CSC2/455 Software Analysis and Improvement
Value Numbering

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URCS
Outline

Review

An Introduction to Code Optimization

Local Value Numbering (LVN)

Postscript
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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, out later this week)
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 * 8 can be replaced with a << 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”
Link-time Optimization

- 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
Link Time Optimizers

- 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

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

\[ ed = (a_0 - a_1)^2 + (b_0 - b_1)^2 \]

Optimized code sequence:

\[
\begin{align*}
  t1 &= a_0 - a_1 \\
  t2 &= t1 * t1 \\
  t3 &= b_0 - b_1 \\
  t4 &= t3 * t3 \\
  ed &= t2 + t4
\end{align*}
\]
Where does this code arise?

- High-level languages
- AST to 3-address code generation rules
  - e.g. array indexing
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).
Compiler structure

- 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

t1 = a0 - a1

t2 = a0 - a1

t3 = t1 * t2


t4 = b0 - b1

t5 = b0 - b1

t6 = t4 * t5

ed = t3 + t6
Example case: Assigning value numbers

t1 = a0 - a1  # 2 = 0 - 1
t2 = a0 - a1  # 2 = 0 - 1
t3 = t1 * t2  # 3 = 2 * 2

t4 = b0 - b1  # 6 = 4 - 5
t5 = b0 - b1  # 6 = 4 - 5
t6 = t4 * t5  # 7 = 6 * 6

ed = t3 + t6  # 8 = 3 + 7
After optimization

\[
\begin{align*}
t1 &= a_0 - a_1 \quad \#\ 2 = 0 - 1 \\
t3 &= t1 \times t1 \quad \#\ 3 = 2 \times 2 \\
t4 &= b_0 - b_1 \quad \#\ 6 = 4 - 5 \\
t6 &= t4 \times t4 \quad \#\ 7 = 6 \times 6 \\
ed &= t3 + t6 \quad \#\ 8 = 3 + 7
\end{align*}
\]

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 $x \neq y$?
  - $t_1 = c + d$; $t_2 = t_1 + e$
  - $t_3 = d + e$; $t_4 = t_3 + c$
  - Here: is $t_2$ equal to $t_4$?
  - (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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• Chapter 8 of Cooper and Turczon
  • Up to (but not including) 8.4.2