Lecture 9

Semantic Analysis

The semantic analysis phase of compiler connects variable definition to their uses ,and checks that each expression has a correct type.
This checking called "**static type checking**" to distinguish it from "**dynamic type checking**" during execution of target program. This phase is characterized be the maintenance of symbol tables mapping identifiers to their types and locations.

Examples of static type checking:-

1. **Type checks :** A compiler should report an error if an operator is applied to an incompatible operand.
2. **Flow of control checks:-** Statements that cause flow of control to leave a construct must have some place to which to transfer the flow of control. For example, a "*break*" statement in 'C' language causes control to leave the smallest enclosing *while* , *for* , or *switch* statement ;an error occurs if such an enclosing statement does not exist.
3. **Uniqueness checks:-** There are situations in which an object must be defined exactly once. For example, in 'Pascal' language, an identifier must be declared uniquely.
4. **Name-related checks:-** Sometimes, the same name must appear two or more times. For example, in **'Ada'** language a loop or block may have a name that appear at the beginning and end of the construct. The compiler must check that the same name is used at both places.

<u>Type system:-</u>

The design of type checker for a language is based on information about the syntactic constructs in the language, the notation of types, and the rules for assigning types to language constructs.
The following excerpts are examples of information that a compiler writer might have to start with.

- If both operands of the arithmetic operators "*addition*", "*subtraction*", and "*multiplication*" are of type *integer* , then the result is of type *integer*.

- The result of Unary **&** operator is a pointer to the object referred to by the operand. If the type of operand is *T* , the type of result is ' pointer to *T* '.

We can classify type into :

1. **Basic type:** This type are the atomic types with no internal structure , such as *Boolean, Integer, Real, Char, Subrange, Enumerated,* and a special basic types " *type-error , void* ".
2. **Construct types:** Many programming languages allows a programmer to construct types from *basic types* and other *constructed types.* For example *array, struct, set.*
3. **Complex type:** Such as *link list, tree, pointer.*

Type system:- is a collection of rules for assigning type expressions to the various parts of a program. A type checker implements a *type system.*

Specification of a simple type checker:-

The type checker is a translation scheme that synthesizes the type of each expression from the types of its subexpressions. In this section, we specify a type checker for simple language in which the type of each identifier must be declared before the identifier is used.
Suppose the following grammar to generates program, represented by *nonterminal* P, consisting of a sequence of declarations D followed by a single expression E.

$$P \longrightarrow D \,;\, E$$

$$D \longrightarrow D \,;\, D \mid \text{id} : T$$

$$T \longrightarrow \text{char} \mid \text{int} \mid \text{array[num] of } T \mid \uparrow T$$

$$E \longrightarrow \text{literal} \mid \text{num} \mid \text{id} \mid E \text{ mod } E \mid E[E] \mid E\uparrow$$

Type checker (translation scheme) produce the following part that saves the type of an identifier:

P $\longrightarrow$ D;E	
D $\longrightarrow$ D;D	
D $\longrightarrow$ id:T	{addtype(id.entry,T.type)}
T $\longrightarrow$ char	{T.type=char}
T $\longrightarrow$ int	{T.type=int}
T $\longrightarrow$ $\uparrow$T1	{T.type=pointer(T1.type)}
T $\longrightarrow$ array[num] of T1	{T.type=array(1..num.val,T1.type)}

- **The type checking of expression:** the following some of semantic rules:

E $\longrightarrow$ literal	{E.type=char}	//constants represented
E $\longrightarrow$ num	{E.type=int}	// = =

We can use a function *lookup*(e) to fetch the type saved in *ST* ,if identifier " e " appears in an expression:

E $\longrightarrow$ id {E.type=lookup(id.entry)}

The following expression formed by applying (mod) to two subexpression:

E $\longrightarrow$ E1 mod E2 {E.type= if E1.type=int and E2.type=int then int
Else type-error }

An array reference:

E $\longrightarrow$ E1[E2] { E.type= if E2.type=int and E1.type=array[s,t] then t
Else type-error}

E $\longrightarrow$ E1$\uparrow$ { E.type= if E1.type=pointer(t) then t
Else type-error}

- **The type checking of statements :**

S $\longrightarrow$ id=E {S.type=if id.type = E.type then void
Else type-error)}

S $\longrightarrow$ if E then S1 {S.type= if E.type=boolean then S1.type
Else type-error }

S $\longrightarrow$ while E do S1 {S.type= if E.type=boolean then S1.type
Else type-error }

S $\longrightarrow$ S1 ; S2 { S.type= if S1.type=void and S2.type=void then void
Else type-error}

Lecture 10

Intermediate Code Generation (IR)

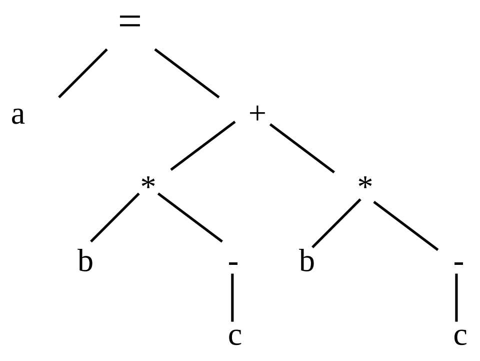
IR is an internal form of a program created by the compiler while translating the program from a *H.L.L* to *L.L.L.*(*assembly* or *machine code*),from IR the back end of compiler generates *target code*.

Although a source program can be translated directly into the target language,some benefits of using a machine independent IR are:

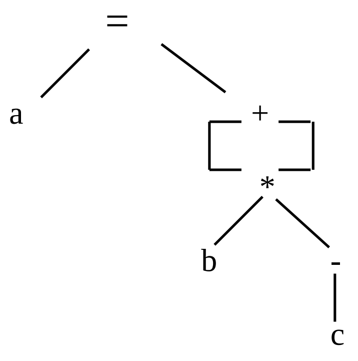
1. A compiler for different machine can be created by attaching a back end for a new machine into an existing front end.
2. Certain optimization strategies can be more easily performed on IR than on either original program or L.L.L.
3. An IR represents a more attractive form of target code.

Intermediate Languages:-

1. Syntax Tree and Postfix Notation are tow kinds of intermediate representations, for example **a=b*-c+b*-c**

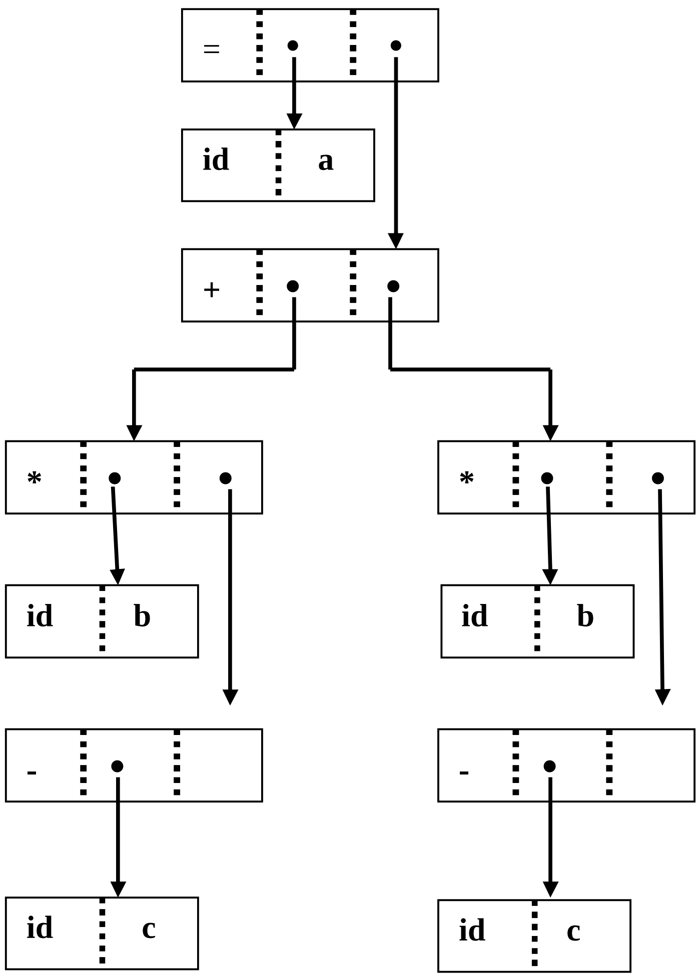


Syntax Tree



DAG

- A *DAG* give the same information in syntax tree but in compact way because common subexpressions are identified.
- *Postfix notation* is a linearized representation of a syntax tree, for example: **a b c - * b c - * + =**
- Two representation of above syntax tree are:



0	id	b	
1	id	c	
2	-	1	
3	*	0	2
4	id	b	
5	id	c	
6	-	5	
7	*	4	6
8	+	3	7
9	id	a	
10	=	9	8
	….	…..	…..
	…..	…..	…..

1

2

2. Three-Address Code is a sequence of statements of the general form :

   X=Y op Z // op is binary arithmetic operation

   For example : *x + y * z*

   *t1 = y * z*
   t2 = x + t1

where t1 ,t2 are compiler generated temporary.

Types of three address code statement:-

1. Assignment statements of the form *X=Y op Z* (where op is a binary arithmetic or logical operator).
2. Assignment instructions of the form *X= op Y* (op is a unary operator).
3. Copy statements of the form *X=Y* .
4. Unconditional jump (*Goto L*).
5. Conditional jump (*if X relop Y goto L*).
6. *Param X* & *Call P,N* for procedure call and and return *Y* , for example :

```
Param    x1
Param    x2
……..
Param    xn
Call     P,n
```

7. Index assignments of the form X=Y[i] & X[i]=Y.
8. Address & Pointer Assignments

X= &Y
*X= * Y*
**X= Y*

Example : a= b * -c + b * -c

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

Three address code
For syntax tree

```
t1 = - c
t2 = b * t1
t5 = t2 + t2
a = t5
```

Three address code
For DAG

Note: Three-address statements are a kin to assembly code statements can have symbolic labels and there are statements for flow of control.

Implementation of Three Address Code :-

In compiler , three-address code can be implement as records, with fields for operator and operands.

1. **Quadruples :-** It is a record structure with four fields:
    - **OP** // operator
    - **arg1 , arg2** // operands
    - **result**

2. **Triples :-** To avoid entering temporary into *ST* , we might refer to a temporary value by position of the statement that compute it . So three address can be represent by record with only three fields:

    - **OP** // operator
    - **arg1 , arg2** // operands

Example: a = b * -c + b * -c

i. By Quadruples

Position	OP	arg1	arg2	result
0	-	c		t1
1	*	b	t1	t2
2	-	c		t3
3	*	b	t3	t4
4	+	t2	t4	t5
5	=	t5		a

ii. By Triples

Position	OP	arg1	arg2
0	-	c	
1	*	b	(0)
2	-	c	
3	*	b	(2)
4	+	(1)	(3)
5	=	a	(4)

Lecture 11

Code Optimization

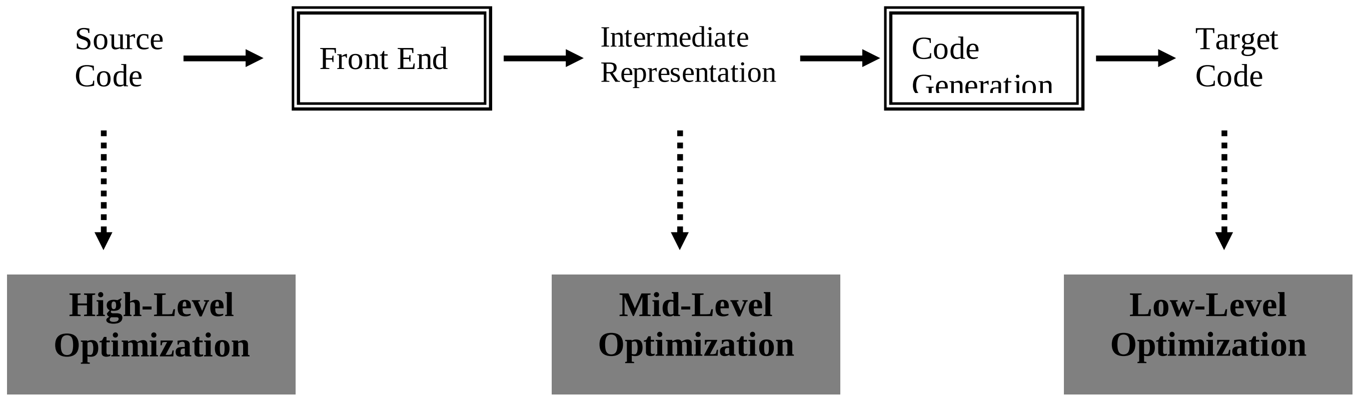
Compilers should produce target code that is as good as can be written by hand. This goal is achieved by program transformations that are called " Optimization " . Compilers that apply code improving transformations are called " Optimizing Compilers ".

Code optimization attempts to increase program efficiency by restructuring code to simplify instruction sequences and take advantage of machine specific features:-

- Run Faster , or
- Less Space , or
- Both (Run Faster & Less Space).

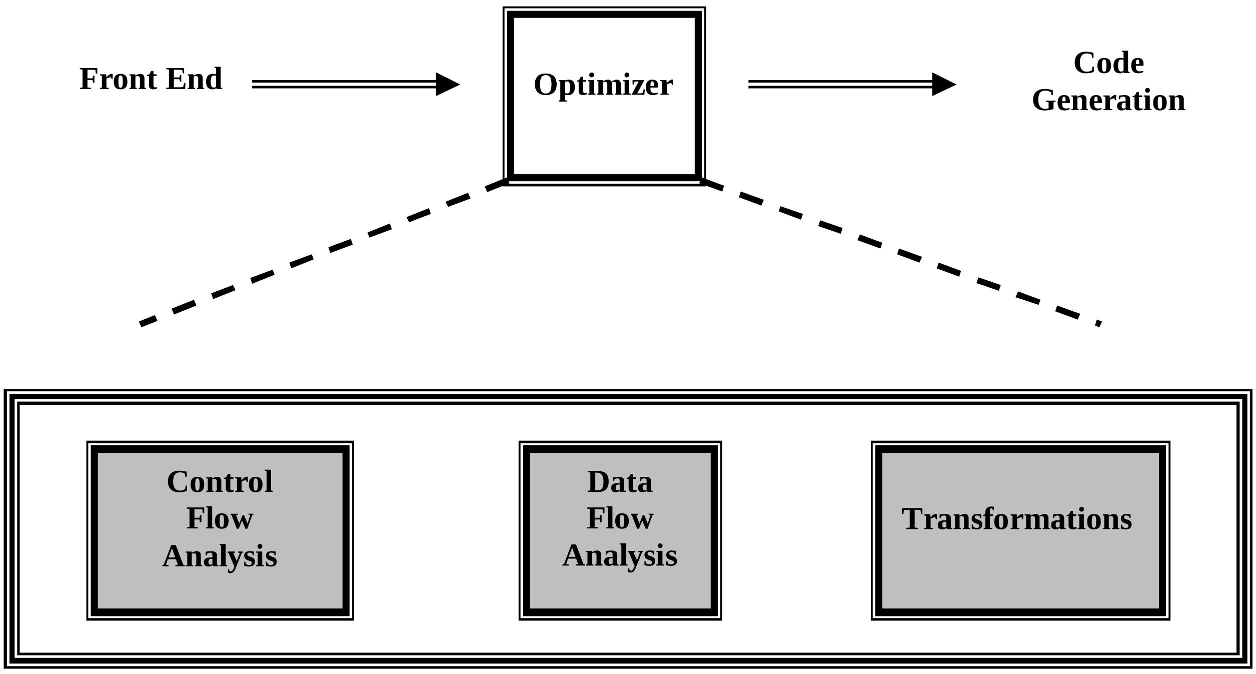
The transformations that are provided by an optimizing compiler should have several properties:-

1. A transformation must preserve the meaning of program. That is , an optimizer must not change the output produce by program for an given input, such as **division by zero.**
2. A transformation must speed up programs by a measurable amount.



Places for Optimization

This lecture concentrates on the transformation of intermediate code (Mid-Optimization or Independent Optimization),this optimization using the following organization:-



Organization of the Optimizer

This organization has the following advantages :-

1. The operations needed to implement high-level constructs are made explicit in the intermediate code.
2. The intermediate code can be independent of the target machine, so the optimizer does not have to change much if the code generator is replaced by one for different machine.

<u>Basic Blocks:-</u>

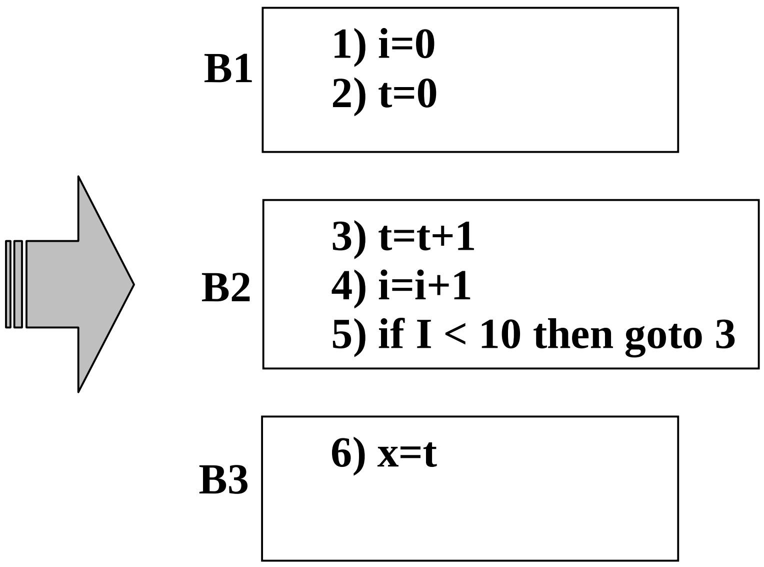
The code is typically devided into a sequence of "Basic Blocks". A Basic Block is a sequence of straight-line code,with no branches " In " or " Out " except a branch "In" at the top of block and a branch "Out" at the bottom of block.

- **Set of Basic Block :** The following steps are used to set the Basic Block:
    1. **Determine the Block beginning:**
        - **i- The First instruction**
        - **ii- Target of conditional & unconditional Jumps.**
        - **iii- Instruction follow Jumps.**

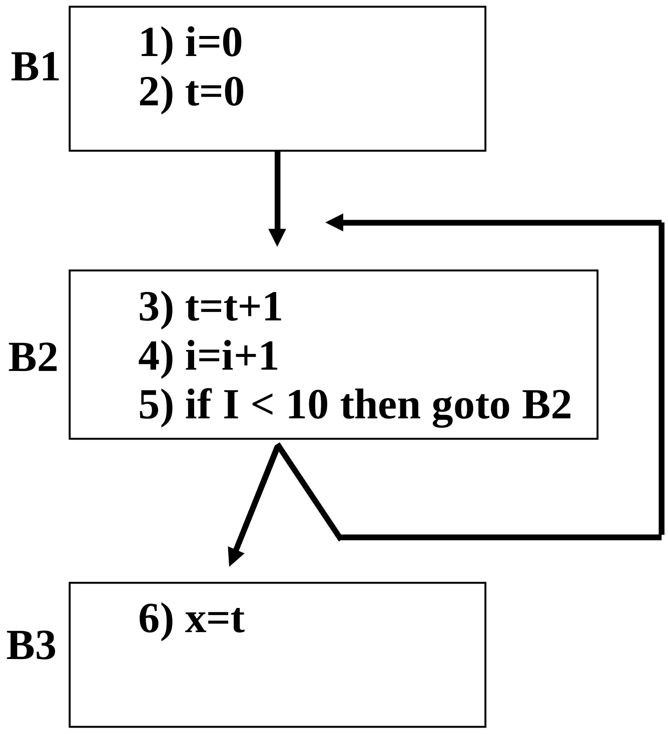
2. **Determine the Basic Blocks:**
   i-There is Basic Block for each Block beginning.
   ii-The Basic Block consist of the Block beginning and runs until the next Block beginning or program end.

Example\\

1) i=0
2) t=0
3) t=t+1
4) i=i+1
5) if I < 10 then goto 3
6) x=t



Basic Blocks



Control Flow

Lecture 12

Data – Flow Analysis (DFA)

In order to do code optimization a compiler needs to collect information about program as a whole and to distribute this information to each block in the flow graph. DFA provides information about how the execution of a program may manipulate its data , and it provides information for *global optimization* .

There are many DFA that can provide useful information for optimizing transformations. One data-flow analysis determines how definitions and uses are related to each other, another estimates what value variables might have at a given point, and so on. Most of these DFAs can be described by data flow equations derived from nodes in the flow graph.

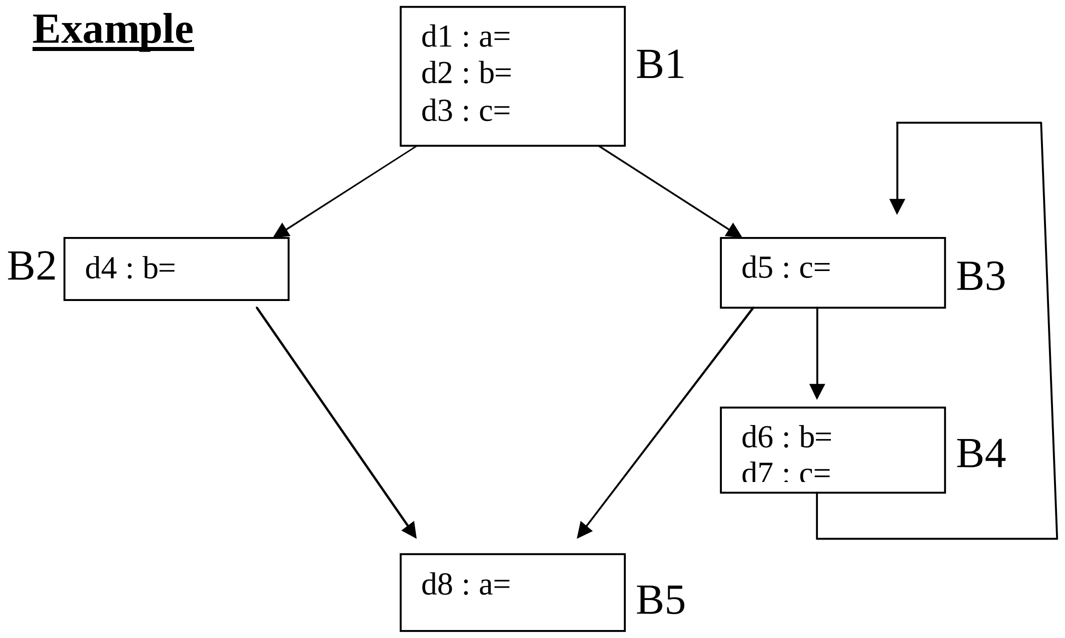
Reaching Definitions Analysis: All definitions of that variable, which reach the beginning of the block, as follow:

1. **Gen**[B] : contains all definitions *d:v=e* , in block B that *v* is not defined after *d* in B.
2. **Kill**[B] : if *v* is assigned in B , then Kill[B] contains all definitions *d:v=e*,in block different from B.
3. **In**[B] : the set of definitions reaching the beginning of B.

   $$\textbf{In[B]} = \cup\ \textbf{Out[H]} \qquad \text{where } H \in \text{Pred[B]}$$
4. **Out[B]** : the set of definitions reaching the end of B.

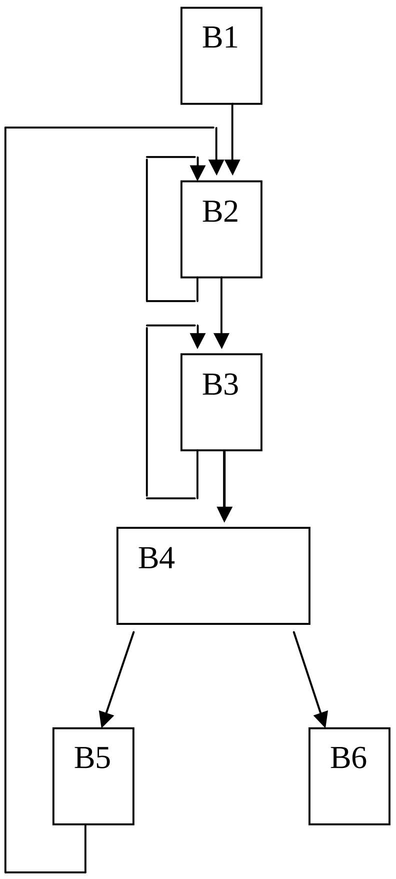
   $$\textbf{Out[B]} = \textbf{Gen[B]} \cup (\ \textbf{In[B]} - \textbf{Kill[B]}\ )$$

Example



Block	Gen	Kill	In	Out
B1	d1d2d3	d4d5d6d7d8	Ø	d1d2d3
B2	d4	d2d6	d1d2d3	d1d3d4
B3	d5	d3d7	d1d2d3d6d7	d1d2d5d6
B4	d6d7	d2d3d4d5	d1d2d5d6	d1d6d7
B5	d8	d1	d1d2d3d4d5d6	d2d3d4d5d6d8

Loop Information: The simple iterative loop which causes the repetitive execution of one or more *basic blocks* becomes the prime area in which optimization will be considered.Here we determine all the loops in program and limit *headers* & *preheaders* for every loop, for example:



Flow Graph

Loop No.	Header	Preheader	Blocks
1	B2	B1	2-3-4-5-2
2	B2	B1	2-2
3	B3	B2	3-3

Loop Information

Lecture 13

Code Optimization Methods

A transformation of program is called " *Local* " if it can performed by looking only at the statements in a *Basic Block*, otherwise, it is called " *Global* " .

Local Transformations:

1. Structure-Preserving Transformations:-
    - Common Subexpression Elimination
    - Dead Code Elimination

2. Algebraic Transformations:-This transformations uses to change the set of expressions ,computed by a basic block, with an algebraically equivalent set. The useful ones are those that simplify expressions or replace expensive operations by cheaper one, such as:

$$\left.\begin{array}{l} x{:=}x+0 \\ x{:=}x*1 \\ x{:=}x/1 \end{array}\right\} \quad \textit{Eliminated}$$

$$x{:=}\ y\text{\^{}}2 \quad \Longrightarrow \quad x{:=}y*y$$

Another class of algebraic transformations is ***Constant Folding*** ,that is, we can evaluate constant expressions at compiler time and replace the constant expressions by their values, for example, the expression 2*3.14 would be replaced by 6.28.

Global Transformations:

1. Common Subexpression Elimination

$$\begin{array}{lcl} a=b+c & & a=b+c \\ c=b+c & \Rightarrow & c=a \\ d=b+c & & d=b+c \end{array}$$

2. Dead Code Elimination**:** Variable is *dead* if never used

$$\begin{array}{lcl} x=y+1 & & \\ y=1 & \Rightarrow & y=1 \\ x=2*z & & x=2*z \end{array}$$

3. Copy Propagation

Origin	**Copy Propagation**	**Dead Code**
x=t3	***x=t3***	
a[t2]=t5	***a[t2]=t5***	***a[t2]=t5***
a[4]=x	***a[4]=t3***	***a[4]=t3***
Goto B2	***Goto B2***	***Goto B2***

4. Constant Propagation

Origin	**Copy Propagation**	**Dead Code**
x=3	***x=3***	
a[t2]=t5	***a[t2]=t5***	***a[t2]=t5***
a[4]=x	***a[4]=3***	***a[4]=3***
Goto B2	***Goto B2***	***Goto B2***

5. Loop Optimization

- **Code Motion:** An important modification that decreases the amount of code in a loop is *Code Motion.* If result of expression does not change during loop(*Invariant Computation*),can hoist its computation out of the loop.

```
For(i=0;i<n;i++)
    A[i]=a[i]+( x*x )/( y*y );

c=( x*x )/( y*y );
 For(i=0;i<n;i++)
    A[i]=a[i]+c;
```

- **Strength Reduction:** Replaces expensive operat--ions (Multiplies, Divides)by cheap ones (Adds, Subs)**.**For example, suppose the following expression**:**

For(i=1;i<n;i++){v=4*i;s=s+v;} ***i*** *is induction variable*

Then:

v=0;
For(i=1;i<n;i++){ v=v+4; s=s+v; }

Induction Variable: is a variable whose value changes by a constant amount on each loop iteration.

Lecture 14

Code Generation

In computer science, code generation is the process by which a compiler's code generator converts some internal representation of source code into a form(e.g., machine code)that can be readily executed by a machine.

Issues in the Design of a Code Generator:-

1. **Input to the Code Generator :**The input to the code generator consists of the intermediate representation of the source program(Optimized IR),together with information in ST that is used to determine the Run Time Addresses of the data objects denoted by the names in IR. Finally, the code generation phase can therefore proceed on the assumption that its input is free of the errors.
2. **Target Programs :** The output of the code generator is the target program. The output code must be **Correct** and of **high Quality**, meaning that it should make effective use of the resources of the target machine. Like the IR ,this output may take on a variety of forms:
   a. **Absolute Machine Language //** Producing this form as output has the advantage that it can placed in a fixed location in memory and immediately executed. A small program can be compiled and executed quickly.
   b. **Relocatable Machine Language //** This form of the output allows subprograms to be compiled separately. A set of relocatable object modules can be linked together and loaded for execution by linking-loader.
3. **Memory Management :** Mapping names in the source program to addresses of data objects in run time memory. This process is done cooperatively by the Front-end & code generator.
4. **Major tasks in code generation :** In addition to the basic conversion from IR into a linear sequence of machine instructions, a typical code generator tries to <u>optimize the generated code</u> in some way. The generator may try to use

faster instructions, use fewer instructions ,exploit available registers ,and avoid redundant computations. Tasks which are typically part of a compiler's code generation phase include:

i. Instruction selection: Is a compiler optimization that transforms an internal representation of program into the final compiled code(either Binary or Assembly).The quality of the generated code is determined by its Speed & Size. For example, the three address code (x=y+z) can be translated into:

```
MOV   y,R0
ADD   z,R0
MOV   R0,x
```

If three-address code is :

```
a=b+c
d=a+e
```

then the target code is :

```
MOV   b,R0
ADD   c,R0
MOV   R0,a
MOV   a,R0
ADD   e,R0
MOV   R0,d
```

Finally, A target machine with "**Rich**" instruction set may be provide several ways of implementing a given operation. For example, if the target machine has an "increment" instruction (**INC**) ,then the IR a=a+1 may be implemented by the single instruction (INC a) rather than by a more obvious sequence :

```
MOV  a,R0
ADD  #1,R0
MOV  R0,a
```

ii. Instruction Scheduling : In which order to put those instructions. Scheduling is a *speed optimization*. The order in which computations are performed can effect the efficiency of the target code, because some computation orders require fewer registers to hold intermediate results than others.

iii.Register Allocation : Is the process of multiplexing a large number of target program variables onto a small number of CPU registers. The goal is to keep as many operands as possible in registers to maximize the execution speed of software programs (*instructions involving register operands are usually shorter and faster than those involving operands in memory*).

Hitch your Wagon to a Star

References

1. MOGENSEN, Torben Ægidius. “**Introduction to compiler design**”. Springer Nature, 2024.

2. SINGH, Ajit. “***Compiler Design***”. Ajit Singh, 2024.

3. CAI, Shubin, et al. ComPAT: “**A Compiler Principles Course Assistant. In: *International Conference on Knowledge Science”***, *Engineering and Management*. Singapore: Springer Nature Singapore, 2024. p. 74-83.

4. A.Aho,R.Sethi,J.D.Ullman," **Compilers- Principles, Techniques and Tools**" Addison-Weseley,2007

5. J.Tremblay,P.G.Sorenson,"**The Theory and Practice of Compiler Writing** ", McGRAW-HILL,1985

6. W.M.Waite,L.R.Carter,"**An Introduction to Compiler Construction**", Harper Collins,New york,1993

7. A.W.Appel, "**Modern Compiler Implementation in ML**", CambridgeUniversity Press,1998