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 next 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
• 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”
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

```
a.c
cc
a.o
cc
b.c
cc
b.o
ld
libc
ld
a.out
```
• 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
dir                       # 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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ed = (a0 - a1) * (a0 - a1) + (b0 - b1) * (b0 - b1)

Optimized code sequence:

t1 = a0 - a1

 t2 = t1 * t1

 t3 = b0 - b1

 t4 = t3 * t3

 ed = t2 + t4
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 \textit{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

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

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

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

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 $x == y$?
  - $a = 1 \times c$
  - $b = c$

- 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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• 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/