Compiler Theory

(Intermediate Code Generation - Abstract Syntax + 3 Address Code)

006

Why intermediate code ?

- Details of the source language are confined to the front-end (analysis phase) of a compiler, while details of the target machine are confined to the back-end (synthesis) part.
- This saves a considerable amount of effort since with m front-ends and n back-ends we have m*n compilers.

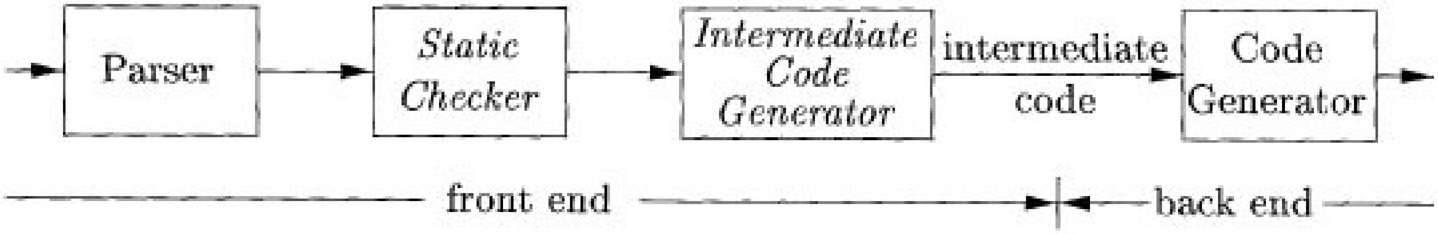


Figure 6.1: Logical structure of a compiler front end

Intermediate representations

- *Syntax Trees*
  - *Code is represented in the form of a tree where nodes represent constructs in the source program; the children of a node represent the meaningful components of a construct.*
- *Three-Address Code*
  - *Made up of instructions of the general form x=y op z*
  - *X, y and z are the three addresses.*
- C
  - Often used as an intermediate representation. e.g. LOTOS language

Directed Acyclic Graphs (i)

- Nodes in a syntax tree represent constructs in the source program
- A DAG is used to identify common sub-expressions. e.g. a+a*(b-c)+(b-c)*d
- By doing so it gives the compiler important hints on how to generate efficient code to evaluate the expressions.

DAG for a+a*(b-c)+(b-c)*d

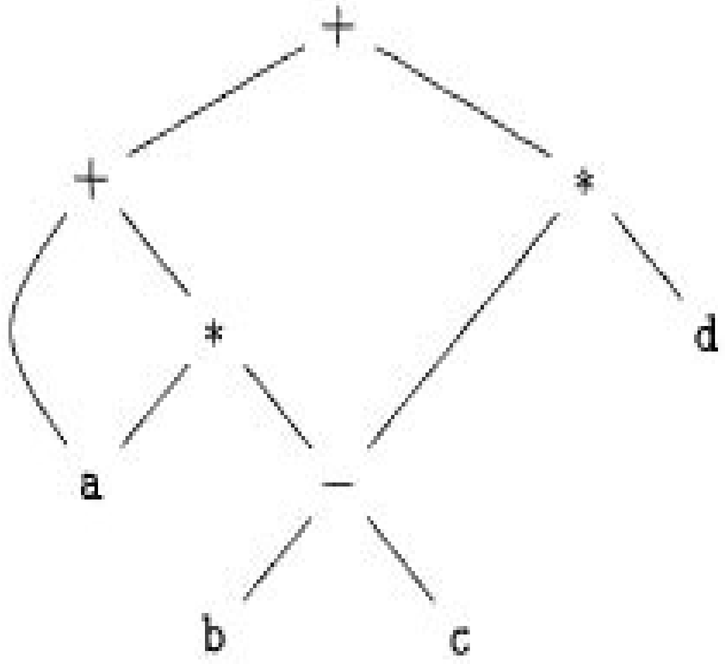
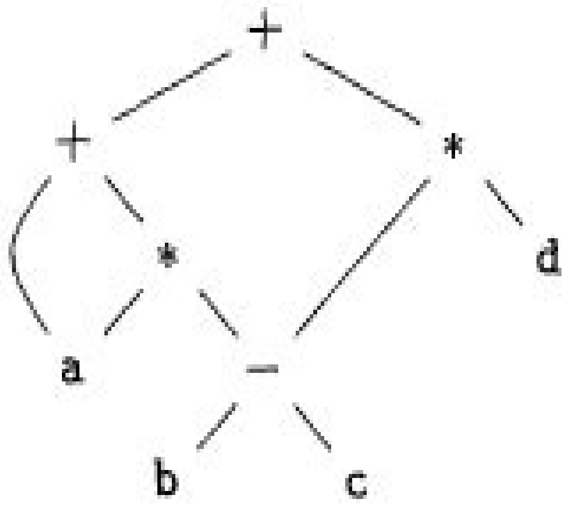


Figure 6.3: Dag for the expression a + a * (b - c) + (b - c) * d

Three Address Code (TAC)

- An alternative form of intermediate (lower level) representation.
- x+y*x becomes
  - $t_1 = y * z$
  - $t_2 = x + t_1$
- For expressions TAC is very similar to syntax trees.
- For statements it would produce labels and jumps in a similar fashion to machine code.

TAC for a+a(b-c)+(b-c)*d*



(a) DAG

$t_1 = b - c$

$t_2 = a * t_1$

$t_3 = a + t_2$

$t_4 = t_1 * d$

$t_5 = t_3 + t_4$

(b) Three-address code

Figure 6.8: A DAG and its corresponding three-address code

Addresses and Instructions

- An address can be
  - A name : source program names
    - In an implementation we would have these as pointers pointing towards the symbol table.
  - A constant
  - A compiler-generated temporary
    - To store temporary results

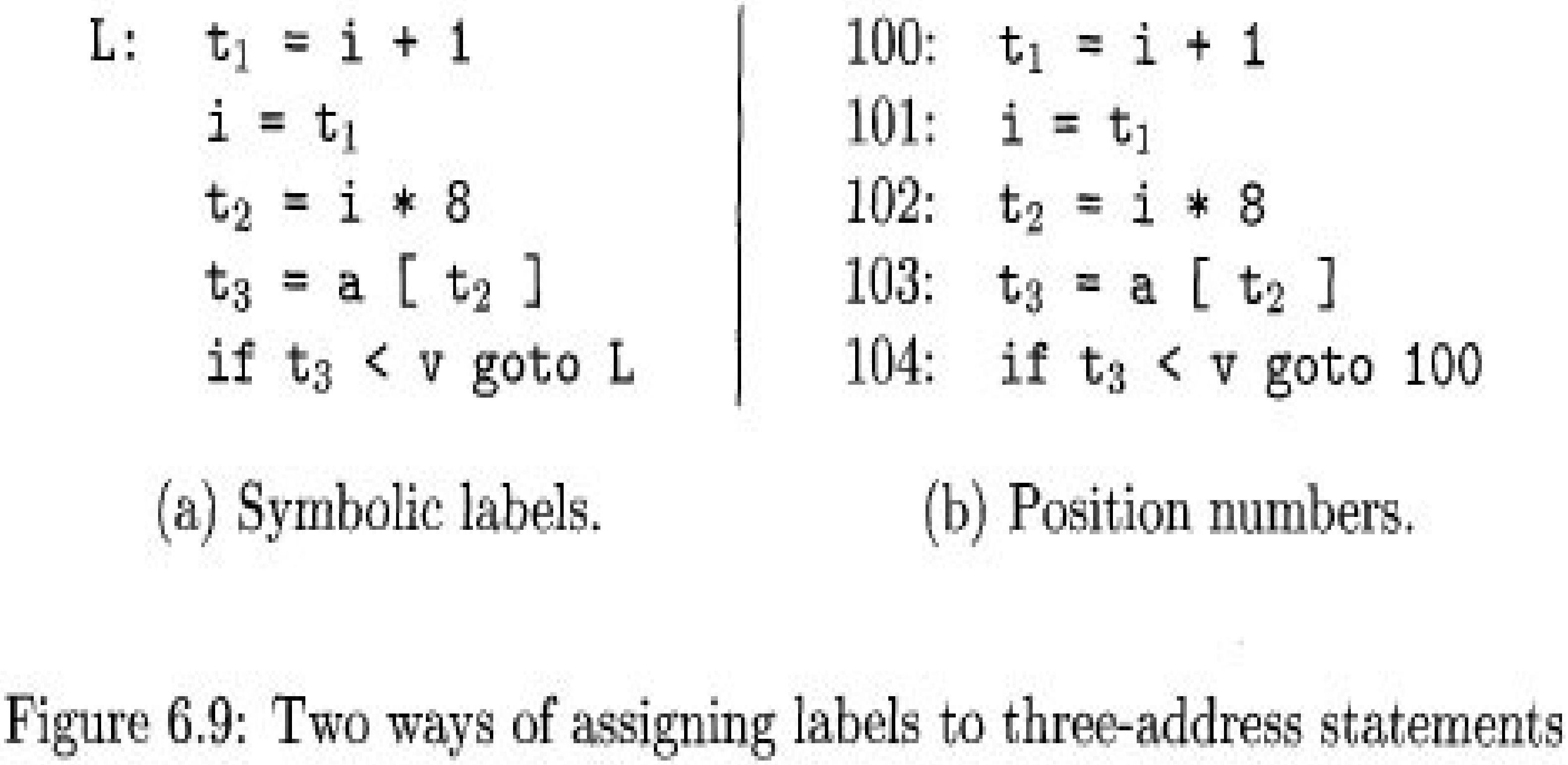
Addresses and Instructions (i)

- Assignment instructions
  - x = y *op* z where op is binary
  - x = op y where op is unary (-, !, type casting)
- Copy Instructions
  - x = y
- Jumps
  - Unconditional : goto L
  - Conditional :
    - if x goto L
    - ifFalse x goto L
    - if x relop y goto L

Addresses and Instructions (ii)

- Procedure Calls and returns
  - Parameters : param x
  - Procedure with n params: call p,n
  - Function with n params : y = call f,n
- Indexed Array[] Access
  - x = y[i]
  - x[i] = y
- Address and Pointer Assignments (no need to be covered)
  - x = &y
  - x = *y
  - *x = y

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



```
L:   t1 = i + 1
     i = t1
     t2 = i * 8
     t3 = a [ t2 ]
     if t3 < v goto L
```

(a) Symbolic labels.

```
100:   t1 = i + 1
101:   i = t1
102:   t2 = i * 8
103:   t3 = a [ t2 ]
104:   if t3 < v goto 100
```

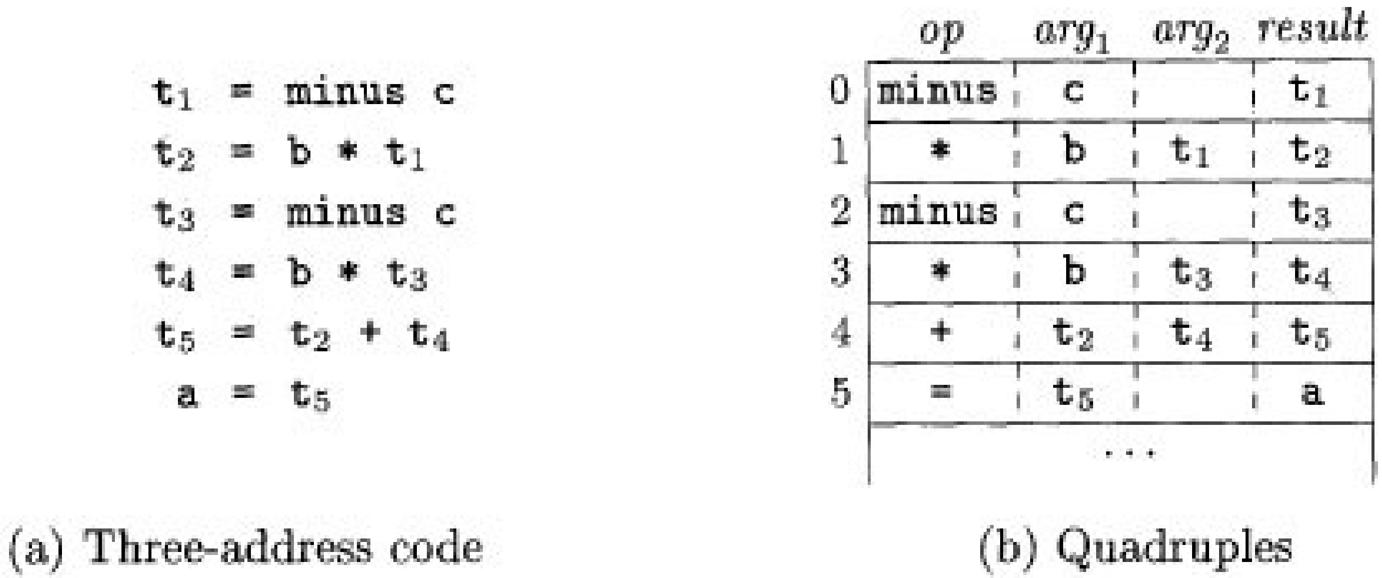
(b) Position numbers.

Figure 6.9: Two ways of assigning labels to three-address statements

Quadruples and Triples

- Data structures to hold three address code instructions.
- A Quadruple has four fields (x = y+z)
  - Op (+)
  - Arg1 (y)
  - Arg2 (z)
  - Result (x)

An example ...



t_1 = minus c
t_2 = b * t_1
t_3 = minus c
t_4 = b * t_3
t_5 = t_2 + t_4
a = t_5

(a) 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
	...			

(b) Quadruples

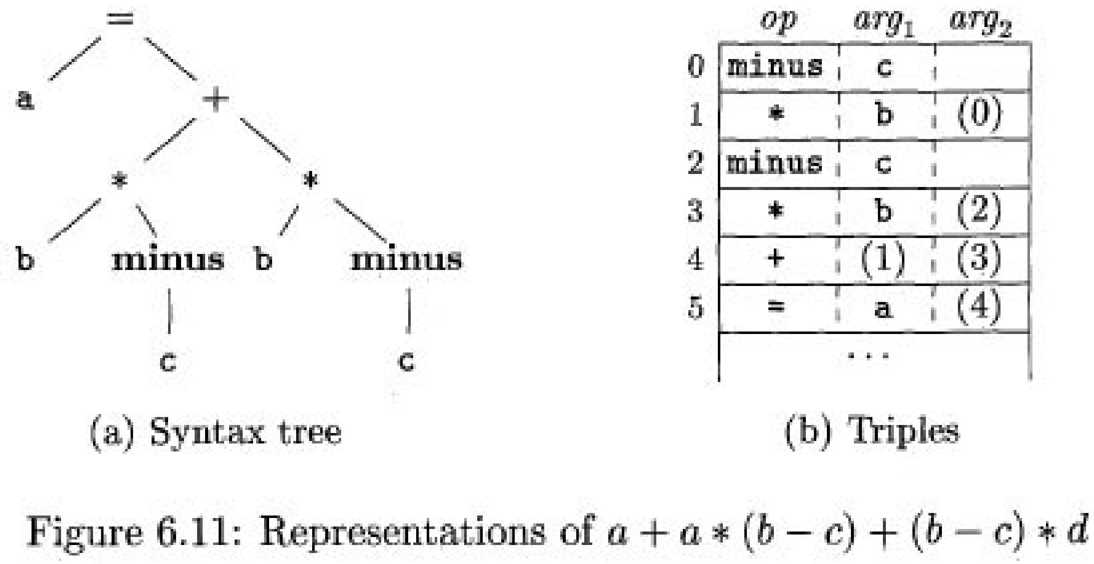
Figure 6.10: Three-address code and its quadruple representation

- Note that in an actual implementation a,b and c should be pointers to the symbol table.

Triples

- Omit result field.
- Instead of a result field we can use pointers to the triple structure itself.
- This makes DAG and triple representation practically identical, since we are pointing to a node.
- In next example (n) indicates position n in the triple structure

An example ...



(a) 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)
	...		

(b) Triples

Figure 6.11: Representations of $a + a * (b - c) + (b - c) * d$

- Note similarity ...

Code Generation

- This is the final phase of a compiler
- Takes an intermediate representation and generates the equivalent target program
- Code optimisation (if any) occurs between the intermediate and target code generation
- We require that the code
    - is correct and
    - effectively uses the resources on the target machine
    - Is itself efficient in generating code

Code Generation

- Whoever is designing the code generator must have a very good knowledge of the architecture of the target hardware and operating system.
- Should keep in mind
  - Memory management
  - Instruction selection
  - Register allocation
  - Evaluation order
- We shall look at generic issues

Input to the Code Generator

- Consists of
  - Intermediate Code produced by front end
  - Symbol Table to determine the runtime addresses of the data objects denoted by the names in the intermediate representation

- The underlying machine memory is byte-addressable and would have a number (say n) of general-purpose registers.

Assembly Language Instructions

- Most instructions consist of an operator, followed by a target, followed by a list of source operands.
- A label may precede an instruction
- We the next few slides we shall look at a number of different instruction classes.

Load Operations

- LD *dst*, *addr*
  - <u>Loads the value</u> in location *addr* into location *dst*.
  - *dst* = *addr*
  - LD *r*, *x* loads the value at addr x into r
  - LD *r1*, *r2* loads the contents of register *r2* into register *r1*

Store operations

- ST *x*, *r*
  - Stored the value in register r into the location x.
  - This instruction denotes the assignment x = r.
  - Note difference from LD

Computation Operators

- OP *dst*, *src1*, *src2*
  - OP would be ADD, SUB etc
  - *dst*, *src1*, *src2* are locations
  - Applies operation OP to the values in locations *src1* and *src2*, and place the result of this operation in location *dst*
  - ADD r1, r2, r3 computes r1=r2+r3
  - Unary OP do not have *src2*

Unconditional Jumps

- BR L
  - Causes control to branch to the machine instruction with label L
  - BR stands for branch

Conditional Jumps

- Bcond *r*, *L*
  - Where *r* is a register and *L* is a label
  - Cond stands for any of the of the common tests on values eg. *LT*, *GT*, etc
  - BLTZ *r*, *L* causes a jump to label *L* if the value in register *r* is less than zero, and allows control to pass to the next machine instruction if not.

3AC to machine code (x=y-z)

- LD R1, y // R1 = y
- LD R2, z // R2 = z
- SUB R1, R1, R2 // R1 = R1 - R2
- ST x, R1 // x = R1

3AC to machine code (if x<y goto L)

- LD R1, x // R1 = x
- LD R2, y // R2 = y
- SUB R1, R1, R2 // R1 = R1 - R2
- BLTZ R1, M // if R1<0 jump M

Instruction Selection

- Instruction selection effects
  - Execution speed and
  - Size
- A rich instruction set may provide several ways to perform any given operation.
- Typical e.g. … INC x instruction replaces ADD x + 1;

Register Allocation

- Instructions involving registry operands are usually shorter and much faster than those involving memory operands. For this reason utilization of registers is important in generating fast code.
- The use of registers is often subdivided into two problems
  - During register allocation, we select the set of variables that will reside in registers at a point in the program
  - During subsequent register assignments, we pick the specific register that the variable will be stored in
- Optimal assignment of registers is NP-complete ... hence some heuristics have to be used.

Standard code optimizations (i)

- Common Sub Expression
  - An expression E is called a common sub-expression if E was previously computed and the values of the variables in E have not changed. In such cases we can use the previously computed value of E.
- Copy Propagation
  - Reorganises assignment statements so that:
    - x = y
    - z = x
  - Becomes
    - x = y
    - z = y

Standard code optimizations (ii)

- Dead Code Elimination
  - A variable is 'live' at a point in a program if its value can be used subsequently, otherwise it is 'dead'. Statements may compute values that are never used in a program.
  - e.g. Computing expressions values which are never assigned
  - e.g. If (debug) then print ... and someone (using data flow analysis) the compiler can deduce that debug is always false. Check and print code can be removed.

Standard code optimizations (iii)

- copy propagations + dead code elimination
  - x = t3
  - a[t2] = t5
  - a[t4] = x
  - goto b2
- Elimination of copy propagation
  - x= t3
  - a[t2] = t5
  - a[t4] = t3
  - goto b5
- Elimination of dead code
  - a[t2] = t5
  - a[t4] = t3
  - goto b5

Standard code optimizations (iii)

- Loop optimisation
  - Loops are an important place where optimisations may occur. Clearly we try to reduce the number of instructions inside the loop ! One option is to use code motion (and maintain semantics)
  - This transformation takes out of the loop any expressions that have the same evaluation independent of the number of times the loop executes (loop-invariant computation) and places it before the loop.
  - e.g. while (i <= (limit-1)) .... limit – 1 can be computed before the loop !! i <= t where t = limit-1