Programming Languages & Translators

COMPILER OPTIMIZATION

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These slides are motivated from Prof. Alex Aiken and Prof. Calvin Lin

Optimization

- Optimization is our last compiler phase
- Most complexity in modern compilers is in the optimizer
  - Also by far the largest phase
- Optimizations are often applied to intermediate representations of code

When should we perform optimizations?

- On AST
  - Pro: Machine independent
  - Con: Too high level
- On assembly language
  - Pro: Exposes optimization opportunities
  - Con: Machine dependent
  - Con: Must reimplement optimizations when retargetting
- On an intermediate language
  - Pro: Machine independent
  - Pro: Exposes optimization opportunities

Intermediate Languages

- Intermediate language = high-level assembly
  - Uses register names, but has an unlimited number
  - Uses control structures like assembly language
  - Uses opcodes but some are higher level
    - E.g., push translates to several assembly instructions
  - Most opcodes correspond directly to assembly opcodes

Three-Address Intermediate Code

- Each instruction is of the form
  - x := y op z (binary operation)
  - x := op y (unary operation)
  - y and z are registers or constants
  - Common form of intermediate code
- The expression x + y * z is translated
  - t1 := y * z
  - t2 := x + t1
  - Each subexpression has a "name"

Optimization Overview

- Optimization seeks to improve a program's resource utilization
  - Execution time (most often)
  - Code size
  - Network messages sent, etc.
- Optimization should not alter what the program computes
  - The answer must still be the same

A Classification of Optimizations

- For languages like C there are three granularities of optimizations
  1. Local optimizations
     - Apply to a basic block in isolation
  2. Global optimizations
     - Apply to a control-flow graph (method body) in isolation
  3. Inter-procedural optimizations
     - Apply across method boundaries
- Most compilers do (1), many do (2), few do (3)

Cost of Optimizations

- In practice, a conscious decision is made not to implement the fanciest optimization known
- Why?
  - Some optimizations are hard to implement
  - Some optimizations are costly in compilation time
  - Some optimizations have low benefit
  - Many fancy optimizations are all three!
- Goal: Maximum benefit for minimum cost

Local Optimizations

- The simplest form of optimizations
- No need to analyze the whole procedure body
  - Just the basic block in question
- Example: algebraic simplification

Algebraic Simplification

- Some statements can be deleted
  - x := x + 0
  - x := x * 1
- Some statements can be simplified
  - x := x * 0 ⇒ x := 0
  - y := y ** 2 ⇒ y := y * y
  - x := x * 8 ⇒ x := x << 3
  - x := x * 15 ⇒ t := x << 4; x := t - x

  (on some machines << is faster than *; but not on all!)

Constant Folding

- Operations on constants can be computed at compile time
  - If there is a statement x := y op z
  - And y and z are constants
  - Then y op z can be computed at compile time
- Example: x := 2 + 2 ⇒ x := 4
- Example: if 2 < 0 jump L can be deleted
- When might constant folding be dangerous?

Flow of Control Optimizations

- Eliminate unreachable basic blocks:
  - Code that is unreachable from the initial block
    - E.g., basic blocks that are not the target of any jump or "fall through" from a conditional
- Why would such basic blocks occur?
- Removing unreachable code makes the program smaller
  - And sometimes also faster
    - Due to memory cache effects (increased spatial locality)

Single Assignment Form

- Some optimizations are simplified if each register occurs only once on the left-hand side of an assignment
- Rewrite intermediate code in single assignment form

```
x := z + y              b := z + y
a := x          ⇒       a := b
x := 2 * x              x := 2 * b
```

(b is a fresh register)

- More complicated in general, due to loops

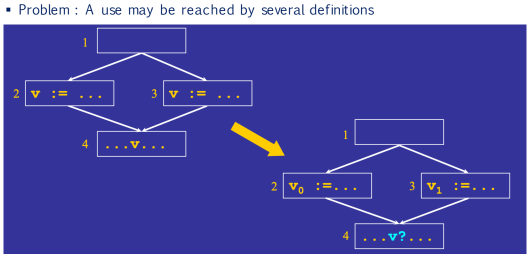
Static Single Assignment (SSA) Form

- Idea
  - Each variable has only one static definition
  - Makes it easier to reason about values instead of variables
  - The point of SSA form is to represent use-def information explicitly
- Transformation to SSA
  - Rename each definition
  - Rename all uses reached by that definition
- Example:

```
v := …                   v0 := …
… := … v …               … := … v0 …
v := …         ⟶         v1 := …
… := … v …               … := … v1 …
v := …                   v2 := …
… := … v …               … := … v2 …
```

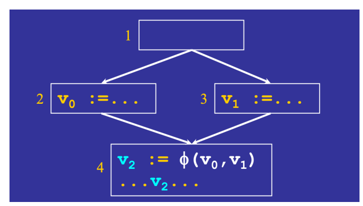
SSA and Control Flow

- Problem : A use may be reached by several definitions



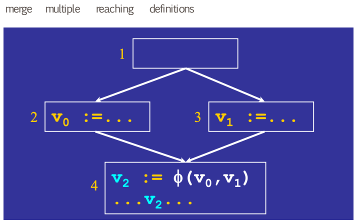
SSA and Control Flow (cont)

- Merging Definitions
  - ø-functions merge multiple reaching definitions



SSA and Control Flow (cont)

- Merging Definitions
  - ø-functions merge multiple reaching definitions



SSA vs. use-def chain

- SSA form is more constrained
- Advantages of SSA
  - More compact
  - Some analyses become simpler when each use has only one def
  - Value merging is explicit
  - Usually, easier to update and manipulate
- Furthermore
  - Eliminates false dependenc es (simplifying context)

SSA vs. use-def chain

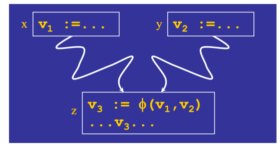
- Worst case du-chains?

```
switch (c1) {
      case 1: x = 1; break;
      case 2: x = 2; break;
      case 3: x = 3; break;
}
switch (c2) {
      case 1: y1 = x; break;
      case 2: y2 = x; break;
      case 3: y3 = x; break;
      case 4: y4 = x; break;
}
```

m defs and n uses leads to mxn du chains

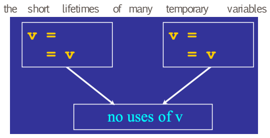
Transformation to SSA Form

- Two steps
  - Insert ∅-functions
  - Rename variables
- Basic Rule of Place ∅-Functions?
  - If two distinct (non-null) paths x->z and y->z converge at node z, and nodes x and y contain definitions of variable v, then we insert a ∅-function for v at z



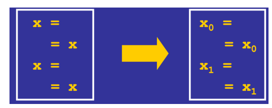
Approaches to Placing ∅-Functions

- Minimal
  - As few as possible subject to the basic rule
  - How is this sub-optimal?
- Briggs-Minimal
  - Same as minimal, except v must be live across some edge of the CFG
    - Briggs Minimal will not place a ∅ function in this case because v is not live across any CFG edge.
    - Exploits the short lifetimes of many temporary variables



SSA: Variable Renaming

- When we see a variable on the LHS, create a new name for it
- When we see a variable on the RHS, use appropriate subscript
- Easy for straight forward code



- Harder when there's control flow
  - For each use of x, find the definition of x that dominates it

Common Subexpression Elimination

- If
  - Basic block is in single assignment form
  - A definition x := is the first use of x in a block
- Then
  - When two assignments have the same rhs, they compute the same value
- Example:

x := y + z		x := y + z
…	⇒	…
w := y + z		w := x

(the values of x, y, and z do not change in the … code)

Copy Propagation

- If w := x appears in a block, replace subsequent uses of w with uses of x
  - Assumes single assignment form
- Example:

b := z + y		b := z + y
a := b	⇒	a := b
x := 2 * a		x := 2 * b

- Only useful for enabling other optimizations
  - Constant folding
  - Dead code elimination

Copy Propagation and Constant Folding

- Example:

```
a := 5              a := 5
x := 2 * a    ⇒     x := 10
y := x + 6          y := 16
t := x * y          t := x << 4
```

Copy Propagation and Dead Code Elimination

- If
  - w := rhs appears in a basic block
  - w does not appear anywhere else in the program
- Then the statement w := rhs is dead and can be eliminated
  - Dead = does not contribute to the program's result
  - Example: (a is not used anywhere else)

```
x := z + y        b := z + y        b := z + y
a := x      ⇒     a := b      ⇒     x := 2 * b
x := 2 * a        x := 2 * b
```

Applying Local Optimizations

- Each local optimization does little by itself
- Typically optimizations interact
  - Performing one optimization enables another
- Optimizing compilers repeat optimizations until no improvement is possible
  - The optimizer can also be stopped at any point to limit compilation time

An Example

- Initial code:

```
a := x ** 2
b := 3
c := x
d := c * c
e := b * 2
f := a + d
g := e * f
```

An Example

- Algebraic optimization:

```
a := x ** 2        a := x * x
b := 3             b := 3
c := x             c := x
d := c * c         d := c * c
e := b * 2         e := b << 1
f := a + d         f := a + d
g := e * f         g := e * f
```

An Example

- Copy Propagation:

```
a := x * x         a := x * x
b := 3             b := 3
c := x             c := x
d := c * c         d := x * x
e := b << 1        e := 3 << 1
f := a + d         f := a + d
g := e * f         g := e * f
```

An Example

- Constant folding:

```
a := x * x
b := 3
c := x
d := x * x
e := 3 << 1
f := a + d
g := e * f
```

```
a := x * x
b := 3
c := x
d := x * x
e := 6
f := a + d
g := e * f
```

An Example

- Common subexpression elimination:

```
a := x * x
b := 3
c := x
d := x * x
e := 6
f := a + d
g := e * f
```

```
a := x * x
b := 3
c := x
d := a
e := 6
f := a + d
g := e * f
```

An Example

- Copy propagation:

```
a := x * x
b := 3
c := x
d := a
e := 6
f := a + d
g := e * f
```

```
a := x * x
b := 3
c := x
d := a
e := 6
f := a + a
g := 6 * f
```

An Example

- Dead code elimination:

```
a := x * x
b := 3
c := x
d := a
e := 6
f := a + a
g := 6 * f
```

```
a := x * x
f := a + a
g := 6 * f
```

Peephole Optimizations on Assembly Code

- These optimizations work on intermediate code
  - Target independent
  - But they can be applied on assembly language also
- Peephole optimization is effective for improving assembly code
  - The "peephole" is a short sequence of (usually contiguous) instructions
  - The optimizer replaces the sequence with another equivalent one (but faster)

Peephole Optimizations (Cont.)

- Write peephole optimizations as replacement rules

  $i_1, \ldots, i_n \rightarrow j_1, \ldots, j_m$

  where the rhs is the improved version of the lhs
- Example:

  move $a $b, move $b $a → move $a $b
  - Works if move $b $a is not the target of a jump
- Another example

  addiu $a $a i, addiu $a $a j → addiu $a $a i+j

Peephole Optimizations (Cont.)

- Many (but not all) of the basic block optimizations can be cast as peephole optimizations
  - Example: addiu $a $b 0 → move $a $b
  - Example: move $a $a → –
  - These two together eliminate addiu $a $a 0
- As for local optimizations, peephole optimizations must be applied repeatedly for maximum effect

Local Optimizations: Notes

- Intermediate code is helpful for many optimizations
- Many simple optimizations can still be applied on assembly language
- "Program optimization" is grossly misnamed
  - Code produced by "optimizers" is not optimal in any reasonable sense
  - "Program improvement" is a more appropriate term