CSC2/455 Software Analysis and Improvement
Value Numbering

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Jan 23, 2023
URCS
Outline

Review

An Introduction to Code Optimization

Local Value Numbering (LVN)

Postscript
What we know how to do so far

- ASTs to 3-address code
- 3-address code to Basic Blocks
- Basic blocks to Control Flow Graphs
- (Tested in second assignment, already out)
Some Useful Background Material

- Not needed if you have CSC 2/454
- Otherwise, read Cooper and Turczon:
  - Chapter 6 (“The Procedure Abstraction”)
  - Chapter 7 (“Code Shape”)
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Basic Goals

- Reduce execution time ("performance")
  - Most of our time spent on this topic
- Reduce code size
  - Was hugely important, less so in the past decade or so
  - Increasingly important again (small devices, slow memory, etc.)
- Code size reduction *often* improves performance
  - Instructions that do not execute consume no time
  - Better cache behaviour
  - But not always...
Can’t programmers write fast code?

Major impediments:

- High-level languages
  - Productivity is more important than performance(?)
  - But lose control over machine

- Complex machines
  - Out-of-order superscalar machines

- “Simple” machines
  - Very-long instruction word (VLIW) machines
Classifying Optimizations

- At what level of code should we look at to identify optimization opportunities?
- What additional information about the program can help us?
Peephole Optimizations

- Look at a window (or “peephole”) of instructions in 3-address code
  - Usually within a basic block
- Example: Strength reduction
  - Replacing costly operations (e.g. multiply) by cheaper operations (e.g. shifts)
  - \( a \times 8 \) can be replaced with \( a \ll 3 \)
- Usually implemented by pattern matching over a pre-defined library
  - Library usually constructed by reading books like *Hacker’s Delight* or *Matters Computational: Ideas, Algorithms, Source Code*
Local optimizations

- Look at basic blocks only
- Remember:
  - If one instruction in basic block executes, *all* instructions execute
  - Can assume instructions execute one after the other
- Major limitation
  - Size (Length) of basic block
Increasing the size of basic blocks

- “Region” analysis
- Many forms:
  - Extended Basic Blocks
  - Superblocks
  - Hyperblocks
- Basic idea, use a trace to build a larger basic block
  - a trace is an execution path
Global optimizations

- Global means *procedure* level
  - A procedure has a single entry and exit
  - E.g. C functions
  - *not* global as in global variables
- A global analysis usually operates on a control-flow graph
- Sometimes called “intraprocedural” analysis
Interprocedural (Whole program) Optimizations

- Operates on the entire source code of a program
- Sometimes called “context-sensitive analysis”
  - Allows compiler to distinguish invocations of the same function
  - More opportunities for optimization!
- Must keep track of function calls
  - Usually, in a structure called the “call graph”
• Traditional compiler flow
  • Program contains multiple translation units (usu. a .c file)
  • Translation unit to object (.o file)
  • Combine object files and libraries ("link") to generate executable
  • Usually hidden by a compiler driver like gcc
• Misses opportunities for cross-object optimizations
- LLVM LTO
- GCC LTO
- These require that object files be in compiler-specific intermediate representations
  - LLVM Bitcode for LLVM
  - GIMPLE for GCC
- Nice case studies of Firefox being compiled with LTO online
  - Search for “Firefox LTO Link Time Optimization”
Runtime (Dynamic) optimization

- Optimization while a program is running
- Sometimes a necessity:
  - E.g., JavaScript
- Sometimes called Just-in-time (JIT) compilation
  - because mostly associated with JIT VMs
- Big advantage:
  - Have nearly all the information required to optimize program
- Big disadvantage?
Examples of Dynamic Optimizers

- Java
  - Hotspot VM
- JavaScript
  - V8
- Python
  - PyPy
- Your-language-here
  - RPython (used to build PyPy)
  - Graal and Truffle
Most optimizers only look at source code

But additional information can help:

- What is the most common direction of this branch? (see gcc’s __builtin_expect)
- What is the most likely target of this indirect function call?

General technique: *profile-based optimization* or *profile-guided optimization (PGO)*

- Instrument program to generate statistics (i.e. profile)
- Generate statistics on program run
- Compiler recompiles code based on gathered profile
Profile-guided Optimization using GCC

```bash
gcc -fprofile-generate program.c  # instrumented executable
./program                        # gathers profile data
gcc -fprofile-use program.c      # PGO executable
```

- This instruments the code to gather:
  - statistics of values in expressions
  - branch probabilities

- These values are gathered ("profiled") when the program is run

- The feedback gathered during a run can be used for:
  - Inlining functions
  - Laying out code
  - Loop unrolling, etc.
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Getting rid of redundant calculations

\[ ed = (a_0 - a_1)(a_0 - a_1) + (b_0 - b_1)(b_0 - b_1) \]

Optimized code sequence:

\[
\begin{align*}
t_1 &= a_0 - a_1 \\
t_2 &= t_1 \times t_1 \\
t_3 &= b_0 - b_1 \\
t_4 &= t_3 \times t_3 \\
ed &= t_2 + t_4
\end{align*}
\]
Where does this code arise?

- High-level languages
- AST to 3-address code generation rules
  - e.g. array indexing
  - \( x = A[i][j] + A[i][j+1] \)?
Array indexing example

t1 = i * dimsize(A, 1)
t2 = t1 + j
t3 = *(A + t2)

t4 = i * dimsize(A, 1)
t5 = t4 + j
t6 = t5 + 1
t7 = *(A + t6)

x = t3 + t7

dimsize(A, dim) is a function that returns an integer indicating the size of dimension \textit{dim} of array A (0 or 1).
- Compilers rewrite and lower your code
- Can introduce significant redundancy in the process
- Logically cleaner (and simpler!) to reduce redundancy using dedicated *passes*
  - Keeps rewrites (incl. translation) simple
Value Numbering

- Value numbering is a local optimization
- Assigns numbers to each value in the basic block
  - Literals
  - Variables
  - Expressions
  - $VN(x)$ is the number assigned to $x$
- Design $VN(x)$ such that:
  - $VN(x) == VN(y)$ if-and-only-if (iff) $x == y$
**Example case**

\[
\begin{align*}
t1 &= a0 - a1 \\
t2 &= a0 - a1 \\
t3 &= t1 \times t2 \\
t4 &= b0 - b1 \\
t5 &= b0 - b1 \\
t6 &= t4 \times t5 \\
ed &= t3 + t6
\end{align*}
\]
Example case: Assigning value numbers

\[ t1 = a0 - a1 \quad \# \ 2 = 0 - 1 \]
\[ t2 = a0 - a1 \quad \# \ 2 = 0 - 1 \]
\[ t3 = t1 * t2 \quad \# \ 3 = 2 * 2 \]
\[ t4 = b0 - b1 \quad \# \ 6 = 4 - 5 \]
\[ t5 = b0 - b1 \quad \# \ 6 = 4 - 5 \]
\[ t6 = t4 * t5 \quad \# \ 7 = 6 * 6 \]
\[ \text{ed} = t3 + t6 \quad \# \ 8 = 3 + 7 \]
After optimization

t1 = a0 - a1  # 2 = 0 - 1
\[ t3 = t1 \times t1 \]  # 3 = 2 \times 2
\[ t4 = b0 - b1 \]  # 6 = 4 - 5
\[ t6 = t4 \times t4 \]  # 7 = 6 \times 6
\[ \text{ed} = t3 + t6 \]  # 8 = 3 + 7

Algorithms in Figure 8.2, 8.4 of Cooper and Turczon
Quality of $VN(x)$

- What happens if your $VN(x)$ assigns different values to $VN(x)$ and $VN(y)$ when $x == y$?
  - $a = 1 * c$
  - $b = c$

- What happens if your $VN(x)$ assigns the same value to $VN(x)$ and $VN(y)$ when $x \neq y$?
  - $t1 = c + d$; $t2 = t1 + e$
  - $t3 = d + e$; $t4 = t3 + c$
  - Here: is $t2$ equal to $t4$?
  - (assume $c$, $d$ and $e$ are float)
Completeness and Soundness

- Let \( \star \) represent true statements, \( \ast \) represent false statements
- Let there be a procedure \( P \) that takes a statement as input and determines if it is true or not
- If \( P(\star) = T \) and \( P(\ast) = F \) for all \( \star \) and \( \ast \), \( P \) is sound and complete
- Usually, though \( P(\star) = \)? or \( P(\ast) = \)?, i.e. \( P \) is incomplete
- Additionally, if \( P(\ast) \) never returns true, \( P \) is sound
Completeness and Soundness

- **Completeness**
  - Can we prove all true statements?
  - e.g., can we derive equality for all expressions that are equal?
  - False Negative, we say “no”, when it is actually “yes” [Type II error]

- **Soundness**
  - Roughly, are all statements that have proofs actually true?
  - e.g., we can never derive equality for expressions that are not equal
  - False Positive, we say “yes”, when it is actually “no” [Type I error]
Why limit ourselves to basic blocks?

What would happen if we ran value numbering across basic blocks?
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References

- Chapter 8 of Cooper and Turczon
  - Up to (but not including) 8.4.2
- Spare time reading (rec. for PhD students)
  - Livshits et al., 2015, In defense of Soundiness: A Manifesto, Communications of the ACM
  - Also see, http://soundiness.org/