CSC2/455 Software Analysis and Improvement
Value Numbering

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URCS

Outline

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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")

Outline

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

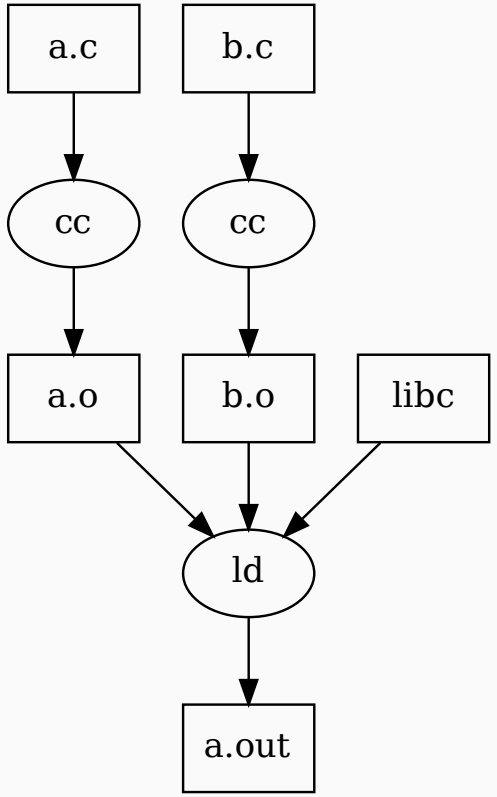
- Global means *procedure* level
  - A procedure has a single entry and exit
  - E.g. C functions
  - *not* global as in global variables
- A global analysis usually operates on a control-flow graph
- Sometimes called "intraprocedural" analysis

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"

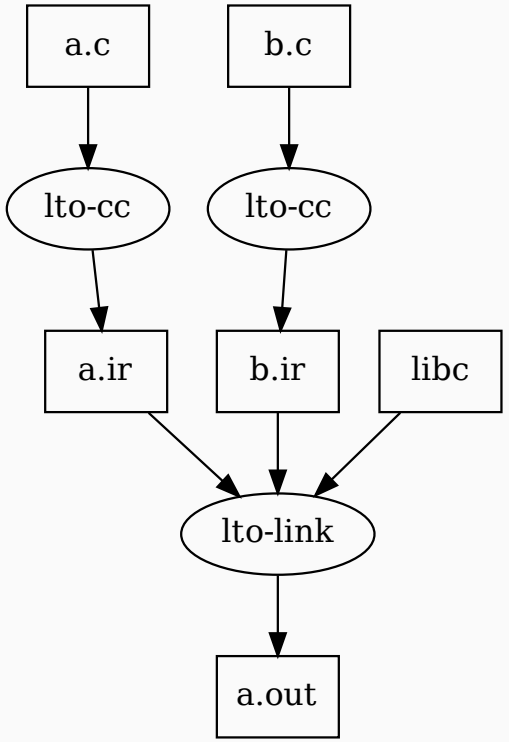
Link-time Optimization

- 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

Additional Information: Profiles

- 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.

Outline

Getting rid of redundant calculations

```
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 *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 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

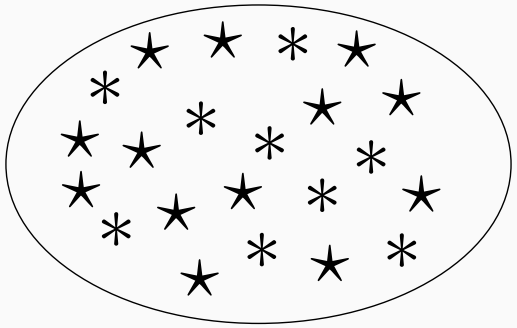
```
t1 = a0 - a1      # 2 = 0 - 1
t3 = t1 * t1      # 3 = 2 * 2

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

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, $*$ 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 $P(*) = F$ for all $\star$ and $*$, P is sound and complete
- Usually, though $P(\star) =?$ or $P(*) =?$, i.e. P is incomplete
- Additionally, if $P(*)$ 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?

Outline

References

- Chapter 8 of Cooper and Turczon
  - Up to (but not including) 8.4.2