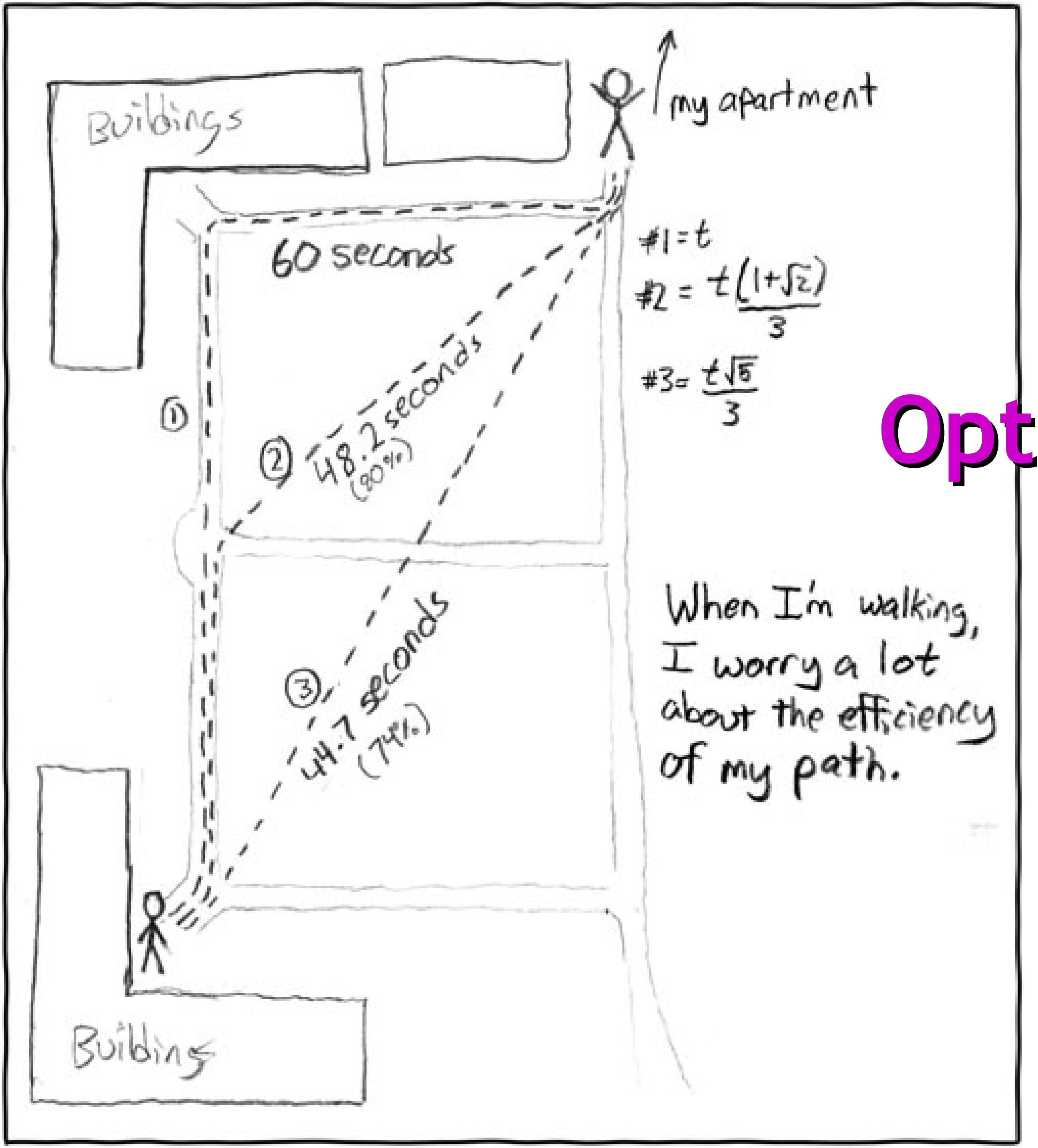
Local Optimizations

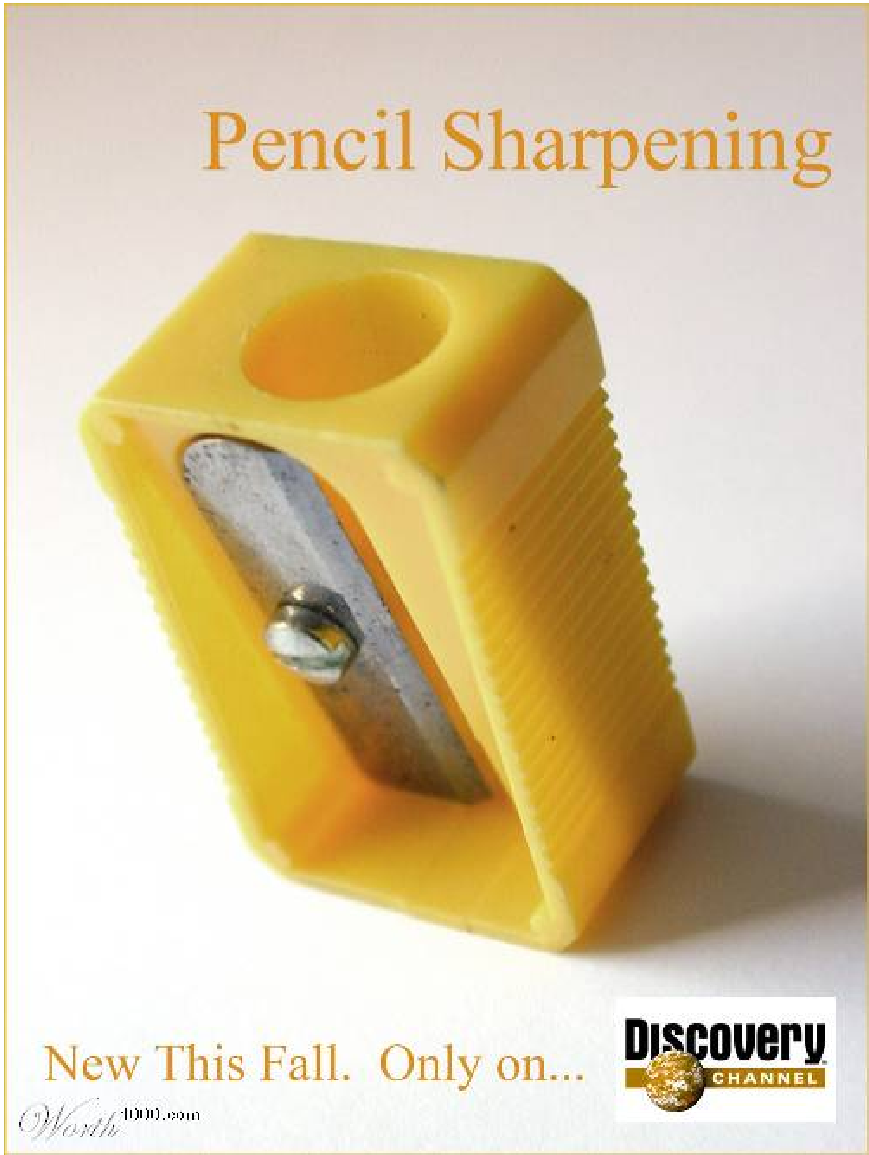


One-Slide Summary

- 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.

Lecture Outline

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



Why Optimize?

- What's the point?
- Do we care about this in real life?

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

You do *not* have to know assembly language.

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

Three-Address Intermediate Code

- Each instruction is of the form

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

  - 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

Generating Intermediate Code

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

  $\text{igen}(e_1 + e_2, t) =$

  $\text{igen}(e_1, t_1)$ *(t_1 is a fresh register)*

  $\text{igen}(e_2, t_2)$ *(t_2 is a fresh register)*

  $t := t_1 + t_2$

- Unlimited number of registers

  ⇒ simple code generation

An Intermediate Language

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: +, -, *

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

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

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`

Basic Block Example

- Consider the basic block

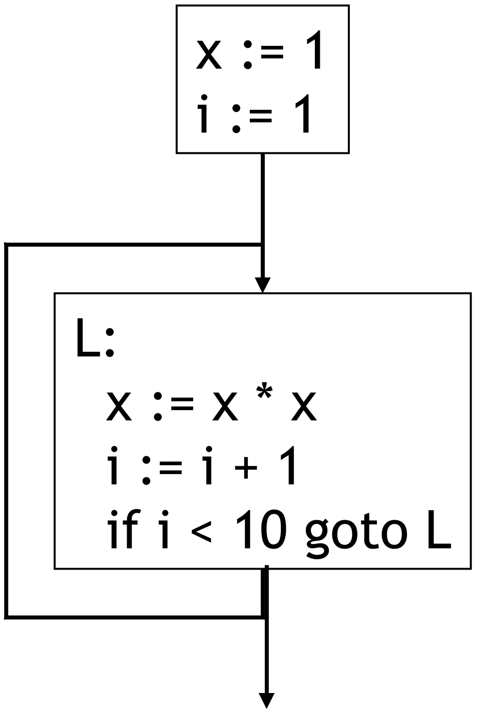
```
1. L1:
2.     t := 2 * x
3.     w := t + x
4.     if w > 0 goto L2
```

- 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?

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**

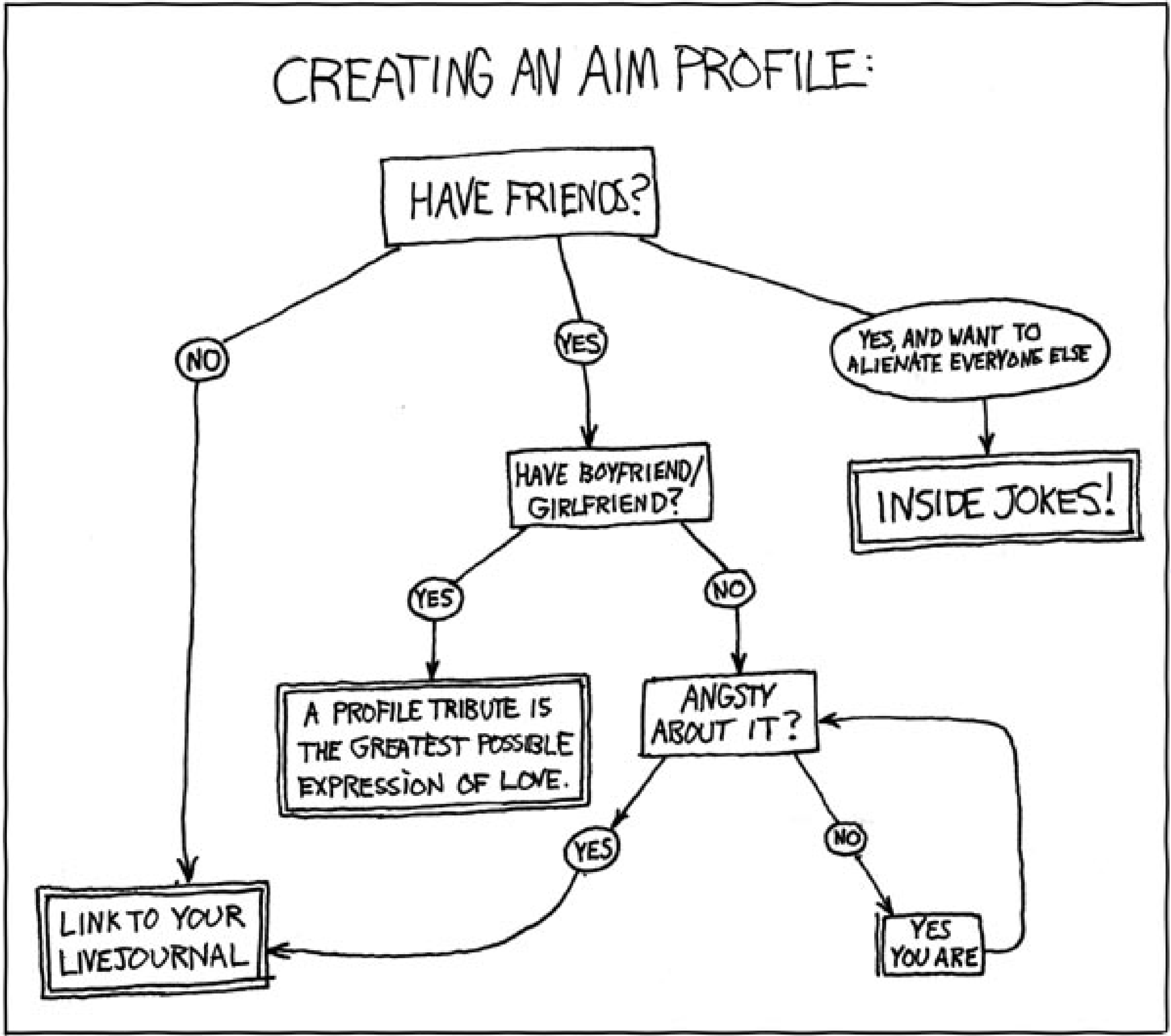
Control-Flow Graphs. Example.



x := 1
i := 1

L:
  x := x * x
  i := i + 1
  if i < 10 goto L

- 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



CFG
$\simeq$
Flow Chart

Optimization Overview

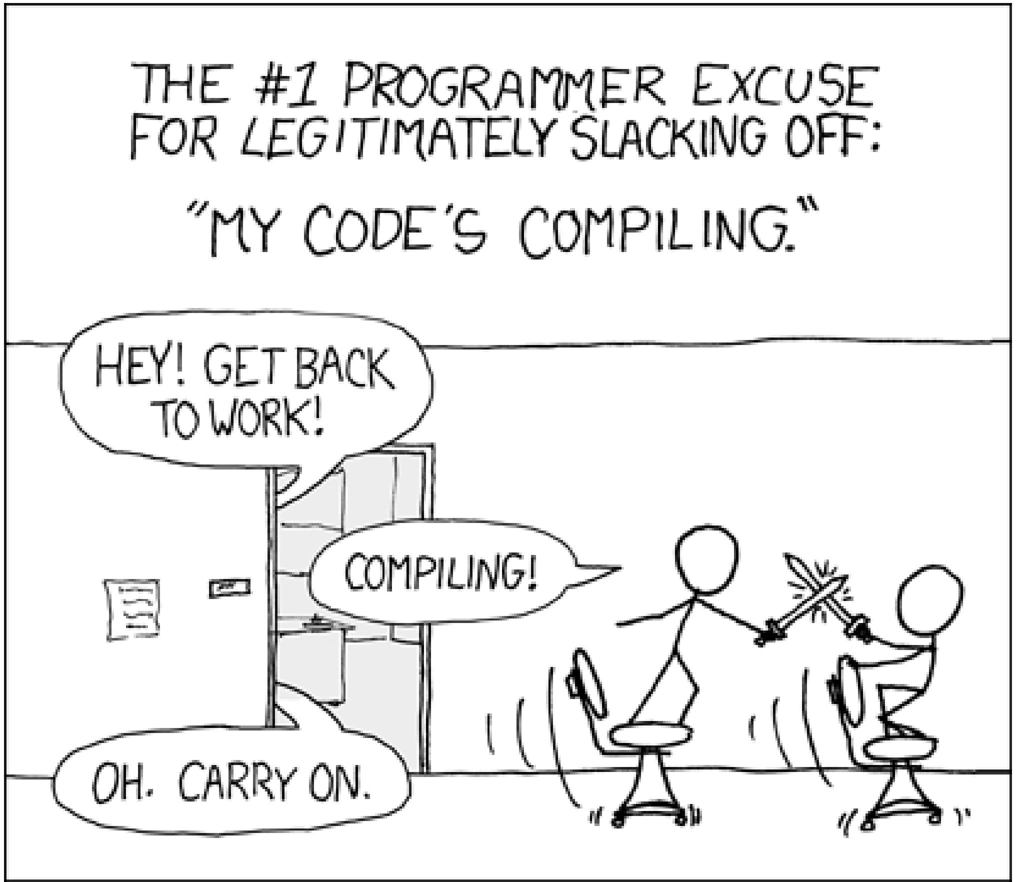
- **Optimization** seeks to improve a program’s utilization of some resource
  - Execution time (most often)
  - Code size
  - Network messages sent
  - Battery power used, etc.
- Optimization should *not* alter what the program computes
  - The answer must still be the same

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)

Cost of Optimizations

- In practice, a conscious decision is made *not* to implement the fanciest optimization known
- Why?



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

Q: Movies (363 / 842)

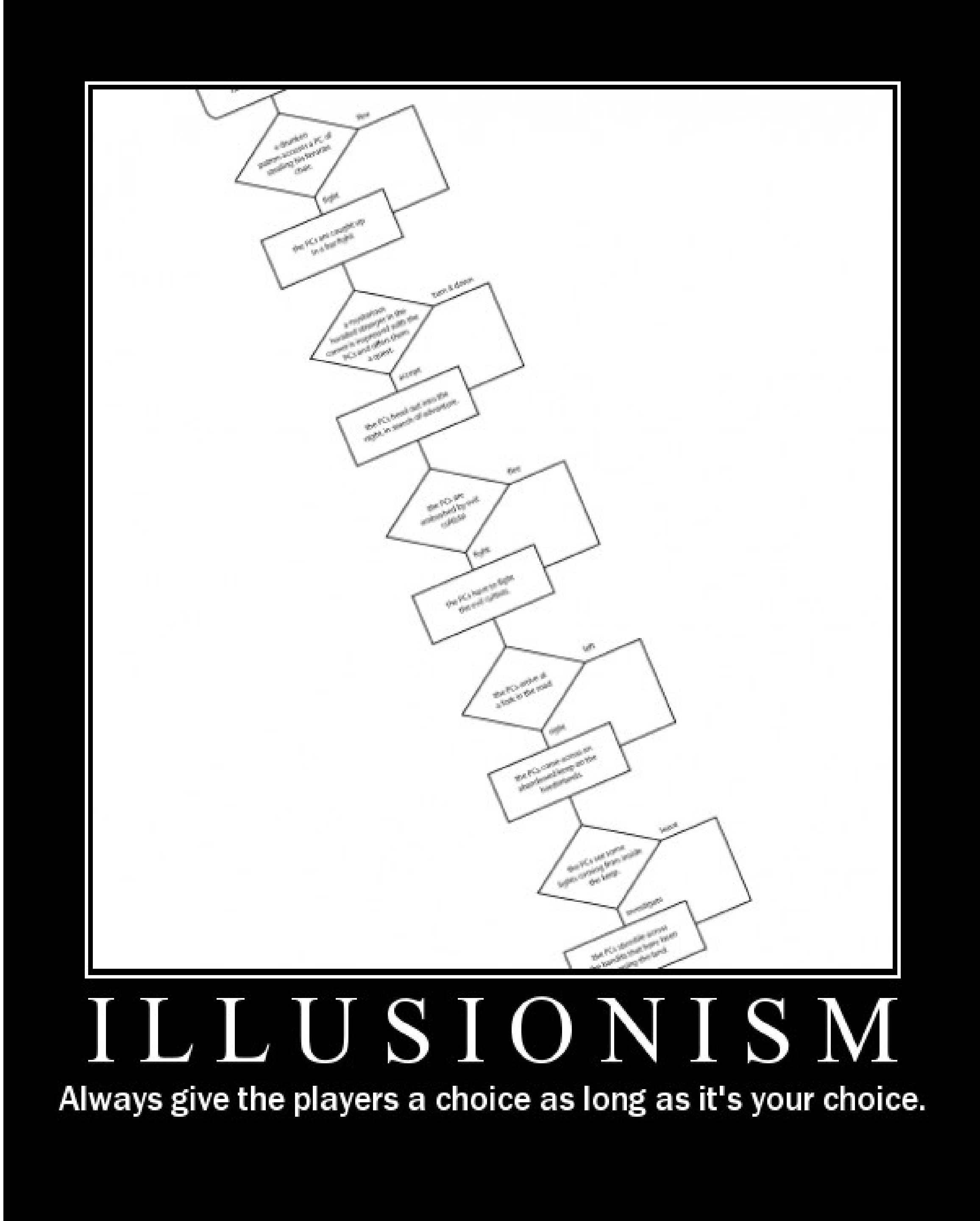
- This 1993 comedy film also starring Andie MacDowell "begins" with the following radio banter: *"Rise and shine, campers, and don't forget your booties 'cause it's cooooold out there today. / It's cold out there every day. What is this, Miami Beach? / Not hardly. So the big question on everybody's lips / -- On their chapped lips -- / their chapped lips is, does Phil feel lucky?"*

Q: Cartoons (674 / 842)

- This 1953 Warner Brothers' cartoon mouse is known for his cry of *"Arriba! Arriba! Andele!"*

CFG

- This CFG stuff sounds complicated ...
- Can't we skip it for now?



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”

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 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?

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)

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**

$$\begin{array}{lcl} x := a + y & & x := a + y \\ a := x & \Rightarrow & a_1 := x \\ x := a * x & & x_1 := a_1 * x \\ b := x + a & & b := x_1 + a_1 \end{array}$$

(x_1 and a_1 are fresh temporaries)

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

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

- Why is single assignment important here?

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         ⇒       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.

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
```

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 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

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 + b
f := a + d
g := e * f
```

An Example

- Copy propagation:

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

An Example

- Copy propagation:

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

An Example

- Constant folding:

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

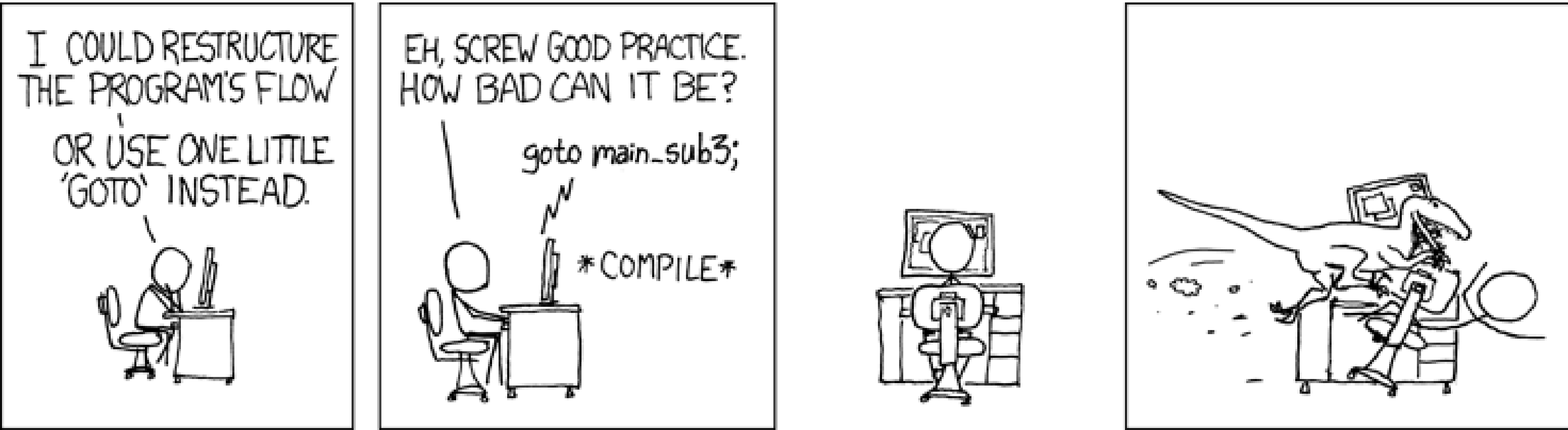
```
a := x * x
```

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

- This is the final form

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?



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

Homework

- PA4 due tomorrow
  - Use spiffy auto-testing feature
- Reading for Thursday (basic blocks, etc.)
- Midterm 2 – Tuesday April 15 (19 days)