Local Optimizations

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Lecture Outline

- Wrap up operational semantics: Dispatch
- Optimization
  - Introduction
  - Intermediate code
  - Local optimizations

Dispatch

$e_0.f(e_1, \ldots, e_n)$

1. Eval args in order
2. Eval e_0

Order seems odd.

Can it affect the result?

Dispatch

$e_0.f(e_1, \ldots, e_n)$

1. Eval args in order
2. Eval e_0
3. Let X be the dynamic type of e_0 value
4. Get definition of f from X
5. Create n new locations for args
6. Update E to map formals to new locations
7. Update S to map new locs to arg values
8. Set self to e_0 value
9. Eval body of f

Notation: $\text{Impl}(A, f) = (x_1, x_2, \ldots, x_n, e_{body})$

x_i – formal parameters

e_{body} – body of function

$$so, E, S \vdash e_1 : v_1, S_1$$

$$\ldots$$

$$so, E, S_{n-1} \vdash e_n : v_n, S_n$$

$$so, E, S_n \vdash e_0 : v_0, S_{n+1}$$

e_0 evaluated with all side effects of $e_1 \ldots e_n$

$$\overline{so, E, S \vdash e_0.f(e_1, \ldots, e_n) : v, S_{n+3}}$$

$$so, E, S \vdash e_1 : v_1, S_1$$

$$\ldots$$

$$so, E, S_{n-1} \vdash e_n : v_n, S_n$$

$$so, E, S_n \vdash e_0 : v_0, S_{n+1}$$

$$v_0 = X(a_1 = l_1, \ldots, a_m = l_m) \quad \leftarrow \text{get class and attributes of object}$$

$$\overline{}$$

$$so, E, S \vdash e_0.f(e_1, \ldots, e_n) : v, S_{n+3}$$

$$
\frac{
\begin{array}{l}
so, E, S \vdash e_1 : v_1, S_1 \\
\ldots \\
so, E, S_{n-1} \vdash e_n : v_n, S_n \\
so, E, S_n \vdash e_0 : v_0, S_{n+1} \\
v_0 = X(a_1 = l_1, \ldots, a_m = l_m) \\
impl(X, f) = (x_1, x_2, \ldots, x_n, e_{body})
\end{array}
}{
so, E, S \vdash e_0.f(e_1, \ldots, e_n) : v, S_{n+3}
}
$$

formals & body of f

$$so, E, S \vdash e_1 : v_1, S_1$$

$$\dots$$

$$so, E, S_{n-1} \vdash e_n : v_n, S_n$$

$$so, E, S_n \vdash e_0 : v_0, S_{n+1}$$

$$v_0 = X(a_1 = l_1, \dots, a_m = l_m)$$

$$impl(X, f) = (x_1, x_2, \dots, x_n, e_{body})$$

$$l_{xi} = newloc(S_{n+1}) \text{ for } i = 1, \dots, n$$

new locations for arguments

$$\overline{so, E, S \vdash e_0.f(e_1, \dots, e_n) : v, S_{n+3}}$$

$$
\frac{\begin{array}{l}
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l_{xi} = newloc(S_{n+1}) \text{ for } i = 1, \ldots, n \\
E' = \underbrace{[a_1 : l_1, \ldots a_m : l_m]}_{\text{start with X attributes only}} \underbrace{[x_1/l_{x1}, \ldots, x_n/l_{xn}]}_{\text{then bind formals to new locations}}
\end{array}}{so, E, S \vdash e_0.f(e_1, \ldots, e_n) : v, S_{n+3}}
$$

$$so, E, S \vdash e_1 : v_1, S_1$$

$$\ldots$$

$$so, E, S_{n-1} \vdash e_n : v_n, S_n$$

$$so, E, S_n \vdash e_0 : v_0, S_{n+1}$$

$$v_0 = X(a_1 = l_1, \ldots, a_m = l_m)$$

$$impl(X, f) = (x_1, x_2, \ldots, x_n, e_{body})$$

$$l_{xi} = newloc(S_{n+1}) \text{ for } i = 1, \ldots, n$$

$$E' = [a_1 : l_1, \ldots a_m : l_m][x_1/l_{x1}, \ldots, x_n/l_{xn}]$$

$$S_{n+2} = S_{n+1}[v_1/l_{x1}, \ldots, v_n/l_{xn}]$$

↑ assign actuals to formals

$$\frac{}{so, E, S \vdash e_0.f(e_1, \ldots, e_n) : v, S_{n+3}}$$

$$so, E, S \vdash e_1 : v_1, S_1$$

$$\dots$$

$$so, E, S_{n-1} \vdash e_n : v_n, S_n$$

$$so, E, S_n \vdash e_0 : v_0, S_{n+1}$$

$$v_0 = X(a_1 = l_1, \dots, a_m = l_m)$$

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$$S_{n+2} = S_{n+1}[v_1/l_{x1}, \dots, v_n/l_{xn}]$$

look carefully

$$v_0, E', S_{n+2} \vdash e_{body} : v, S_{n+3}$$

$$so, E, S \vdash e_0.f(e_1, \dots, e_n) : v, S_{n+3}$$

Optimization

OPTIMIZATION

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

Optimization

- Optimization is our last compiler phase

- Most complexity in modern compilers is in the optimizer
  - Also by far the largest phase

- First, we need to discuss intermediate languages

INTERMEDIATE LANGUAGES

Why Intermediate Languages?

- 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

$$x := y \text{ op } z$$

$$x := \text{op } y$$

  - y and z are registers or constants
  - Common form of intermediate code
- The expression $x + y * z$ is translated

$$t_1 := y * z$$

$$t_2 := x + t_1$$

  - Each subexpression has a "name"

Generating Intermediate Code

- Similar to assembly code generation
- But use any number of IL registers to hold intermediate results

Generating Intermediate Code (Cont.)

- igen(e, t) function generates code to compute the value of e in register t
- Example:

  igen(e_1 + e_2, t) =

  igen(e_1, t_1) (t_1 is a fresh register)

  igen(e_2, t_2) (t_2 is a fresh register)

  t := t_1 + t_2

- Unlimited number of registers

  ⇒ simple code generation

An Intermediate Language

$$
\begin{aligned}
P &\rightarrow S\ P \mid \varepsilon \\
S &\rightarrow \text{id} := \text{id op id} \\
&\quad \mid \text{id} := \text{op id} \\
&\quad \mid \text{id} := \text{id} \\
&\quad \mid \text{push id} \\
&\quad \mid \text{id} := \text{pop} \\
&\quad \mid \text{if id relop id goto L} \\
&\quad \mid \text{L:} \\
&\quad \mid \text{jump L}
\end{aligned}
$$

- id's are register names
- Constants can replace id's
- Typical operators: +, -, *

Definition. Basic Blocks

- A <u>basic block</u> is a maximal sequence of instructions with:
  - no labels (except at the first instruction), and
  - no jumps (except in the last instruction)

- Idea:
  - Cannot jump into a basic block (except at beginning)
  - Cannot jump out of a basic block (except at end)
  - A basic block is a single-entry, single-exit, straight-line code segment

Basic Block Example

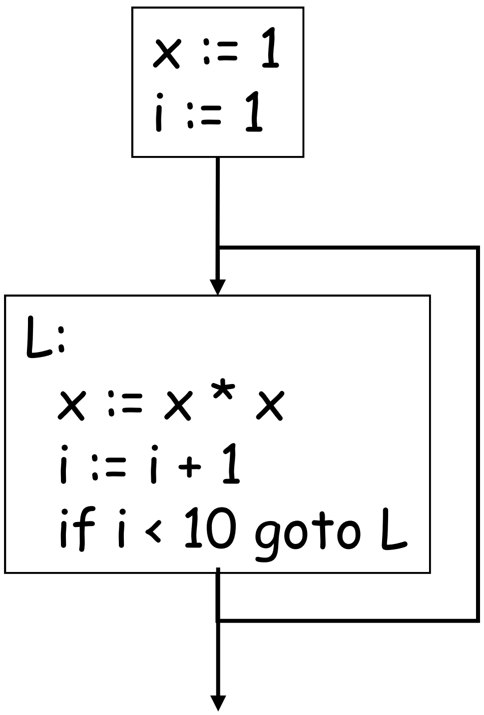
- Consider the basic block
  1. L:
  2. t := 2 * x
  3. w := t + x
  4. if w > 0 goto L'

- (3) executes only after (2)
  - We can change (3) to w := 3 * x

Definition. Control-Flow Graphs

- A control-flow graph is a directed graph with
  - Basic blocks as nodes
  - An edge from block A to block B if the execution can pass from the last instruction in A to the first instruction in B
    - E.g., the last instruction in A is jump L_B
    - E.g., execution can fall-through from block A to block B

Example of Control-Flow Graphs



- The body of a method (or procedure) can be represented as a control-flow graph
- There is one initial node
- All "return" nodes are terminal

LOCAL OPTIMIZATIONS

A Classification of Optimizations

- For languages like C and Cool 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 $\Rightarrow$ x := 4
- Example: if 2 < 0 jump L can be deleted
- *Can do many of these on the AST.*

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

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	$\Rightarrow$	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
  - <u>Dead</u> = 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	$\Rightarrow$	a := b	$\Rightarrow$	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
b := 3
c := x
d := c * c
e := b * 2
f := a + d
g := e * f
```

An Example

- Algebraic optimization:

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

An Example

- Copy propagation:

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

An Example

- Copy propagation:

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

An Example

- Constant folding:

```
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
```

An Example

- Common subexpression elimination:

```
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
```

An Example

- Copy propagation:

```
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
```

An Example

- Dead code elimination:

```
a := x * x




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

- This is the final form

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 $\rightarrow$ move $a $b
  - Example: move $a $a $\rightarrow$
  - 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
- Next time: global optimizations