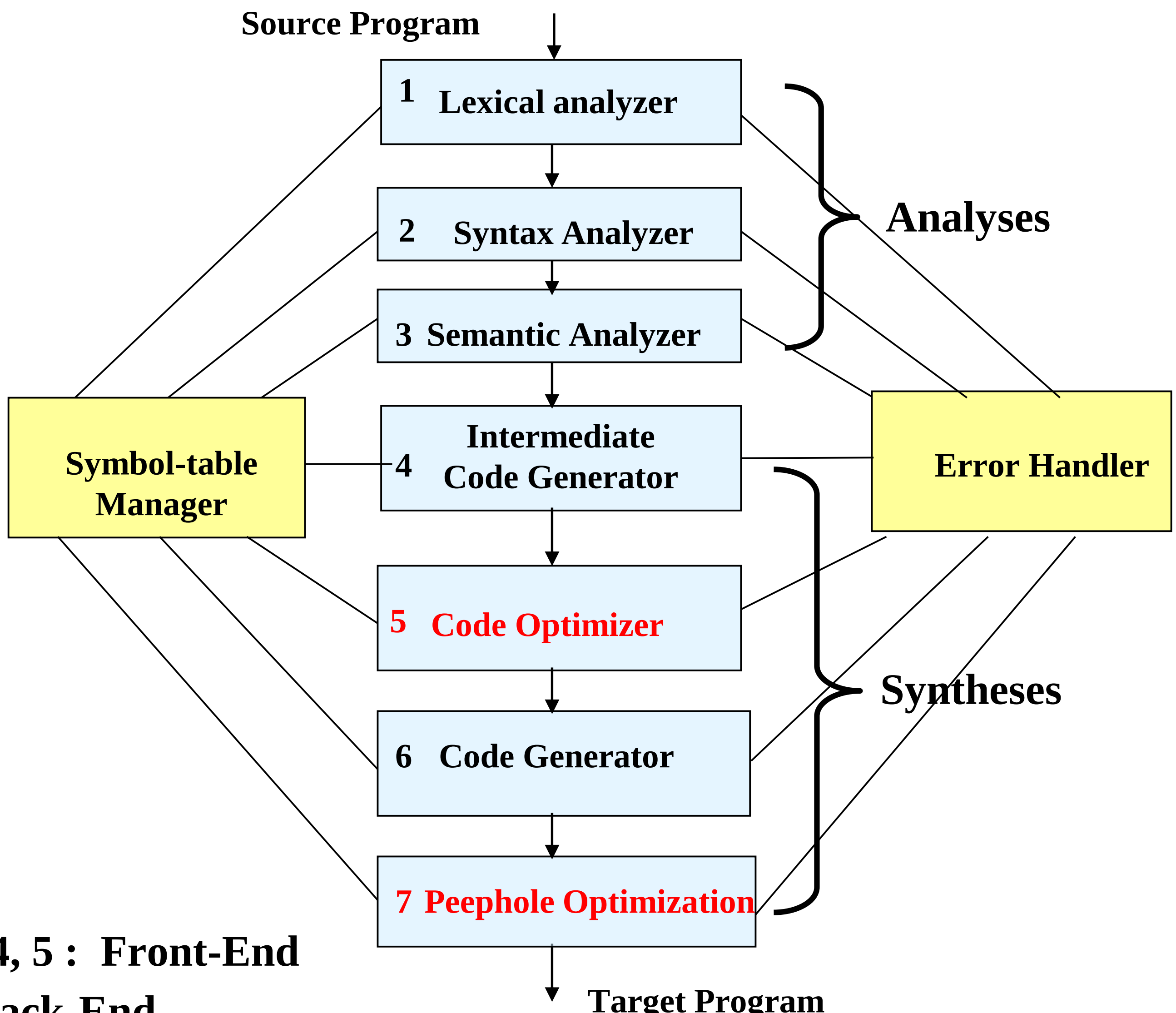
40-414 Compiler Design

Local Optimizations

Lecture 11

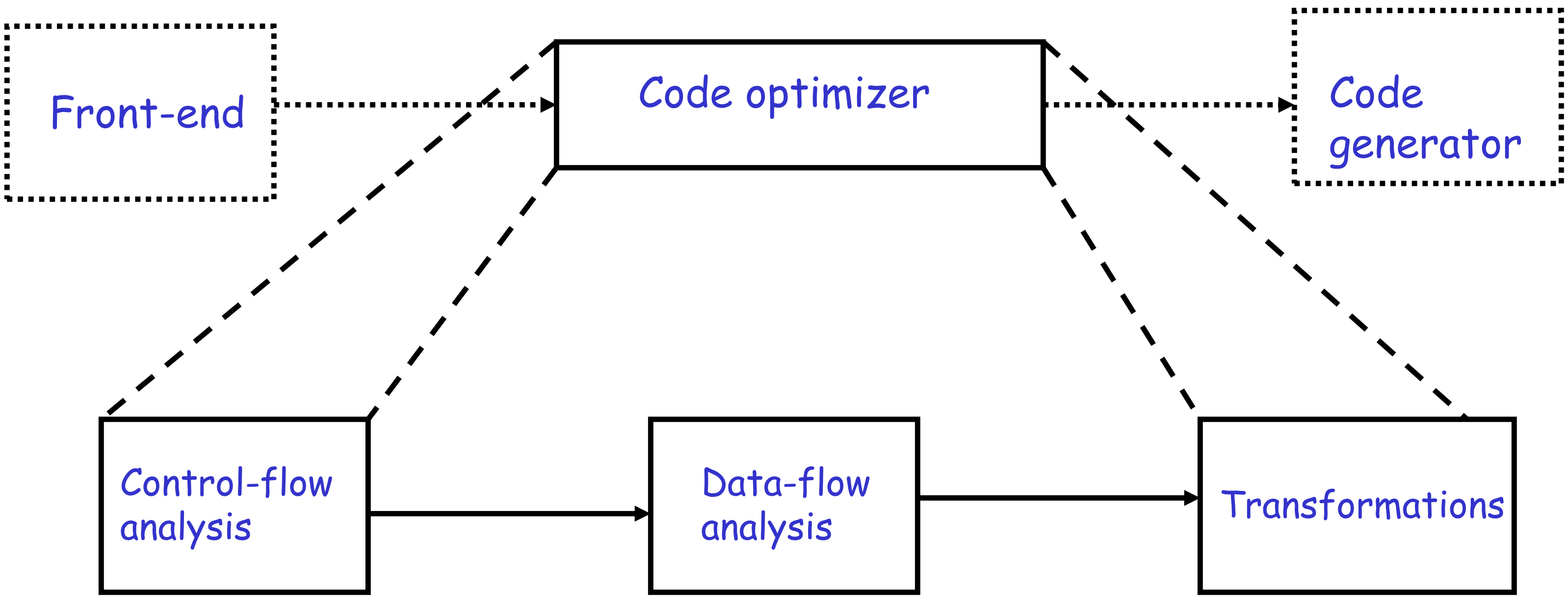
Compiler Front-end and Back-end (Revisited)



1, 2, 3, 4, 5 : Front-End

6, 7 : Back-End

Organization of a Code Optimizer



Optimization

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

- First, we need to discuss 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
    - 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

An Intermediate Language

$P \rightarrow S\ P \mid \varepsilon$

$S \rightarrow$ id := id op id

| id := op id

| id := id

| if id relop id goto L

| L:

| jump L

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

Definition. 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)
  - A basic block is a single-entry, single-exit, straight-line code segment

Basic Block Example

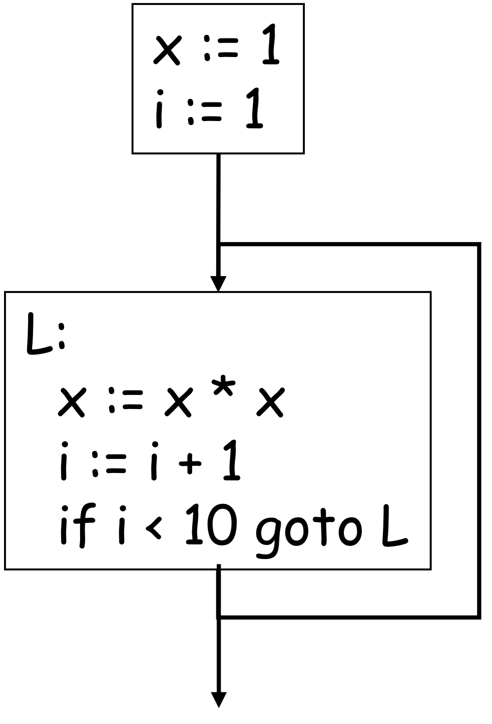
- Consider the basic block
  1. L:
  2. t := 2 * x
  3. w := t + x
  4. if w > 0 goto L'

- (3) executes only after (2)
  - We can change (3) to w := 3 * x
  - Can we eliminate (2) as well?

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

Optimization Overview

- Optimization seeks to improve a program's resource utilization
  - Execution time (most often)
  - Code size
  - Memory usage
  - Disk access

- 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), 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

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)

Flow of Control Optimizations (Cont.)

- Why would unreachable basic blocks occur?

  - Debug mode

    #define DEBUG 0

    If (DEBUG) then …
  - Libraries
  - Result of other optimizations

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	$\Rightarrow$	a := b
x := 2 * x		x := 2 * b

(b is a fresh register)

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~~ 5	⇒	x := 10
y := ~~x~~ 10 + 6		y := 16
t := x * ~~y~~ 16		t := x << 4 or t := 160

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		b := z + y
a := x	⇒	a := b	⇒	a := b	⇒	x := 2 * b
x := 2 * a		x := 2 * a		x := 2 * b		
	turn to single assignment form		*copy propagation*		*dead code elimination*	

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

Loop Optimization

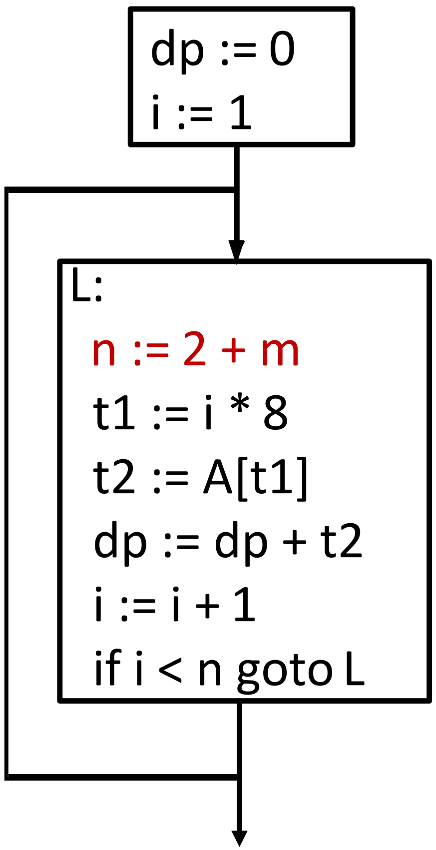
1. Code Motion

2. Reduction in Strength

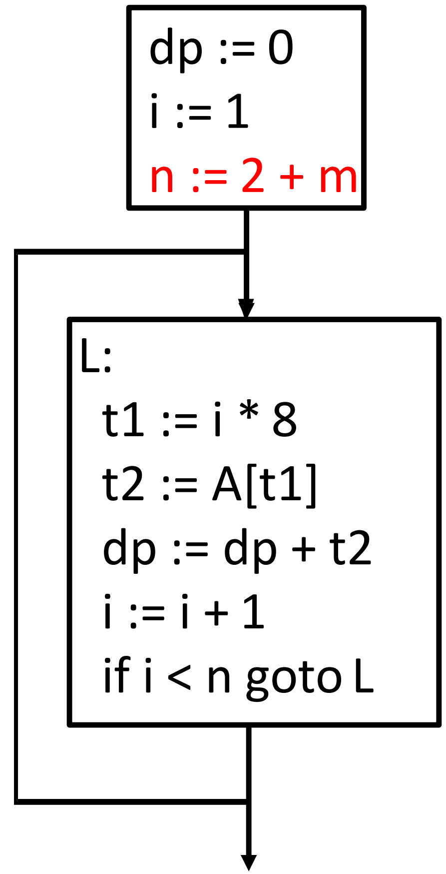
3. Induction Variables elimination

Code Motion

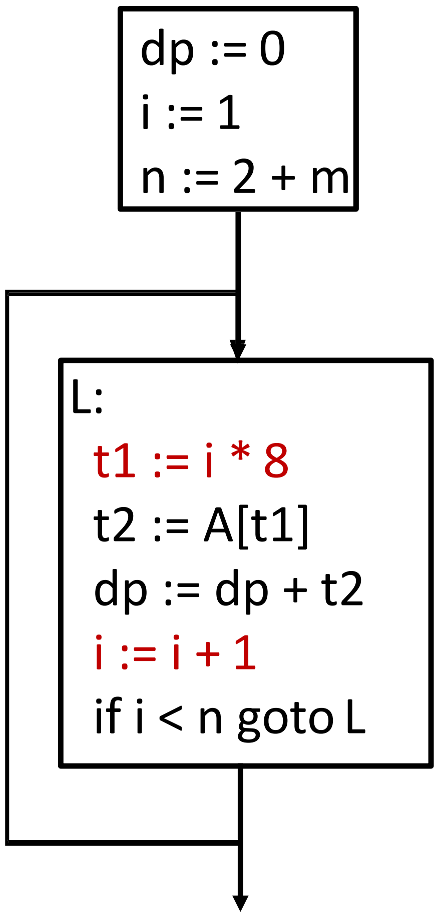
- 'n := 2 + m' can be moved out of the loop



⇒

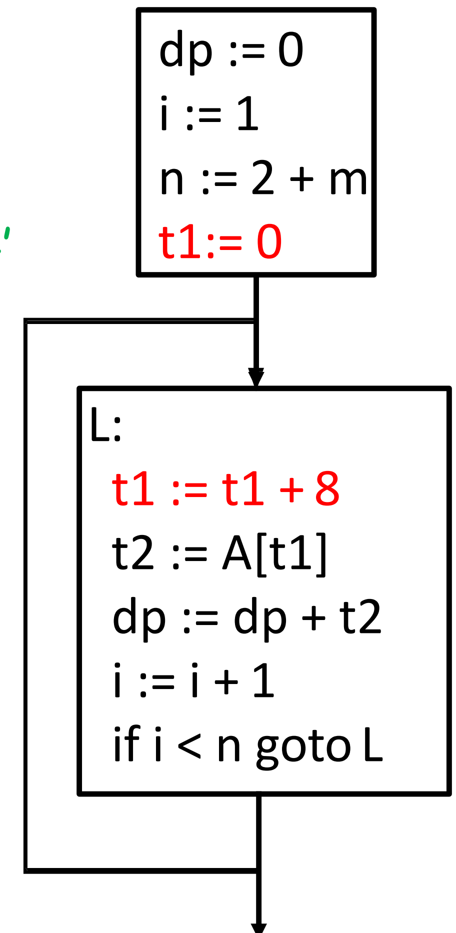


Reduction in Strength

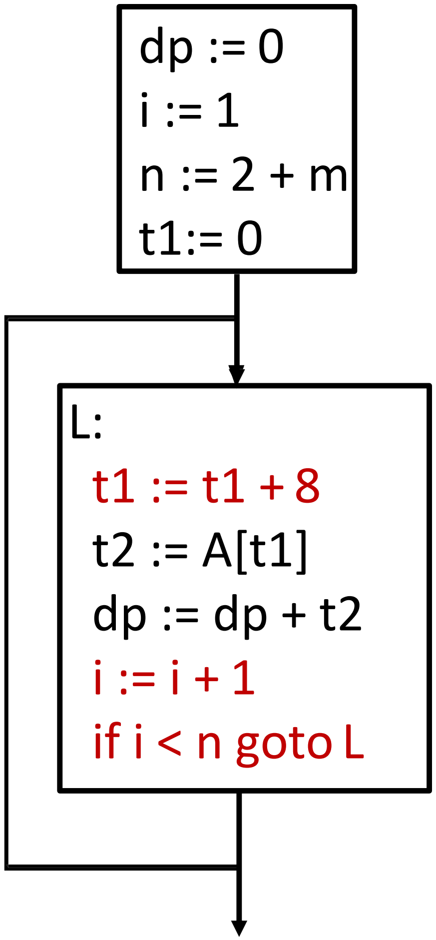


- i is increased by 1
- t1 is increased by 8
- '*' can be replaced by '+'

⇒

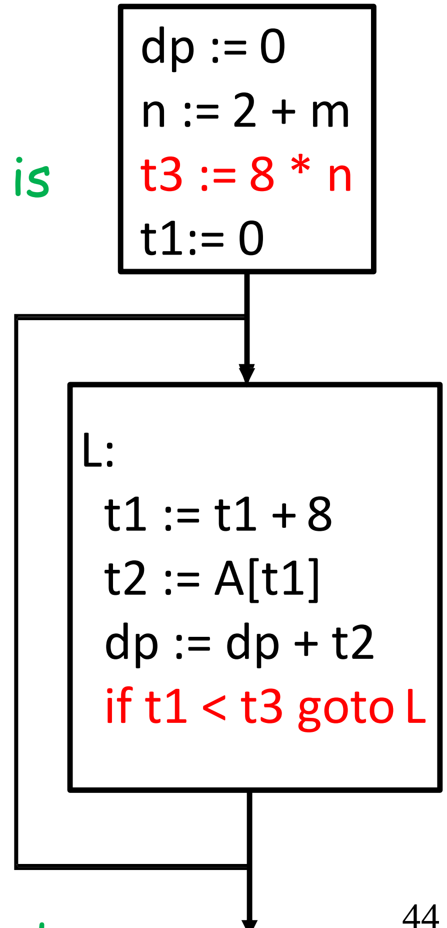


Induction Variables Elimination



- i and t1 here are regarded as '*induction variables*'
- i can be removed and t1 is used instead

⇒

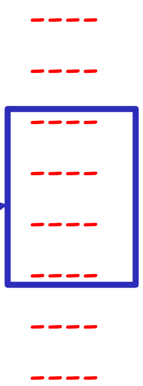


- 'i := i + 1' is then a dead code and can be removed

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.)

3AC

```
x := y + 1;
z := x + 2;
```

Machine Code

```
move  $a y
addiu $a $a 1
move  x $a
move  $a x   <- This move statement is not needed
addiu $a $a 2
move  $a z
```

Peephole Optimizations (Cont.)

Use of specialized instructions

```
move  $a a
addiu $a $a 1     ⇒   increment a
move  a $a
```

Peephole Optimizations (Cont.)

Some machine codes can be deleted

```
multu $a $a 1
addiu  $a $a 0
```

Using shift to left instead of multiplication by powers of 2

Using shift to right instead of division into powers of 2

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

Question?

Which of the following are valid local optimizations for the given basic block? Assume that only g and x are referenced outside of this basic block.

```
1   a := 1
2   b := 3
3   c := a + x
4   d := a * 3
5   e := b * 3
6   f := a + b
7   g := e - f
```

- [ ] Copy propagation: Line 4 becomes d := a * b.
- [ ] Common subexpression elimination: Line 5 becomes e := d.
- [ ] Dead code elimination: Line 3 is removed.
- [ ] After many rounds of valid optimizations, the entire block can be reduced to g := 5.