Verified expression graph optimization in GraalVM

Formal Methods Australia 2022

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6^{th} June 2022

Outline

1. Introduce *GraalVM*.
2. Introduce and *motivate* our research.
3. *Live demo* some of our work.
4. Explain the Isabelle/HOL representation.

Question

What is GraalVM™?

GraalVM

A State-of-the-Art *Optimizing* Compiler.

Key points on GraalVM

1. Open-source and written in Java.[1]

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1. Open-source and written in Java.[1]
2. Polyglot[2] compiler through partial evaluation.
3. JIT and AOT compilation modes.

---

[1] `https://github.com/oracle/graalvm`

[2] Multiple languages

Our goal

Verify the correctness of *optimizations* in the *GraalVM* compiler.

Two questions

1. Why verify the *optimizations*?
2. Why verify *GraalVM*?

Why verify the optimizations?

Compiler bugs are *bad*.

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Why verify the optimizations? [Yang et al., 2011]

GCC $\frac{75}{79} \approx 90\%$

Clang $\frac{183}{202} \approx 95\%$

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1. Comprehensive optimization suite.
2. Actively developed.
3. Unique/novel/challenging IR.
4. Partial evaluation relies heavily on optimizations.

Two questions

1. ~~Why verify the *optimizations*?~~
2. ~~Why verify *GraalVM*?~~

Bonus question

Why *verify* compilers at all?

Why verify the optimizations? [Yang et al., 2011]

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$\frac{0}{0} \approx$ ¯_(ツ)_/¯

Question

How do we verify an optimization?

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Answer

Use *Isabelle/HOL* to show that the optimized program refines the unoptimized program, thus the optimization is *semantics preserving*.

Steps to prove an optimization

1. A definition of what *any program* will do in *any state*.
2. Demonstrate that for *all states*: The unoptimized program will *behave the same* as the optimized program.

   i.e. semantics are preserved.

* Where we say *program* we mean the *intermediate representation* of the program

Steps to prove an optimization

1. ~~A definition of what *any program* will do in *any state*~~.
   [Webb et al., 2021]

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These proofs were hard…

Question

Why were these proofs hard?

Back to GraalVM™...

A simple program

```
» cat PositiveAdd.java

static int positiveAdd(int x, int y) {
    if ((((x - y) + y) - (x - y)) > 0) {
        return x + y;
    } else {
        return x - y;
    }
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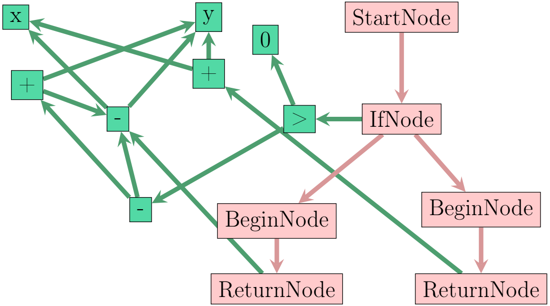

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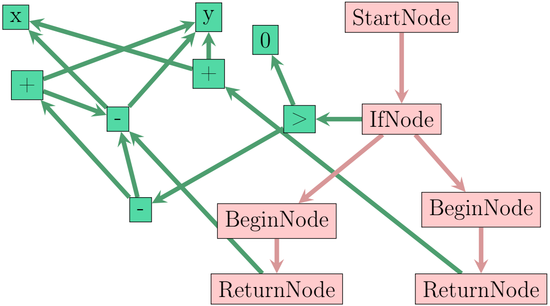


A mess!

Question

Why the mess?

Question

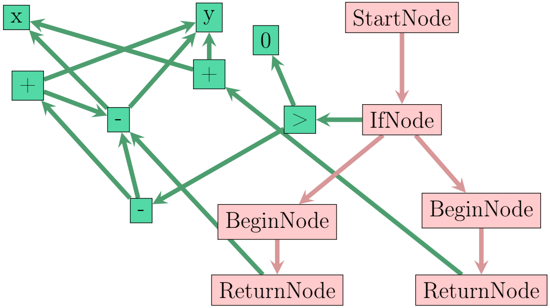
Why the mess?

Answer

It's very efficient [Click and Cooper, 1995].

Common subexpressions (or subgraphs) of the program can be *shared*.
Each unqiue expression is evaluated and stored once.

Important points on the GraalVM IR



- Expressions and control-flow are combined into one graph structure.
- Common sub-expressions are shared.
- Control-flow and data-flow (expressions) can have cycles.

Question

Why were these proofs hard?

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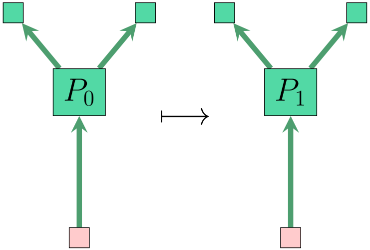
Why were these proofs hard?

Answer

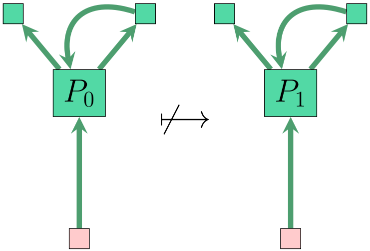
Graph updates can affect any expressions that share the updated expression.

We have to explicitly show that potential *cycles and self-reference* maintain semantic preservation.

Optimizing a graph



Optimizing a graph



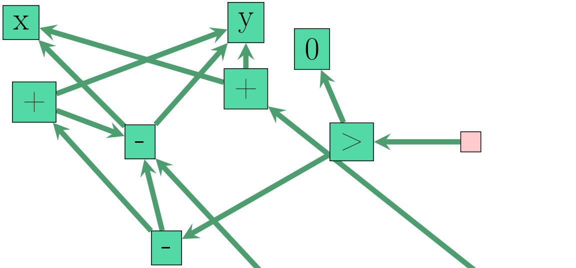
Optimizing a graph

Every optimization proof requires an *inductive proof* to satisfy *self-reference*.

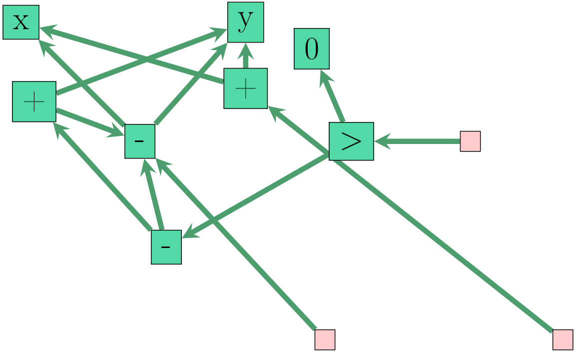
Solution

Represent expressions as *trees* rather than *graphs*.

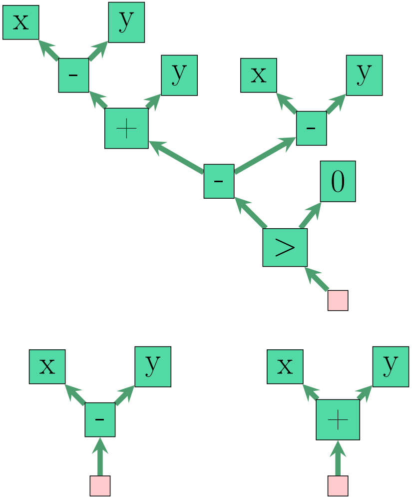
Recall our program graph



Removing sharing offers tree structures



$\longmapsto$



Added benefit

Trees enable natural infix encoding of optimization rules.

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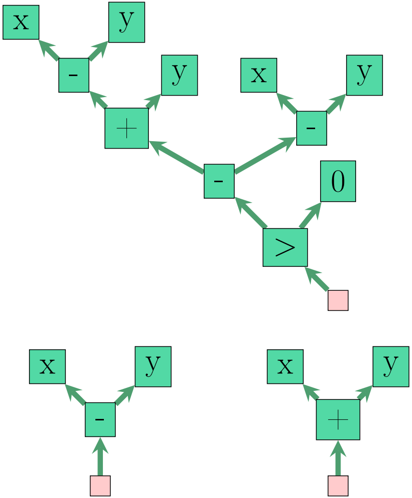
e.g. $x + 0 \longmapsto x$

How can we optimize these trees?



How about?

1. $(x - y) + y \longmapsto x$
2. $x - (x - y) \longmapsto y$

Wait...

Are these optimizations *correct*?

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What about *integer overflow*?

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What about *floating-point* arithmetic?

Wait...

Are these optimizations *correct*?

What about *integer overflow*?

What about *floating-point* arithmetic?

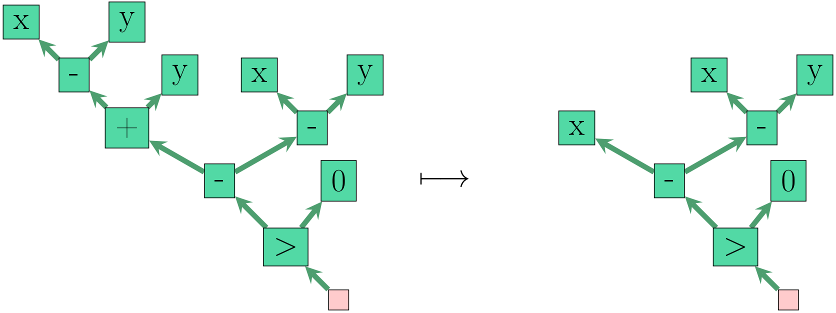
What about *side-effecting* operations?

Live demo

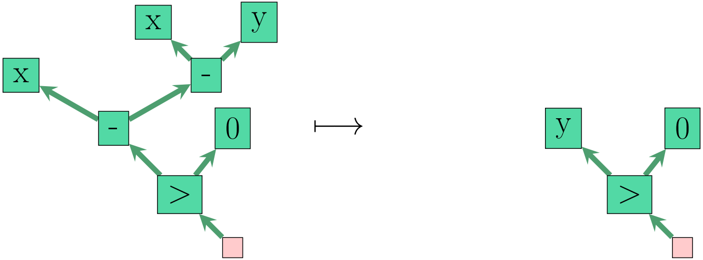
1. Show $(x - y) + y \longmapsto x$
2. Show $x - (x - y) \longmapsto y$

Now we have proofs

Let's apply the optimizations!



$$(x - y) + y \longmapsto x$$



$$x - (x - y) \longmapsto y$$

The fun part

How we represent and prove these optimizations.

Expression Trees

datatype *IRExpr* =
  UnaryExpr IRUnaryOp IRExpr
  | *BinaryExpr IRBinaryOp IRExpr IRExpr*
  | *ConditionalExpr IRExpr IRExpr IRExpr*
  | *ParameterExpr nat Stamp*
  | *LeafExpr nat Stamp*
  | *ConstantExpr Value*

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datatype *IRUnaryOp* =
UnaryAbs
| *UnaryNeg*
| *UnaryNot*
...

datatype *IRBinaryOp* =
BinAdd
| *BinMul*
| *BinSub*
...

Expression Semantics

Evaluating expressions depends on

- p a list of values of the parameters to the method
- m a mapping storing already evaluated leaf nodes
  - such as results from method calls

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Evaluating expression e to value v is represented by

Method parameters

Value

$$[\boxed{\mathrm{m}}, \boxed{\mathrm{p}}] \vdash \boxed{\mathrm{e}} \mapsto \boxed{\mathrm{v}}$$

Pre-calculated values

Expression

Expression Semantics

$$\frac{\mathit{valid\text{-}value}\ (\mathit{constantAsStamp}\ c)\ c}{[m,p] \vdash \mathit{ConstantExpr}\ c \mapsto c} \tag{1}$$

$$\frac{i < |p| \qquad \mathit{valid\text{-}value}\ s\ p_{[i]}}{[m,p] \vdash \mathit{ParameterExpr}\ i\ s \mapsto p_{[i]}} \tag{2}$$

$$\frac{[m,p] \vdash \mathit{xe} \mapsto v \qquad \mathit{unary\text{-}eval}\ \mathit{op}\ v \neq \mathit{UndefVal}}{[m,p] \vdash \mathit{UnaryExpr}\ \mathit{op}\ \mathit{xe} \mapsto \mathit{unary\text{-}eval}\ \mathit{op}\ v} \tag{3}$$

$$\frac{[m,p] \vdash \mathit{xe} \mapsto x \qquad [m,p] \vdash \mathit{ye} \mapsto y \qquad \mathit{bin\text{-}eval}\ \mathit{op}\ x\ y \neq \mathit{UndefVal}}{[m,p] \vdash \mathit{BinaryExpr}\ \mathit{op}\ \mathit{xe}\ \mathit{ye} \mapsto \mathit{bin\text{-}eval}\ \mathit{op}\ x\ y} \tag{4}$$

$$\frac{\mathit{val} = m\ n \qquad \mathit{valid\text{-}value}\ s\ \mathit{val}}{[m,p] \vdash \mathit{LeafExpr}\ n\ s \mapsto \mathit{val}} \tag{5}$$

Expression refinement

For $e2$ to be an correct optimization of $e1$ we require that

- whenever $e1$ evaluates to a value v in some context $[m, p]$, so does $e2$.
- $e2$ *refines* $e1$,

$$(e2 \leq e1) = (\forall\, m\ p\ v.\ [m,p] \vdash e1 \mapsto v \longrightarrow [m,p] \vdash e2 \mapsto v)$$

- $e2$ may be well formed in more contexts than $e1$, e.g. $x - x \geq 0$

Expression Semantics

$$\frac{\mathit{valid\text{-}value}\ (\mathit{constantAsStamp}\ c)\ c}{[m,p] \vdash \mathit{ConstantExpr}\ c \mapsto c} \tag{6}$$

$$\frac{i < |p| \qquad \mathit{valid\text{-}value}\ s\ p_{[i]}}{[m,p] \vdash \mathit{ParameterExpr}\ i\ s \mapsto p_{[i]}} \tag{7}$$

$$\frac{[m,p] \vdash xe \mapsto v \qquad \mathit{unary\text{-}eval}\ op\ v \neq \mathit{UndefVal}}{[m,p] \vdash \mathit{UnaryExpr}\ op\ xe \mapsto \mathit{unary\text{-}eval}\ op\ v} \tag{8}$$

$$\frac{[m,p] \vdash xe \mapsto x \qquad [m,p] \vdash ye \mapsto y \qquad \mathit{bin\text{-}eval}\ op\ x\ y \neq \mathit{UndefVal}}{[m,p] \vdash \mathit{BinaryExpr}\ op\ xe\ ye \mapsto \mathit{bin\text{-}eval}\ op\ x\ y} \tag{9}$$

$$\frac{\mathit{val} = m\ n \qquad \mathit{valid\text{-}value}\ s\ \mathit{val}}{[m,p] \vdash \mathit{LeafExpr}\ n\ s \mapsto \mathit{val}} \tag{10}$$

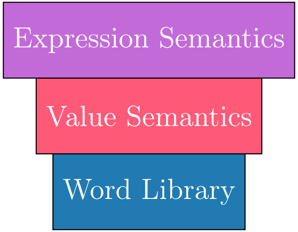
Value Semantics

$$
\begin{array}{l}
\textbf{fun } \textit{intval-add} :: \textit{Value} \Rightarrow \textit{Value} \Rightarrow \textit{Value} \textbf{ where}\\
\quad \textit{intval-add } (\textit{IntVal32 } v1)\ (\textit{IntVal32 } v2) = (\textit{IntVal32 } (v1+v2))\ |\\
\quad \textit{intval-add } (\textit{IntVal64 } v1)\ (\textit{IntVal64 } v2) = (\textit{IntVal64 } (v1+v2))\ |\\
\quad \textit{intval-add } \text{-}\ \text{-} = \textit{UndefVal}
\end{array}
$$

$$
\begin{array}{l}
\textbf{fun } \textit{intval-xor} :: \textit{Value} \Rightarrow \textit{Value} \Rightarrow \textit{Value} \textbf{ where}\\
\quad \textit{intval-xor } (\textit{IntVal32 } v1)\ (\textit{IntVal32 } v2) = (\textit{IntVal32 } (v1\ \textit{XOR}\ v2))\ |\\
\quad \textit{intval-xor } (\textit{IntVal64 } v1)\ (\textit{IntVal64 } v2) = (\textit{IntVal64 } (v1\ \textit{XOR}\ v2))\ |\\
\quad \textit{intval-xor } \text{-}\ \text{-} = \textit{UndefVal}
\end{array}
$$

$$
\begin{array}{l}
\textbf{fun } \textit{bin-eval} :: \textit{IRBinaryOp} \Rightarrow \textit{Value} \Rightarrow \textit{Value} \Rightarrow \textit{Value} \textbf{ where}\\
\quad \textit{bin-eval BinAdd } v1\ v2 = \textit{intval-add } v1\ v2\ |\\
\quad \textit{bin-eval BinXor } v1\ v2 = \textit{intval-xor } v1\ v2\ |\\
\ldots
\end{array}
$$

Our Proof Approach



With those definitions

We can start proving!

In summary

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- *reduces the proof burden* by a factor of 5 (by line count), while proving a significantly stronger property, and
- includes *termination* as a proof-obligation.

Future work

- Expand on *proof automation*.

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- Extend the DSL to *factor out common side conditions*.

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- Expand on *proof automation*.
- Extend the DSL to *factor out common side conditions*.
- Resume work *control-flow optimizations*.

Thank you!

Any questions?

References

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