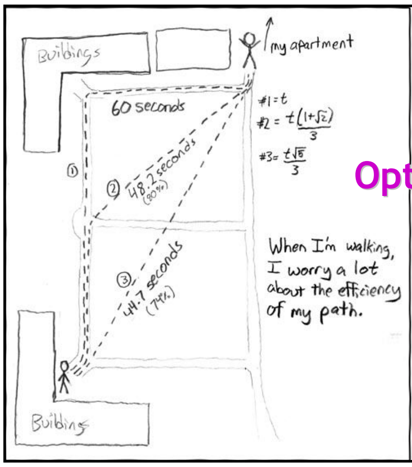



# Local Optimizations

#1

## One-Slide Summary

- An **optimization** changes a program so that it computes the same answer in less time (or using less of some other resource).
- We represent the program using a special **intermediate form**.
- Each method is viewed as a **control flow graph** where the nodes as **basic blocks** of instructions with known entry and exit points. The instructions have been changed so that a **single assignment** defines each variable.

#2

## Lecture Outline

- Intermediate code
- Local optimizations
- Next time: larger-scale program analyses

#3

## When To Optimize?

- When to perform optimizations
  - On AST (just like type checking)
    - Pro: Machine independent
    - Cons: Too high level
  - On assembly language (compilers only)
    - Pro: Exposes optimization opportunities
    - Cons: Machine dependent
    - Cons: Must reimplement optimizations when retargetting
  - On an intermediate language
    - Pro: Machine independent
    - Pro: Exposes optimization opportunities
    - Cons: One more language to worry about

#4

## Intermediate Languages

- Each compiler uses its own **intermediate language**
  - IL design is still an active area of research
- Intermediate language = high-level assembly language
  - 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

#5

## Three-Address Intermediate Code

- Each instruction is of the form

  x := y op z
  - y and z can be only registers, variables or constants
- Common form of intermediate code
- The AST expression x + y * z is translated as

  $t_1$ := y * z

  $t_2$ := x + $t_1$
  - Each **subexpression** lives in a temporary

#6

## Generating Intermediate Code

- 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

#7

## An Intermediate Language

P → S P | ε
S → id := id op id
  | id := op id
  | id := id
  | push id
  | id := pop
  | if id relop id goto L
  | L:
  | jump L

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

#8

## Basic Blocks

- A **basic block** 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)
  - Each instruction in a basic block is executed after all the preceding instructions have been executed

#9

## Basic Block Example

- Consider the basic block
  1. L1:
  2. t := 2 * x
  3. w := t + x
  4. if w > 0 goto L2
- No way for (3) to be executed without (2) having been executed right before
  - We can change (3) to w := 3 * x
  - Can we eliminate (2) as well?

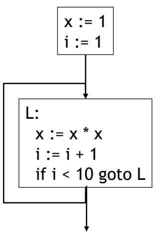
#10

## Control-Flow Graphs

- A **control-flow graph** is a directed graph:
  - Basic blocks as nodes
  - An edge from block A to block B if the execution can flow 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., the execution can fall-through from block A to block B
- Frequently abbreviated as **CFG**

#11

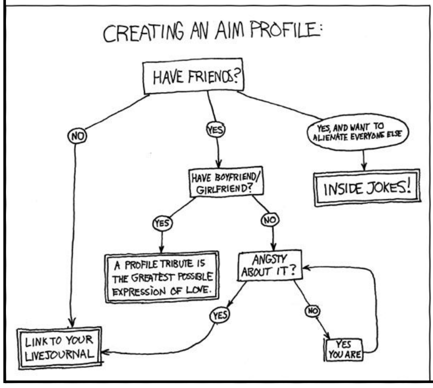
## Control-Flow Graphs. Example.




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

#12

## CFG $\simeq$ Flow Chart




#13

## Optimization Overview

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

#14

## 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) and very few do (3)
- Some interpreters do (1), few do (2), basically none do (3)

#15

## 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 terms of compilation/interpretation time
  - The fancy optimizations are both hard and costly
- The goal: maximum improvement with minimum of cost

#16

## Local Optimizations

- The simplest form of optimizations
- No need to analyze the whole procedure body
  - Just the basic block in question
- Example:
  - algebraic simplification
  - constant folding
  - Python 2.5 does stuff like this if you say “-O”

#17

## 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!)

#18

## Constant Folding

- Operations on constants can be computed before the code executes
- In general, if there is a statement

  x := y op z

  - And y and z are constants
  - Then y op z can be computed early
- Example: x := 2 + 2 ⇒ x := 4
- Example: if 2 < 0 jump L can be deleted
- When might **constant folding** be dangerous?

#19

## Flow of Control Optimizations

- Eliminating **unreachable code**:
  - Code that is unreachable in the control-flow graph
  - Basic blocks that are not the target of any jump or "fall through" from a conditional
  - Such basic blocks can be eliminated
- 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)

#20

## Single Assignment Form

- Most optimizations are simplified if each assignment is to a temporary that *has not appeared already* in the basic block
- Intermediate code can be rewritten to be in **single assignment form**

| | | |
|---|---|---|
| x := a + y | | x := a + y |
| a := x | ⇒ | $a_1$ := x |
| x := a * x | | $x_1$ := $a_1$ * x |
| b := x + a | | b := $x_1$ + $a_1$ |

($x_1$ and $a_1$ are fresh temporaries)

#21

## Single Assignment vs. Functional Programming

- In functional programming variable values do not change
- Instead you make a new variable with a similar name
- Single assignment form is just like that!

| | | |
|---|---|---|
| x := a + y | | let x = a + y in |
| $a_1$ := x | $\simeq$ | let $a_1$ = x in |
| $x_1$ := $a_1$ * x | | let $x_1$ = $a_1$ * x in |
| b := $x_1$ + $a_1$ | | let b = $x_1$ + $a_1$ in |

#22

## Common Subexpression Elimination

- Assume:
  - Basic block is in single assignment form
- Then all assignments with same rhs compute the same value *(why?)*
- Example:

| | | |
|---|---|---|
| x := y + z | | x := y + z |
| … | $\Rightarrow$ | … |
| w := y + z | | w := x |

- Why is single assignment important here?

#23

## Copy Propagation

- If w := x appears in a block, all subsequent uses of w can be replaced with uses of x
- Example:

| | | |
|---|---|---|
| b := z + y | | b := z + y |
| a := b | $\Rightarrow$ | a := b |
| x := 2 * a | | x := 2 * b |

- This does not make the program smaller or faster but might enable other optimizations
  - Constant folding
  - Dead code elimination (we'll see this in a bit!)
- Again, single assignment is important here.

#24

## 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
```

#25

## 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
```

#26

## Applying Local Optimizations

- Each local optimization does very little by itself
- Typically optimizations *interact*
  - Performing one optimizations enables other opts
- Typical optimizing compilers repeatedly perform optimizations until no improvement is possible
- Interpreters and JITs must be fast!
  - The optimizer can also be stopped at any time to limit the compilation time

#27

## An Example

- Initial code:

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

#28

## An Example

- Algebraic optimization:

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

#29

## An Example

- Algebraic optimization:

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

#30

## An Example

- Copy propagation:

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

#31

## An Example

- Copy propagation:

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

#32

## An Example

- Constant folding:

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

#33

## An Example

- Constant folding:

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

#34

## An Example

- Common subexpression elimination:

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

#35

## An Example

- Common subexpression elimination:

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

#36

## An Example

- Copy propagation:

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

#37

## An Example

- Copy propagation:

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

#38

## An Example

- Dead code elimination:

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

#39

## An Example

- Dead code elimination:

```
a := x * x



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

- This is the final form

#40

## Cool and Intermediate Form

- Cool does not have goto
- Cool does not have break
- Cool does not have exceptions

- How would you make basic blocks from a Cool AST?

#41

## Local Optimization Notes

- Intermediate code is helpful for many optimizations
  - Basic Blocks: known entry and exit
  - Single Assignment: one definition per variable
- "Program optimization" is grossly misnamed
  - Code produced by "optimizers" is not optimal in any reasonable sense
  - "Program improvement" is a more appropriate term
- Next: larger-scale program changes

#42

## Homework

- PA4 due this Friday March 30th (3 days)
- Midterm 2 – Thursday April 12 (17 days)

#43