CC Week 1 and 2

Prepared for: 7th Sem, CE, DDU

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Ref. Book: Compiler: Principles, techniques and tools by Aho, Ullman and Sethi, 2nd Ed., Pearson Education

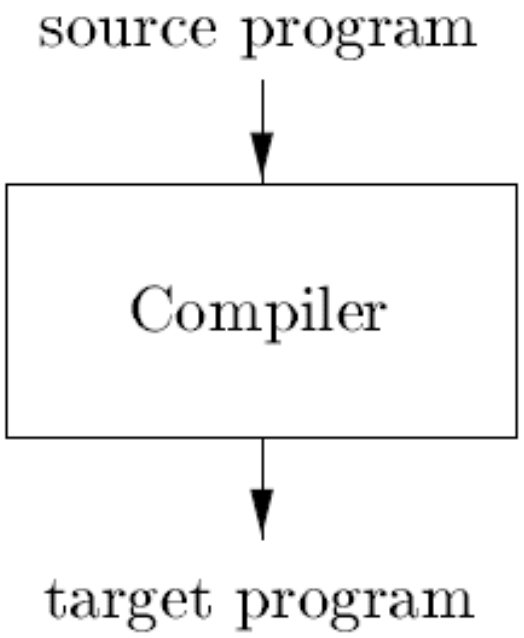
Contents

Introduction

- **Programming languages** are notations for describing computations to people and to machines.
- But, before a program can be run, it first must be translated into a form in which it can be executed by a computer.
- The software systems that do this translation are called **compilers**.

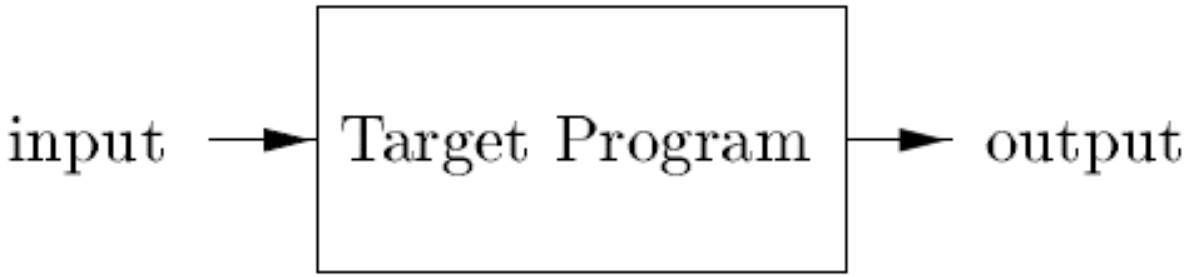
Compiler

- A **compiler** is a program that can read a program in one language the **source language** and translate it into an equivalent program in another language the **target language**.



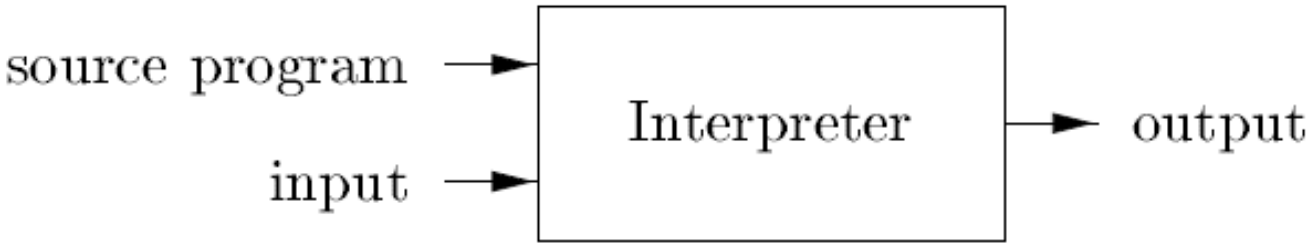
Running the target program

- If the target program is an **executable machine-language program**,
  - it can then be called by the user to process inputs
  - and produce outputs.



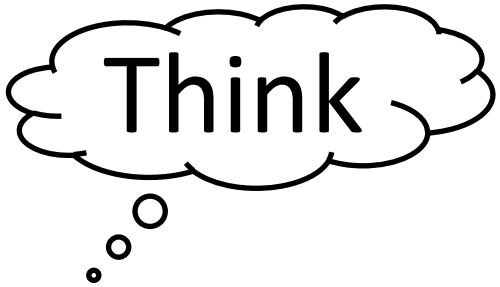
Interpreter

- Instead of producing a target program as a translation, an **interpreter** appears to directly execute the operations specified in the source program on inputs supplied by the user.



Compiler vs. Interpreter

- The machine-language target program produced by a **compiler** is usually much **faster than an interpreter** at mapping inputs to outputs.
- An **interpreter**, however, can usually give **better error diagnostics than a compiler**, because it executes the source program statement by statement.

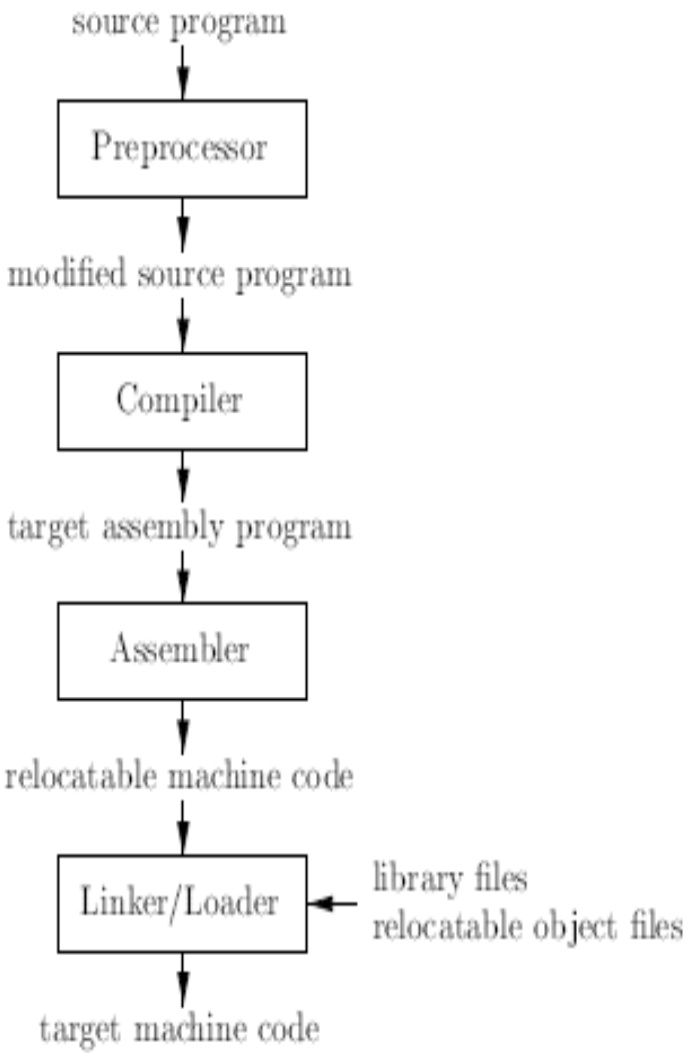


1. What is the difference between a compiler and an interpreter?
2. What are the advantages of

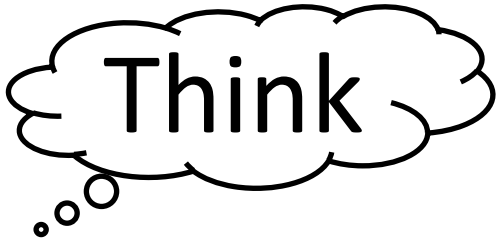
   (a) a compiler over an interpreter

   (b)an interpreter over a compiler

Language Processing System



- Large programs are often compiled in pieces, so the relocatable machine code may have to be linked together with other relocatable object files and library files into the code that actually runs on the machine.
- The **linker** resolves external memory addresses, where the code in one file may refer to a location in another file.
- The **loader** then puts together all of the executable object files into memory for execution.

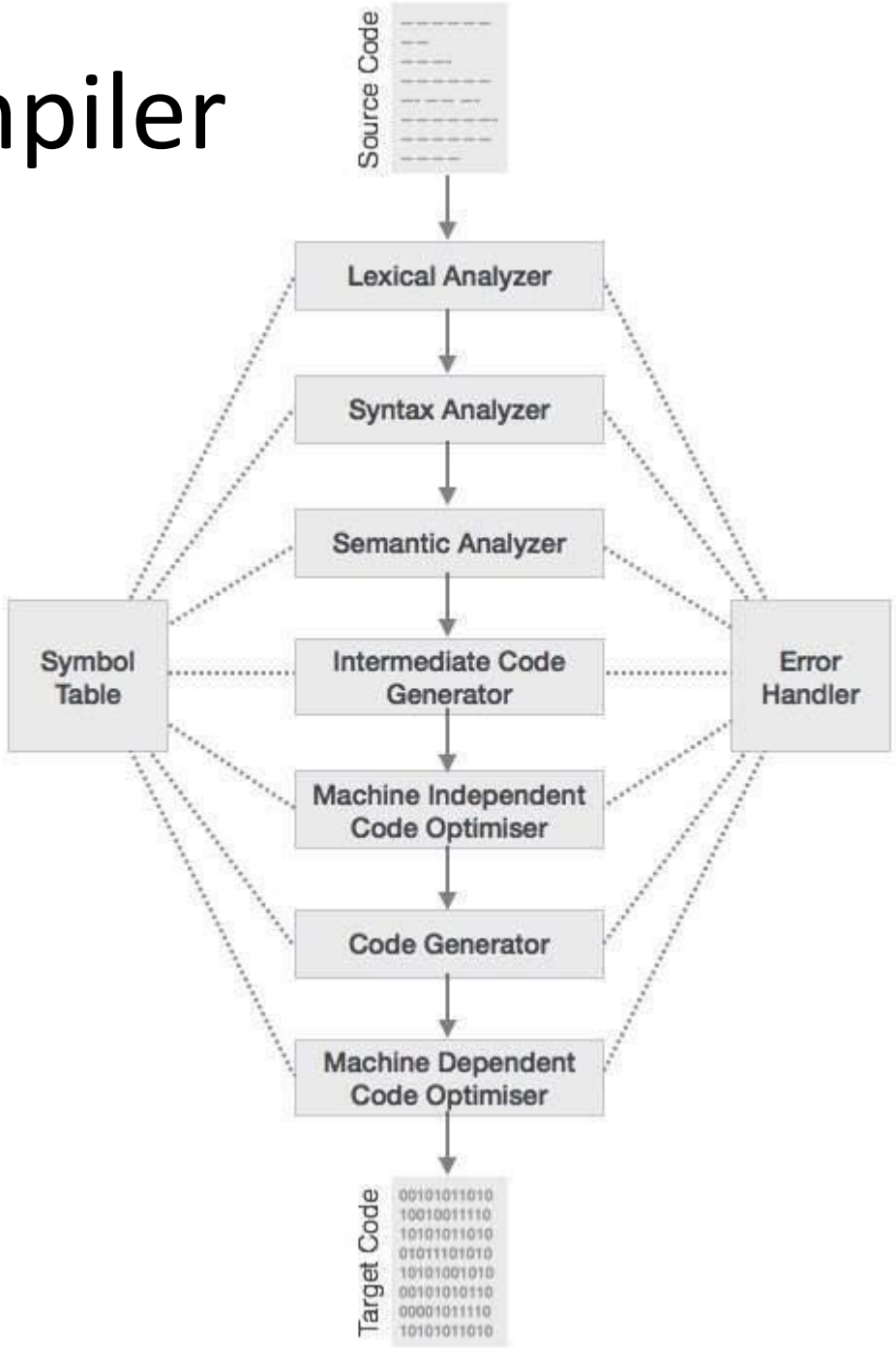


1. What advantages are there to a language-processing system in which the compiler produces assembly language rather than machine language?

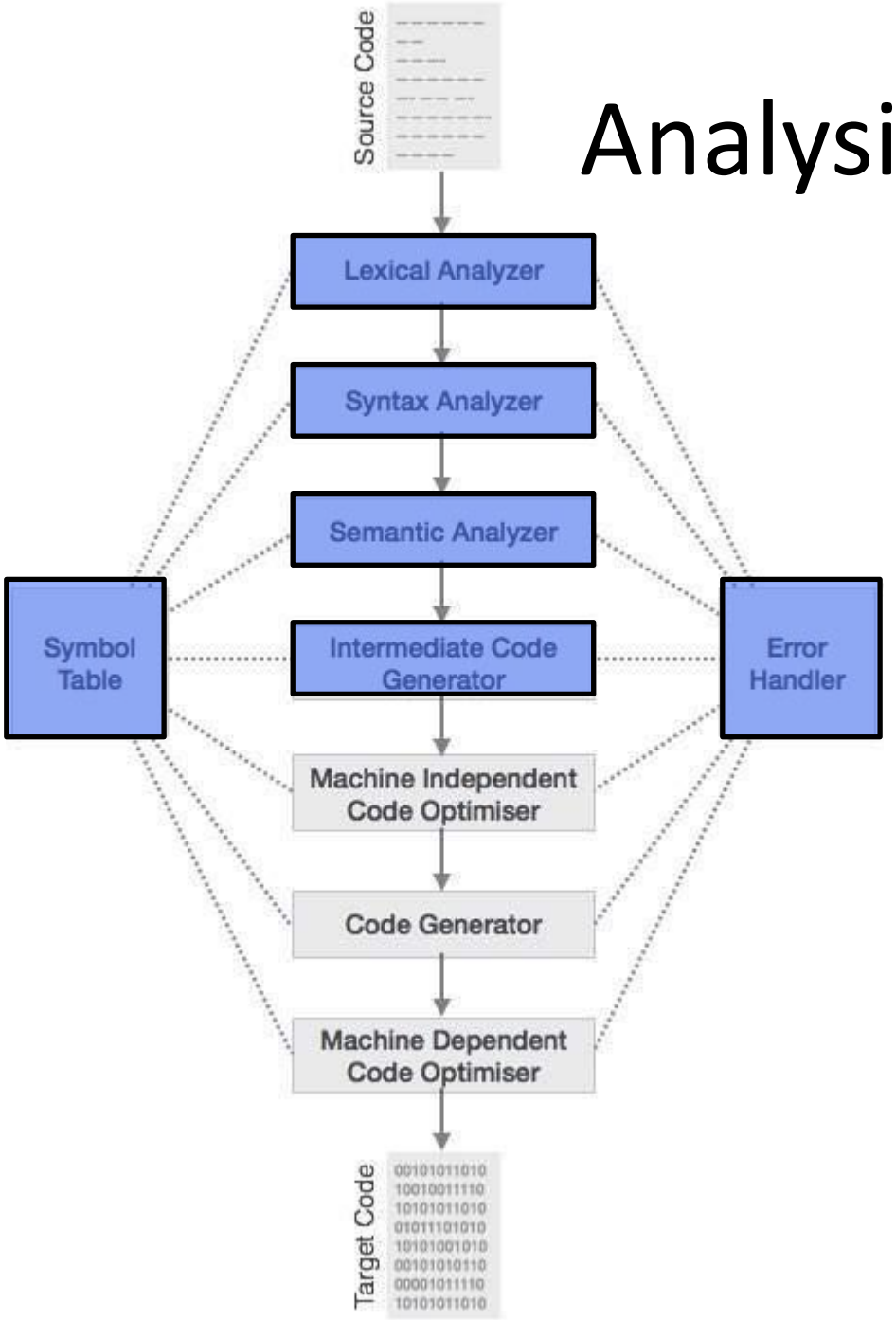
2. A compiler that translates a high-level language into another high-level language is called **a source-to-source translator**.

   What advantages are there to using C as a target language for a compiler?

Phases of Compiler

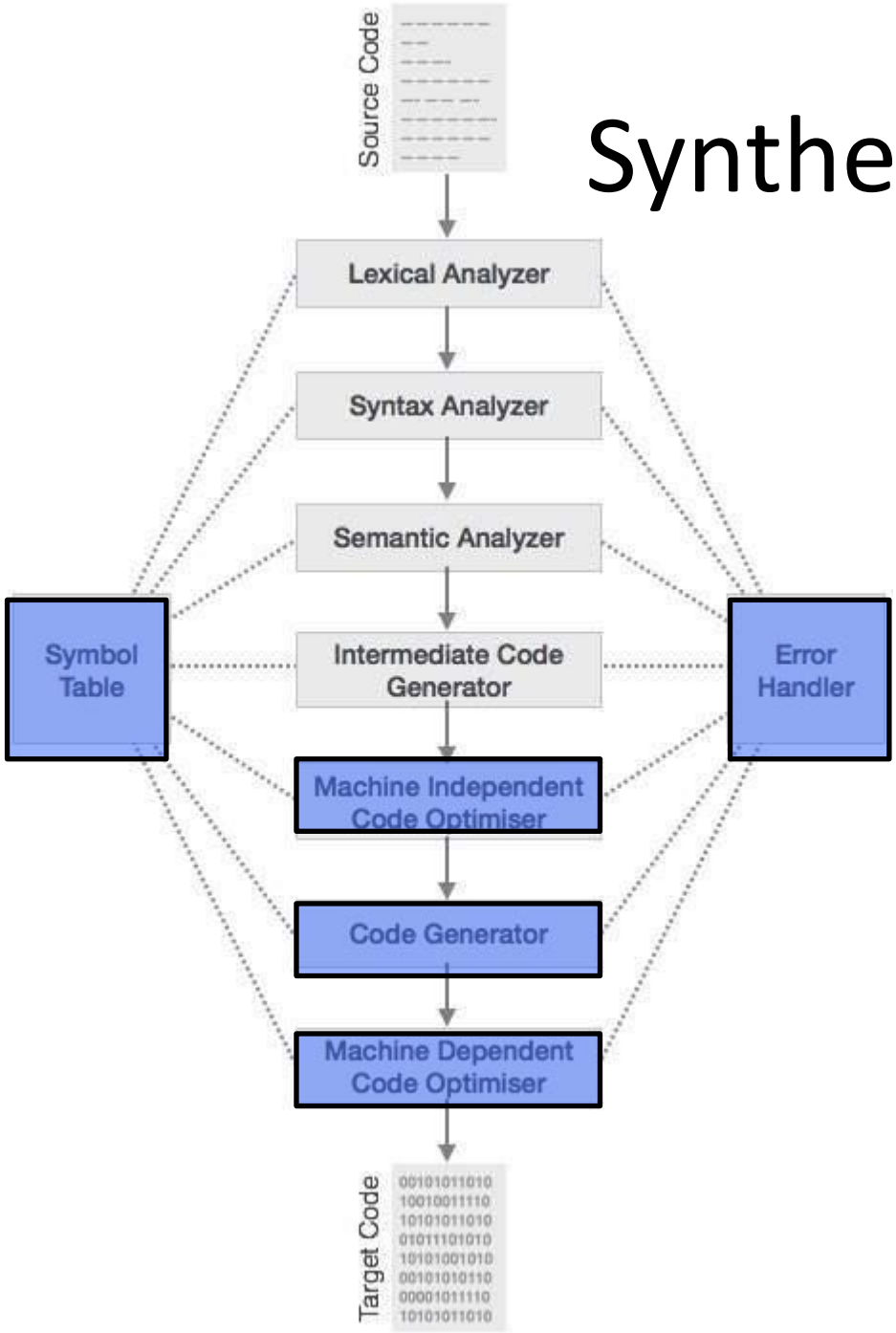


Analysis Part



- The **analysis part** is often called the front end of the compiler.
- The **analysis part** also collects information about the source program and stores it in a data structure called **a symbol table**, which is passed along with the intermediate representation to the synthesis part.

Synthesis Part



- The **synthesis part** constructs the desired target program from the intermediate representation and the information in the symbol table.

Analysis Part (Step 1 & 2)

- **Lexical Analysis or Scanning**
  - The **lexical analyzer** reads the stream of characters making up the source program and groups the characters into meaningful sequences called **lexemes**.
  - For each lexeme, the lexical analyzer produces as output a token of the form **<token-name; attribute-value>**

- **Syntax analysis or Parsing**
  - The **parser** uses the rest components of the tokens produced by the lexical analyzer to create a tree-like intermediate representation (**syntax tree**) that depicts the grammatical structure of the token stream.

Analysis Part (Step 3 & 4)

- **Semantic Analysis**
  - The semantic analyzer uses the syntax tree and the information in the symbol table to check the source program for semantic consistency with the language definition.
  - Type checking and type conversion (coercions) are part of semantic analysis.

- **Intermediate Code Generator**:
  - After syntax and semantic analysis of the source program, many compilers generate an explicit low-level or machine-like intermediate representation (e.g. three-address code) which should be easy to produce and it should be easy to translate into the target machine.

Symbol Table Management

- The **symbol table** is a data structure containing a record for each variable name, with fields for the attributes of the name.

- The data structure should be designed to allow the compiler **to add** the record for each name **quickly** and **to store or retrieve data** from that record **quickly**.

Synthesis Part (Step 5)

- **Code Optimization**:
  - The machine-independent code-optimization phase attempts to improve the intermediate code so that **better** target code will result.
  - Usually better means **faster**, but other objectives may be desired, such as **shorter code**, or target code that consumes **less power**.

Synthesis Part (Step 6)

- **Code Generation**:
  - The code generator takes as input an intermediate representation of the source program and maps it into the **target language**.
  - If the target language is **machine code**, registers or memory locations are selected for each of the variables used by the program
  - Then, the intermediate instructions are translated into sequences of machine instructions that perform the same task.

Synthesis Part (Step 6)

  - A crucial aspect of code generation is the **judicious assignment of registers to hold variables**.
  - The organization of storage at run-time depends on the language being compiled.
- Storage-allocation decisions are made either during intermediate code generation or during code generation.

Synthesis Part (Step 7)

- **Machine Dependent Code Optimization**:
  - Machine-dependent optimization 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.

Code Optimization

- **Code Optimization** aims at improving the execution efficiency of a program.

- This is achieved in two ways:
  1. **Redundancies** in a program are **eliminated**.
  2. **Computations** in a program are **rearranged** or **rewritten** to make it **execute efficiently**.

- Code optimization must not change the meaning of a program.

Scope of optimization

1. Optimization seeks to improve a program rather than the algorithm used in a program.

   Thus, ***replacement of an algorithm by a more efficient algorithm is beyond the scope of optimization***.

2. Efficient code generation for a specific target machine (e.g. by fully exploiting its instruction set) is also beyond its scope; it belongs in the back end of the compiler.

   The optimization techniques are thus independent of both the PL(programming language) and the target machine.

Two pass schematic for language processing

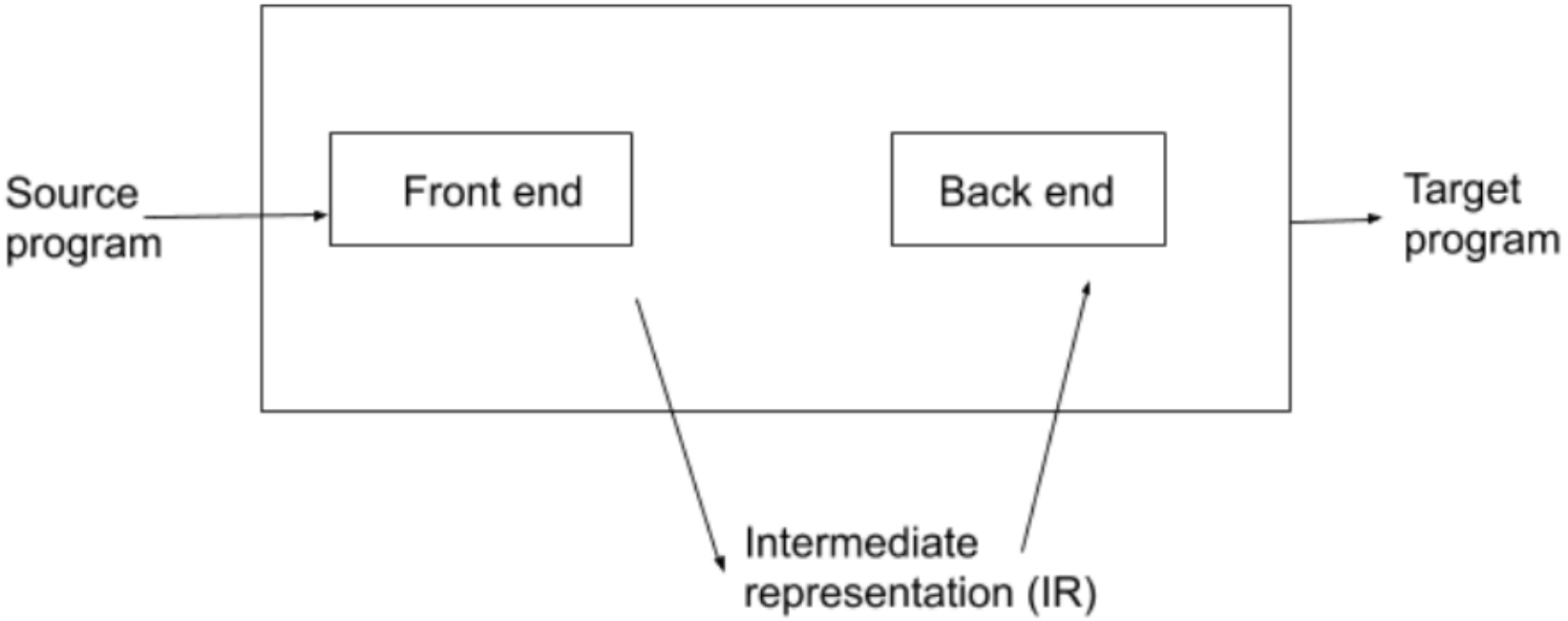


Figure 1 Two pass schematic for language processing

Schematic of an optimizing compiler

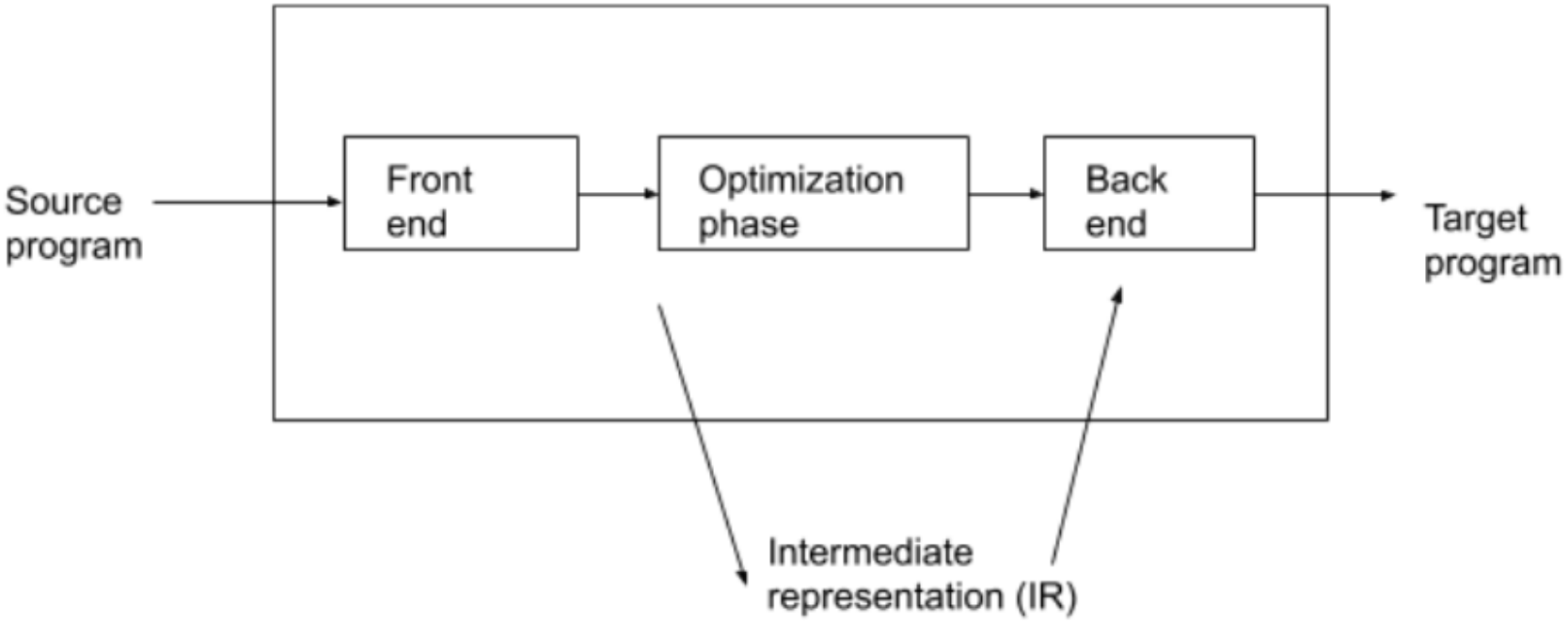


Figure 2 Schematic of an optimizing compiler

Optimizing Transformations

- An ***optimizing transformation*** is a rule for rewriting a segment of a program to improve its execution efficiency without affecting its meaning.

- Optimizing transformations are classified into ***local*** **and** ***global*** transformations depending on whether they are applied over small segments of a program consisting of a few source statements or over large segments consisting of loops or function bodies.

- The reason for this distinction is the difference in the costs and benefits of the optimizing transformations.

Few of the optimizing transformations

1. Compile time evaluation
2. Elimination of common subexpression
3. Dead code elimination
4. Frequency reduction
5. Strength reduction

Compile time evaluation

- Execution efficiency can be improved by performing certain actions specified in a program during compilation itself.
- This eliminates the need to perform them during execution of the program, thereby reducing the execution time of the program.

- ***Constant folding*** is the main optimization of this kind.
- When all operands in an operation are constants, the operation can be performed at compilation time.
- The result of the operation, also a constant, can replace the original evaluation in the program.

Compile time evaluation

- Example

  An assignment a:=3.14157 / 2 can be replaced by a:=1.570785, thereby eliminating a division operation.

Elimination of common subexpressions

- **Common subexpressions** are occurrences of expressions yielding the same value.

  (Such expressions are called **equivalent expressions**.)

- Let CS_i designate a set of common subexpressions.
- It is possible to eliminate an occurrence $e_j \in CS_i$ if, no matter how the evaluation of e_j is reached during the execution of the program, the value of some $e_k \in CS_i$ would have been already computed.
- Provision is made to save this value and use it at the place of occurrence of e_j

Elimination of common subexpressions

```
a := b * c                          t := b * c
---                        →        a := t
x := b * c + 5.2                    ---
                                    x := t + 5.2
```

- Here CS_i contains two occurrences of b*c.
- The second occurrence of b*c can be eliminated because the first occurrence of b*c is always evaluated before the second occurrence is reached during the execution of the program.
- The value computed at the first occurrence is saved in **t**.
- This value is used in the assignment to x.

Dead code elimination

- The code which can be omitted from a program without affecting its result is called ***dead code***.
- Dead code is detected by checking whether the value assigned in an assignment statement is used anywhere in the program.

  •

  An assignment x := <exp> constitutes dead code if the value assigned to x is not used in the program, no matter how control flows after executing this assignment.
- **Note** that <exp> constitute dead code only if its execution does not produce side effects, i.e. only if it does not contain function calls.

Frequency reduction

- Execution time of a program can be reduced by moving code from a part of a program which is executed very frequently to another part of the program which is executed fewer times.

- For example, the transformation of *loop optimization* moves **loop invariant code** out of a loop and places it prior to loop entry.

Frequency reduction

- Here, **x := 25 * a** is loop invariant. Hence in the optimized program it is computed only once before entering the **for** loop.
- **y := x + z** is not loop invariant. Hence it cannot be subjected to frequency reduction.

```
for i := 1 to 100 do
begin
  z := i
  x := 25 * a
  y := x+z
End
```

→

```
x := 25 * a
for i := 1 to 100 do
begin
  z := i
  y := x+z
end
```

Strength reduction

- The strength reduction optimization replaces the occurrence of a time consuming operation (a **high strength** operation) by an occurrence of a faster operation (a **low strength** operation).
- e.g. replacement of a multiplication by an addition.

```
for i := 1 to 10 do
begin
  ---
  k := i*5
  ---
end
```

→

```
itemp := 5
for i :=1 to 10 do
begin
  ---
  k := itemp
  ---
  itemp := itemp+5
end
```

Strength reduction

- **Note** that strength reduction optimization is **not** performed on operations involving **floating point operands** because finite precision of floating point arithmetic cannot guarantee equivalence of results after strength reduction.

Practice…

1. r = 20; area = (22/7) * r * r;
2. a = b + c; p = q + r; d = c + r; x = b + c;
3. x = (y – (50/100));
4. for(i=0; i<n ;i++){
   sum = sum + i;
   a = x * y;
   }
5. q = 10; if(q == 0) { p = r + s; }
6. a = b * 4;

Hint..

1. r = 20; area = (22/7) * r * r; (Compile time evaluation: constant folding)
2. a = b + c; p = q + r; d = c + r; x = b + c (common subexpression elimination)
3. x = (y – (50/100)); (compile time evaluation)
4. for(i=0; i<n ;i++){

   sum=sum+i;

   a = x * y;

   } (Frequency reduction by moving loop invariant code)
5. q = 10; if(q == 0) { p = r + s; } (dead code elimination)
6. a = b * 4; (strength reduction)

Three Address Code

- In **three-address code**, there is **at most one operator** on the right side of an instruction; that is, no built-up arithmetic expressions are permitted.
- Thus, a source-language expression like **x + y * z** might be translated into the sequence of three-address instructions

  t1 = y * z

  t2 = x + t1

  where t1 and t2 are compiler-generated temporary names.

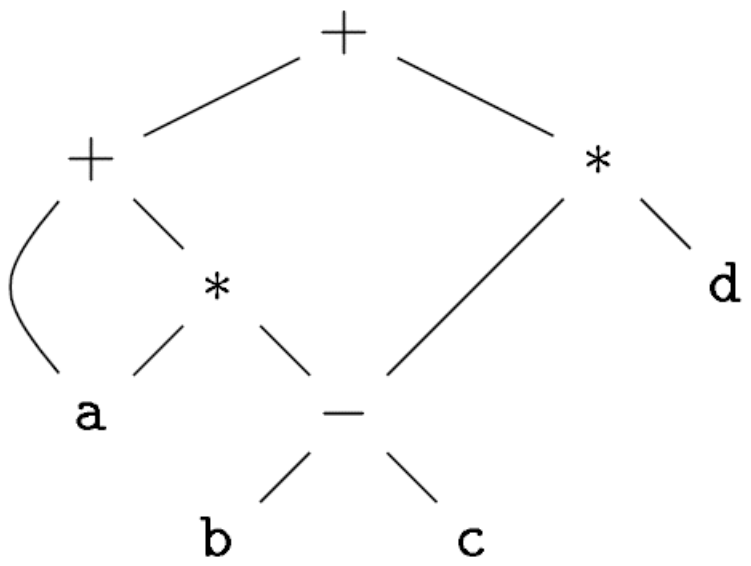
Benefits

- Desirable for target-code generation and optimization
  - multi-operator arithmetic expressions and of nested flow-of-control statements are unravelled

- The code can be rearranged easily
  - use of names for the intermediate values computed by a program

Three-address code is a linearized representation of a syntax tree or a DAG in which explicit names correspond to the interior nodes of the graph.

DAG (Directed Acyclic Graph) of a + a * (b - c) + (b - c) * d



Three address code

t1 = b - c

t2 = a * t1

t3 = a + t2

t4 = t1 * d

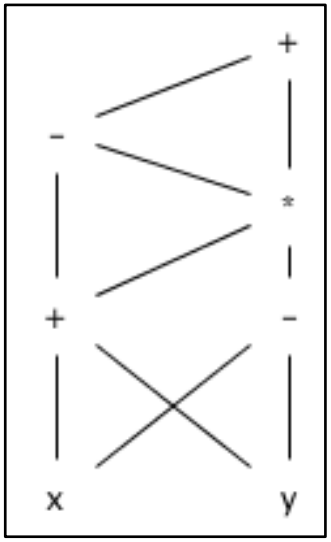
t5 = t3 + t4

Construct DAG for the following:

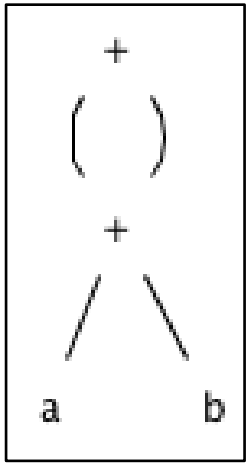
- ((x + y) – ((x + y) * (x - y))) + ((x + y) * (x - y))
- (a + b) + (a + b)
- a + b + a + b
- a + a + (a + a + a + (a + a + a + a))

Dragon book 2nd ed. Exercise for Section 6.1

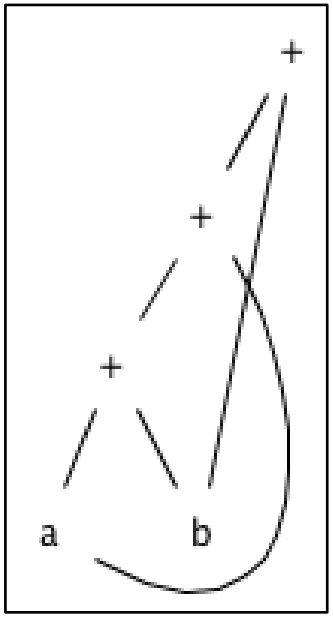
((x + y) – ((x + y) * (x - y))) + ((x + y) * (x - y))



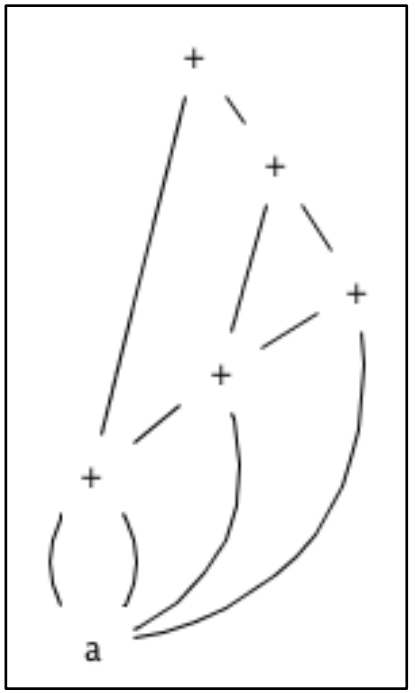
(a + b) + (a + b)



a + b + a + b



a + a + (a + a + a + (a + a + a + a))



Three address code = Address + Instructions

Address in Three address code

1. **A name.**
   - For convenience, we allow source-program names to appear as addresses in three-address code.
   - In an implementation, a source name is replaced by a pointer to its symbol-table entry, where all information about the name is kept.
2. **A constant.**
   - In practice, a compiler must deal with many different types of constants and variables.
   - Type conversions within expressions can be both implicit as well as explicit.

Address in Three address code

3. **A compiler-generated temporary.**
   - It is useful, especially in optimizing compilers, to create a distinct name each time a temporary is needed.
   - These temporaries can be combined, if possible, when registers are allocated to variables.

Symbolic labels

- Symbolic labels will be used by instructions that alter the flow of control.
- A **symbolic label** represents the index of a three-address instruction in the sequence of instructions.
- Actual indexes can be substituted for the labels, either by making a separate pass or by “backpatching”.

Three-address instruction forms

1. **Assignment instructions** of the form **x = y op z**,
   - where op is a binary arithmetic or logical operation,
   - and x, y, and z are addresses.
2. **Assignments** of the form **x = op y**,
   - where op is a unary operation.
   - Essential unary operations include unary minus, logical negation, and conversion operators that, for example, convert an integer to a floating-point number.
3. **Copy instructions** of the form **x = y**,
   - where x is assigned the value of y.
4. **An unconditional jump goto L**.
   - The three-address instruction with label L is the next to be executed.

Three-address instruction forms

5. **Conditional jumps** of the form **if x goto L** and **ifFalse x goto L**.
   - These instructions execute the instruction with label L next if x is true and false, respectively.
   - Otherwise, the following three-address instruction in sequence is executed next, as usual.
6. **Conditional jumps** such as **if x relop y goto L**,
   - which apply a **relational operator** (<, ==, >=, etc.) to x and y, and execute the instruction with label L next if x stands in relation relop to y.
   - If not, the three-address instruction following if x relop y goto L is executed next, in sequence.

Three-address instruction forms

7. **Procedure calls and returns** are implemented using the following instructions for procedure and function call
   - **param x for parameters**
   - **call p, n**
   - **y = call p, n**

e.g.

```
param x1
param x2
...
param xn
call p, n
```

- generated as part of a call of the procedure p(x1; x2; : : : ; xn).

Three-address instruction forms

- The integer n, indicating the number of actual parameters in **“call p, n,”** is not redundant because calls can be nested.

- That is, some of the first param statements could be parameters of a call that comes after p returns its value; that value becomes another parameter of the later call.

Three-address instruction forms

8. **Indexed copy instructions** of the form **x = y[i]** and **x[i]=y**.
   - The instruction x = y[i] sets x to the value in the location i memory units beyond location y.
   - The instruction x[i]=y sets the contents of the location i units beyond x to the value of y.

Three-address instruction forms

9. **Address and pointer assignments** of the form **x = &y**, **x = *y**, and ***x = y**.
   - The instruction x = &y sets the r-value of x to be the location (l-value) of y. Presumably y is a name, perhaps a temporary, that denotes an expression with an l-value such as A[i][j], and x is a pointer name or temporary.
   - In the instruction x = *y, presumably y is a pointer or a temporary whose r-value is a location. The r-value of x is made equal to the contents of that location.
   - Finally, *x = y sets the r-value of the object pointed to by x to the r-value of y.

Representation of 3 address instruction

- Quadruple
- Triple
- Indirect triple

Quadruple

- A **quadruple (or just "quad")** has four fields, which we call op, arg1, arg2, and result. The op field contains an internal code for the operator.
- E.g. a = b * -c + b * -c ;

```
t1 = minus c
t2 = b * t1
t3 = minus c
t4 = b * t3
t5 = t2 + t4
 a = t5
```

Three-address code

	op	arg_1	arg_2	*result*
0	minus	c		t_1
1	*	b	t_1	t_2
2	minus	c		t_3
3	*	b	t_3	t_4
4	+	t_2	t_4	t_5
5	=	t_5		a
		...		

Quadruples

Triple

- A **triple** has only three fields, which we call op, arg1, and arg2.
- Instead of the temporary t1, in a triple representation would refer to position (0).
- Parenthesized numbers represent pointers into the triple structure itself. The positions or pointers to positions are called **value numbers**.

```
t1 = minus c
t2 = b * t1
t3 = minus c
t4 = b * t3
t5 = t2 + t4
 a = t5
```

Three-address code

	op	arg_1	arg_2	*result*
0	minus	c		t_1
1	*	b	t_1	t_2
2	minus	c		t_3
3	*	b	t_3	t_4
4	+	t_2	t_4	t_5
5	=	t_5		a
	...			

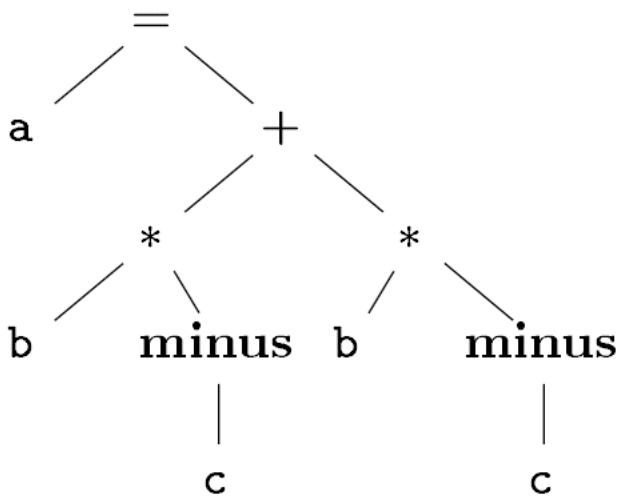
Quadruples

	op	arg_1	arg_2
0	minus	c	
1	*	b	(0)
2	minus	c	
3	*	b	(2)
4	+	(1)	(3)
5	=	a	(4)
	...		

Triples

Syntax tree

a = b * -c + b * -c ;



Syntax tree

	op	arg_1	arg_2
0	minus	c	
1	*	b	(0)
2	minus	c	
3	*	b	(2)
4	+	(1)	(3)
5	=	a	(4)
	...		

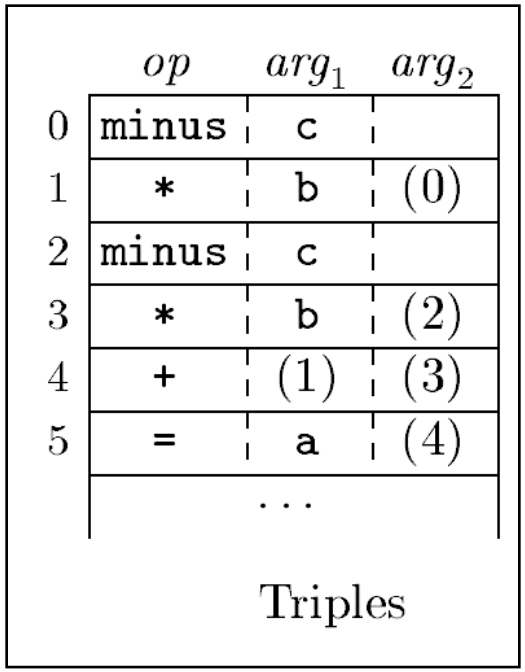
Triples

Advantage of Quadruple over triple

- A benefit of **quadruples over triples** can be seen in an optimizing compiler, where instructions are often moved around.
- With quadruples, if we move an instruction that computes a temporary t, then the instructions that use t require no change.
- With triples, the result of an operation is referred to by its position, so moving an instruction may require us to change all references to that result.

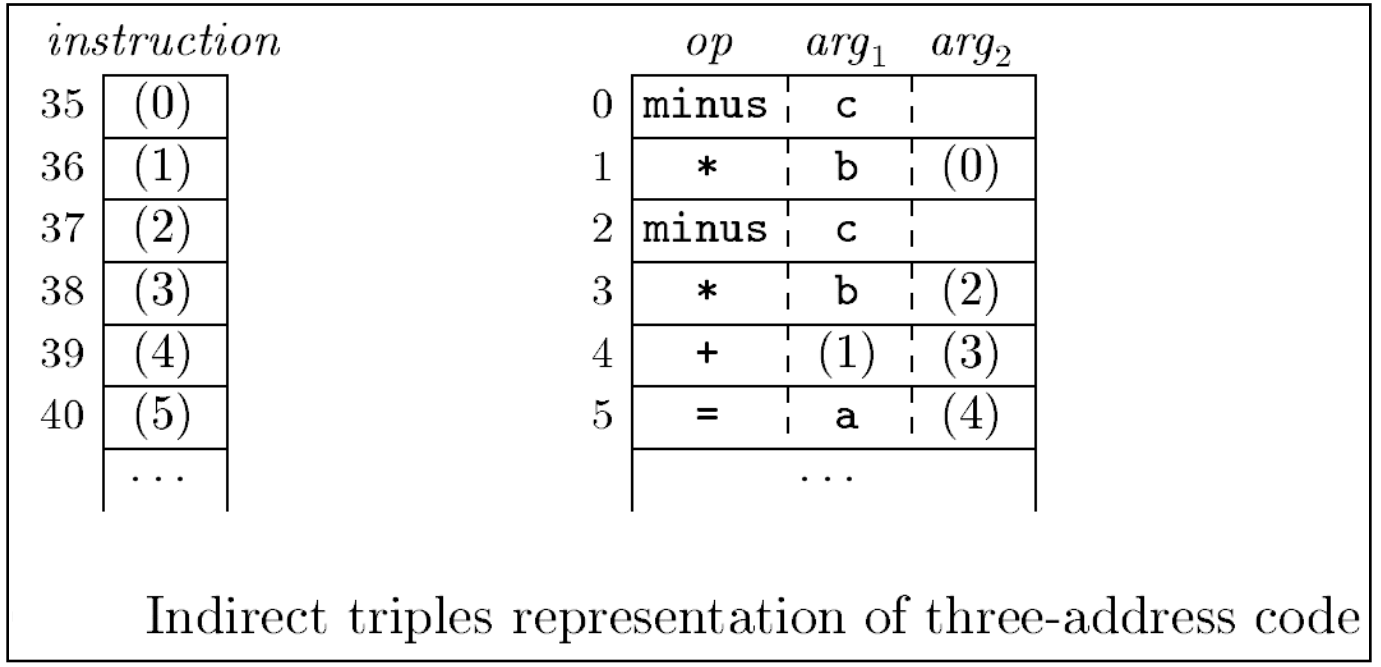
Indirect triple

- **Indirect triples** consist of a listing of pointers to triples, rather than a listing of triples themselves.



	op	arg_1	arg_2
0	minus	c	
1	*	b	(0)
2	minus	c	
3	*	b	(2)
4	+	(1)	(3)
5	=	a	(4)
	...		

Triples



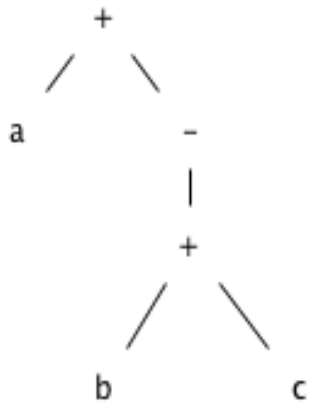
instruction	
35	(0)
36	(1)
37	(2)
38	(3)
39	(4)
40	(5)
	...

	op	arg_1	arg_2
0	minus	c	
1	*	b	(0)
2	minus	c	
3	*	b	(2)
4	+	(1)	(3)
5	=	a	(4)
	...		

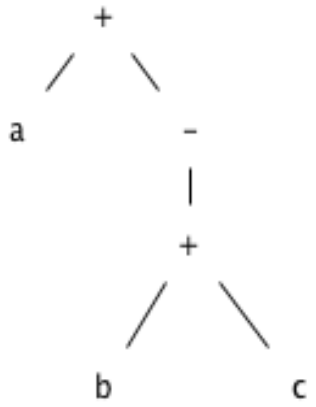
Indirect triples representation of three-address code

Translate the arithmetic expression **a + - (b + c)** into:
a) Syntax tree b) Quadruples c) Triples d) Indirect triples

Translate the arithmetic expression **a + - (b + c)** into:
a) Syntax tree b) Quadruples c) Triples d) Indirect triples

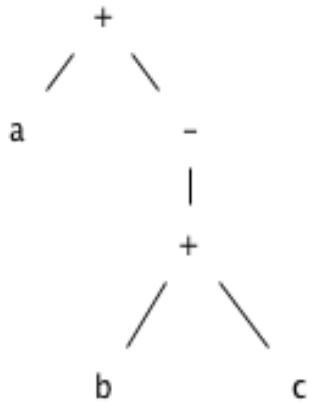


Translate the arithmetic expression **a + - (b + c)** into:
a) Syntax tree b) Quadruples c) Triples d) Indirect triples



op	arg1	arg2	result
+	b	c	t1
minus	t1		t2
+	a	t2	t3

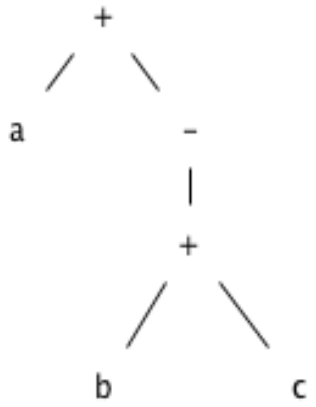
Translate the arithmetic expression **a + - (b + c)** into:
a) Syntax tree b) Quadruples c) Triples d) Indirect triples



op	arg1	arg2	result
+	b	c	t1
minus	t1		t2
+	a	t2	t3

	op	arg1	arg2
0	+	b	c
1	minus	(0)	
2	+	a	(1)

Translate the arithmetic expression **a + - (b + c)** into:
a) Syntax tree b) Quadruples c) Triples d) Indirect triples



op	arg1	arg2	result
+	b	c	t1
minus	t1		t2
+	a	t2	t3

	op	arg1	arg2
0	+	b	c
1	minus	(0)	
2	+	a	(1)

instruction			op	arg1	arg2
15	(0)	0	+	b	c
16	(1)	1	minus	(0)	
17	(2)	2	+	a	(1)

Quick Sort code fragment

```
void quicksort(int m, int n){
/* recursively sorts a[m] through a[n] */
int i, j; int v, x;
if (n <= m) return;
    /* fragment begins here */
    i = m-1; j = n; v = a[n];
    while (1) {
        do i = i+1; while (a[i] < v);
        do j = j-1; while (a[j] > v);
        if (i >= j) break;
            x = a[i]; a[i] = a[j]; a[j] = x; /* swap a[i], a[j] */
    }
    x = a[i]; a[i] = a[n]; a[n] = x; /* swap a[i], a[n] */
    /* fragment ends here */
    quicksort(m,j); quicksort(i+1,n);
}
```

Generating Three address code for given code fragment

- **i = m-1;**
- **j = n;**
- **v = a[n];**

(1) i = m-1

(2) j = n

(3) t1 = 4 * n

(4) v = a[t1]

Here, it is assumed that int occupies 4 bytes.

Generating Three address code for given code fragment

```
do i = i + 1;
   while (a[i] < v);
```

(5) i = i + 1
(6) t2 = 4 * i
(7) t3 = a[t2]
(8) if t3<v goto (5)

```
do j = j - 1;
   while (a[j] > v);
```

(9) j = j - 1
(10) t4 = 4 * j
(11) t5 = a[t4]
(12) if t5>v goto (9)

Generating Three address code for given code fragment

if (i >= j) break;	(13) if i>=j goto **(23)**
x = a[i];	(14) t6 = 4 * i (15) x = a[t6]
a[i] = a[j];	(16) t7 = 4 * i (17) t8 = 4 * j (18) t9 = a[t8] (19) a[t7] = t9
a[j] = x; **/* swap a[i], a[j] */**	(20) t10 = 4 * j (21) a[t10] = x
} //closing of while(1)	(22) goto (5)

Generating Three address code for given code fragment

x = a[i];	(23) t11 = 4*i (24) x = a[t11]
a[i] = a[n];	(25) t12 = 4*i (26) t13 = 4*n (27) t14 = a[t13] (28) a[t12] = t14
a[n] = x; **/* swap a[i], a[n] */**	(29) t15 = 4*n (30) a[t15] = x

Graph Representation of intermediate code

1. Partition the intermediate code into **basic blocks**, which are maximal sequences of consecutive three-address instructions with the properties that
   a) The flow of control can only enter the basic block through the first instruction in the block. That is, there are **no jumps into the middle** of the block.
   b) Control will leave the block **without halting or branching**, except possibly at the last instruction in the block.
2. The basic blocks become the **nodes** of a flow graph, whose **edges** indicate which blocks can follow which other blocks.

Basic Blocks

- Our first job is to partition a sequence of three-address instructions into **basic blocks**.

- We begin a new basic block with the **first instruction** and keep adding instructions **until** we meet **either a jump, a conditional jump, or a label on the following instruction**.

- In the absence of jumps and labels, the control proceeds sequentially from one instruction to the next.

Algorithm 1: Partitioning three-address instructions into basic blocks.

INPUT:

A sequence of three-address instructions.

OUTPUT:

A list of the basic blocks for that sequence in which each instruction is assigned to exactly one basic block.

METHOD:

First, we determine those instructions in the intermediate code that are leaders, that is, the first instructions in some basic block. The instruction just past the end of the intermediate program is not included as a leader.

Algorithm 1: Partitioning three-address instructions into basic blocks.

The rules for finding leaders are:

1. The first three-address instruction in the intermediate code is a leader.
2. Any instruction that is the target of a conditional or unconditional jump is a leader.
3. Any instruction that immediately follows a conditional or unconditional jump is a leader.

Then, for each leader, its basic block consists of itself and all instructions up to but not including the next leader or the end of the intermediate program.

Example: Source code to set a 10 x 10 matrix to an identity matrix

```
for i from 1 to 10 do
        for j from 1 to 10 do
                a[i; j] = 0.0;
for i from 1 to 10 do
        a[i; i] = 1.0;
```

Three address code

1. i = 1
2. j = 1
3. t_1 = 10 * i
4. t_2 = t_1 + j
5. t_3 = 8 * t_2
6. t_4 = t_3 – 88
7. a[t_4] = 0.0
8. j = j + 1
9. if j <= 10 goto (3)
10. i = i + 1
11. if i <= 10 goto (2)
12. i = 1
13. t_5 = i – 1
14. t_6 = 88 * t5
15. a[t_6] = 1.0
16. i = i + 1
17. if i <= 10 goto (13)

Note: Size of double is 8 bytes

Instruction 1 is a leader by rule (1) of Algorithm 1

1. **i = 1**
2. j = 1
3. $t_1 = 10 * i$
4. $t_2 = t_1 + j$
5. $t_3 = 8 * t_2$
6. $t_4 = t_3 - 88$
7. $a[t_4] = 0.0$
8. j = j + 1
9. if j <= 10 goto (3)
10. i = i + 1
11. if i <= 10 goto (2)
12. i = 1
13. $t_5 = i - 1$
14. $t_6 = 88 * t5$
15. $a[t_6] = 1.0$
16. i = i + 1
17. if i <= 10 goto (13)

To find the other leaders, we first need to find the jumps.

1. i = 1
2. j = 1
3. $t_1 = 10 * i$
4. $t_2 = t_1 + j$
5. $t_3 = 8 * t_2$
6. $t_4 = t_3 - 88$
7. $a[t_4] = 0.0$
8. j = j + 1
9. if j <= 10 goto (3)
10. i = i + 1
11. if i <= 10 goto (2)
12. i = 1
13. $t_5 = i - 1$
14. $t_6 = 88 * t5$
15. $a[t_6] = 1.0$
16. i = i + 1
17. if i <= 10 goto (13)

By rule (2), the targets of these jumps are leaders

1. **i = 1**
2. **j = 1**
3. **t_1 = 10 * i**
4. $t_2 = t_1 + j$
5. $t_3 = 8 * t_2$
6. $t_4 = t_3 - 88$
7. $a[t_4] = 0.0$
8. j = j + 1
9. if j <= 10 goto (3)
10. i = i + 1
11. if i <= 10 goto (2)
12. i = 1
13. **t_5 = i – 1**
14. $t_6 = 88 * t5$
15. $a[t_6] = 1.0$
16. i = i + 1
17. if i <= 10 goto (13)

by rule (3), each instruction following a jump is a leader

1. **i = 1**
2. **j = 1**
3. **t_1 = 10 * i**
4. $t_2 = t_1 + j$
5. $t_3 = 8 * t_2$
6. $t_4 = t_3 – 88$
7. $a[t_4] = 0.0$
8. j = j + 1
9. if j <= 10 goto (3)
10. **i = i + 1**
11. if i <= 10 goto (2)
12. **i = 1**
13. **t_5 = i – 1**
14. $t_6 = 88 * t5$
15. $a[t_6] = 1.0$
16. i = i + 1
17. if i <= 10 goto (13)

So, finally we have the leaders

1. **i = 1**
2. **j = 1**
3. **t_1 = 10 * i**
4. $t_2 = t_1 + j$
5. $t_3 = 8 * t_2$
6. $t_4 = t_3 - 88$
7. $a[t_4] = 0.0$
8. j = j + 1
9. if j <= 10 goto (3)
10. **i = i + 1**
11. if i <= 10 goto (2)
12. **i = 1**
13. **t_5 = i – 1**
14. $t_6 = 88 * t5$
15. $a[t_6] = 1.0$
16. i = i + 1
17. if i <= 10 goto (13)

Basic Blocks

1. i = 1 **B1**
2. j = 1 **B2**
3. $t_1 = 10 * i$
4. $t_2 = t_1 + j$
5. $t_3 = 8 * t_2$
6. $t_4 = t_3 - 88$ **B3**
7. $a[t_4] = 0.0$
8. j = j + 1
9. if j <= 10 goto (3)

10. i = i + 1
11. if i <= 10 goto (2) **B4**

12. i = 1 **B5**
13. $t_5 = i - 1$
14. $t_6 = 88 * t5$
15. $a[t_6] = 1.0$
16. i = i + 1
17. if i <= 10 goto (13) **B6**

Flow Graphs

- Once an intermediate-code program is partitioned into basic blocks, we represent the flow of control between them by a flow graph.

- The nodes of the flow graph are the basic blocks.

- There is an edge from block B to block C if and only if it is possible for the first instruction in block C to immediately follow the last instruction in block B.

There are two ways an edge could be justified:

1. There is a conditional or unconditional jump from the end of B to the beginning of C.
2. C immediately follows B in the original order of the three-address instructions, and B does not end in an unconditional jump.

- We say that B is a predecessor of C, and C is a successor of B.

Entry and Exit nodes

- There is an edge from the **entry** to the first executable node of the flow graph, that is, to the basic block that comes from the first instruction of the intermediate code.
- There is an edge to the **exit** from any basic block that contains an instruction that could be the last executed instruction of the program.
- If the final instruction of the program is not an unconditional jump, then the block containing the final instruction of the program is one predecessor of the exit, but so is any basic block that has a jump to code that is not part of the program.

Flow graph for intermediate code to set a 10 x 10 matrix to an identity matrix:

- The **entry points to basic block B_1**, since B_1 contains the first instruction of the program.

- The **only successor of B_1 is B_2**, because B_1 does not end in an unconditional jump, and the leader of B_2 immediately follows the end of B_1.

i.e. ENTRY → B1 → B2

Flow graph for intermediate code to set a 10 x 10 matrix to an identity matrix:

- Block **B_3 has two successors**.
- One is **itself**, because the leader of B_3, instruction **3**, is the **target** of the conditional jump at the end of **B_3, instruction 9**.
- The **other successor is B_4**, because control can fall through the conditional jump at the end of B_3 and next enter the **leader of B_4**.

B3 → B3

↓

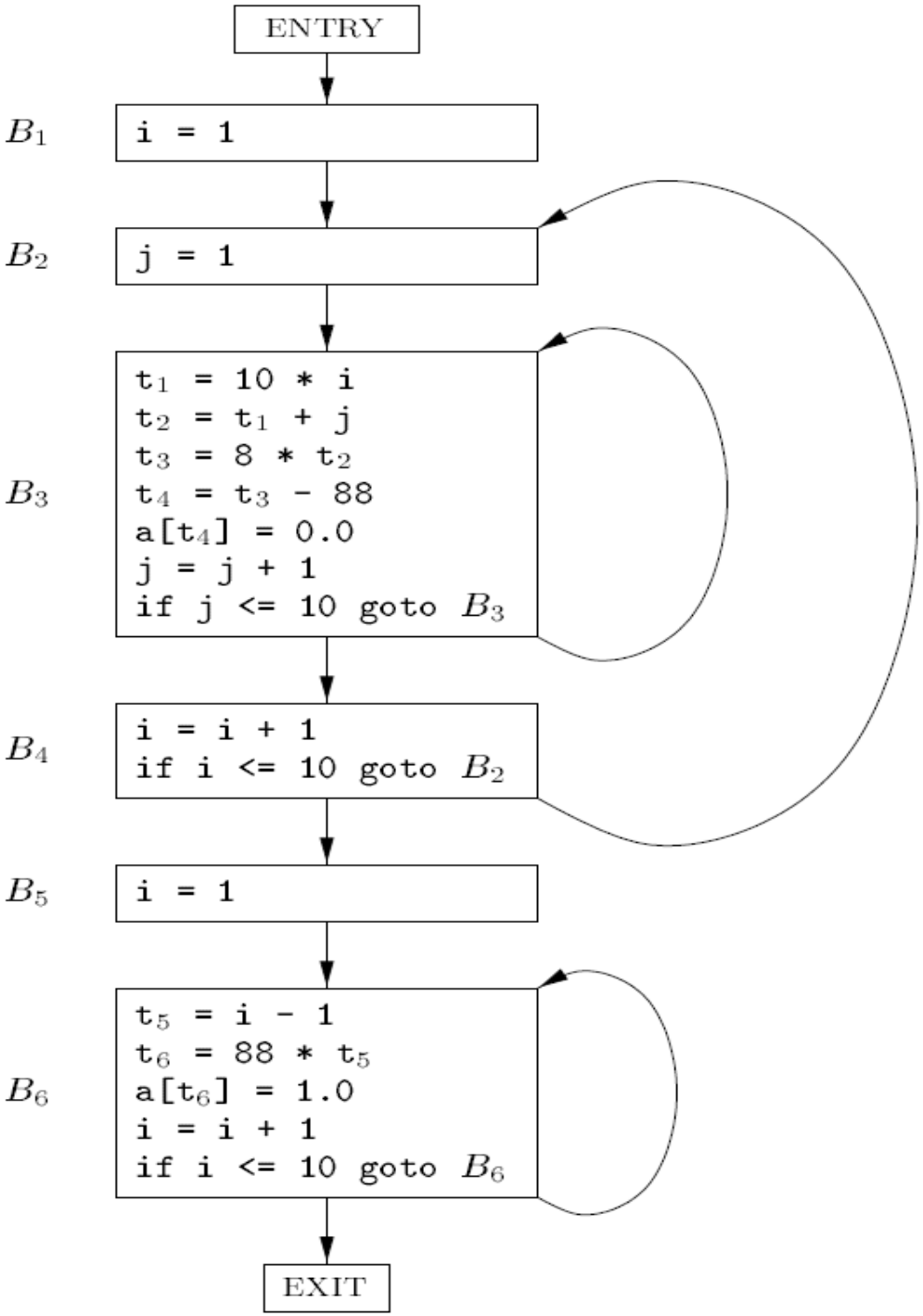
B4

Flow graph for intermediate code to set a 10 x 10 matrix to an identity matrix:

- Only **B_6 points to the exit** of the flow graph, since the only way to get to code that follows the program from which we constructed the flow graph is to fall through the conditional jump that ends B_6.

  B6 → EXIT

Complete Flow Graph



Three Address Code for Quicksort code fragment

(1) i = m-1
(2) j = n
(3) t1 = 4*n
(4) v = a[t1]
(5) i = i+1
(6) t2 = 4*i
(7) t3 = a[t2]
(8) if t3<v goto (5)
(9) j = j-1
(10) t4 = 4*j
11) t5 = a[t4]
(12) if t5>v goto (9)
(13) if i>=j goto (23)
(14) t6 = 4*i
(15) x = a[t6]
(16) t7 = 4*i
(17) t8 = 4*j
(18) t9 = a[t8]
(19) a[t7] = t9
(20) t10 = 4*j
(21) a[t10] = x
(22) goto (5)
(23) t11 = 4*i
(24) x = a[t11]
(25) t12 = 4*i
(26) t13 = 4*n
(27) t14 = a[t13]
(28) a[t12] = t14
(29) t15 = 4*n
(30) a[t15] = x

What next??

- Find Leaders
- Decide the blocks
- Design flow graph by determining edges.

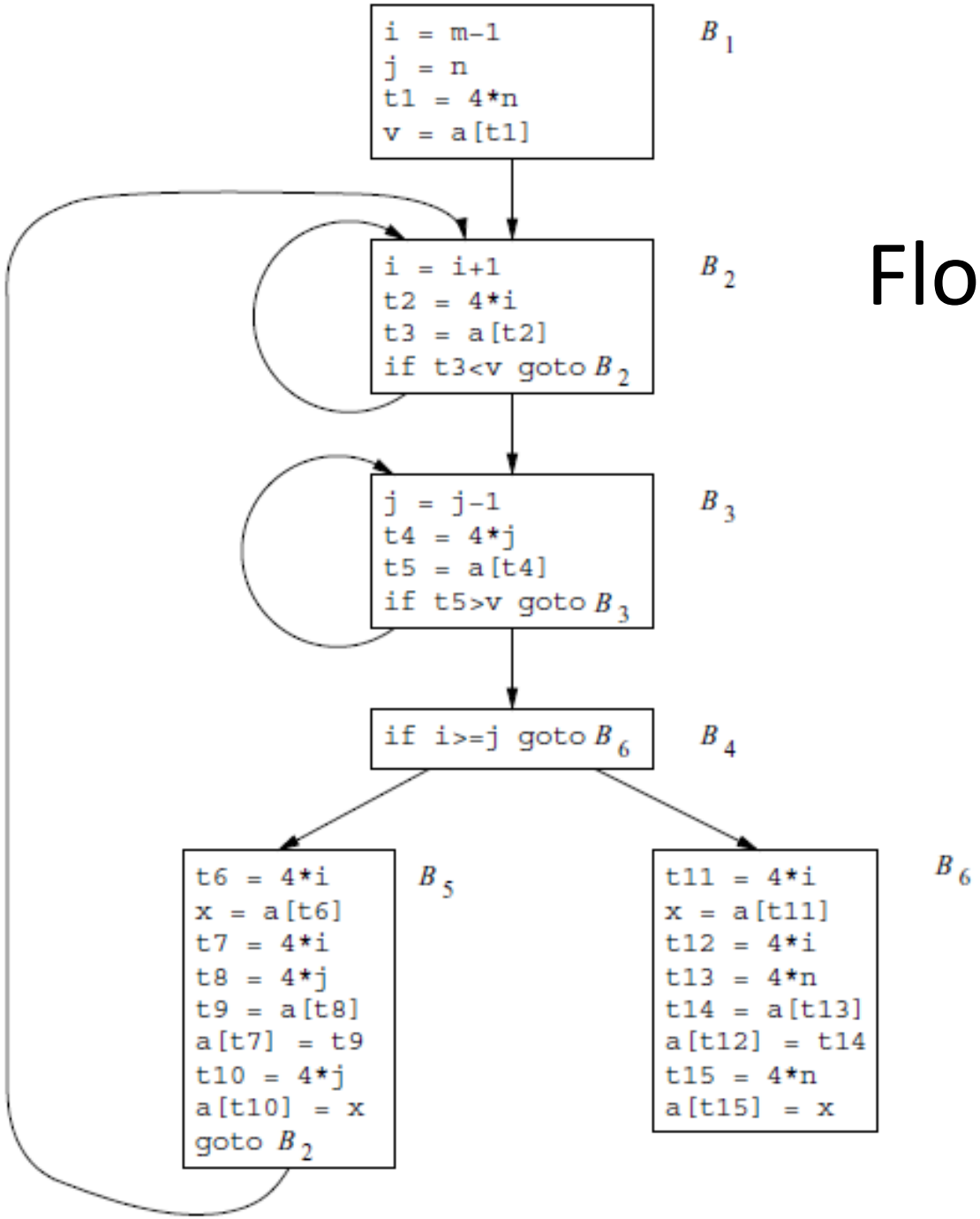
Leaders

- First, instruction **1** is a leader by rule (1) of Algorithm 1.
- To find the other leaders, we first need to find the jumps. In this example, there are three jumps, all conditional, at instructions 8,12,13 and 22. By rule (2), the targets of these jumps are leaders; they are instructions **5**, **9**, and **23**, respectively.
- Then, by rule (3), each instruction following a jump is a leader; those are instructions **9, 13, 14** and **23**.

- We conclude that the leaders are instructions **1, 5, 9, 13, 14 and 23**

Blocks

- Block 1 is 1 to 4
- Block 2 is 5 to 8
- Block 3 is 9 to 12
- Block 4 is 13
- Block 5 is 14 to 22
- Block 6 is 23 to 30


i = m-1
j = n
t1 = 4*n
v = a[t1]
B1
i = i+1
t2 = 4*i
t3 = a[t2]
if t3<v goto B2
B2
j = j-1
t4 = 4*j
t5 = a[t4]
if t5>v goto B3
B3
if i>=j goto B6
B4
t6 = 4*i
x = a[t6]
t7 = 4*i
t8 = 4*j
t9 = a[t8]
a[t7] = t9
t10 = 4*j
a[t10] = x
goto B2
B5
t11 = 4*i
x = a[t11]
t12 = 4*i
t13 = 4*n
t14 = a[t13]
a[t12] = t14
t15 = 4*n
a[t15] = x
B6

Flow graph