CD - UNIT-5

RUNTIME ENVIRONMENTS

(1) Stack allocation of space :

(i) Activation Tree :-

→ An activation tree is used to determine the way the control flows between procedures.

~~→ During flow of control~~

→ During Program execution, the control flow is sequential among procedures.

→ In a procedure, the execution begins at the starting point of its body.

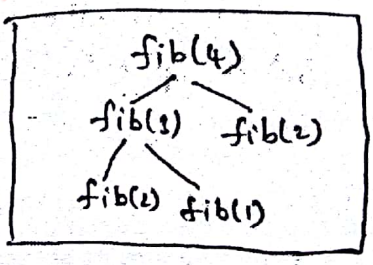
→ At the end of the procedure, control is returned to the calling instruction.

→ Each execution of the procedure is called an activation.

→ The activation tree depicts how control enters and leaves activations.

→ Activation tree for the Procedure Call fib(4) is shown in fig.

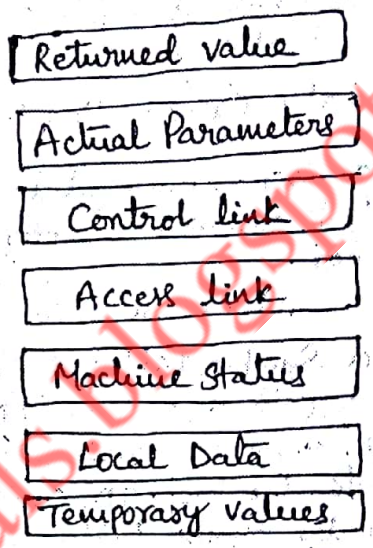
→ The activation tree is a graph of function calls.



(ii) Activation Record:-

→ Activation Record (or) frame is a contiguous block of storage that contains all the information required for a single execution of a Procedure

→ An Activation Record consists of seven fields shown in fig.



An Activation Record

Temporary Values

→ This field holds all the temporary values that are used in the evaluation of expressions.

Local Data

→ This field holds all the data that is local to a procedure.

Machine Status

→ This field saves the status of the machine when a call to Procedure occurs.

Access link

→ This is an optional field.

→ This field holds a link to data (non-local) held in other activation records.

Control link

→ This is also optional field that contains a link to caller's activation record.

Actual Parameters

→ This field contains the actual parameters that are used by the calling procedure to pass them to the called Procedure.

Returned Value

→ This field contains a return value that is used by the called procedure to return to the calling procedure.

2 Access to Non Local Data on the Stack

Q14. Explain how allocation strategies can access non local variable.

Answer : Model Paper-II, Q6(a)

A nonlocal variable is a variable which is defined locally in a procedure.

The Scope Rules of a Language

The **lexical-scope** or **statical-scope rule** determines the declaration of a name based on the program text alone. Examples of languages that use this scope rule are Pascal, C and Ada.

The **dynamic-scope rule** determines the declaration of a name on sun time based on the current activation records. The languages Lisp, APL and Snobol use this scope rule.

Lexical-scope in C

'C' does not allow nested procedure declarations, therefore the lexical-scope rules for C are simple. In a C program the declaration of variables is followed by procedure definitions (procedures in C are called functions). A function is said to have a reference to a non local name *x* iff *x* is declared outside any function. The scope of *x* is within the functions that follow its declaration. There is a hole if *x* is redeclared with in function.

For example consider the following 'C' program.

```
int x;
f1( )
{
x = x – 10;
}
f2( )
{
  ----
}
f3( )
{
  x = x + 10;
}
main( )
{
  x = 10;
}
```

In this example '*x*' is declared outside all the functions, therefore its scope is in all functions.

The stack allocation strategy used for local names can also be used for lexically-scoped languages that donnot allow nested procedures. A name declared outside any procedure is a non local storage for all non local names memory is allocated statically at compile time. As we know the position of this storage, when a procedure references a non local name we simple use the static address of that name to access its value.

All other names are local to a procedure whose storage is within the current activation record which is at the top of the stack and accessible through the *top* pointer. This scheme does not work with nested procedures because an access to a non local may refer to data deep in the stack.

An advantage of static allocation for non locals is that, procedures can be passed as parameters and returned as results. In the absence of nested procedures a name which is non local to one procedure is non local to all procedures. Therefore, any procedures regardless how is it activated can use static address of that non local. When a procedure is returned as a result, the non locals of that procedure can be accessed similarly because they are bound to store allocated memory statically for them.

Lexical-scope in Pascal

Pascal allows the nested procedure declaration. That is, it is possible to define one procedure inside the other. In Pascal, the scope of a non local name *x* is in the scope of the most closely nested declaration of *x*.

For example, consider the following Pascal program for sorting an array.

```
Program sort(in, out);
  var x : array[0..10] of integer;
    t : integer;
  procedure insert;
    var i : integer;
    begin
      -----
      x
      ----
      end {insert};
  Procedure swap(i, j : integer);
    begin
      t := x[i];
    x[i] := x[j];
    x[j] := t
  end { swap };
```

```
procedure quick sort(y, z : integer);
    var l, m : integer;
    function split(a, b : integer) : integer;
    var i, j : integer;
      begin
        -----
          x
        -----
          m
        -----
          swap(i, j);
      end { split};
    begin
      -----
    end{quicksort};
begin
    -----
end{sort}
```

In the above program sort consists of three procedures. They are, insert, swap and quick sort. The function split is nested within the procedure quick sort.

The function split references a non local *x*. According to most closely nested rule it is declared in the main program sort procedure. This rule also applies to procedure names, the procedure swap called by split is non local to split because it is declared in the main program sort.

To implement lexical scope we define nesting depth of a procedure. The nesting depth of the main program is, each time we go from an enclosing to an enclosed procedure the nest depth is incremented by 1. Therefore, the nesting depth for above program is given as,

sort : nesting depth 1

quick sort : nesting depth 2

split : nesting depth 3

We identify the nesting depth of a name from the nesting depth of the procedure in which it is declared. The nesting depth of names *i*, *x* and *m* defined is split in to 1, 2 and 3 respectively.

3. Heap Management :

Q15. What are the two basic functions performed by memory manager? Also list the properties desired for a memory manager.

Answer :

The two basic functions of memory manager include,

1. Memory allocation
2. Memory deallocation.

1. Memory Allocation

In this the memory manager maintains a contiguous chunk of free space of memory in heap storage. This memory is allocated to the program which has made a memory request for a variable or object. If the allocated size of variable is available in heap then allocation is done directly. Otherwise, the needed size is made available by increasing storage space. This can be done by getting sequential bytes of virtual memory from operating system. If the space is completely filled up, then this information (about no free space is available) is redirected to the application program by the memory manager.

2. Memory Deallocation

In this the memory manager returns the deallocated space back to the pool of free space. This free space get mixed up with the already available free space in heap. This deallocated memory can later be reused for other allocation requests.

Properties of Memory Manager

Properties of memory manager are as follows,

(i) Maintaining Space Efficiency

Space efficiency can be obtained by reducing the fragmentation of the program. To achieve this, the memory manager minimizes the amount of total heap space required by the program. Due to which a larger program can run on fixed virtual address space.

(ii) Maintaining Program Efficiency

Program efficiency can be achieved if the memory manager efficiently utilizes the available subsystem memory. This utilization helps to run the program at a faster rate.

(iii) Minimizing Over Head

The overhead can be minimized if allocation and deallocation operation are performed efficiently. As these are the frequent operations performed by memory manager.

CD5-2

CODE GENERATION

4 Issues in the Design of Code Generation

Q16. Explain the issues in the design of code generator. Nov.-12, Set-2, Q8(b)

OR

Write in detail about the issues in the design of a code generator. Nov.-12, Set-4, Q8(a)

OR

What are the issues in code generation process? Explain in detail.

Answer : (Model Paper-III, Q8(a) | Nov.-11, Set-2, Q8(a))

The following are the design issues of a code generator,

1. Input

The input to the code generator are the intermediate representation of the source code and the information in the symbol table. The symbol table gives the run-time addresses of names used in the intermediate representation.

The intermediate code generated by the code generator can be represented in several ways. These are linear representations such as postfix notation, graphical representation such as syntax trees and dags. Virtual machine representations such as stack machine code and three-address representations such as quadruples.

It is assumed that before the code generation phase begins, the source code is scanned, parsed and translated into intermediate representation by the front end. The values of names used in the intermediate representation are represented such that they can be directly manipulated by the target machine.

It is also assumed that the necessary type checking has been done and the input is free of errors. So, the code generation phase can proceed with these assumptions.

2. Output

The output of code generator is an object code. The object code can be produced in several forms. Various forms of object code are,

(a) Absolute machine code
(b) Relocatable machine code
(c) Assembly language code.

Each form of an object code has its own advantages and disadvantages.

(a) Absolute Machine Code

An absolute machine language program places the generated code in memory at some fixed location and executes the program immediately. For example, student-job compilers such as WATFIV, PASSGO and PL/C produce output as an absolute machine code. An advantage of absolute machine code is that the small programs can be compiled and executed quickly. But it can't call modules in other languages and compile subprograms separately. This form of object code is very fast compared to other forms.

(b) Relocatable Machine Code

Producing an output as a relocatable-machine language program allows compitation of subprograms separately. It also allows calling already compiled programs from an object module in other languages. After compiling a set of object modules, it requires a linking loader to link them together and load for execution. At little expense of linking and loading, which makes it slower we achieve great flexibility in computing subprograms separately.

(c) Assembly Language Code

An assembly language program makes the code generation process easier.

Assembly language code is mainly used in machines having less memory where complier requires several passes to execute them. This form of object code is slowest when compared to others.

3. Memory Management

The code generator along with front end performs mapping between the names (stored in the source program) and the addresses of data objects (stored in run-time memory). The entries in the symbol table names are created when their declarations are encountered while examining a procedure. The amount of storage required for a name depends on its data type. The relative address for the name can be determined from the symbol table information. When a name appears in a three-address statement, it refers to the symbol table entry for that name. The labels in three-address statements must be converted to addresses of instructions while generating the machine code.

4. Selection of Machine Instructions

It is difficult to select an instruction due to the nature of instruction set of the target machine. There are two important factors, the first is the uniformity and another is completeness of the instruction set. A target machine must support each data type in a uniform manner otherwise special handling is required to handle an exception to the general rule.

Other factors that make it difficult to select an instruction are instruction speeds and machine idioms. If the efficiency of the target program is not considered, then instruction selection is straight forward. For example, we create a code selection for each type of three-address statement that can be used to generate the target code for that construct. For example, if the form of three-address statement is as $a : b + c$ then, every such statement would be translated into the following sequence.

```
MOV b, R1
ADD c, R1
MOV R1, a
```

But, generating code as a statement-by-statement produces poor code.

The speed and size determines the quality of the generated code. A target machine with rich set of instructions can perform an operation in several ways. It is possible that an implementation generates the correct target code but it is inefficient. For example, three-address statement $x : = x + 1$ (incrementing variable x by 1) can be more efficiently implemented as a single instruction INC (if the target machine has it in its instruction set) than implementing as the following sequence.

```
MOV x, R0
ADD #1, R0
MOV R0, x
```

The instruction speed also matters to produce good code sequences. But, it is often difficult to obtain accurate timing information. It is also difficult to determine which code sequence is best for the given three-address construct because this decision is based on the context where that context appears.

5. Allocating Registers

Machine instructions are small and faster in comparison to the memory instruction. This is because the machine instructions uses register while the memory instruction uses operands for its execution. Therefore, to generate a good code, the register must be efficiently utilized. To efficiently utilize registers, the following points must be considered.

- During register allocation, the variables that currently present in register should be selected.
- During register assignment, the specific register that will hold a variable should be selected.

However, such assignment is a tedious task assignment of registers to variables even in the case of single-register values. Further certain register-usage conventions are imposed by the hardware and/or the operating system of the target machine.

Another difficulty in register allocation is register-pairs (an even and next odd register) requirement of certain machines for some operands and results. For example, the IBM system/370 machine requires that the operations integer multiplication and integer division must involve register pairs.

6. Evaluation Order

The dramatic affect of evaluating the order of machine instruction is on the efficiency of the target code. Some evaluation order uses fewer registers than others to temporarily hold the intermediate results. Thus the choice of selecting best order of evaluation is difficult. The problem can be solved if target code for three-address statements is generated in the order in which they appear.

7. Code Generation

The most important issue of code generator is to produce a precise code. This issue is significant because a code generator might face a number of special cases. The main design goal is to design a code generator which is easy to implement, test and maintain.

5 The Target Language

Q17. Explain in detail about a simple target machine model.

Answer : Model Paper-IV, Q6(b)

Simple Target Machine Model

A target machine model containing n general purpose registers i.e., R_0, R_1, R_2, ..., R_{n-1} can model a three address machine using the instructions like,

1. Load
2. Store
3. Computation
4. Unconditional jumps
5. Conditional jumps.

1. Load

This operation, loads the value of one location to other location. This operation is of form LD location1, location2.

Example

(i) LD destination, address

The above instruction loads the value in address location to destination location.

(ii) LD r_1, x

The above instruction loads the value present in location x to register r_1.

(iii) LD r_1, r_2

This type of instruction is called as register-to-register copy instruction. The above instruction loads the content of register r_2 to register r_1.

2. **Store**

This operation stores the content of one register to some desired location (say *x*). The store operation is of form,

ST location, register

Example

ST a, r_2

The above instruction stores the content of register r_2 into location *a*.

3. **Computation**

This operation performs various operations like addition, subtraction, multiplication and division on values present on source1 and source2 and later store the result on some specified location. The code operation is of form,

op destination, source1, source2

Here, 'op' specify operation.

Example

ADD r_1, r_2, r_3

The above instruction add the value present on r_2 and r_3 and later stores the result on r_1.

4. **Unconditional Jumps**

This instruction is of type,

BR L

Where, BR stands for branch and L stands for label.

The above instruction allow control to branch to machine instruction along with label.

5. **Conditional Jumps**

This instruction is of form,

B cond r, L

Here,

'cond' represents common test performed on values of register *r*.

r stands for register and

L stands for label.

6. Addresses in the Target Code

Q18. Describe the code generation for simple procedure calls and returns using static allocation.

Answer :

The process of code generation can be illustrated by the address statements like call, return, halt and action using the static allocation. The code generator determines the size and layout of activation records by using the name related information recorded in symbol table. In static allocation, the implementation of procedure calls having no arguments i.e., call callee can be performed using two target machine instructions as shown below,

ST callee.StaticArea #here + 20

BR callee.CodeArea

The *ST* instruction is responsible for storing the return address at the starting point of the activation record for the callee while the *BR* instruction is responsible for transfering control to the first entry in the target code of the callee.

The attributes **callee.StaticArea** and **callee.CodeArea** are constants refering to the address of memory location holding the return address (i.e., the first location of the activation record) and the address of first entry of the called procedure in the code area respectively.

In the ST instruction, the operand #here + 20 represents the address of the instruction that appears immediately after BR instruction, which is nothing but the return address. The value, #here represents the address of current instruction and the symbol #represents immediate constant. Also, the sequence two instructions contains 3 constants. Thus, the entire sequence requires (2 + 3 = 5) – 5 words or 20 bytes. In general, caller do not exist for the first procedure. So in this case, HALT is the last instruction with a return control to the operating system. But, in case of procedure (other than the first one), its code termination occurs with a return control to the caller procedure. The implementation of return callee statement can be performed using BR instruction as follows,

BR *callee.staticArea.

This instruction is responsible for transfering control to the first location in the activation record of called procedure. Consider the following three address code

```
action 1              //code for main
call q
action 2
halt
action 3              //code for q
return.
```

The target code for the above three address code is given below,

```
1000 : ACTION1                  //code formain
1020 : ST 3064, # 1040 ....     //stored.return address 1040 in location 3064
1032 : BR 2000....              //call q
1040 : ACTION 2
1060 : HALT...                  //return to the operating system
2000 : ACTION 3...              //code for q
2020 : BR *3064
...
...
3000 :                          //The activation record for main is at location 3000 - 3063.
3004 :
3064 :                          //The activation record for q is at location 3064-4051.
3068 :
```

In the above target code, assume that procedures **'main'** and **'q'** starts at locations **1000** and **2000** respectively. Also, assume that each instruction requires 20 bytes. Finally, assume that activation record for procedure **"main"** is statically allocated at location **3000** and for **'q'** procedure at location 3064.

The instruction that begins at location 1000 is responsible for implementing the following statements of main procedure.

```
Action 1;
Call q;
Action 2;
Halt;
```

At location **1020**, the **ST** instruction is responsible for storing the return address **1040** in the first location of activation record of called procedure **'q'**. Similarly, location **1032**, the **BR** instruction is responsible for transferring control to the target code of called procedure **'q'**. Once the execution of **ACTION 3** at location **2000** is completed, the **BR** instruction at location **2020** is executed. Now, ***3064** contains **1040** from the above call sequence at location **1020**. Once the code for procedure **'q'** ends, control returns to the called procedure i.e., at location **1040**. Now, the main procedure restarts its execution.

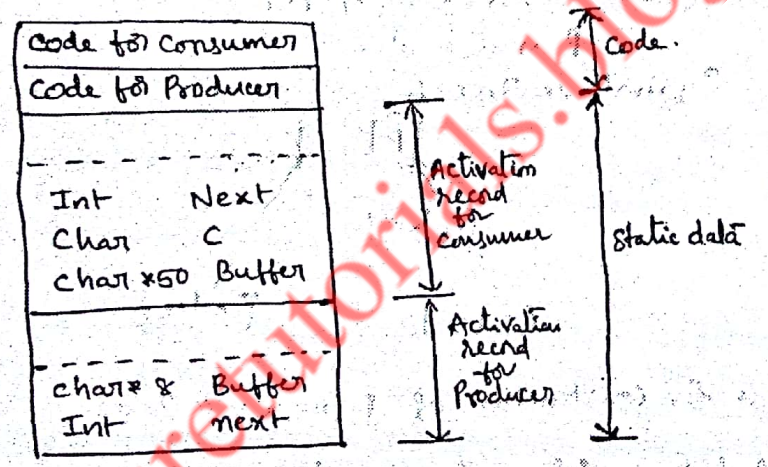
(7) Storage allocation Strategies:

(i) Static Allocation Strategy:-

→ Static Allocation strategy allocates the memory for all data objects at compile time.
→ The program variables are bound to the storage once it is allocated to them.
→ As the binding of variables for storage is done at compile time which do not change at runtime.
→ Therefore a runtime support package is not required.
→ This strategy implements static binding.
→ In static binding, each time a procedure is called the variables are bound to the same storage locations.

Ex:-

- FORTRAN allocates the memory for program variables of all subprograms irrespective of whether a subprogram is active (or) not.
- Static storage for Local Identifiers of Producer/consumer program is represented as



(ii) Stack Allocation Strategy:-

→ In this strategy, storage is allocated as a stack when a procedure is called for execution.
→ An activation record containing the information required for executing a procedure is pushed on the top of the stack.
→ Each time an activation record is pushed, the local variables of a procedure are bound to a new storage.
→ The values of local variables are lost when an activation record is popped out of the stack.
→ This happens when a procedure is terminated.
→ The memory space freed by popping an activation record can then be used to push another activation record.
→ A register stores value of the top of the stack.

8. **Basic Blocks:**

- A Basic Block is a collection of three-address statements in which flow of control enters at the beginning and leaves at the end without halt or possibility of branching except at the end.
- Every statement in a basic block is a three-address statement.

Example:

a=(b*c)/d+k

The three-address statements are,

t1:=b*c
t2:=t1/d
a:=t2+k

Algorithm for Partitioning into Basic Blocks:

- This algorithm is used to partition a sequence of three address statements into basic blocks.

Input: A sequence of three-address statements.

Output: A list of basic blocks with each three-address statement in exactly one block.

Method:

- We first determine the set of leaders, i.e, the first statements of basic blocks.
- The rules used are,
  i)The first statement is a leader.
  ii)Any statement that is the target of a conditional or unconditional goto is a leader.
  iii)Any statement that immediately follows a goto or conditional goto statement is a leader.
- A Basic Block is drawn for each leader followed by the set of statements.
- No Basic Block can have more than one leader.

9. **FLOW GRAPH:**

- A Flow Graph is a graphical representation of three-address statements.
- It is used to show the flow of control information to the set of basic blocks of a program.
- It consists of nodes and edges.
- A node of a flow graph is a basic block that performs some computations.
- An initial node consists of a block whose leader is the first statement.
- There is a directed edge from one node to another representing the flow of control between blocks.
- There is an edge from block B1 to block B2 if
  -In the execution sequence B2 immediately follow B1.
  -The last statement of B1 contains a conditional or unconditional jump to the leader(first statement) of B2.
- We say that predecessor of block B2 is block B1 and a successor of block B1 is block B2.

Example:

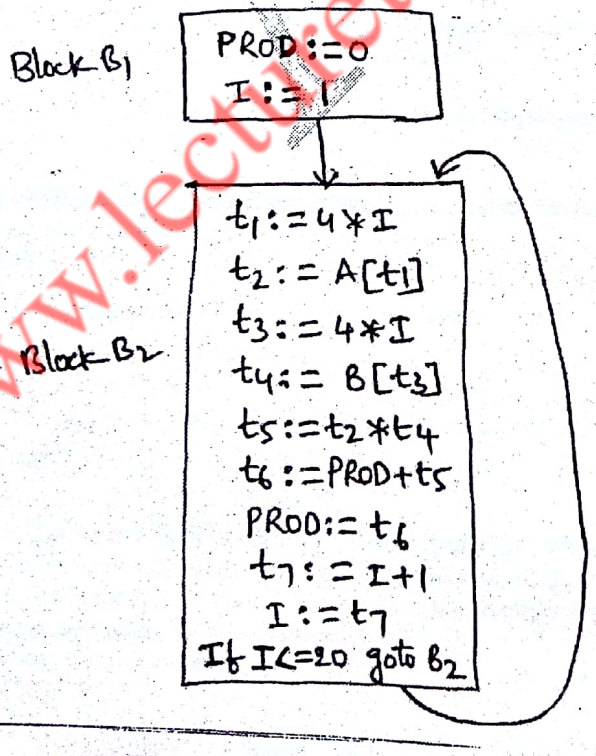
Consider the following program that finds the dot product of two vectors x and y of length 10.

```
begin
        PROD:=0;
        I:=1;
        do
            begin
                PROD:=PROD+A[I]*B[I];
                I:=I+1;
            end
        while I<=20
    end
```

- The flow graph for the given program is constructed by first converting the program into three-address statements.
- The sequence of three-address statements are

1. PROD:=0
2. I:=1
3. t1:=4*I
4. t2:=A[t1]
5. t3:=4*I
6. t4:=B[t3]
7. t5:=t2*t4
8. t6:=PROD+t5
9. PROD:=t6
10. t7:=I+1
11. I:=t7
12. if I<:=20 goto 3

- By applying the algorithm for partitioning into basic blocks, the code contains statement 1 is a leader(rule 1) and statement 3 is a leader(rule 2).So the code contains two blocks.Then the flow graph for the code is



FLOW GRAPH

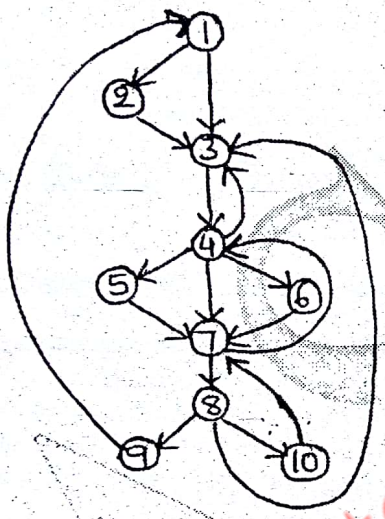
2.1. Loops in a FLOWGRAPH:

- Loop is a collection of nodes in a flow graph.
- Loops in a flow graph are of 4 types
  i)Dominators ii)Natural Loops iii)Inner Loops iv)Pre-headers

i) Dominators:

- A node 'D' is said to be dominator node, if it dominates another node 'N'.
- The general format to represent the dominators is
  D dom N
- D dom N means, in the flow graph every path from the initial node to N goes through the node D.
- Entry of a loop dominates all the nodes in the loop.
- Every node dominates itself.

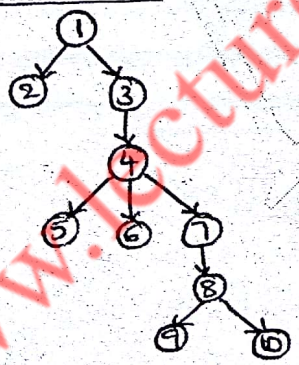
Flowgraph



Dominator Representation

1	DOM	all the nodes
2	DOM	2
3	DOM	all the nodes except 1,2
4	DOM	all the nodes except 1,2,3
5	DOM	5
6	DOM	6
7	DOM	7,8,9,10
8	DOM	8,9,10
9	DOM	9
10	DOM	10

- The dominated information is represented in a tree is called as Dominator tree.



ii) Natural Loops:

- A good way to find all the loops in a flow graph is to search for edges in the flow graph whose heads dominate their tails.
- If a→b is an edge, 'b' is the head and 'a' is the tail. Such edges are called back edges.
- Given a back edge N→D, we define the natural loop of the edge to be 'd' plus the set of nodes that can reach N without going through D
- Node D is the header of the loop.

- Natural loop of the edge 10→7 consists of nodes 7,8,10.
- Since 8 and 10 are the nodes that can reach 10 without going through 7.

(*) Algorithm for constructing the Natural loops

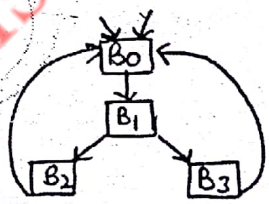
Input:- A flowgraph GF and a back edge N→D

Output:- A set of loop of all nodes in the Natural loop of N→D

```
Procedure Insert(M)
M is not in loop then
        Loop = {Loop} ∪ {M}
        Push(M)
end
/* Main Program */
Stack = empty
Loop = {D}
Insert(N)
While (Stack not empty)
   {
     Pop(M)
     for(each predecessor P of M)
        Insert(P)
   }
```

iii) **Inner Loops:**

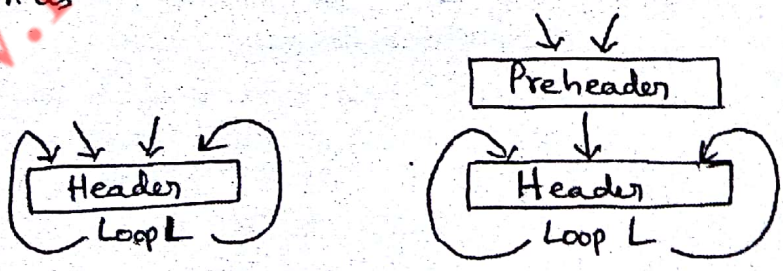
- A loop that contains no other loop is called an inner loop.
- One of the property of the loops is that unless two loops have the same header, they are either disjoint or one is entirely contained within the other(nested).
- When two loops have the same header, it is difficult to tell which is the inner loop.
- Thus, we assume that, when two natural loops have the same header, but neither is nested within the other, they are combined and treated as a single loop.



Two Loops with the same header

iv) **Pre-headers:**

- Some transformations require the control to move statements before the header.
- Thus, we can begin treatment of a loop L by creating a new block, called the Preheader.
- The Preheader has only the header as successor and all edges which entered the header of L from outside L, now enter the preheader.
- Edges from inside loop L to the header are not changed.
- This is shown as



(a) Before (b) after

Introduction of the preheaders

Q22. Explain reducible and non-reducible flow graphs with an example.

Answer :

Reducible Flow Graphs

A flow graph G_F is said to be reducible, if its edges can be divided into two disjoint groups i.e., forward edges and back edges and it has two properties. They are as follows,

1. The back edges group contains only those edges whose heads dominates their tails.
2. The forward edges make an acyclic graph, with every node reachable from the initial node of 'G_F'.

Almost all the flow graphs are reducible. For example, flow graphs for statements like while-do, continue, if-then-else, break and goto are reducible.

In reducible flow graphs, there are no jumps in the middle of the loop from outside. Hence, entry into a loop is through its header.

The example of reducible flow graph is as shown in figure (1).

Example

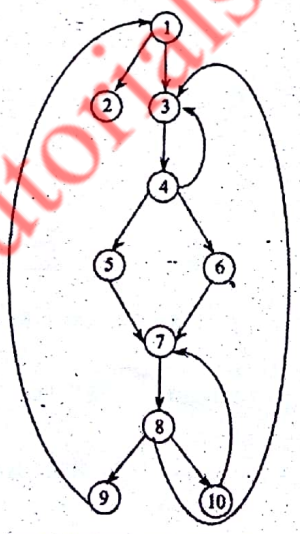


Figure (1): Reducible Flow Graph

The back edges in a flow graph can be found and eliminated if DOM (Dominance) relation for a flow graph is known. To cross check whether the above flow graph is reducible or not, remove the back edges $4 \rightarrow 3$, $10 \rightarrow 7$, $8 \rightarrow 3$ and $9 \rightarrow 1$. As these are the back edges and the remaining are forward edges, the graph is acyclic (after removal of back edges) and hence reducible.

Non-reducible Flow Graphs

There are some flow graphs which are not reducible, such a flow graph is as shown in figure (2).

Example

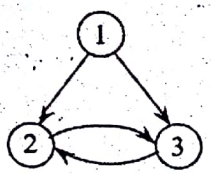


Figure (2): Non-reducible Flow Graph

Here, there are no back edges as no head of an edge dominates its tail. As, the cycle $2 \rightarrow 3$ can be entered at two different places, node 2 and node 3, the flow graph is non-reducible. However, it can be reducible if the complete flow graph is acyclic.

Non-reducible flow graphs are very rare. Languages like Modula 2 and Bliss allow programs with reducible flow graphs only.

Q24. Why next-use information is required for generating object code?

Model Paper-III, Q6(b)

Answer :

In a three-address statement, the use of a name is defined as follows. If a statement i assigns a value to x and there is another statement j that uses x as an operand and there are no other assignments to x between the statements i and j, then it is said that there is next use of x computed at i in statement j.

In order to determine the next use of a name, first determine the ends of basic blocks by making a backward pass over each basic block. Next we scan each block in the backward direction and determine the next use and liveness of each name x. If x has next use in the block, then it is recorded in the symbol table otherwise we determine whether the name is live outside this block and record it in the symbol table. From data-flow analysis, we can determine which names are live outside each block. If live-variable analysis is not done, then it is assumed that all non-temporary names are live outside each block. Some temporary names are also considered live across blocks if it is permitted by the code generation algorithm or code optimization algorithm. Such temporaries are marked to distinguish them from non-live temporaries.

In the backward scan of a basic block, when we reach a three-address statement such as $x := y$ op z we do the following.

1. Attach the information found about next use and liveness of x, y and z from symbol table to the to statement i.
2. In the symbol table, set the entry for x to "not live" and "no next use".
3. In the symbol table, set the entry for y and z to "live" and their next use to i.

The order of steps (2) and (3) is not interchangeable because x may be y or z.

The same steps are performed for three-address statement i of the form $x := y$ or $x := op\ y$ by ignoring z.

Applications of Next-Use Information

Machine instructions involving registers are shorter and faster than the instructions involving operands in memory. Therefore, it is important to utilize registers efficiently. If a name held in register is no longer needed, then the register can be used to assign it to some other name. That is storing a name in register only if it will be used subsequently.

The information about next use of a name has a number of applications.

1. It can be used to assign space for attribute values.
2. It assists in register assignment.
3. It can be used to assign storage for temporary names.

Reuse of Temporaries

It is sometimes convenient to create a distinct name for each temporary name during optimization. But, each time a temporary name is created, it must be allocated space to hold temporary value. The amount of space required grows with the number of temporaries. The space can be saved if the temporary names are reused.

From the next-use information we can pack two temporaries into the same location if they are not live simultaneously. The storage for temporaries is allocated by examining each in turn.

A temporary that does not contain a line temporary is assigned to the first location in the field for temporaries. If it is not possible to assign a temporary name to any previously created location, then the storage for it is allocated in the data area for the current procedure. Most often, temporaries are packed into registers rather than memory locations.

In the following example, the six temporaries in the basic block are packed into two locations t_1 and t_2.

$$\begin{array}{ll} t_1 := x * y & t_1 := x * y \\ t_2 := x + x & t_2 := x + x \\ t_3 := 5 * t_2 \quad \Rightarrow & t_2 := 5 * t_2 \\ t_4 := t_1 * t_3 & t_1 := t_1 * t_2 \\ t_5 := y * y & t_2 := y * y \\ t_6 := t_4 + t_5 & t_1 := t_1 + t_2 \end{array}$$

10 A Simple Code Generator

Q25. Explain in brief about simple code generator. Also explain simple code generator algorithm with the function GETREG.

Answer : **Model Paper-II, Q6(b)**

Simple Code Generator

A simple code generator algorithm helps in generating code for single basic block. This algorithm uses three address instruction inorder to keep track of values stored in register. This helps in identifying the location of values in their respective register and also for avoiding unnecessary loads and stores operations.

This algorithm explains the efficient use of register based on following four principles.

1. They are used for storing few or all the operands associated with an executing operations.
2. They are used for managing runtime storage which include managing of,
   (i) Run-time stack
   (ii) Stack pointers.
3. They are used for storing global values which belong to a block and is used in another blocks.
4. They are used for storing the result of subexpression (when a larger expression is being computed), there by making themselves a good temporaries.

Algorithm

Code generation algorithm uses sequential three-address statements consisting a basic block as input. The algorithm consists of the following steps which are performed for each three-address statement of the form, $x := y\ op\ z$.

1. Call a function GETREG to determine the location L for storing result of expression $y\ op\ z$. L could be a register (usually) or a memory location.
2. Look up the entry for y in the address descriptor to determine y' (one of) the current location (x) of y. If y is currently. In both the register and the memory location, then take y' in register. If y is not in L then generate machine instruction move y', L move a copy of y in L.
3. Generate the machine instruction op z', L where z' indicates the current location of z. Again if z is in both the register and the memory location, then take z' value in register. Update x's address descriptor to indicate that x is in L. If L is in register, then update the register descriptor of L to indicate that it contains x value. Finally, delete x from all other register descriptors.
4. If y and z are in registers, there are no next uses of these operands and they are not live at the end of the block, then update their register descriptors to indicate that those registers no longer contain the values of y and/or z after executing the instruction $x := y\ op\ z$.

The same steps are required to generate the code for three-address statements of the form $x := op\ y$.

A three-address statement of the form $x := y$ is a special case. There are two cases to generate code for such statements.

Case (i) : y is in Register

If this is the case, we simply update the address and register descriptors to record that x value is available in a register containing the value of y. If there is no next use of y and it is not live at the end of the block, then the register no longer holds y value.

Case (ii) : y is in Memory Location

If y is in memory locations, then we can't record that x value is in the location of y since changing the value of y can't preserve the value of x. Therefore, we use a function GETREG to determine a register to hold the value of y in it and then make that register as the location of y.

An alternative is to generate the instruction MOV y, x. This is preferred if there is no next use of x in the block.

The GETREG function is defined as given below,

GETREG Function

For a three-address statement $x := y\ op\ z$, the function GETREG returns a location L to store the value of x.

1. If a register holds the value of only one variable i.e., y (a copy statement $x := y$ causes a register to hold, the value of more than one variable) and after the execution of $x := y\ op\ z$, y is not live and has no next use, then return the location for L as the register of y.
2. If condition 1 fails, then return an empty register for L, if available.
3. If condition 2 fails, then determine whether there is next use of variable x in the block or op is an operator such that it requires a register (e.g. indexing) then do the following.
   - Find an occupied register R such that it is referenced furthest in the future or whose value is also available in the memory.
   - Generate the instruction MOV R, M to store the value of R into a memory location M if it is not already in M.
   - If the register R holds the value of more than one variable, then generate a MOV instruction for each variable in R to save its value.
4. If x has no next uses or there is no suitable occupied register, then return the memory location of x as L.

By processing the three-address statements in the basic block the variables that are live are stored on memory location by generating MOV instructions.

If the register descriptor specify the name of variables that are present in registers, then the address descriptor will determine whether the same name is already present in its memory location or not. The live variable information obtained by data-flow analysis among blocks also specify what variables are present on exit so that they can be stored. If no such information is obtained by data flow analysis, then all user-defined variables are considered as live at the end of the block.

Example

Consider the three-address code for the assignment statement $r = (x + y) * (x - z) + (x - z)$

$t_1 := x + y$

$t_2 := x - z$

$t_3 := t_1 * t_2$

$r := t_3 + t_2$

It is assumed that a, b and c are always in memory and the temporaries t_1, t_2 and t_3 are not in memory unless their values are explicitly stored by MOV instructions.

For the above sequence of three-address statements, the code generation algorithm produces the following code.

Three-address	Generated Code Statement	Contents of Register Descriptor	Content of Address Descriptor
		All registers are empty	
$t_1 := x + y$	MOV x, R_0	R_0 holds t_1	t_1 is in R_0
	ADD y, R_0		
$t_2 := y - z$	MOV x, R_1	R_0 holds t_1	t_1 is in R_0
	SUB z, R_1	R_1 holds t_2	t_2 is in R_1
$t_1 := t_1 * t_2$	MUL R_1, R_0	R_0 holds t_3	t_3 is in R_0
		R_1 holds t_2	t_2 is in R_1
$r := t_3 + t_2$	ADD R_1, R_0	R_0 holds r	r is in R_0
	MOV R_0, r		r is in R_0 and memory

When the GETREG function is called for the location to compute t_1 it returns R_0 as it is available. Since x value is not in R_0 it is loaded into it by generating the instruction MOV x, R_0 then we generate instruction ADD y, R_0. Next we update the register descriptor to indicate that R_0 holds the value of t.

Similarly the code for other statements is generated. After the statement $r = t_3 + t_2$ the register R_1 becomes empty because the variable t_2 contained in it has no next use. Since the variable r is live at the end of the block, it is stored in memory location by generating the instruction MOV R_0, r.

Q26. Describe in detail about a simple code generator with the appropriate algorithm.

Answer :

Nov.-12, Set-3, Q8

A simple code generator can be defined as an algorithm which generates code for a single basic block. The task of this algorithm is to consider a three-address instruction and keep a record of values stored in registers in order to avoid useless production of loads and stores.

The code generation algorithm uses register and address descriptors. They help in register allocation.

Register Descriptor

A register descriptor keeps the information about each register. It associates with each register a list of variables whose values are held in that register. Initially all registers in a register descriptor are empty. As the process of code generation for a block progresses, each register holds a value of zero or more variables at any instant of time. The information stored in a register descriptor is needed whenever there is a need of a new register.

Address Descriptor

An address descriptor also known as variable descriptor, keeps information about locations of each variable where the current value of the variable can be found at run time. The locations could be a register, memory address or both because the variable was just loaded from memory into register and its value has not changed. This information can be stored in the symbol table and used to access a name.

With the use of descriptors, one can determine what values are present in registers and reuse them, if needed be. Also reclaim registers when it is known that the values held in registers are no longer required in subsequent code or sending the values back into appropriate memory locations.

Example

Consider the basic block and its corresponding dag representation given below.

$$l_1 : t_1 = x * y$$
$$x = t_1$$
$$t_2 = y - 1$$
$$y = t_2$$
$$t_3 = y == 0$$

if false t_2 goto l_1

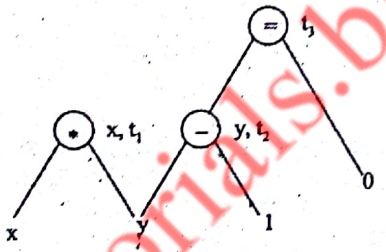


Figure: Dag

Now consider the generation of TM code. Assume that there are three registers R_0, R_1 and R_2 and there are four address descriptors namely inRegister (rno), isGlobal (goffset), isTemp (toffset) and isConst (val). Assume also, that x and y are in global location 0 and 1 respectively. Global location can be accessed through the *gp* register and temporary locations can be accessed through the *mp* register.

Initially all the registers are empty. The address descriptor table begins before code generation for the basic block as given below,

Variable Name	Address
x	isGlobal (1)
y	isGlobal (0)
t_1	—
t_2	—
t_3	—
1	isConst (1)
0	isConst (0)

Initially the register descriptor is empty.

Suppose that the following code is generated.

```
LD   0, 1 (gp)      /* load x into R0 */
LD   1, 0 (gp)      /* load y into R1 */
MUL 0, 0, 1         /* Multiply R0 and R1 and store result into R0 */
```

Now, the address descriptor table contents would be,

Variable Name	Address
x	inRegister (0)
y	isGlobal (0), inRegister (1)
t_1	inRegister (0)
t_2	—
t_3	—
1	isConst (1)
0	isConst (0)

and the register descriptor is,

Register	Variables
0	x, t_1
1	y
2	–

Now the subsequent code generated is,

LDC 2, 1 (0) /* load constant value 1 into R_2 */

SUB 1, 1, 2 /* Subtract R_1 and R_2 and stores result into R_1 */

Now, the address descriptor table given as,

Variable Name	Address
x	inRegister (0)
y	inRegister (1)
t_1	inRegister (0)
t_2	inRegister (1)
t_3	—
1	isConst (1), inRegister (2)
0	isConst (0)

and the register descriptor is given as follows,

Register	Variables
0	x, t_1
1	y, t_2
2	1

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SHORT QUESTIONS WITH SOLUTIONS

Q1. What is an activation tree?

Answer : *Model Paper-I, Q1(a)*

An activation tree is a tree that shows how control enters and leaves activations.

In an activation tree,

(i) Every node corresponds to activation of a procedure

(ii) The root node corresponds to the activation of main program.

(iii) The node for activation of procedure '*p*' is said to be parent of node for activation of procedure '*q*' iff the flow of control sequence is from '*p*' to '*q*'.

(iv) The node for activation of procedure '*p*' is said to be the left of the node for activation of procedure '*q*' iff the lifetime of '*p*' occurs earlier than the lifetime of '*q*'.

Q2. What is an activation record?

Answer :

Activation record or frame is a contiguous block of storage that contains all the information required for a single execution of a procedure. An activation record consists of seven fields as shown in the figure.

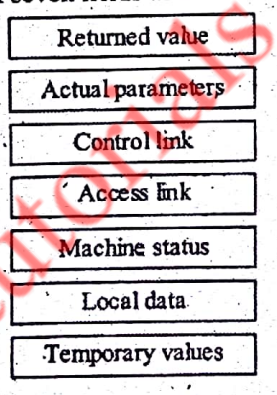

Figure: An Activation Record

Q3. Describe about access links and displays.

Answer :

Access Links

In this method a pointer called an access link is added to each activation record. If procedure p1 is nested immediately within p2 then the access link in p1's activation records points to the access link in p2's activation record which is the most recent activation of p2.

Displays

This method maintains an array *d* of pointers to activation records called a *display*. An array element *d*[*i*] points to the activation containing the storage for nonlocal *x* with nesting depth *i*.

CD5.7

Q4. List the basic functions and properties of memory manager.

Answer :

Functions of Memory Manager

The two basic functions of memory manager includes,

(i) Memory allocation

(ii) Memory deallocation.

Properties of Memory Manager

The properties of memory manager include,

(i) Maintainence of space efficiency

(ii) Maintenance of program efficiency

(iii) Minimizing over head.

Q5. Write a short note on code generation and list the generic issues in the design of code generator.

Answer : Model Paper-II, Q1(e)

Code Generation

Code generation phase is the last phase of compiler. It is an important phase of the compilation because, in this phase the compiler convert the intermediate code into machine or assembly code. Moreover, the allocation of memory to variable in source program is also done by this phase. The code generator assigns register to variable in the program.

Design Issues of Code Generator

(i) Input

(ii) Output

(iii) Memory management

(iv) Selection of machine instruction

(v) Allocating register

(vi) Evaluation order

(vii) Code generation.

Q6. Define Basic block.

Answer :

A basic block is bunch of three-address statements, such that the flow of control if once enters a block of statements then flow continuously without stopping or pausing and ends at the end of the block.

Every statement in a basic block is a three-address statement.

In an assignment statement,

$a := b * c$

a is defined by using b and c.

Thus, we can say that the above statement defines 'a' and uses 'b' and 'c'.

A symbol or a variable or a name is known as a live symbol or name if its value is used in future or from that point. Similarly, a name is known as a dead symbol, if its value is not going to be used in the rest of the program.

Q7. What is flow graph?

Answer : Model Paper-III, Q1(e)

A flow graph is a graphical representation of three-address statements. It is used to show the flow of control information to the set of basic blocks of a program. It consists of nodes and edges. A node of a flow graph is a basic block that performs some computations. An initial node consists of a block whose leader is the first statement. There is a directed edge from one node to another representing the flow of control between blocks. There is an edge from block B1 to block B2.

Q8. Discuss briefly about natural loops and inner loops of flow graph.

Answer :

Natural Loops

In a flow graph, if there exist a back edge $n \rightarrow b$, then the natural loop of the edge 'b' is given along with a set of nodes that do not go through 'b' to reach 'n'. In the edge $n \rightarrow b$, b is the head and n is the tail.

Inner Loops

A loop that does contain any other loop is called an inner loop. For example, the flow graph given in the below figure (1), has an inner loop $4 \rightarrow 2$ i.e., the path from 2-3-4.

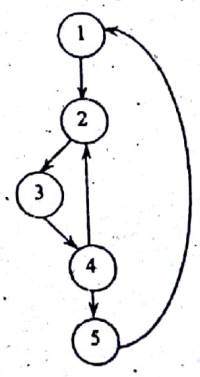

Figure: Flow Graph with an Inner Loop $4 \rightarrow 2$

Q9. What are reducible and non-reducible flow graphs?

Answer : Model Paper-IV, Q1(e)

Reducible Flow Graphs

A flow graph G_f is said to be reducible, if its edges can be divided into two disjoint groups i.e., forward edges and back edges and it has two properties. They are as follows,

1. The back edges group contains only those edges whose heads dominates their tails.
2. The forward edges make an acyclic graph, with every node reachable from the initial node of 'G_f'.

Almost all the flow graphs are reducible. For example, flow graphs for statements like while-do, continue, if-then-else, break and goto are reducible. In reducible flow graphs, there are no jumps in the middle of the loop from outside. Hence, entry into a loop is through its header.

Example

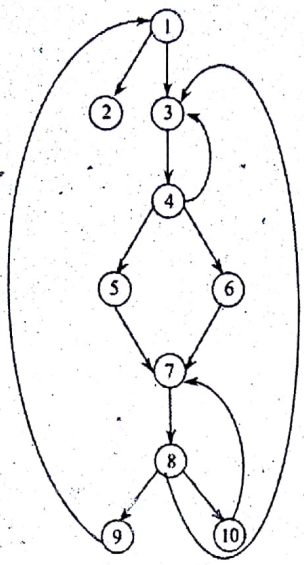

Figure: Reducible Flow Graph

Non-reducible Flow Graphs

There are some flow graphs which are not reducible, such a flow graph is as shown in the below figure.

Example

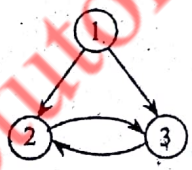

Figure: Non-reducible Flow Graph

Q10. What are the applications of Next-use information?

Answer :

Machine instructions involving registers are shorter and faster than the instructions involving operands in memory. Therefore, it is important to utilize registers efficiently. If a name held in register is no longer needed, then the register can be used to assign it to some other name. That is storing a name in register only if it will be used subsequently.

The information about next use of a name has a number of applications.

1. It can be used to assign space for attribute values.
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3. It can be used to assign storage for temporary names.