CSc 453 — Compilers and Systems Software

13 : Intermediate Code I

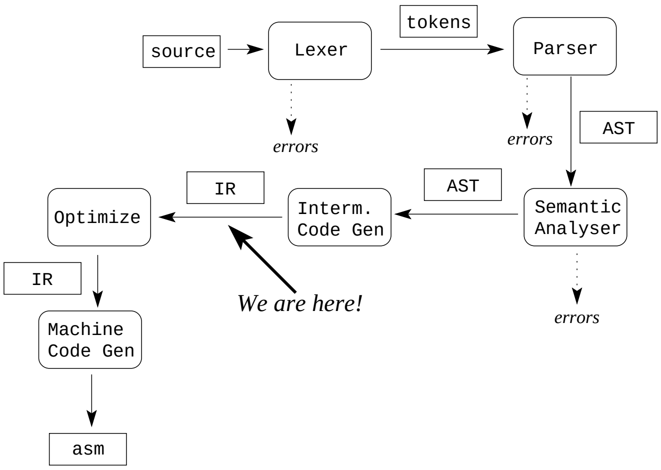
Christian Collberg
Department of Computer Science
University of Arizona
collberg@gmail.com

October 18, 2009

1

Introduction

2 Compiler Phases



3 Intermediate Representations

- Some compilers use the AST as the only intermediate representation. Optimizations (code improvements) are performed directly on the AST, and machine code is generated directly from the AST.
- The AST is OK for machine-independent optimizations, such as **inlining** (replacing a procedure call with the called procedure's code).
- The AST is a bit too high-level for machine code generation and machine-dependent optimizations.

4 Intermediate Representations. . .

- For this reason, some compilers generate a lower level (simpler, closer to machine code) representation from the AST. This representation is used during code generation and code optimization.

5 Intermediate Code

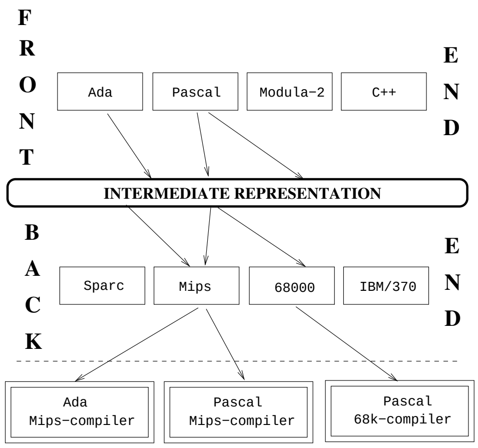
Advantages of:

1. Fitting many front-ends to many back-ends,
2. Different development teams for front- and back-end,
3. Debugging is simplified,
4. Portable optimization.

Requirements:

1. Architecture independent,
2. Language independent,
3. Easy to generate,
4. Easy to optimize,
5. Easy to produce machine code from.

6 Mix-and-Match Compilers



7 UNCOL

- A representation which is both architecture and language independent is known as an **UNCOL**, a **Universal Compiler Oriented Language**.
- UNCOL is the **holy grail** of compiler design – many have search for it, but no-one has found it. Problems:
  1. Programming language semantics differ from one language to another,
  2. Machine architectures differ.

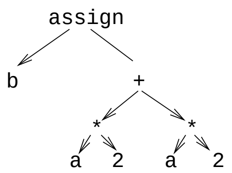
8 Intermediate Code...

- There are several different types of intermediate representations:
  1. Tree-Based.
  2. Graph-Based.
  3. Tuple-Based.
  4. Linear representations.
- All representations contain the same information. Some are easier to generate, some are easy to generate simple machine code from, some are easy to generate **good** code from.
- **IR** — Intermediate Representation.

9

Postfix Notation

10 Postfix Notation



Infix: `b :=` $(a * 2) + (a * 2)$
Postfix: `b a 2 * a 2 * + :=`

- Postfix notation is a parenthesis free notation for arithmetic expression. It is essentially a linearized representation of an abstract syntax tree.
- In postfix notation an operator appears **after** its operands.
- Very simple to generate, very compact, easy to generate straight-forward machine code from, difficult to generate **good** machine code from.

11

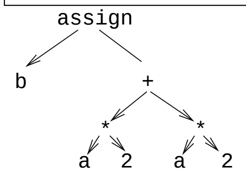
Tree & DAG Representations

12 Tree & DAG Representation

- Trees make good intermediate representations. We can represent the program as a sequence of **expression trees**. Each assignment, procedure call, or jump becomes one individual tree in the forest.
- **Common Subexpression Elimination** (CSE): Even if the same (sub-) expression appears more than once in a procedure, we should only compute its value **once**, and save the result for future reference.
- One way of doing this is to build a **graph** representation, rather than a tree. In the following slides we see how the expression $a * 2$ gets two subtrees in the tree representation and one subtree in the DAG representation.

13 Tree & DAG Representation...

$\boxed{\text{b} := (a * 2) + (a * 2)}$

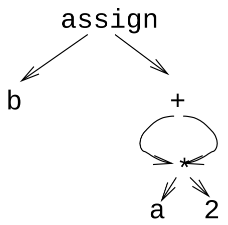


Linearized Tree

Nr	Op	Arg$_1$	Arg$_2$
1	**ident**	a	
2	**int**	2	
3	**mul**	1	2
4	**ident**	a	
5	**int**	2	
6	**mul**	4	5
7	**add**	3	6
8	**ident**	b	
9	**assign**	8	7

14 Tree & DAG Representation...

$\boxed{\text{b} := (a * 2) + (a * 2)}$

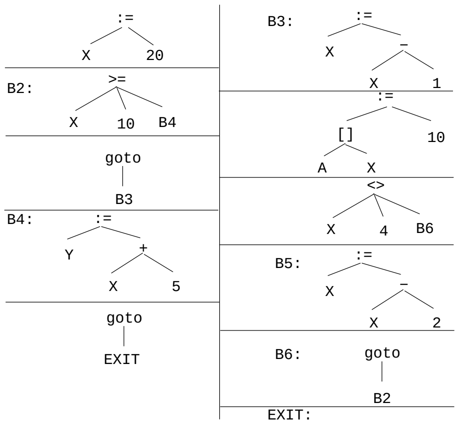


Linearized Dag

Nr	Op	Arg$_1$	Arg$_2$
1	**ident**	a	
2	**int**	2	
3	**mul**	1	2
4	**add**	3	3
5	**ident**	b	
6	**assign**	5	4

15 Sequence of Expression Trees

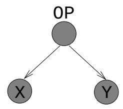
```
X := 20;
WHILE X < 10 DO
   X := X-1;
   A[X] := 10;
   IF X = 4 THEN
      X := X - 2;
   ENDIF;
ENDDO;
Y := X + 5;
```



16 Building DAGs...

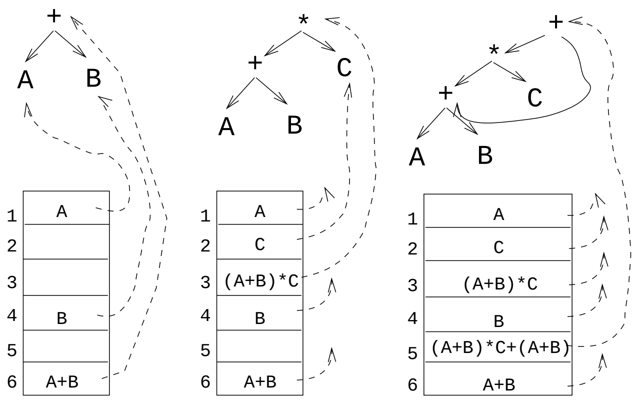
- Repeatedly add subtrees to build DAG. Only add subtrees not already in DAG. Store subtrees in a hash table. This is the **value-number** algorithm.

- For every insertion of a subtree, check if $(X\ \texttt{OP}\ Y) \in \texttt{DAG}$.




```
PROCEDURE InsertNode (
   OP : Operator; L, R :  Node) :  Node;
BEGIN
   V := hashfunc (OP, L, R);
   N := HashTab.Lookup (V, OP, L, R);
   IF N = NullNode THEN
      N := NewNode (OP, L, R);
      HashTab.Insert (V, N);
   END;
   RETURN N;
END InsertNode;
```

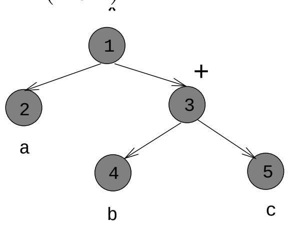
17 Building DAGs – Example



18 Building DAGs

- From an expression/expression tree such as the one on the left we might generate the machine code (for some fictitious architecture) on the right:

$a * (b + c)$




```
LOAD     b, r0
LOAD     c, r1
ADD      r0, r1, r2
LOAD     a, r3
MUL      r2, r3, r4
```

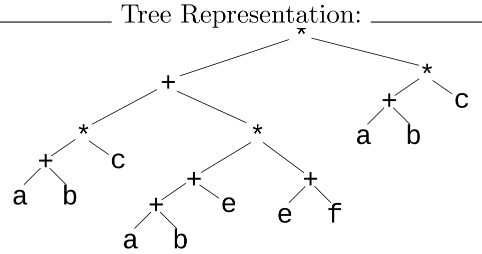
- Can we generate better code from a DAG than a tree?

19 Building DAGs...

Example Expression:

$$[(a + b) * c + \{(a + b) + e\} * (e + f)] * [(a + b) * c]$$

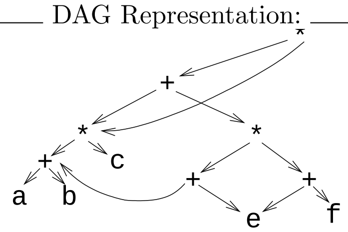
Tree Representation:



20 Building DAGs...

$$[(a + b) * c + \{(a + b) + e\} * (e + f)] * [(a + b) * c]$$

DAG Representation:



21 Building DAGs...

- Generating machine code from the tree yields 21 instructions.

Code from Tree

```
LOAD  a, r0        ; a
LOAD  b, r1        ; b
ADD   r0, r1, r2   ; a+b
LOAD  c, r0        ; c
MUL   r0, r2, r3   ; (a+b)*c
LOAD  a, r0        ; a
LOAD  b, r1        ; b
ADD   r0, r1, r2   ; a+b
LOAD  e, r0        ; e
ADD   r2, r0, r4   ; (a+b)+e
LOAD  f, r0        ; f
LOAD  e, r1        ; e
ADD   r0, r1, r0   ; f+e
MUL   r4, r0, r4   ; {(a+b)+e}*
                   ; (e+f)
ADD   r3, r4, r4
; Code for (a+b)*c into r3
MUL   r4, r3, r0
```

22 Building DAGs...

- Generating machine code from the DAG yields only 12 instructions.

Code from DAG

```
LOAD  a, r0        ; a
LOAD  b, r1        ; b
ADD   r0, r1, r2   ; a+b
LOAD  c, r0        ; c
MUL   r0, r2, r3   ; (a+b)*c
LOAD  e, r4        ; e
ADD   r4, r2, r1   ; (a+b)+e
LOAD  f, r0        ; f
ADD   r0, r4, r0   ; f+e
MUL   r1, r0, r0
ADD   r0, r3, r0
MUL   r0, r3, r0
```

23

Tuple Codes

24 Three-Address Code

- Another common representation is **three-address code**. It is akin to **assembly code**, but uses an infinite number of **temporaries** (registers) to store the results of operations.
- There are three common realizations of three-address code: **quadruples**, **triples** and **indirect triples**.

Types of 3-Addr Statements:

`x := y op z` Binary arithmetic or logical operation. Example: `Mul`, `And`.

`x := op y` Unary arithmetic, conversion, or logical operation. Example: `Abs`, `UnaryMinus`, `Float`.

`x := y` Copy statement.

25 Three-Address Code...

goto L Unconditional jump.

if `x relop y` **goto L** Conditional jump. `relop` is one of `<,>,<=`, etc. If `x relop y` evaluates to `True`, then jump to label L. Otherwise continue with the next tuple.

param X; **call P,** n Make X the next parameter; make a procedure call to `P` with n parameters.

x := y[i] Indexed assignment. Set `x` to the value in the location `i` memory units beyond `y`.

26 Three-Address Code...

x := ADDR(y) Address assignment. Set `x` to the address of `y`.

x := IND(y) Indirect assignment. Set `x` to the value stored at the address in `y`.

IND(x) := y Indirect assignment. Set the memory location pointed to by `x` to the value held by `y`.

27 Three-Address Code...

- Many three-address statements (particularly those for binary arithmetic) consist of one operator and three addresses (identifiers or temporaries):

$$\boxed{\mathrm{b} := (a * 2) + (a * 2)}$$

t_1	:=	a	**mul**	2
t_2	:=	a	**mul**	2
t_3	:=	t_1	**add**	t_2
b	:=	t_3		

28 Three-Address Code...

- There are several ways of implementing three-address statements. They differ in the amount of space they require, how closely tied they are to the symbol table, and how easily they can be manipulated.
- During optimization we may want to move the three-address statements around.

29 Three-Address Code — Quadruples

- Quadruples can be implemented as an array of records with four fields. One field is the operator.
- The remaining three fields can be pointers to the symbol table nodes for the identifiers. In this case, literals and temporaries must be inserted into the symbol table.

b := $(a * 2) + (a * 2)$

Nr	Res	Op	Arg$_1$	Arg$_2$
(1)	t_1	**mul**	a	2
(2)	t_2	**mul**	a	2
(3)	t_3	**add**	t_1	t_2
(4)	b	**assign**	t_3	

30 Three-Address Code — Triples

- **Triples** are similar to quadruples, but save some space.
- Instead of each three-address statement having an explicit **result** field, we let the statement itself represent the result.
- We don't have to insert temporaries into the symbol table.

b := $(a * 2) + (a * 2)$

Nr	Op	Arg$_1$	Arg$_2$
(1)	**mul**	a	2
(2)	**mul**	a	2
(3)	**add**	(1)	(2)
(4)	**assign**	b	(3)

31 Three-Address Code — Indirect Triples

- One problem with triples ("The Trouble With Triples?"[a]) is that they cannot be moved around. We may want to do this during optimization. We can fix this by adding a level of indirection, an array of pointers to the "real" triples.

b := $(a * 2) + (a * 2)$

Abs	Real
(1)	(10)
(2)	(11)
(3)	(12)
(4)	(13)

Nr	Op	Arg$_1$	Arg$_2$
(11)	**mul**	a	2
(12)	**mul**	a	2
(13)	**add**	(11)	(12)
(14)	**:=**	b	(13)

[a] This is a joke. It refers to the famous Star Trek episode "The Trouble With Tribbles." OK, so it's not funny.

32

Summary

33 Readings and References

- Read Louden:

  Intermediate Code 398–407

- Or, read the Dragon book:

  Postfix notation 33

  DAGs & Value Number Alg. 290–293

  Intermediate Languages 463–468, 470–473

34 Summary

- We use an intermediate representation of the program in order to isolate the back-end from the front-end.
- A high-level intermediate form makes the compiler retargetable (easily changed to generate code for another machine). It also makes code-generation difficult.
- A low-level intermediate form make code-generation easy, but our compiler becomes more closely tied to a particular architecture.
- A basic block is a *straight-line* piece of code, with no jumps in or out except at the beginning and end.

35

Homework

36 Homework I

- Translate the program below into quadruples, triples, and a 'sequence of expression trees.'

```
PROGRAM P;
VAR X : INTEGER; VAR Y : REAL;
BEGIN
   X := 1; Y := 5.5;
   WHILE X < 10 DO
      Y := Y + FLOAT(X);
      X := X + 1;
      IF Y > 10 THEN Y := Y * 2.2; ENDIF;
   ENDDO;
END.
```

37 Homework II

Consider the following expression:

$$((x * 4) + y) * (y + (4 * x)) + (z * (4 * x))$$

1. Show how the value-number algorithm builds a DAG from the expression (remember that $+$ and $*$ are commutative).
2. Show the resulting DAG when stored in an array.
3. Translate the expression to postfix form.
4. Translate the expression to indirect triple form.

38 Homework III

- Translate the program below into quadruples, triples, and a 'sequence of expression trees.'

```
PROGRAM P;
VAR X : INTEGER; VAR Y : REAL;
BEGIN
   X := 1; Y := 5.5;
   WHILE X < 10 DO
      Y := Y + FLOAT(X);
      X := X + 1;
      IF Y > 10 THEN Y := Y * 2.2; ENDIF;
   ENDDO;
END.
```

39

Tree Code Example

40 Tree Code

`record ProcBegin (Name,Level,VarSize,FormalSize,LineNo)` The beginning of each procedure is marked by a `ProcBegin` instruction.

Attributes: `Name` is the name of the procedure. `Level` is the declaration level of the procedure. `VarSize` is the amount of local data (in bytes) required for the procedure. `FormalSize` is the size of the actual parameters passed to the procedure.

Children: None.

`record ProcEnd (Name,Level,VarSize,FormalSize,LineNo)` Same attributes as `ProcBegin`

41 Tree Code...

`record VarDecl (Name,Type,Level,Offset,Size,LineNo)` Each *global* variable is given an explicit declaration in the intermediate code.

Attributes: `Type` is one of the strings `"INT"`, `"CHAR"`, `"STRING"`, `"REAL"`, or `"STRUCT"`. `Offset` gives the relative address of the variable

Children: None.

`record Store (Type,Des,Expr,LineNo)` `Store` instructions are generated from assignment statements.

Attributes: `Type` is the type.

Children: `Des` is the subtree which computes the address (L-value) at which the new value should be stored. `Expr` is a subtree computing the R-value.

42 Tree Code...

`record VarRef (Type,Name,Level,LineNo)` `VarRef` nodes are used to refer to the **address** of a global or local variable.

Attributes: `Level` is the static nesting level at which the variable was declared.

Children: None.

`record Literal (Type,Value,LineNo)` `Literal` nodes represent integer, real, character, or string constants.

Attributes: Type is as for `VarDecl`, but there are no `"STRUCT"` constants.

Children: None.

43 Tree Code...

`record BinExpr (Op,Type,Left,Right,LineNo)` `BinExpr` instructions represent binary arithmetic.

Attributes: Type is either `"INT"` or `"REAL"`. `Op` is one of `"+"`, `"-"`, `"*"`, `"/"`, or `"%"`.

Children: `Left` and `Right` are subtrees holding the left and right hand sides of the arithmetic operator, respectively.

`record Load (Type,Des,LineNo)` `Load` instructions represent the loading of an R-value from an L-value.

Attributes: `Type` is the type of the loaded value.

Children: `Des` is the subtree which computes the address (L-value) whose R-value should be loaded.

44 Tree Code...

`record Branch (Op,Type,Left,Right,Label,LineNo)` Conditional branch, equivalent to `'IF Left Op Right THEN GOTO Label'`.

Attributes: Type is `"INT"`, `"CHAR"`, or `"REAL"`. `Op` is one of `"="`, `"<"`, `">"`, `"#"`, `"<="`, `">="`. `Label` is the number of the label to which we should jump.

Children: `Left` and `Right` are expression subtrees computing the arguments to the comparison operator.

`record Goto (Label,LineNo)` Unconditional branch.

Attributes: `Label` is the label number to which we should jump.

`record Label (Number,LineNo)` A program location to which a `Branch` or `Goto` may jump.

Attributes: `Number` is the label number.

45 Tree Code...

`record ProcCall (Name, Actuals, Level, LineNo)` Procedure call.

Attributes: `Name` is the name of the procedure. `Level` is the level at which the procedure is declared.

Children: `Actuals` is the list of actual parameters.

`record Field (BaseAddress,Name,Offset,LineNo)` Compute the address of a field within a record variable, i.e. `BaseAddress + Offset`.

Attributes: `Offset` is the offset of the field within the record variable.

Children: `BaseAddress` is a subtree computing the address of the record variable.

46 Tree Code...

`record Index (BaseAddress,IndexExpr,ElementSize,ElementCount,LineNo)` Compute the address of an array element, i.e. `BaseAddress + IndexExpr * ElementSize`. If $0 >$ `IndexExpr` $\geq$ `ElementCount` then a run-time error message should be generated.

Attributes: `ElementSize` is the size of the array elements. `ElementCount` is the length of the array.

Children: `BaseAddress` and `IndexExpr` are subtrees computing the address of the beginning of the array the number of the indexed array element.

47 Tree Code...

`record Actual (Type,Number,Offset,Expr,LineNo)` Pass the value of `Expr` as argument to a procedure call.

Attributes: If `Type="STRUCT"` then the formal is passed by reference, otherwise by value. `Number` is the argument number, `Offset` is the relative address within the activation record.

Children: `Expr` is the subtree computing the value (or address) of the actual.

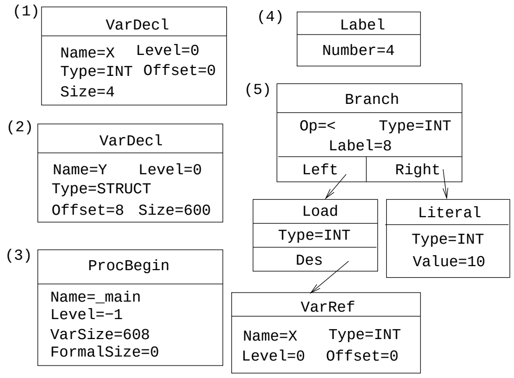
`record FormalRef(Type,Name,Level,Offset,Number,LineNo)` Reference to the value of a formal parameter. Similar to `VarRef`.

Attributes: `Level` is the static nesting level at which the formal is declared. If `Type="STRUCT"` then the formal is passed by reference, otherwise by value.

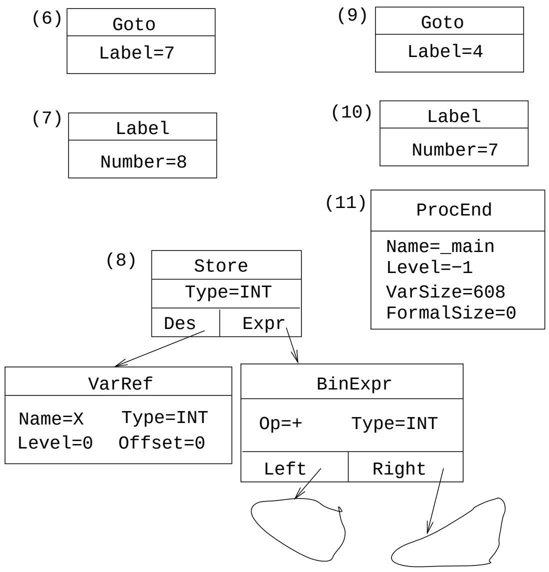
Children: None.

48 Example I (a)

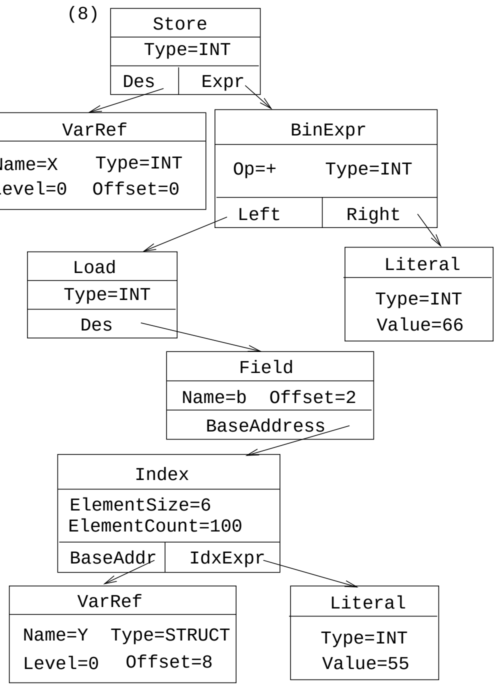
```
PROGRAM P;
TYPE R=RECORD[a;CHAR;b:INTEGER];
TYPE A=ARRAY 100 OF R;
VAR X:INTEGER;
VAR Y:A;
BEGIN
   WHILE X<10 DO
      X := Y[55].b + 66;
   ENDDO;
END.
```



49 Example I (b)



50 Example I (c)



51 Example I (d)

```
(1) [VarDecl]: Name='X':Level=0:Type=INT:Offset=0:Size=4
(2) [VarDecl]: Name='Y':Level=0:Type=STRUCT:Offset=8:Size=600
(3) [ProcBegin]: Name='_main':Level=-1:VarSize=608:FormalSize=0
(4) [Label]: Number=4
(5) [Branch]: Op='<':Type=INT:Label=8
       Left=
          [Load]: Type=INT
               Des=
                  [VarRef]: Name='X':Type=INT:Level=0:Offset=0
       Right=
          [Literal]: Type=INT:Value='10'
(6) [Goto]: Label=7
(7) [Label]: Number=8
```

52 Example I (e)

```
(8) [Store]: Type=INT
       Des=
          [VarRef]: Name='X':Type=INT:Level=0:Offset=0
       Expr=
          [BinExpr]: Op='+':Type=INT
            Left= [SEE NEXT SLIDE]
            Right=
               [Literal]: Type=INT:Value='66'
(9) [Goto]: Label=4
```

```
(10 [Label]: Number=7
(11 [ProcEnd]: Name='_main':Level=-1:VarSize=608:FormalSize=0
```

53 Example I (e)

```
Expr=
   [BinExpr]: Op='+':Type=INT
   Left=
      [Load]: Type=INT
          Des=
             [Field]: Name='b':Offset=2
                BaseAddress=
                   [Index]: ElementSize='6':ElementCount=100
                       BaseAddress=
                          [VarRef]: Name='Y':Type=STRUCT:
                                    Level=0:Offset=8
                       IndexExpr=
                          [Literal]: Type=INT:Value='55'
```