Alive: Provably Correct InstCombine Optimizations

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Can We Trust Compilers?

- Any large software project will have bugs
- LLVM is no exception
  - CSmith project found 203 bugs by random testing
- InstCombine is especially buggy

[LLVMbugs] instcombine fix

Casey Carter ccarter@cs.uiuc.edu
Thu, 05 Dec 2002 15:28:32 -0600

- Next message: [LLVMbugs] instcombine fix
- **Messages sorted by:** [date] [thread] [subject] [author]

```
This is a multi-part message in MIME format.
--------------010607030400040301000502
Content-Type: text/plain; charset=us-ascii; format=flowed
Content-Transfer-Encoding: 7bit

I noticed that one of the reassociate regression tests --
2002-07-09-DominanceProblem -- was failing.  instcombine was transforming

%A.neg = sub int 0, %A
%.neg = sub int 0, 1
%X = add int %.neg, 1
%Y.neg.ra = add int %A, %X
%r = add int %A.neg, %Y.neg.ra
ret int %r

into

%Y.neg.ra = add int %A, 0
%r = add int %A.neg, %Y.neg.ra
ret int %r

without reexamining %Y.neg.ra to see that it is clearly replacable by
%A.  The problem is that instcombine's runOnFunction does not add uses
of a constant-folded instruction into its worklist for examination.
```

[LLVMbugs] [Bug 1976] New: instcombine doesn't fold x*y+x*z to x*(y+z)

bugzilla-daemon at cs.uiuc.edu bugzilla-daemon at cs.uiuc.edu
Sat Feb 2 22:41:40 CST 2008

- Previous message: [LLVMbugs] [Bug 1975] dag isel emitter isels wrong flag result
- Next message: [LLVMbugs] [Bug 1976] instcombine doesn't fold x*y+x*z to x*(y+z)
- **Messages sorted by:** [date] [thread] [subject] [author]

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http://llvm.org/bugs/show_bug.cgi?id=1976

```
           Summary: instcombine doesn't fold x*y+x*z to x*(y+z)
           Product: libraries
           Version: trunk
          Platform: All
        OS/Version: All
            Status: NEW
          Severity: enhancement
          Priority: P2
         Component: Scalar Optimizations
        AssignedTo: nicholas at mxc.ca
        ReportedBy: nicholas at mxc.ca
                CC: llvmbugs at cs.uiuc.edu


Created an attachment (id=1369)
 --> (http://llvm.org/bugs/attachment.cgi?id=1369)
proposed patch (a little ugly)

Instcombine should be able to fold:

define i8 @test1(i8 %x, i8 %y, i8 %z) {
  %A = mul i8 %x, %y
  %B = mul i8 %x, %z
  %C = add i8 %A, %B
  ret i8 %C
}

into this:
```

[LLVMbugs] [Bug 1066] NEW: Assertion failed in InstCombine

bugzilla-daemon at cs.uiuc.edu bugzilla-daemon at cs.uiuc.edu
Sat Dec 23 18:07:40 CST 2006

- Previous message: [LLVMbugs] [Bug 1065] Crash in InstCombine
- Next message: [LLVMbugs] [Bug 1066] Assertion failed in InstCombine
- **Messages sorted by:** [date] [thread] [subject] [author]

---

http://llvm.org/bugs/show_bug.cgi?id=1066

```
           Summary: Assertion failed in InstCombine
           Product: libraries
           Version: trunk
          Platform: PC
        OS/Version: Linux
            Status: NEW
          Severity: normal
          Priority: P2
         Component: Scalar Optimizations
        AssignedTo: unassignedbugs at nondot.org
        ReportedBy: asl at math.spbu.ru


$ ./opt -instcombine bugpoint-reduced-simplified.bc -o test_bc.bc -f
opt: /home/asl/proj/llvm/src/lib/VMCore/Value.cpp:157: void
llvm::Value::replaceAllUsesWith(llvm::Value*): Assertion `New->getType() ==
getType() && "replaceAllUses of value with new value of different type!"' failed.
./opt((anonymous namespace)::PrintStackTrace()+0x1f)[0x836a7ff]
/lib/libc.so.6(abort+0xeb)[0xb7d81133]
/lib/libc.so.6(__assert_fail+0xeb)[0xb7d794f3]
./opt[0x832f26c]

Bytecode attached
```

[LLVMbugs] [Bug 2295] New: incorrect optimization (instcombine)

bugzilla-daemon at cs.uiuc.edu bugzilla-daemon at cs.uiuc.edu
Wed May 7 17:41:31 CDT 2008

- Previous message: [LLVMbugs] [Bug 2025] llvm-gcc4.2 won' t build if using LLVM release build and boostrap enabled
- Next message: [LLVMbugs] [Bug 2295] incorrect optimization (instcombine)
- **Messages sorted by:** [date] [thread] [subject] [author]

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http://llvm.org/bugs/show_bug.cgi?id=2295

```
           Summary: incorrect optimization (instcombine)
           Product: new-bugs
           Version: unspecified
          Platform: PC
        OS/Version: Windows NT
            Status: NEW
          Severity: normal
          Priority: P2
         Component: new bugs
        AssignedTo: unassignedbugs at nondot.org
        ReportedBy: scott.llvm at h4ck3r.net
                CC: llvmbugs at cs.uiuc.edu


Created an attachment (id=1621)
 --> (http://llvm.org/bugs/attachment.cgi?id=1621)
.ll to demonstrate mis-optimization

Using LLVM 2.2:

llvm-as -f x.ll
opt -instcombine -f x.bc -o x.opt.bc
lli x.bc
lli x.opt.bc

The first outputs (as expected):
90 (Z)
and the second (optimized) incorrectly outputs:
33 (!)

I was unable to get bugpoint to work, but the attached file has been manually
minimized (73 lines). Happens with "opt -std-compile-opts" also, but "opt
-instcombine" is all that's necessary.

It appears two different pointers into allocated memory are being conflated.
```

[LLVMbugs] [Bug 3953] New: Instcombine quadratic in add chain length

bugzilla-daemon at cs.uiuc.edu bugzilla-daemon at cs.uiuc.edu
Mon Apr 6 16:10:20 CDT 2009

[LLVMbugs] [Bug 3953] New: Instcombine quadratic in add chain length

- Previous message: [LLVMbugs] [Bug 3678] Invalid input/output constraint when compiling FreeBSD's libm/ OpenSSL on AMD64
- Next message: [LLVMbugs] [Bug 3954] New: [ARM] An asm causes an assert.
- **Messages sorted by:** [date] [thread] [subject] [author]

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http://llvm.org/bugs/show_bug.cgi?id=3953

```
           Summary: Instcombine quadratic in add chain length
           Product: libraries
           Version: trunk
          Platform: PC
        OS/Version: All
            Status: NEW
          Severity: normal
          Priority: P2
         Component: Scalar Optimizations
        AssignedTo: unassignedbugs at nondot.org
        ReportedBy: jyasskin at google.com
                CC: llvmbugs at cs.uiuc.edu, nlewycky at google.com


Created an attachment (id=2799)
 --> (http://llvm.org/bugs/attachment.cgi?id=2799)
Generator for add chains that make instcombine quadratic

The attached script generates .ll files of the form:

$  ./instcombine_test3.py 3
declare void @use(i32)

define void @foo(i32 %B0) {

  %A1 = add i32 %B0, 1
  %B1 = add i32 %A1, -1
  call void @use(i32 %B1)
```

[LLVMbugs] [Bug 4374] New: incorrect instcombine optimization

bugzilla-daemon at cs.uiuc.edu bugzilla-daemon at cs.uiuc.edu
Fri Jun 12 01:11:06 CDT 2009

- Previous message: [LLVMbugs] [Bug 1285] Fix consistency of FP operators: add -> fadd, etc
- Next message: [LLVMbugs] [Bug 4374] incorrect instcombine optimization
- **Messages sorted by:** [date] [thread] [subject] [author]

---

http://llvm.org/bugs/show_bug.cgi?id=4374

```
           Summary: incorrect instcombine optimization
           Product: libraries
           Version: trunk
          Platform: PC
        OS/Version: Linux
            Status: NEW
          Severity: normal
          Priority: P2
         Component: Scalar Optimizations
        AssignedTo: unassignedbugs at nondot.org
        ReportedBy: llvm at laurentm.net
                CC: llvmbugs at cs.uiuc.edu


The following transfomation is incorrect: fsub(a,fsub(b,c)) =>
fadd(a,fsub(c,b))

For example:

float
func(float a, float b) {
    return -(a - b);
}

llvm-gcc generates:
define float @func(float %a, float %b) nounwind {
entry:
        %tmp3 = sub float %a, %b                ; <float> [#uses=1]
        %tmp4 = sub float -0.000000e+00, %tmp3          ; <float> [#uses=1]
        ret float %tmp4
}
```

[LLVMbugs] [Bug 4908] New: infinite loop in instcombine

bugzilla-daemon at cs.uiuc.edu bugzilla-daemon at cs.uiuc.edu
Sat Sep 5 21:18:40 CDT 2009

- Previous message: [LLVMbugs] [Bug 4907] llvm fails to build, error: 'WeakVH' was not declared
- Next message: [LLVMbugs] [Bug 4908] infinite loop in instcombine
- **Messages sorted by:** [date] [thread] [subject] [author]

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http://llvm.org/bugs/show_bug.cgi?id=4908

```
           Summary: infinite loop in instcombine
           Product: libraries
           Version: trunk
          Platform: PC
        OS/Version: All
            Status: NEW
          Severity: normal
          Priority: P2
         Component: Scalar Optimizations
        AssignedTo: unassignedbugs at nondot.org
        ReportedBy: daniel at zuster.org
                CC: llvmbugs at cs.uiuc.edu


Instcombine loops on:
--
; ModuleID = '<stdin>'
target datalayout =
"e-p:64:64:64-i1:8:8-i8:8:8-i16:16:16-i32:32:32-i64:64:64-f32:32:32-f64:64:64-v64:64:64-v128:128:128-a0:0:64-s0:64:64-f80:128
target triple = "x86_64-apple-darwin10.0"

define void @short2_int_swap(<1 x i16>* nocapture %b, i32* nocapture %c)
nounwind ssp {
entry:
  %arrayidx = getelementptr inbounds <1 x i16>* %b, i64 undef ; <<1 x i16>*>
[#uses=1]
  %tmp2 = load <1 x i16>* %arrayidx               ; <<1 x i16>> [#uses=1]
  %tmp6 = bitcast <1 x i16> %tmp2 to i16          ; <i16> [#uses=1]
  %tmp7 = zext i16 %tmp6 to i32                   ; <i32> [#uses=1]
  %ins = or i32 0, %tmp7                          ; <i32> [#uses=1]
```

[LLVMbugs] [Bug 10267] New: instcombine deoptimizes testcase

bugzilla-daemon at llvm.org bugzilla-daemon at llvm.org
Mon Jul 4 14:38:30 CDT 2011

- Previous message: [LLVMbugs] [Bug 10266] New: MC does not recognise hyphenated VIA instructions
- Next message: [LLVMbugs] [Bug 10267] instcombine deoptimizes testcase
- **Messages sorted by:** [date] [thread] [subject] [author]

---

http://llvm.org/bugs/show_bug.cgi?id=10267

```
           Summary: instcombine deoptimizes testcase
           Product: libraries
           Version: trunk
          Platform: PC
        OS/Version: All
            Status: NEW
          Severity: normal
          Priority: P
         Component: Scalar Optimizations
        AssignedTo: unassignedbugs at nondot.org
        ReportedBy: rafael.espindola at gmail.com
                CC: llvmbugs at cs.uiuc.edu


In the attached testcase, instcombine converts

  %tmp2 = ptrtoint %struct.Shape* %tmp9 to i64
  %and = and i64 %tmp2, -2
  %tmp5 = inttoptr i64 %and to %struct.Shape*
  %tobool = icmp ne %struct.Shape* %tmp5, null
  br i1 %tobool, label %land.lhs.true, label %if.end

land.lhs.true:                                    ; preds = %entry
  %propid = getelementptr inbounds %struct.Shape* %tmp5, i32 0, i32 2

to

  %tobool = icmp ugt %struct.Shape* %tmp9, inttoptr (i64 1 to %struct.Shape*)
  br i1 %tobool, label %land.lhs.true, label %if.end

land.lhs.true:                                    ; preds = %entry
```

[LLVMbugs] [Bug 14893] New: Instcombine miscompiles bool, aka i8 !range[0, 2)

bugzilla-daemon at llvm.org bugzilla-daemon at llvm.org
Thu Jan 10 07:52:53 CST 2013

- Previous message: [LLVMbugs] [Bug 14745] Formatting empty function bodies
- Next message: [LLVMbugs] [Bug 14894] New: c++-analyzer does not define __SSE3__
- **Messages sorted by:** [date] [thread] [subject] [author]

---

http://llvm.org/bugs/show_bug.cgi?id=14893

```
           Bug #: 14893
         Summary: Instcombine miscompiles bool, aka i8 !range[0,2)
         Product: libraries
         Version: trunk
        Platform: All
      OS/Version: All
          Status: NEW
        Severity: normal
        Priority: P
       Component: Scalar Optimizations
      AssignedTo: unassignedbugs at nondot.org
      ReportedBy: geek4civic at gmail.com
              CC: baldrick at free.fr, llvmbugs at cs.uiuc.edu
  Classification: Unclassified


target datalayout =
"e-p:64:64:64-S128-i1:8:8-i8:8:8-i16:16:16-i32:32:32-i64:64:64-f16:16:16-f32:32:32-f64:64:64-f128:128:128-v64:64:64-
v128:128:128-a0:0:64-s0:64:64-f80:128:128-n8:16:32:64"
target triple = "x86_64-redhat-linux"

define zeroext i8 @_Z3BARv() unnamed_addr nounwind uwtable {
entry:
  %r = alloca i8, align 1
  %tmp = call zeroext i8 @_Z3FOORb(i8* %r) nounwind
  %tmp9 = and i8 %tmp, 1
  %tmp1 = icmp eq i8 %tmp9, 0
  br i1 %tmp1, label %"5", label %"3"

"3":                                              ; preds = %entry
  %tmp3 = load i8* %r, align 1, !range !0
```

[LLVMbugs] [Bug 16244] New: instcombine breaks this file

bugzilla-daemon at llvm.org bugzilla-daemon at llvm.org
Thu Jun 6 11:51:35 CDT 2013

- Previous message: [LLVMbugs] [Bug 15069] -Wassign-enum assertion with __attribute__((packed)) enum
- Next message: [LLVMbugs] [Bug 16244] instcombine breaks this file
- **Messages sorted by:** [date] [thread] [subject] [author]

---

http://llvm.org/bugs/show_bug.cgi?id=16244

```
           Bug ID: 16244
          Summary: instcombine breaks this file
          Product: libraries
          Version: trunk
         Hardware: PC
               OS: Linux
           Status: NEW
         Severity: normal
         Priority: P
        Component: Scalar Optimizations
         Assignee: unassignedbugs at nondot.org
         Reporter: rafael.espindola at gmail.com
               CC: llvmbugs at cs.uiuc.edu
   Classification: Unclassified

Created attachment 10637
  --> http://llvm.org/bugs/attachment.cgi?id=10637&action=edit
testcase

This is a reduction from HashCombineRangeBasicTest failing when building with
draggonegg.


This is a recent regression. I am bisecting it.
```

[LLVMbugs] [Bug 16776] New: Instcombine transformation causes poor vector codegen [SSE4]

bugzilla-daemon at llvm.org bugzilla-daemon at llvm.org
Fri Aug 2 09:56:05 CDT 2013

- Previous message: [LLVMbugs] [Bug 16450] Combining CHECK-DAG and CHECK-NOT sometimes causes an incorrect error-less failure
- Next message: [LLVMbugs] [Bug 16777] New: Clang crash caused by SLP vectorizer
- **Messages sorted by:** [date] [thread] [subject] [author]

---

http://llvm.org/bugs/show_bug.cgi?id=16776

```
           Bug ID: 16776
          Summary: Instcombine transformation causes poor vector codegen
                   [SSE4]
          Product: new-bugs
          Version: trunk
         Hardware: PC
               OS: All
           Status: NEW
         Severity: normal
         Priority: P
        Component: new bugs
         Assignee: unassignedbugs at nondot.org
         Reporter: matt at pharr.org
               CC: llvmbugs at cs.uiuc.edu
    Classification: Unclassified

Created attachment 10973
  --> http://llvm.org/bugs/attachment.cgi?id=10973&action=edit
test case

The attached test case does a vector compare of a <16 x i8> value with zero and
then a vector select based on the comparison to negate elements that are less
than zero (i.e. computes the absolute value).  If I run it through llc as is, a
single glorious PABSB instruction is generated:

    pabsb    %xmm0, %xmm0

However, if I run "opt -instcombine bug2.ll | llc -o -", I get a 13 instruction
sequence instead of the PABSB:
```

[LLVMbugs] [Bug 18600] New: [InstCombine] assert "Value::replaceAllUsesWith(<null>) is invalid!"

bugzilla-daemon at llvm.org bugzilla-daemon at llvm.org
Fri Jan 24 08:09:35 CST 2014

- Previous message: [LLVMbugs] [Bug 18599] New: AsmParser::parseDirectiveMacro can't parse recursive macro definition
- Next message: [LLVMbugs] [Bug 18600] [InstCombine] assert "Value::replaceAllUsesWith(<null>) is invalid!"
- **Messages sorted by:** [date] [thread] [subject] [author]

---

http://llvm.org/bugs/show_bug.cgi?id=18600

```
           Bug ID: 18600
          Summary: [InstCombine] assert
                   "Value::replaceAllUsesWith(<null>) is invalid!"
          Product: libraries
          Version: 3.3
         Hardware: PC
               OS: Linux
           Status: NEW
         Severity: normal
         Priority: P
        Component: Scalar Optimizations
         Assignee: unassignedbugs at nondot.org
         Reporter: jfonseca at vmware.com
               CC: llvmbugs at cs.uiuc.edu
    Classification: Unclassified

Created attachment 11930
  --> http://llvm.org/bugs/attachment.cgi?id=11930&action=edit
bugpoint-reduced-simplified.ll

$ gdb --args ~/work/vmware/llvm/llvm/build/linux-x86_64/Debug+Asserts/bin/opt
bugpoint-reduced-simplified.ll -instcombine -disable-output
(gdb) r
Starting program:
/home/jfonseca/work/vmware/llvm/llvm/build/linux-x86_64/Debug+Asserts/bin/opt
bugpoint-reduced-simplified.ll -instcombine -disable-output
[Thread debugging using libthread_db enabled]
Using host libthread_db library "/lib/x86_64-linux-gnu/libthread_db.so.1".
opt: /home/jfonseca/work/vmware/llvm/llvm/lib/IR/Value.cpp:304: void
llvm::Value::replaceAllUsesWith(llvm::Value*): Assertion `New &&
"Value::replaceAllUsesWith(<null>) is invalid!"' failed.
```

[LLVMbugs] [Bug 18745] New: Assertion in InstCombine: "getOperand() out of range!"

bugzilla-daemon at llvm.org bugzilla-daemon at llvm.org
Wed Feb 5 14:15:19 CST 2014

- Previous message: [LLVMbugs] [Bug 18744] New: Clang crashes when instantiating a function template which uses decltype
- Next message: [LLVMbugs] [Bug 18745] Assertion in InstCombine: "getOperand() out of range!"
- **Messages sorted by:** [date] [thread] [subject] [author]

---

http://llvm.org/bugs/show_bug.cgi?id=18745

```
           Bug ID: 18745
          Summary: Assertion in InstCombine: "getOperand() out of range!"
          Product: libraries
          Version: trunk
         Hardware: PC
               OS: All
           Status: NEW
         Severity: normal
         Priority: P
        Component: Scalar Optimizations
         Assignee: unassignedbugs at nondot.org
         Reporter: jordan_rose at apple.com
               CC: llvmbugs at cs.uiuc.edu
   Classification: Unclassified

Compiling the attached file leads to an assertion failure in InstCombine. This
started somewhere between r200568 and r200645. (Unfortunately large range on
this particular buildbot.)

Assertion failed: (i_nocapture < OperandTraits<PHINode>::operands(this) &&
"getOperand() out of range!"), function getOperand, file
/Volumes/Lore/llvm-public/llvm/include/llvm/IR/Instructions.h, line 2178.

---

clang -cc1 -triple x86_64-apple-macosx10.9.0 -emit-obj -disable-free
-main-file-name bufpage.c -mrelocation-model pic -pic-level 2 -mdisable-fp-elim
-relaxed-aliasing -masm-verbose -munwind-tables -target-cpu core2
-target-linker-version 142 -O2 -Wall -Wmissing-prototypes -Wpointer-arith
-Wdeclaration-after-statement -Wendif-labels -Wformat-security -ferror-limit 19
-fmessage-length 0 -fwrapv -stack-protector 1 -mstackrealign -fblocks
```

Why Is InstCombine Buggy?

- It's huge:
  - over 20,000 lines of code
    - visitICmpInst alone is 924 lines
- Complicated to write
- LLVM Semantics are subtle
- Hard to tell when the code is correct

For example…

```
{
  Value *Op1C = Op1;
  BinaryOperator *BO = dyn_cast<BinaryOperator>(Op0);
  if (!BO ||
      (BO->getOpcode() != Instruction::UDiv &&
       BO->getOpcode() != Instruction::SDiv)) {
    Op1C = Op0;
    BO = dyn_cast<BinaryOperator>(Op1);
  }
  Value *Neg = dyn_castNegVal(Op1C);
  if (BO && BO->hasOneUse() &&
      (BO->getOperand(1) == Op1C || BO->getOperand(1) == Neg) &&
      (BO->getOpcode() == Instruction::UDiv ||
       BO->getOpcode() == Instruction::SDiv)) {
    Value *Op0BO = BO->getOperand(0), *Op1BO = BO->getOperand(1);

    // If the division is exact, X % Y is zero, so we end up with X or -X.
    if (PossiblyExactOperator *SDiv = dyn_cast<PossiblyExactOperator>(BO))
      if (SDiv->isExact()) {
        if (Op1BO == Op1C)
          return ReplaceInstUsesWith(I, Op0BO);
        return BinaryOperator::CreateNeg(Op0BO);
      }

    Value *Rem;
    if (BO->getOpcode() == Instruction::UDiv)
      Rem = Builder->CreateURem(Op0BO, Op1BO);
    else
      Rem = Builder->CreateSRem(Op0BO, Op1BO);
    Rem->takeName(BO);

    if (Op1BO == Op1C)
      return BinaryOperator::CreateSub(Op0BO, Rem);
    return BinaryOperator::CreateSub(Rem, Op0BO);
  }
}
```

```
// (X / Y) *  Y = X - (X % Y)
// (X / Y) * -Y = (X % Y) - X
{
  Value *Op1C = Op1;
  BinaryOperator *BO = dyn_cast<BinaryOperator>(Op0);
  if (!BO ||
      (BO->getOpcode() != Instruction::UDiv &&
       BO->getOpcode() != Instruction::SDiv)) {
    Op1C = Op0;
    BO = dyn_cast<BinaryOperator>(Op1);
  }
  Value *Neg = dyn_castNegVal(Op1C);
  if (BO && BO->hasOneUse() &&
      (BO->getOperand(1) == Op1C || BO->getOperand(1) == Neg) &&
      (BO->getOpcode() == Instruction::UDiv ||
       BO->getOpcode() == Instruction::SDiv)) {
    Value *Op0BO = BO->getOperand(0), *Op1BO = BO->getOperand(1);

    // If the division is exact, X % Y is zero, so we end up with X or -X.
    if (PossiblyExactOperator *SDiv = dyn_cast<PossiblyExactOperator>(BO))
      if (SDiv->isExact()) {
        if (Op1BO == Op1C)
          return ReplaceInstUsesWith(I, Op0BO);
        return BinaryOperator::CreateNeg(Op0BO);
      }

    Value *Rem;
    if (BO->getOpcode() == Instruction::UDiv)
      Rem = Builder->CreateURem(Op0BO, Op1BO);
    else
      Rem = Builder->CreateSRem(Op0BO, Op1BO);
    Rem->takeName(BO);

    if (Op1BO == Op1C)
      return BinaryOperator::CreateSub(Op0BO, Rem);
    return BinaryOperator::CreateSub(Rem, Op0BO);
  }
}
```

Improve transition to next slide

Flags can be confusing…

Is This Valid?

```
%L = mul nsw i8 %A, %B
%I = mul nsw i8 %L, %C
```

```
%R = mul nsw i8 %B, %C
%I = mul nsw i8 %A, %R
```

Seemingly just
$(A \times B) \times C = A \times (B \times C)$

Is This Valid?

`%A = -1, %B = 4, %C = 32`

```
%L = mul nsw i8 %A, %B
%I = mul nsw i8 %L, %C
```

```
%R = mul nsw i8 %B, %C
%I = mul nsw i8 %A, %R
```

```
%L = -4
%I = -128
```

Is This Valid?

```
%A = -1, %B = 4, %C = 32
```

```
%L = mul nsw i8 %A, %B
%I = mul nsw i8 %L, %C
```

```
%R = mul nsw i8 %B, %C
%I = mul nsw i8 %A, %R
```

```
%L = -4
%I = -128
```

```
%R = poison
%I = poison
```

Is This Valid?

`%A = -1, %B = 4, %C = 32`

```
%L = mul nsw i8 %A, %B
%I = mul nsw i8 %L, %C
```

```
%R = mul     i8 %B, %C
%I = mul nsw i8 %A, %R
```

`%L = -4`
`%I = -128`

`%R = -128`
`%I = poison`

Is This Valid?

`%A = -1, %B = 4, %C = 32`

```
%L = mul nsw i8 %A, %B
%I = mul nsw i8 %L, %C
```

```
%R = mul     i8 %B, %C
%I = mul     i8 %A, %R
```

`%L = -4`
`%I = -128`

`%R = -128`
`%I = -128`

…but flags are also essential

Flags Aid Optimization

```
%C = mul i8 %A, %B
%R = sdiv i8 %C, %B
```

$$R = (A \times B) \div B$$

Is R = A?

Flags Aid Optimization

%A = 100, %B = 100

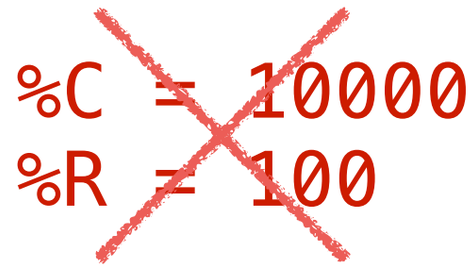
```
%C = mul i8 %A, %B
%R = sdiv i8 %C, %B
```

%C = 10000
%R = 100

Flags Aid Optimization

`%A = 100, %B = 100`

```
%C = mul i8 %A, %B
%R = sdiv i8 %C, %B
```



Too big for i8!

Flags Aid Optimization

```
%C = mul i8 %A, %B
%R = sdiv i8 %C, %B
```

We could do this if we knew that A×B fits in 8 bits

Flags Aid Optimization

More context for why flags are helpful and where they are generated (C)

```
%C = mul nsw i8 %A, %B
%R = sdiv i8 %C, %B
```

We could do this if we knew that A×B fits in 8 bits

…which is just what NSW/NUW are for

Outline

- Motivation
- Introducing Alive
- Language Overview
- Automated Verification
- Code Generation
- Conclusion

Alive: Fast, Safe, Easy

Slower here

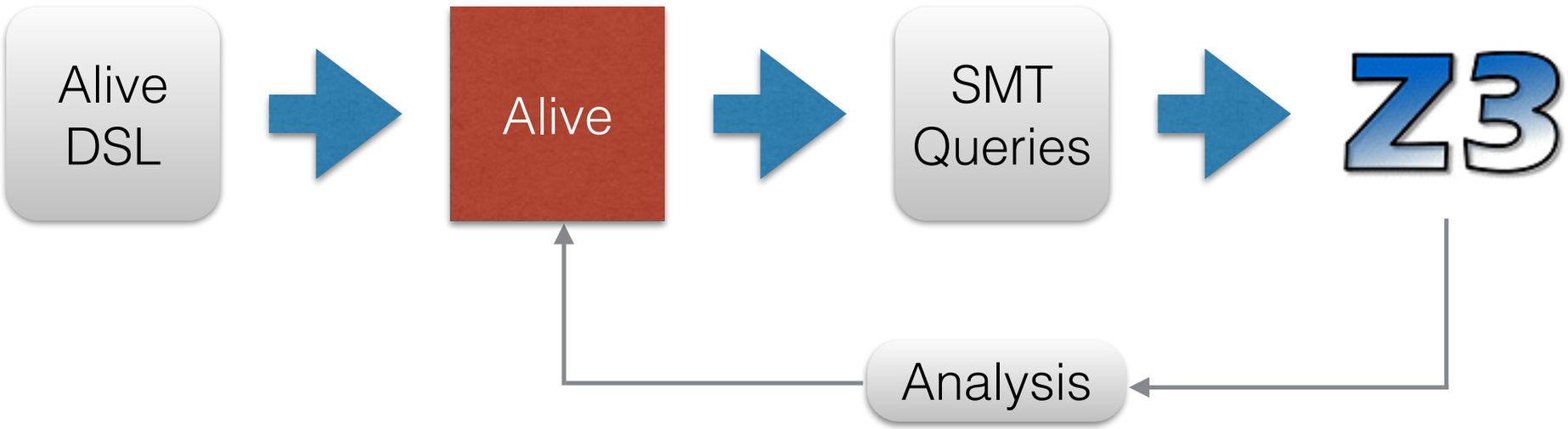
- Write optimizations in LLVM-like DSL
- Automatically verify correctness
- Automatically generate C++ code

```
Name: sdiv exact
%a = sdiv exact %x, %y
%r = mul %a, %y
  =>
%r = %x

Name: sdiv inexact
%a = sdiv %x, %y
%r = mul %a, %y
  =>
%b = srem %x, %y
%r = sub %x, %b
```

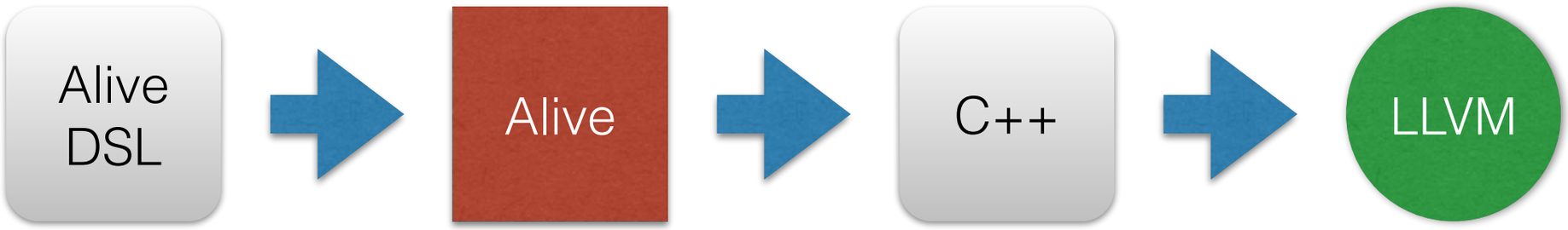
Partial translation

Prove Optimizations Correct



Alive handles all the tricky corners of LLVM's IR

Automatic Code Generation



Alive writes your InstCombine code for you

Why Alive?

- Use of formal methods is not new
  - CompCert—Formally verified C compiler
  - Vellvm—Formal semantics for LLVM in Coq
- Nuno Lopes described verifying InstCombine with SMT solvers last year

Lightweight Formal Methods

- Automation
  - Use SMT to avoid manual proofs
  - Use Alive to avoid writing SMT queries
- High-level specification language

Emphasize that Alive is easier than manual proofs

Alive Languag

More set up. Explain what this does. Additional slide before this?

```
Pre: C2 % (1<<C1) == 0
%s = shl nsw %A, C1
%r = sdiv %s, C2
   =>
%r = sdiv %A, C2/(1<<C1)
```

- $1<<C_1$ divides C_2
- $r_s = (A<<C_1) \div C_2$
- $r_t = A \div (C_2 \div (1<<C_1))$

Alive Language

```
Pre: C2 % (1<<C1) == 0
%s = shl nsw %A, C1
%r = sdiv %s, C2
   =>
%r = sdiv %A, C2/(1<<C1)
```

Precondition

Source

Target

Alive Language

```
Pre: C2 % (1<<C1) == 0
%s = shl nsw %A, C1
%r = sdiv %s, C2
   =>
%r = sdiv %A, C2/(1<<C1)
```

Constants

- Represent arbitrary immediate values
- Expressions permitted in target and precondition

Predicates and Functions

- Predicates can be used in precondition
  - May invoke heuristics in LLVM, e.g., WillNotOverflowSignedAdd
- Functions extend constant language
  - Most apply only to constant values, e.g., umax
  - width(%x) returns the bit width of any value

Predicates and Functions

```
Pre: C < 0 && isPowerOf2(abs(C))
%Op0 = add %Y, C1
%r = mul %Op0, C
  =>
%sub = sub -C1, %Y
%r = mul %sub, abs(C)
```

Checking Correctness

- SMT ("Satisfiability Modulo Theories")
  - Generalizes SAT solving
    - Additional theories for integers, bit vectors, etc.
- Undecidable in general
- Efficient in practice
  - Z3, Boolector, CVC4, etc.

Type Checking

- Translate type constraints to SMT
  - Binary operation arguments and answer have same type
  - Trunc result has fewer bits than argument, etc.
- Find and test all solutions to constraints

Checking Correctness

- Need to show that target *refines* source
  - Target's behavior undefined only when source's is
  - Target returns poison only when source does
  - For all other inputs, target and source yield same result

Checking Correctness

- SMT finds satisfying instances
- Phrase queries as negations:
  - “Find an input where the source is defined but the target is undefined”
- Z3 either finds a counterexample, or shows that none exists

Checking Correctness

- Translation uses Z3's theory of bitvectors
  - Sized, 2s-complement arithmetic
- undef uses theory of quantifiers
  - Optimization must hold for all possible values

Alive Language

```
Pre: C2 % (1<<C1) == 0
%s = shl nsw %A, C1
%r = sdiv %s, C2
  =>
%r = sdiv %A, C2/(1<<C1)
```

Raw SMT

```
(declare-fun C1 () (_ BitVec 4))
(declare-fun C2 () (_ BitVec 4))
(declare-fun %A () (_ BitVec 4))
(assert
    (and
        (and (distinct C2 (_ bv0 4)) true)
        (or
            (and (distinct (bvshl %A C1) (_ bv8 4)) true)
            (and (distinct C2 (_ bv15 4)) true)
        )
        (bvult C1 (_ bv4 4))
        (= (bvashr (bvshl %A C1) C1) %A)
        (= (bvsrem C2 (bvshl (_ bv1 4) C1)) (_ bv0 4))
        (and
            (distinct
                (bvsdiv (bvshl %A C1) C2)
                (bvsdiv %A (bvsdiv C2 (bvshl (_ bv1 4) C1)))
            )
            true
        )
    )
)
(check-sat)
```

i4 Equality Check

Raw SMT

Defined

Non-poison

Precondition

Source

Target

```
(declare-fun C1 () (_ BitVec 4))
(declare-fun C2 () (_ BitVec 4))
(declare-fun %A () (_ BitVec 4))
(assert
    (and
        (and (distinct C2 (_ bv0 4)) true)
        (or
            (and (distinct (bvshl %A C1) (_ bv8 4)) true)
            (and (distinct C2 (_ bv15 4)) true)
        )
        (bvult C1 (_ bv4 4))
        (= (bvashr (bvshl %A C1) C1) %A)
        (= (bvsrem C2 (bvshl (_ bv1 4) C1)) (_ bv0 4))
        (and
            (distinct
                (bvsdiv (bvshl %A C1) C2)
                (bvsdiv %A (bvsdiv C2 (bvshl (_ bv1 4) C1)))
            )
            true
        )
    )
)
(check-sat)
```

i4 Equality Check

Is This Valid?

```
Pre: C2 % (1<<C1) == 0
%s = shl nsw %A, C1
%r = sdiv %s, C2
   =>
%r = sdiv %A, C2/(1<<C1)
```

Is This Valid?

Expand this. Go through each line of counterexample

```
Pre: C2 % (1<<C1) == 0
%s = shl nsw %A, C1
%r = sdiv %s, C2
  =>
%r = sdiv %A, C2/(1<<C1)
```

```
ERROR: Mismatch in values of i4 %r

Example:
%A i4 = 0xF (15, -1)
C1 i4 = 0x3 (3)
C2 i4 = 0x8 (8, -8)
%s i4 = 0x8 (8, -8)
Source value: 0x1 (1)
Target value: 0xF (15, -1)
```

Alive finds a counterexample

Is This Valid?

```
Pre: C2 % (1<<C1) == 0
%s = shl nsw %A, C1
%r = sdiv %s, C2
  =>
%r = sdiv %A, C2/(1<<C1)
```

```
ERROR: Mismatch in values of i4 %r

Example:
%A i4 = 0xF (15, -1)
C1 i4 = 0x3 (3)
C2 i4 = 0x8 (8, -8)
%s i4 = 0x8 (8, -8)
Source value: 0x1 (1)
Target value: 0xF (15, -1)
```

Alive finds a counterexample

`%r = (%A<<C1) / C2` `%r = %A / (C2/(1<<C1))`

Is This Valid?

```
Pre: C2 % (1<<C1) == 0
%s = shl nsw %A, C1
%r = sdiv %s, C2
  =>
%r = sdiv %A, C2/(1<<C1)
```

```
ERROR: Mismatch in values of i4 %r

Example:
%A i4 = 0xF (15, -1)
C1 i4 = 0x3 (3)
C2 i4 = 0x8 (8, -8)
%s i4 = 0x8 (8, -8)
Source value: 0x1 (1)
Target value: 0xF (15, -1)
```

Alive finds a counterexample

`%r = (-1<< 3) / -8` `%r = -1 / (-8/(1<< 3))`

Is This Valid?

```
Pre: C2 % (1<<C1) == 0
%s = shl nsw %A, C1
%r = sdiv %s, C2
  =>
%r = sdiv %A, C2/(1<<C1)
```

```
ERROR: Mismatch in values of i4 %r

Example:
%A i4 = 0xF (15, -1)
C1 i4 = 0x3 (3)
C2 i4 = 0x8 (8, -8)
%s i4 = 0x8 (8, -8)
Source value: 0x1 (1)
Target value: 0xF (15, -1)
```

Alive finds a counterexample

%r = -8 / -8 %r = -1 / (-8/-8)

Is This Valid?

```
Pre: C2 % (1<<C1) == 0
%s = shl nsw %A, C1
%r = sdiv %s, C2
  =>
%r = sdiv %A, C2/(1<<C1)
```

```
ERROR: Mismatch in values of i4 %r

Example:
%A i4 = 0xF (15, -1)
C1 i4 = 0x3 (3)
C2 i4 = 0x8 (8, -8)
%s i4 = 0x8 (8, -8)
Source value: 0x1 (1)
Target value: 0xF (15, -1)
```

Alive finds a counterexample

%r = 1 %r = -1 / 1

Is This Valid?

```
Pre: C2 % (1<<C1) == 0
%s = shl nsw %A, C1
%r = sdiv %s, C2
  =>
%r = sdiv %A, C2/(1<<C1)
```

```
ERROR: Mismatch in values of i4 %r

Example:
%A i4 = 0xF (15, -1)
C1 i4 = 0x3 (3)
C2 i4 = 0x8 (8, -8)
%s i4 = 0x8 (8, -8)
Source value: 0x1 (1)
Target value: 0xF (15, -1)
```

Alive finds a counterexample

`%r = (-1<< 3) / -8` `%r = -1 / (-8/(1<< 3))`

Is This Valid?

```
Pre: C2 % (1<<C1) == 0
%s = shl nsw %A, C1
%r = sdiv %s, C2
  =>
%r = sdiv %A, C2/(1<<C1)
```

```
ERROR: Mismatch in values of i4 %r

Example:
%A i4 = 0xF (15, -1)
C1 i4 = 0x3 (3)
C2 i4 = 0x8 (8, -8)
%s i4 = 0x8 (8, -8)
Source value: 0x1 (1)
Target value: 0xF (15, -1)
```

Alive finds a counterexample

```
%r = (-1<< 3) / -8        %r = -1 / (-8/(1<< 3))
```

Is This Valid?

```
Pre: C2 % (1<<C1) == 0
%s = shl nsw %A, C1
%r = sdiv %s, C2
  =>
%r = sdiv %A, C2/(1<<C1)
```

```
ERROR: Mismatch in values of i4 %r

Example:
%A i4 = 0xF (15, -1)
C1 i4 = 0x3 (3)
C2 i4 = 0x8 (8, -8)
%s i4 = 0x8 (8, -8)
Source value: 0x1 (1)
Target value: 0xF (15, -1)
```

Alive finds a counterexample

$1<<C_1$ wraps when $C_1 = \text{width}(C_1)-1$

This Is Valid

```
Pre: C2 % (1<<C1) == 0 && C1 != width(C1) - 1
%s = shl nsw %A, C1
%r = sdiv %s, C2
  =>
%r = sdiv %A, C2/(1<<C1)
```

Possibly too conservative?

This Is Also Valid

```
Pre: C2 % (1<<C1) == 0
%s = shl nsw %A, C1
%r = sdiv %s, C2
  =>
%r = sdiv %A, C2>>C1
```

ashr never wraps sign

This Is Also Valid

```
Pre: C2 % (1<<C1) == 0
%s = shl nsw %A, C1
%r = sdiv %s, C2
   =>
%r = sdiv %A, C2>>C1
```

```
C2/(1<<C1)
C2>>C1
```

This Is Also Valid

```
Pre: C2 % (1<<C1) == 0
%s = shl nsw %A, C1
%r = sdiv %s, C2
  =>
%r = sdiv %A, C2>>C1
```

```
-8/(1<< 3)
-8>>3
```

This Is Also Valid

```
Pre: C2 % (1<<C1) == 0
%s = shl nsw %A, C1
%r = sdiv %s, C2
  =>
%r = sdiv %A, C2>>C1
```

```
-8/-8
-1
```

Alive Is Already Useful

Goal is to make sure new transformations are correct. Emphasize value for developers

- W ered several incorrect optimizations
  - PR20186, PR21243, PR21244, PR21245, PR21255, PR21256, PR21274

- Alive can check whether proposed fixes are correct

  - Alive has helped improve several patches

Code Generation

- Translating Alive to LLVM Source is mechanical
  - …so let's let our machines do it
- Avoid mistranslations of Alive to C++
- Alive is an order of magnitude smaller than InstCombine

Alive

```
Pre: C1 & C2 == 0 && MaskedValueIsZero(%V2, ~C1)
%A   = or %B, %V2
%op0 = and %A, C1
%op1 = and %B, C2
%r   = or %op0, %op1
  =>
%A   = or %B, %V2
%r   = and %A, (C1 | C2)
```

Explain this more. Point out three things

C++

```
Value *op0, *op1, *B, *A, *V2;
ConstantInt *C1, *C2;

if (match(I, m_Or(m_Value(op0), m_Value(op1)))
      && match(op1, m_And(m_Value(B), m_ConstantInt(C2)))
      && match(op0, m_And(m_Value(A), m_ConstantInt(C1)))
      && match(A, m_Or(m_Specific(B), m_Value(V2)))
      && (C1->getValue() & C2->getValue()) == 0
      && MaskedValueIsZero(V2, ~C1->getValue()))
{
    Value *r =
        BinaryOperator::CreateAnd(A, ConstantExpr::getOr(C1, C2), "", I);
    I->replaceAllUsesWith(r);
    return true;
}
```

Mostly Straightforward

- Instructions in source use LLVM's pattern matching
- Instructions in target become constructors
- Constants become APInt or ConstantInt as needed
- Precondition and constant expressions map recursively to LLVM functions
- There are a few tricky bits…

Target creates constraints

```
%ax = zext %a
%bx = zext %b
%r  = and %ax, %bx
  =>
%c  = and %a, %b
%r  = zext %c
```

- Target is well-typed only if type(%a) = type(%b)
- Source is always well-typed
- Alive introduces an additional check

Explicit Types in Target

```
%ax = zext %a
%bx = zext %b
%r  = and %ax, %bx
  =>
%c  = and %a, %b
%r  = zext %c
```

- Literals and conversions require explicit types
- Alive matches target types to source values

Repeated Source Values

```
%r = add %a, %a
  =>
%r = shl %a, 1
```

- Variables can occur multiple times in source

- Alive uses m_Specific when possible

- Otherwise, introduces a dummy variable and an equality constraint

Future Work

- Fill in missing parts
  - More types (e.g., floating point)
    - More predicates
- Parameterize on instructions
- Deduce flag placement

Let Alive Work for You

- Express optimizations in high-level DSL
- Automatically detect errors
- Use generated code in LLVM
- Open source (https://github.com/nunoplopes/alive)