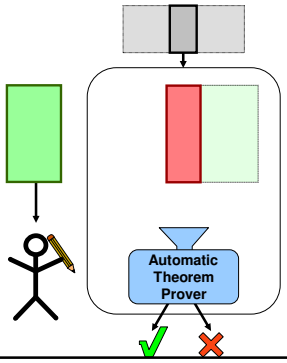
1. **Rhodium is declarative**
2. **Factor out heuristics**
3. **Split verification task**
   - opt-dependent
   - vs. opt-independent

Contribution: three techniques



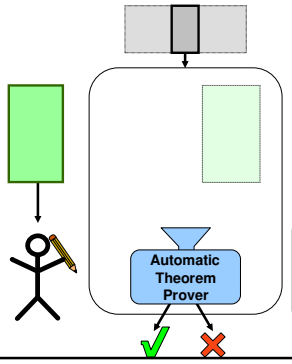
1. **Rhodium is declarative**
2. **Factor out heuristics**
3. **Split verification task**
   - opt-dependent
   - vs. opt-independent

Contribution: three techniques



1. **Rhodium is declarative**
2. **Factor out heuristics**
3. **Split verification task**
   - opt-dependent
   - vs. opt-independent

Contribution: three techniques



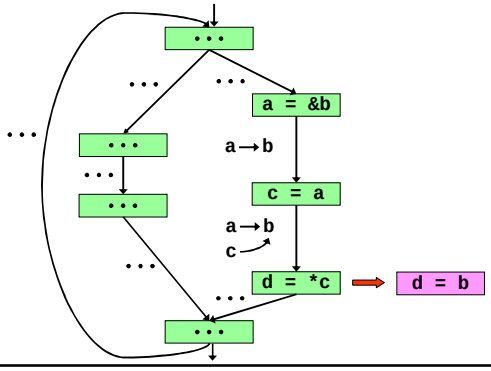
1. **Rhodium is declarative**
2. **Factor out heuristics**
3. **Split verification task**

Result:
- **Expressive language**
- **Automated correctness checking**

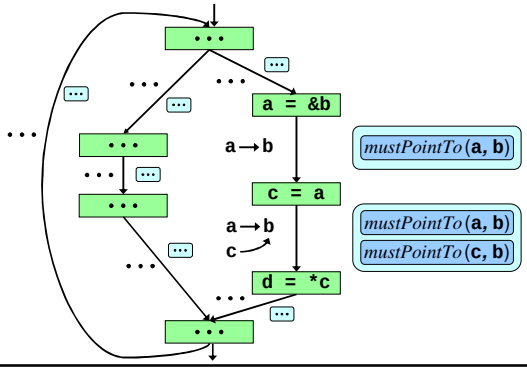
Outline

- Introduction
- Overview of the Rhodium system
- Writing Rhodium optimizations
- Checking Rhodium optimizations
- Evaluation

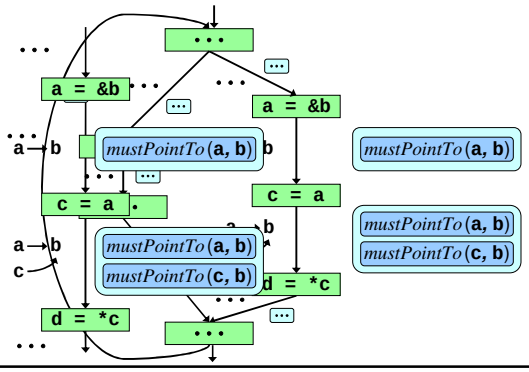
MustPointTo analysis



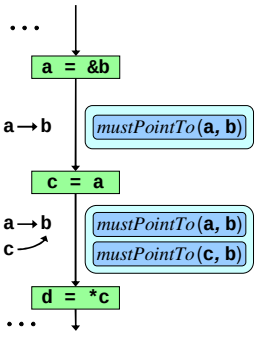
MustPointTo info in Rhodium



MustPointTo info in Rhodium



MustPointTo info in Rhodium

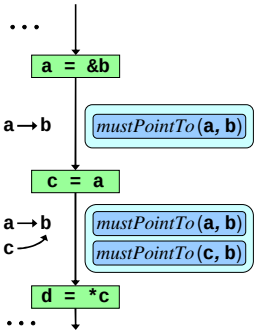


define fact
mustPointTo(X:Var,Y:Var)
with meaning ⟦ *X == &Y* ⟧

Fact correct on edge if:

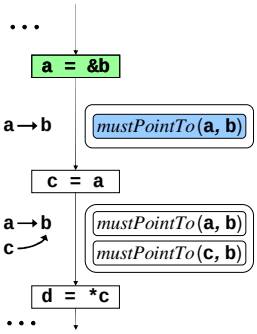
whenever program execution reaches edge, meaning of fact evaluates to true in the program state

Propagating facts



define fact
mustPointTo(X:Var,Y:Var)
with meaning ⟦ *X == &Y* ⟧

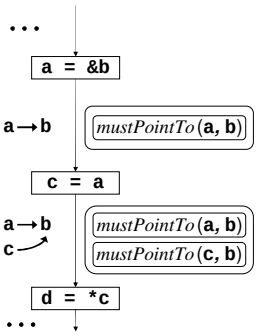
Propagating facts



define fact
mustPointTo(X:Var,Y:Var)
with meaning ⟦ *X == &Y* ⟧

if *currStmt == [X = &Y]*
then *mustPointTo(X,Y)@out*

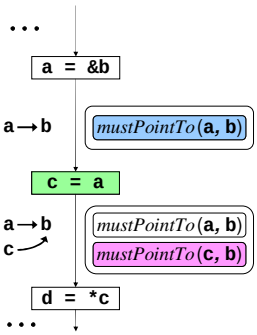
Propagating facts



define fact
mustPointTo(X:Var,Y:Var)
with meaning ⟦ *X == &Y* ⟧

if *currStmt == [X = &Y]*
then *mustPointTo(X,Y)@out*

Propagating facts

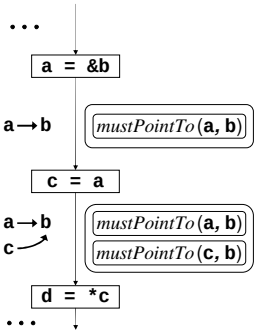


define fact
mustPointTo(X:Var,Y:Var)
with meaning ⟦ *X == &Y* ⟧

if *currStmt == [X = &Y]*
then *mustPointTo(X,Y)@out*

if *mustPointTo(X,Y)@in* ∧
currStmt == [Z = X]
then *mustPointTo(Z,Y)@out*

Propagating facts

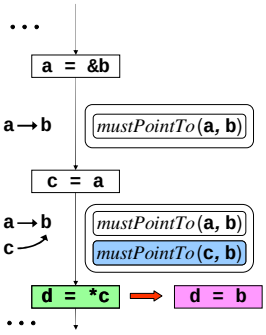


define fact
mustPointTo(X:Var,Y:Var)
with meaning ⟦ *X == &Y* ⟧

if *currStmt == [X = &Y]*
then *mustPointTo(X,Y)@out*

if *mustPointTo(X,Y)@in* ∧
currStmt == [Z = X]
then *mustPointTo(Z,Y)@out*

Transformations



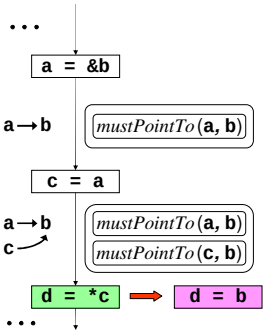
define fact
mustPointTo(X:Var,Y:Var)
with meaning ⟦ *X == &Y* ⟧

if *currStmt == [X = &Y]*
then *mustPointTo(X,Y)@out*

if *mustPointTo(X,Y)@in* ∧
currStmt == [Z = X]
then *mustPointTo(Z,Y)@out*

if *mustPointTo(X,Y)@in* ∧
*currStmt == [Z = *X]*
then transform to *[Z = Y]*

Transformations



define fact
mustPointTo(X:Var,Y:Var)
with meaning ⟦ *X == &Y* ⟧

if *currStmt* == [*X = &Y*]
then *mustPointTo(X,Y)@out*

if *mustPointTo(X,Y)@in* ∧
currStmt == [*Z = X*]
then *mustPointTo(Z,Y)@out*

if *mustPointTo(X,Y)@in* ∧
currStmt == [*Z = *X*]
then transform to [*Z = Y*]

Profitability heuristics

Legal transformations (identified by the Rhodium rules)

Profitability Heuristics

Subset of legal transformations (actually performed)

Profitability heuristic example 1

- Inlining
- Many heuristics to determine when to inline a function
  - compute function sizes, estimate code-size increase, estimate performance benefit
  - maybe even use AI techniques to make the decision
- However, these heuristics do not affect the correctness of inlining
- They are just used to choose which of the correct set of transformations to perform

Profitability heuristic example 2

- Partial redundancy elimination (PRE)

```
a := ...;
b := ...;
if (...) {
   a := ...;
   x := a + b;
} else {
   ...

}
x := a + b;
```

Profitability heuristic example 2

- PRE as code duplication followed by CSE

```
a := ...;
b := ...;
if (...) {
   a := ...;
   x := a + b;
} else {
   ...

}
x := a + b;
```

- Code duplication

Profitability heuristic example 2

- PRE as code duplication followed by CSE

```
a := ...;
b := ...;
if (...) {
   a := ...;
   x := a + b;
} else {
   ...
   x := a + b;
}
x := a + b;
```

- Code duplication
- CSE

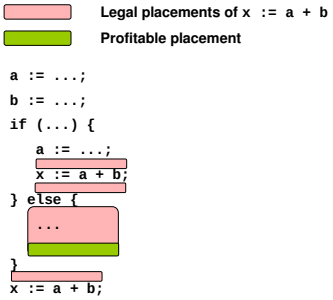
Profitability heuristic example 2

- PRE as code duplication followed by CSE

```
a := ...;
b := ...;
if (...) {
   a := ...;
   x := a + b;
} else {
   ...
   x := a + b;
}
x := x;
```

- Code duplication
- CSE
- self-assignment removal

Profitability heuristic example 2



Semantics of a Rhodium opt

- Run propagation rules in a loop until there are no more changes (optimistic iterative analysis)
- Then run transformation rules
- Then run profitability heuristics
- For better precision, combine propagation rules and transformations rules using our previous composition framework [POPL 02]

More facts

define fact *mustNotPointTo(X:Var,Y:Var)*
with meaning $[\![X \neq \&Y]\!]$

define fact *doesNotPointIntoHeap(X:Var)*
with meaning $[\![\exists\ Y{:}Var\ .\ X == \&Y]\!]$

define fact *hasConstantValue(X:Var,C:Const)*
with meaning $[\![X == C]\!]$

More rules

if *currStmt* == $[X = *A]$ ∧
mustNotPointToHeap(A)@in ∧
∀ *B:Var . mayPointTo(A,B)@in* ⇒
mustNotPointTo(B,Y)
then *mustNotPointTo(X,Y)@out*

if *currStmt* == $[Y = I + BE]$ ∧
varEqualArray(X,A,J)@in ∧
equalsPlus(J,I,BE)@in ∧
¬ *mayDef(X)* ∧ ¬ *mayDefArray(A)* ∧
unchanged(BE)
then *varEqualArray(X,A,Y)@out*

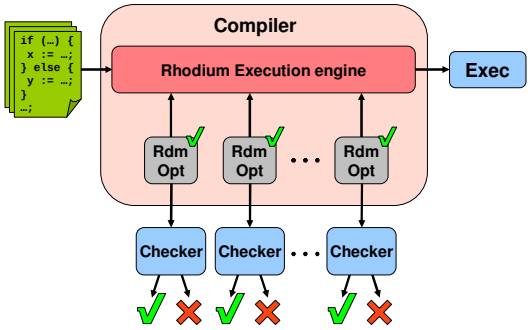
More in Rhodium

- More powerful pointer analyses
  - Heap summaries
- Analyses across procedures
  - Interprocedural analyses
- Analyses that don't care about the order of statements
  - Flow-insensitive analyses

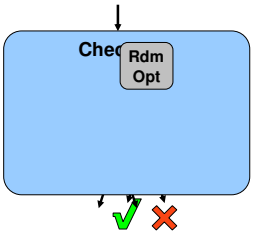
Outline

- Introduction
- Overview of the Rhodium system
- Writing Rhodium optimizations
- Checking Rhodium optimizations
- Evaluation

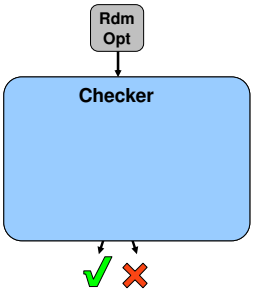
Rhodium correctness checker



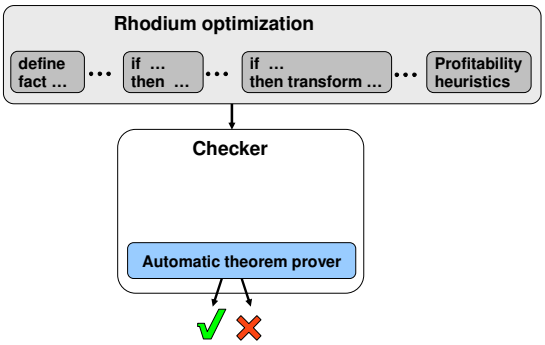
Rhodium correctness checker



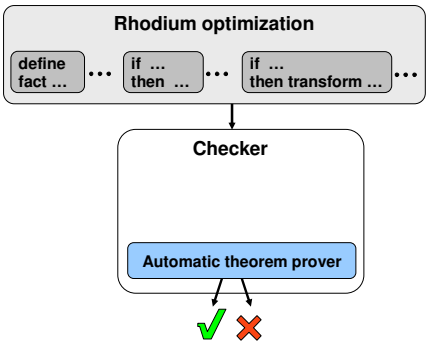
Rhodium correctness checker



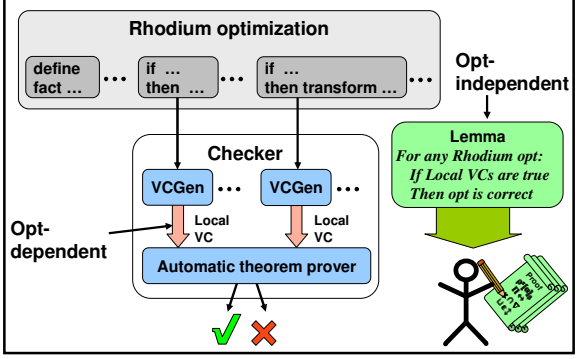
Rhodium correctness checker



Rhodium correctness checker



Rhodium correctness checker



Local verification conditions

define fact *mustPointTo(X,Y)*
with meaning ⟦ *X == &Y* ⟧

if *mustPointTo(X,Y)@in* ∧
currStmt == [Z = X]
then *mustPointTo(Z,Y)@out*

if *mustPointTo(X,Y)@in* ∧
*currStmt == [Z = *X]*
then transform to *[Z = Y]*

Local VCs (generated and proven automatically)

Assume: *All incoming facts are correct*
Show: *Propagated fact is correct*

Assume: *All incoming facts are correct*
Show: *Original stmt and transformed stmt have same behavior*

Local correctness of prop. rules

define fact *mustPointTo(X,Y)*
with meaning ⟦ *X == &Y* ⟧

if *mustPointTo(X,Y)@in* ∧
currStmt == [Z = X]
then *mustPointTo(Z,Y)@out*

mustPointTo(X, Y) •••
Z := X
mustPointTo(Z, Y) •••

Local VC (generated and proven automatically)

Assume: *All incoming facts are correct*
Show: ⟦ *Z == &Y* ⟧ (σ_{out})

Local correctness of prop. rules

define fact *mustPointTo(X,Y)*
with meaning ⟦ *X == &Y* ⟧

if *mustPointTo(X,Y)@in* ∧
currStmt == [Z = X]
then *mustPointTo(Z,Y)@out*

mustPointTo(X, Y) •••
Z := X
mustPointTo(Z, Y) •••

Local VC (generated and proven automatically)

Assume:
⟦ *X == &Y* ⟧ (σ_{in}) ∧
σ_{out} = *step* (σ_{in}, *[Z = X]*)
Show: ⟦ *Z == &Y* ⟧ (σ_{out})

σ_{in} $X \to Y$
Z := X
σ_{out} $Z \xrightarrow{?} Y$

Outline

- Introduction
- Overview of the Rhodium system
- Writing Rhodium optimizations
- Checking Rhodium optimizations
- Evaluation

Dimensions of evaluation

- Ease of use
- Correctness guarantees
- Usefulness of the checker
- Expressiveness

Ease of use

- Ease of use
- Guarantees
- Usefulness
- Expressiveness

- Joao Dias
  - third year graduate student in compilers at Harvard
  - less than 45 mins to write CSE and copy prop
- Erika Rice, summer 2004
  - only knowledge of compilers: one undergrad class
  - started writing Rhodium optimizations in a few days
- Simple interface to the compiler's structures
  - pattern matching
  - "flow functions" familiar to compiler 101 students

Correctness guarantees

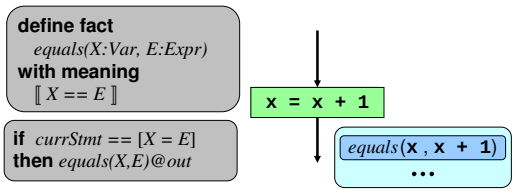
- Ease of use
- **Guarantees**
- Usefulness
- Expressiveness

- Once checked, optimizations are guaranteed to be correct
- Caveat: trusted computing base
  - execution engine
  - checker implementation
  - proofs done by hand once by me
- Adding a new optimization does not increase the size of the trusted computing base

Usefulness of the checker

- Ease of use
- Guarantees
- **Usefulness**
- Expressiveness

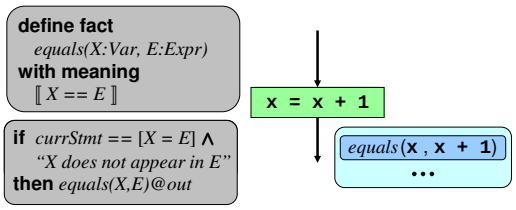
- Found subtle bugs in my initial implementation of various optimizations



Usefulness of the checker

- Ease of use
- Guarantees
- **Usefulness**
- Expressiveness

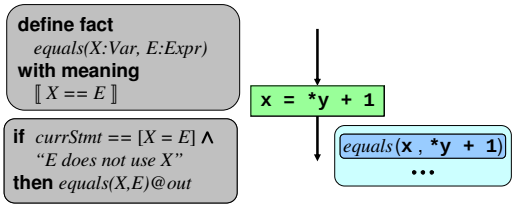
- Found subtle bugs in my initial implementation of various optimizations



Usefulness of the checker

- Ease of use
- Guarantees
- **Usefulness**
- Expressiveness

- Found subtle bugs in my initial implementation of various optimizations



Rhodium expressiveness

- Ease of use
- Guarantees
- Usefulness
- **Expressiveness**

- Traditional optimizations:
  - const prop and folding, branch folding, dead assignment elim, common sub-expression elim, partial redundancy elim, partial dead assignment elim, arithmetic invariant detection, and integer range analysis.
- Pointer analyses
  - must-point-to analysis, Andersen's may-point-to analysis with heap summaries
- Loop opts
  - loop-induction-variable strength reduction, code hoisting, code sinking
- Array opts
  - constant propagation through array elements, redundant array load elimination

Rhodium expressiveness

- Ease of use
- Guarantees
- Usefulness
- **Expressiveness**

- Traditional optimizations:
  - const prop and folding, branch folding, dead assignment elim, common sub-expression elim, partial redundancy elim, partial dead assignment elim, arithmetic invariant detection, and integer range analysis.
- Pointer analyses
  - must-point-to analysis, Andersen's may-point-to analysis with heap summaries
- Loop opts
  - loop-induction-variable strength reduction, code hoisting, code sinking
- Array opts
  - constant propagation through array elements, redundant array load elimination

Expressiveness limitations

- Ease of use
- Guarantees
- Usefulness
- **Expressiveness**

- May not be able to express your optimization in Rhodium
  - opts that build complicated data structures
  - opts that perform complicated many-to-many transformations (e.g.: loop fusion, loop unrolling)
- A correct Rhodium optimization may be rejected by the correctness checker
  - limitations of the theorem prover
  - limitations of first-order logic

Summary

- Rhodium system
  - makes it easier to write optimizations
  - provides correctness guarantees
  - is expressive enough for realistic optimizations
- Rhodium system provides a foundation for safe extensible program manipulators