Course: Compiler Construction

Week 11: Code Optimization

Lecturer: Martha Gichuki

Course Description

- The course begins with a coverage of basic Principles in Compiler Design with an introduction to Formal programming language translation and compiler design concepts; compilers and interpreters.
- A coverage of Language theory, Parsing Context-Free Languages (Top - down and bottom - up parsing), translation specifications and machine- independent code optimization will then follow.

Course Description …

- The main phases of compilation i.e. Lexical, Syntax and Semantic analysis will be taught.
- Code generation and Optimization, Symbol table design, Program compilation, Loading and execution will then be covered.
- Compilation techniques, Optimization, Design of a simple complete compiler will culminate the course.

Learning outcomes Week 11: Code Optimization

At the end of the lecture, you will be able to:

i. Describe code optimization
ii. Describe the objectives of code optimization
iii. Describe various techniques used to optimize code

Introduction

- In compiler design, the term **code optimization** refers to ***attempts*** made by the compiler to produce **more efficient code** compared to the obvious code.
- Code optimization is therefore a contradiction since the code produced by a compiler cannot be guaranteed to be as fast or faster than any other code that performs the same task[1].

1. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 40

Introduction…

- ✓ **Code optimization or improvement** is the attempt to *remove unnecessary instructions in object code*, or the replacement of one sequence of instructions by a faster sequence of instructions that does the same thing.
- ✓ The objectives of code improvement are:

i. To consume fewer resources i.e. CPU and Memory

ii. Deliver high speed[2]

2. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 608

Basic Blocks

- ✓Source codes contain multiple instructions, which are always executed in sequence and are considered as the **basic blocks** of the program.
- ✓These basic blocks do not have any jump statements among them, i.e., when the first instruction is executed, all the instructions in the same basic block will be executed in their sequence of appearance without losing the flow control of the program.
- ✓A program can have various constructs as basic blocks, such as IF-THEN-ELSE, SWITCH-CASE conditional statements and loops such as DO-WHILE, FOR, and REPEAT-UNTIL, among others[3].

3. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 550

Identifying Basic Blocks

✓To identify the basic blocks in a program, the following algorithm can be used:

i. Search ***header statements*** of all the basic blocks from where a basic block starts:
   - ✓First statement of a program.
   - ✓Statements that are target of any branch (conditional/unconditional).
   - ✓Statements that follow any branch statement.

ii. Header statements and the statements following them form a basic block.

iii. A basic block does not include any header statement of any other basic block[4].

4. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 551

Identifying Basic Blocks…

- ✓Basic blocks are important concepts from both code generation and optimization point of view.
- ✓Basic blocks play an important role in **identifying variables**, which are **being used more than once** in a single basic block.
- ✓If any variable is being used more than once, the register memory allocated to that variable need not be emptied unless the block finishes execution[5]

5. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 552

Identifying Basic Blocks[5]…

```
w = 0;
x = x + y;
y = 0;
if( x > z)
   {
    y = x;
    x++;
   }
else
   {
    y = z;
    z++;
   }
w = x + z;
```

Source Code

```
w = 0;
x = x + y;
y = 0;
if( x > z)
```

```
y = x;
x++;
```

```
y = z;
z++;
```

```
w = x + z;
```

Basic Blocks

5. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 552

Code Optimization can be accomplished either locally or globally: -

i. Local code optimization - code improvement happens within a basic block

ii. Global code optimization - where code improvements take into account whatever is happening across basic blocks[6].

6. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 608

Three rules to be followed in Code Optimization process

i. Output code should not change the program meaning.

ii. Optimization should increase program speed and use less number of resources

iii. Optimization process should be fast and should not delay the entire compiling process[7]

7. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 608

Two Categories of Code Optimization processes[8]

A. Machine-Independent Optimization
B. Machine-Dependent Optimization

8. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 608

A. Machine-Independent Code Optimization[9]

- ✓The compiler takes the intermediate code and transforms a part of the code that *does not involve any CPU registers and/or absolute memory locations*.
- ✓**Example:**

```
do
{
item = 10;
value = value + item;
} while(value<100);
```

- ✓This code involves repeated assignment of the identifier item
- ✓In order to save the CPU cycles and use the code on any processor, we re-write the code as follows:-

```
Item = 10;
do
{
   value = value + item;
} while(value<100);
```

9. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 608

B. Machine-Dependent Code Optimization[10]

- ✓This is done after the target code has been generated and when the code is transformed according to the target machine architecture.
- ✓It *involves CPU registers* and may have *absolute memory references rather than relative references*.
- ✓Machine-dependent optimizers put efforts to take maximum advantage of memory hierarchy.

10. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 608

Towards Optimized Code[11]

- ✓Improved Intermediate code can be generated by the compiler through *address calculations and improving loops*
- ✓While generating target code, the compiler can *use memory hierarchy and CPU register*
- ✓Users can *change/rearrange the code or use better algorithms* to write the code
- ✓*Dead code* can be eliminated
- ✓Elimination of *code redundancy* is also possible

11. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 608

Sources of Code Redundancy

- ✓ Presence of several **redundant operations** in a typical program.
- ✓ Sometimes the redundancy happens at the **source level** e.g. programmers may find it more direct and convenient to recalculate some result, leaving it to the compiler to recognize that only one such calculation is necessary.
- ✓ Code redundancy is mostly a side effect of writing programs in a high-level language.
- ✓ In most languages (other than C or C++, where pointer arithmetic is allowed), programmers have no choice but to refer to elements of an array or fields in a structure[12]

12. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 639

1. Redundant instruction elimination

- ✓ At compilation level, the compiler searches for redundant instructions.
- ✓ Multiple loading and storing instructions may carry the same meaning even if some of them are removed[13].
- ✓ **Example: Consider the two instructions below:-**

  MOV x, R0
  MOV R0, R1

✓We remove the first instruction and re-write the instruction as:

  MOV x, R1

13. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 639

2. Data-flow analysis

- ✓ This is a key part of code optimization.
- ✓ Data-Flow analysis engines is one of the compiler construction tools we discussed in lecture 1
- ✓ The engines facilitate the gathering of information about how values are transmitted from one part of a program to the other parts[14].

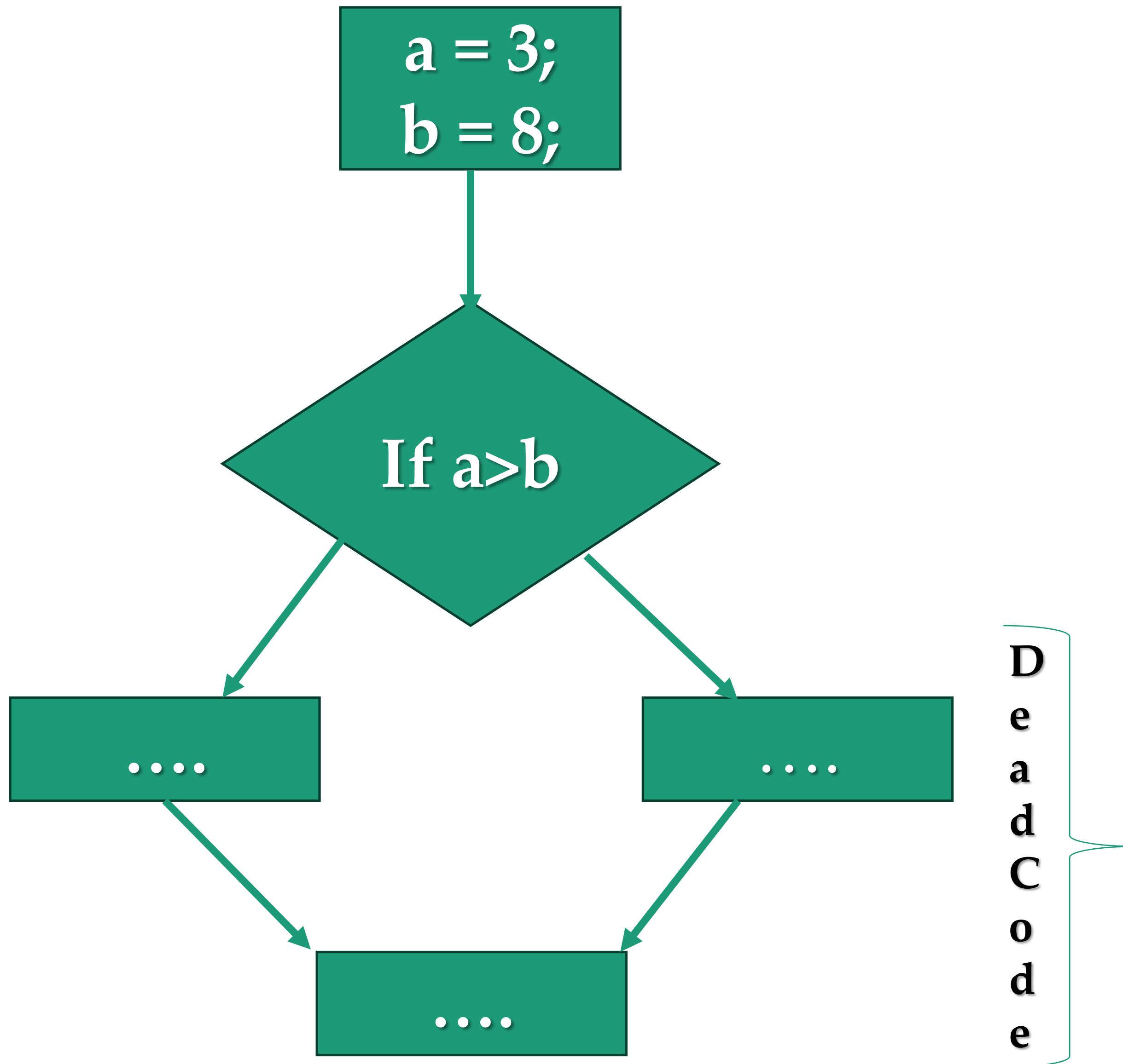
14. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 628

3. Dead Code Elimination

- ✓ Dead code plays no role in any program execution and it refers to statements that are either:-
  - ✓ Never executed or unreachable
  - ✓ Or, if executed their output is never utilized
- ✓ Partially dead code is that whose computed values are used **only under certain circumstances**[15]

15. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 560, 655

Dead Code Elimination[16]



16. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 616

4. Loop Optimization

- ✓ Loop optimization saves on CPU cycles and memory and it can be achieved using the following techniques:-

i. **Strength reduction** - Some expressions consume more CPU cycles, time and memory than others. These should be replaced with cheaper expressions without compromising the output quality

ii. **Loop Invariant Code** - is a code fragment residing in the loop, which computes the same value at each iteration. This code can be **moved out of the loop** by saving it to be computed **only once** instead of with each iteration

iii. **Induction analysis** - An induction variable is one whose value is altered within the loop by a loop-invariant value[17]

17. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 667

a) Strength Reduction

- ✓ There are operations that consume more time and space.
- ✓ Their 'strength' can be reduced by replacing them with other operations that consume less time and space, but produce the same result. Consider the following **examples:-**

i. **x * 2** is computationally expensive and can be replaced by ***x << 1***, which involves only one left shift. Left bit shifting to multiply by any power of two

ii. **x = x*8** can be written as ***x<<3*** (since 2 to the power of 3 is 8).

iii. x = x / 2 can be written as ***x>>1***. Right bit shifting to divide by any power of two.

iv. **a * a** can be written as $\mathbf{a^2}$. The output is the same, but $\mathbf{a^2}$ is much more efficient to implement[18].

18. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 577, 713

b) Loop invariant Code

- ✓ Loop invariant code is partially redundant and can be eliminated by **using a code-motion technique**. Example: -

```
if (condition)
{
a = y OP z;
}
else
{
…
}
c = y OP z;
```

- ✓ Assume that the values of operands (**y** and **z**) are not changed from assignment of variable **a** to variable **c**.
- ✓ If the condition statement is true, then **y OP z** is computed twice, otherwise once[19]

19. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 667

Code motion

- ✓ Code motion can be used to eliminate this redundancy as follows:-

```
if (condition)
{
…
tmp = y OP z;
a=tmp;
…
}
else
{
…
tmp = y OP z;
}
c = tmp;
```

- ✓ Here, regardless of whether the condition is true or false; y OP z should be computed only once[20].

20. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 644

5. Peephole Optimization

- ✓ This optimization technique works locally on the source code to transform it into an optimized code.
- ✓ Working locally, means a small portion of the **code block at hand** is worked on.
- ✓ These methods can be applied on intermediate codes as well as on target codes.
- ✓ A **batch of statements** is analyzed and are checked for possible optimization[21]

21. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 574

6. Unreachable code

- ✓ Unreachable code is a part of the program code that is **never accessed** because of programming constructs. Programmers may have accidently written pieces of code that can never be reached.
- ✓ **Example[22]:**

```
void add_ten(int x)
 {
return x + 10;
printf("value of x is %d", x);
}
```

- ✓ In this code segment, the **printf** statement will never be executed as the program control returns back before it can execute, hence **printf** can be removed.

22. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 575

7. Flow of control optimization[23]

- ✓ There are instances in a code where the program control jumps back and forth without performing any significant task. To achieve optimization, these jumps should be eliminated.
- ✓ Consider the following piece of code:

```
...
MOV R1, R2
GOTO L1
...
L1 : GOTO L2
L2 : INC R1
```

- ✓ In this code, label L1 can be removed as it passes the control to L2.
- ✓ Instead of jumping to L1 and then to L2, the control can directly reach L2, as shown below:

```
...
MOV R1, R2
GOTO L2
...
L2 : INC R1
```

23. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 576

8. Algebraic Expression Simplification

- ✓ Sometimes algebraic expressions can be simplified.
- ✓ **Examples:-**

i. The expression **a = a + 0** can be replaced by **a** itself

ii. The expression **a = a + 1** can simply be replaced by **INC a**[24].

24. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 577

9. Accessing Machine Instructions

- ✓ The target machine can deploy more sophisticated instructions, which can have the capability to perform specific operations much efficiently.
- ✓ If the target code can accommodate those instructions directly, that will not only improve the quality of code, but also yield more efficient results[25].

25. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; Addison- Wesley Pub Co, ISBN: 0201100886 (2007) page 577

Content Covered in Week 11: Code Optimization

At the end of the lecture, we were able to:

i. Describe code optimization

ii. Describe the objectives of code optimization

iii. Describe various techniques used to optimize code

Course Text Books

1. Compilers: Principles, Techniques and Tools, Aho, Lam, Sethi, and Ullman; *Addison- Wesley Pub Co,* ISBN: 0201100886 (2007))
2. Compiler Construction: Principles and practices; Kenneth C. Louden; *Cengage Learning*; 1st edition, ISBN-10 : 0534939724 (1997)
3. Basics of Compiler Design: Torben Mogensen; *DIKU University of Copenhagen Universitetsparken 1 DK-2100 Copenhagen DENMARK* (2007)
4. Engineering a Compiler: 2nd edition; Keith D. Cooper and Linda Torczon; *Morgan Kaufmann Publishers* ISBN: 978-0-12-088478-0 (2003)
5. Compiler Design: Santanu Chattopadhyay; *PHI Learning Publishers*, ISBN 812032725X, 9788120327252 (2005)