CSc 453

Compilers and Systems Software

13 : Intermediate Code I

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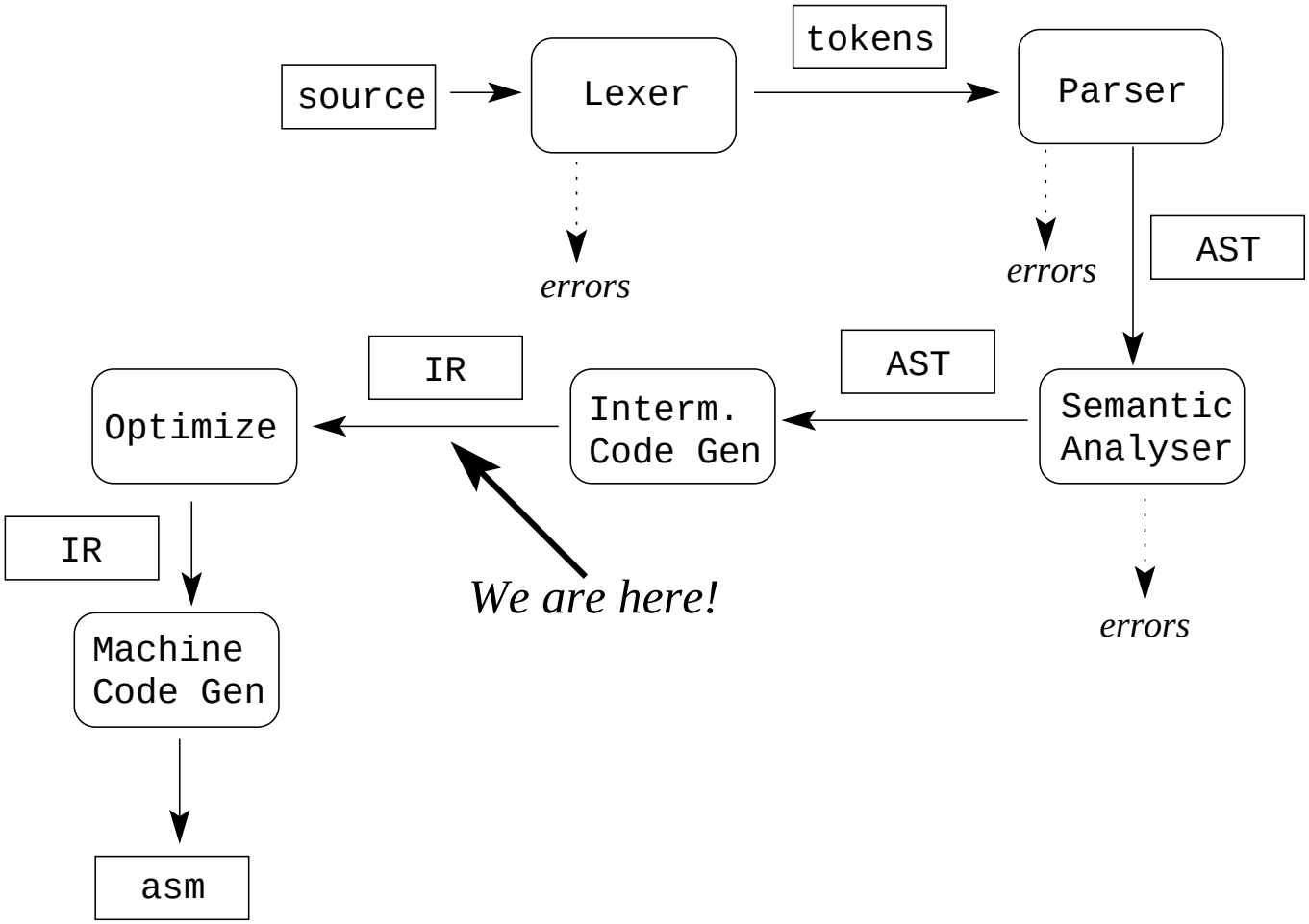
Introduction

Compiler Phases



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.

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.

Intermediate Code

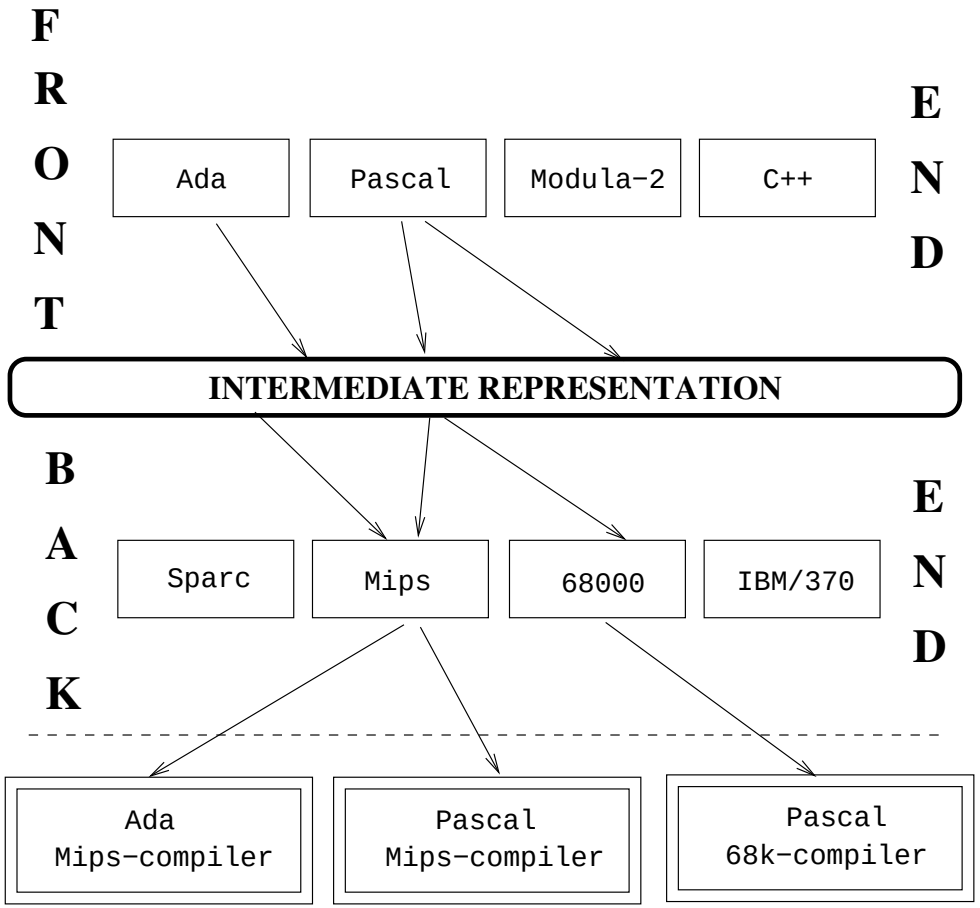
Advantages of:

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.

Mix-and-Match Compilers



UNCOL

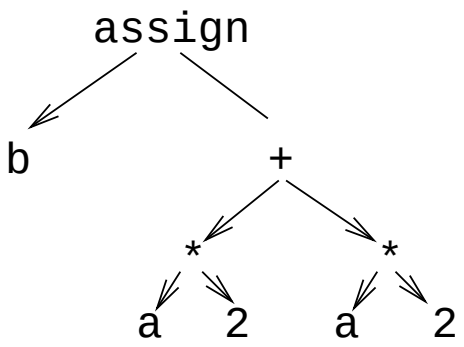
- A representation which is both architecture and language independent is known as an **UNCOL**, a **Universal Compiler Oriented Language**.
- UNCOL is the **holy grail** of compiler design – many have search for it, but no-one has found it. Problems:
  1. Programming language semantics differ from one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

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.

Postfix Notation

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.

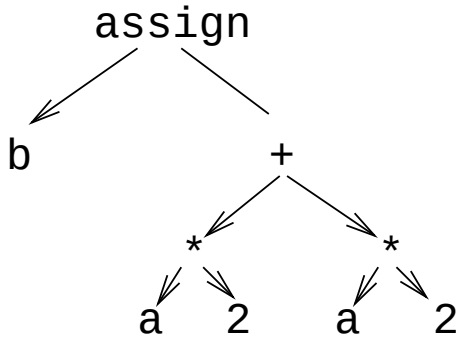
Tree & DAG Representations

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.

Tree & DAG Representation...

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

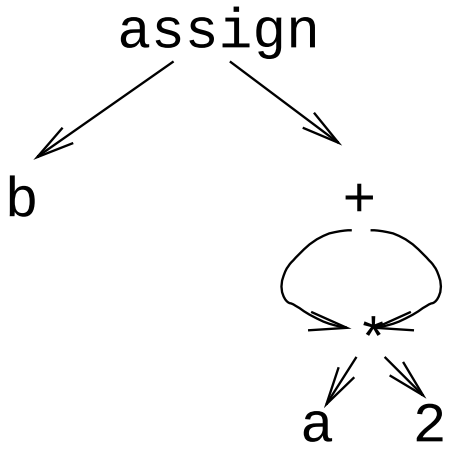


Linearized Tree

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

Tree & DAG Representation...

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

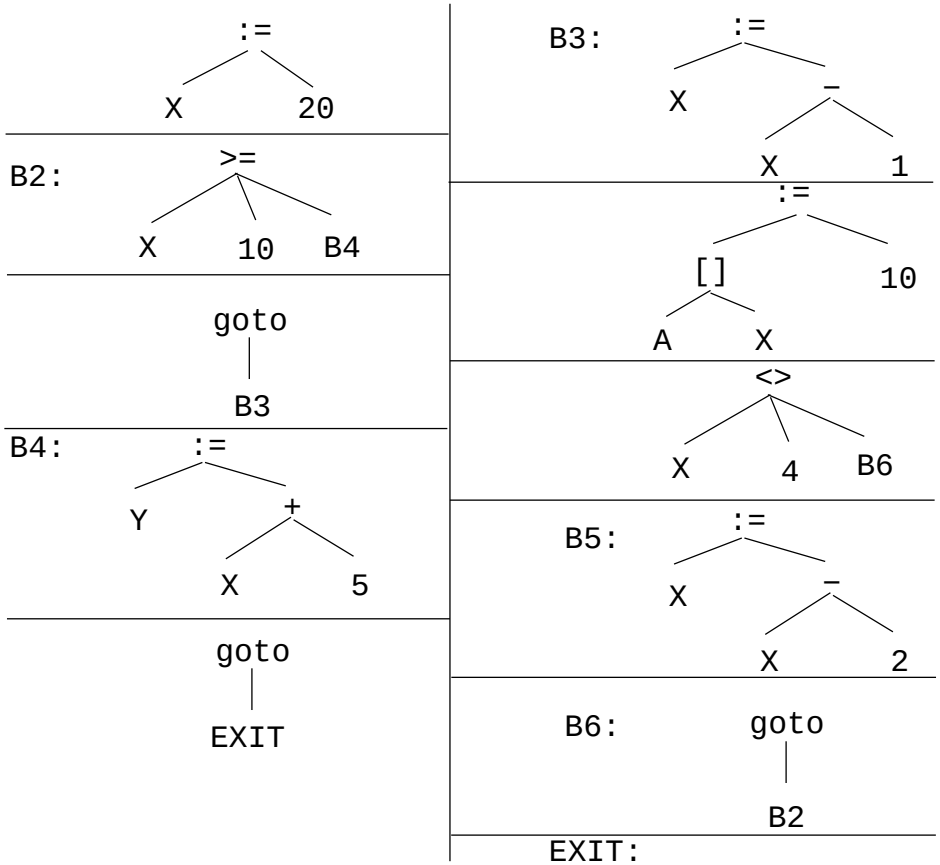


Linearized Dag

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

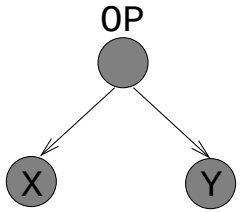
Sequence of Expression Trees

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



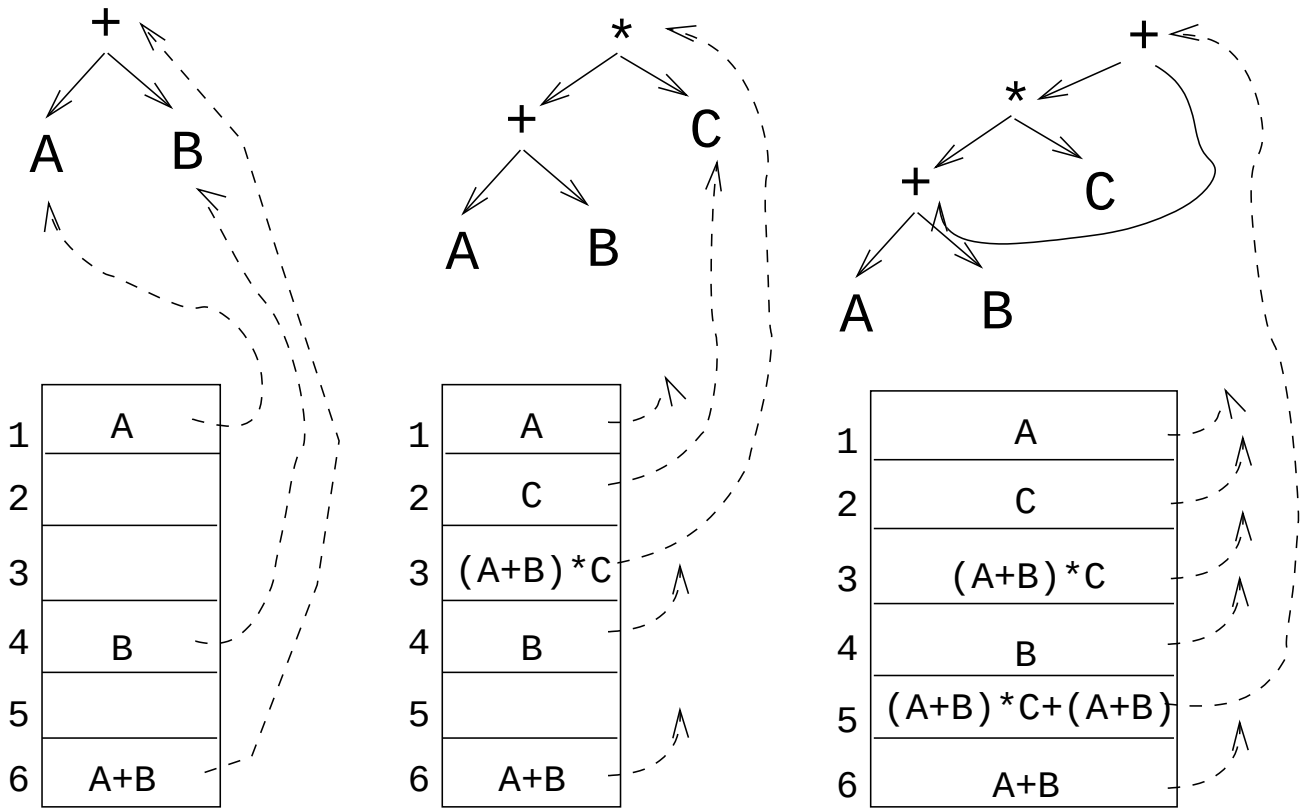
Building DAGs...

- 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;
```

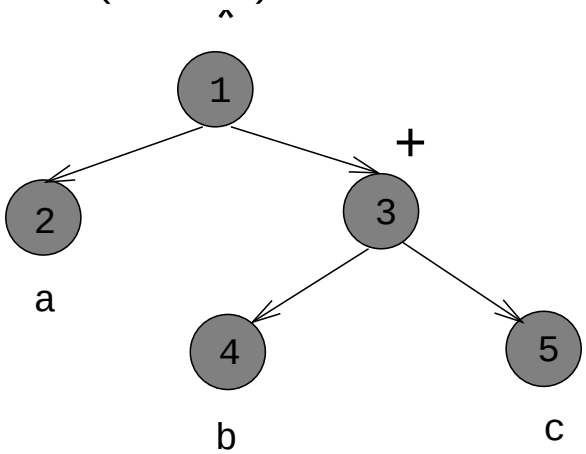
Building DAGs – Example



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
```

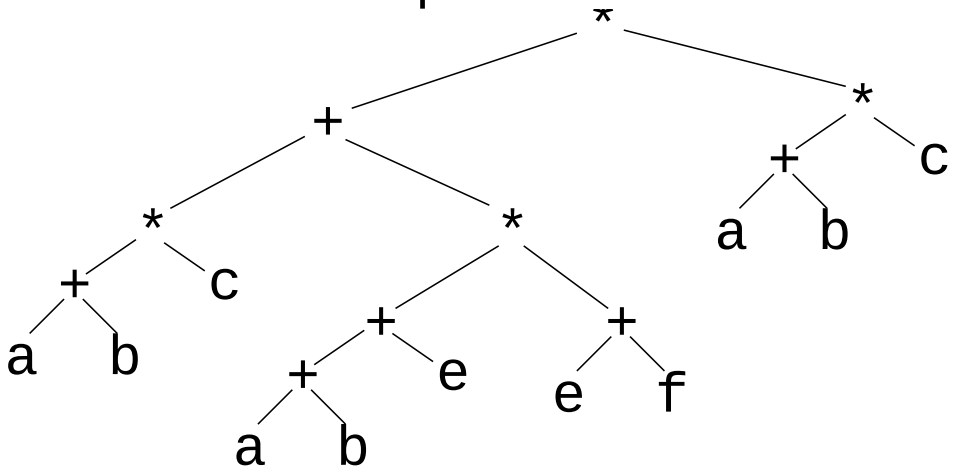
- Can we generate better code from a DAG than a tree?

Building DAGs...

Example Expression:

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

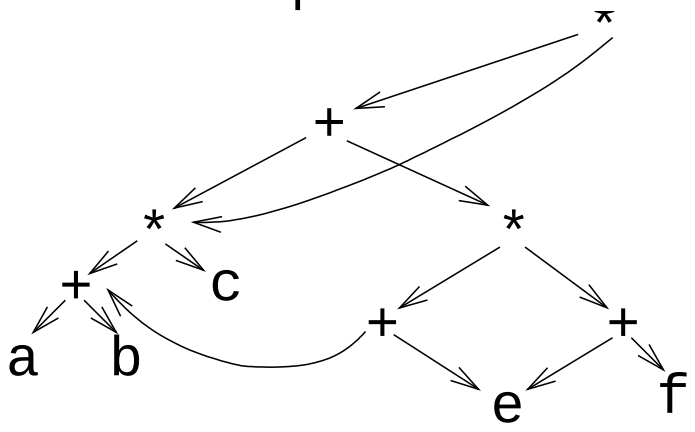
Tree Representation:



Building DAGs...

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

DAG Representation:



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
```

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) -
LOAD  f, r0          ; f
ADD   r0, r4, r0     ; f + e
MUL   r1, r0, r0
ADD   r0, r3, r0
MUL   r0, r3, r0
```

Tuple Codes

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:

$\boxed{x := y \text{ op } z}$	Binary arithmetic or logical operation. Example: `Mul`, `And`.
$\boxed{x := \text{op } y}$	Unary arithmetic, conversion, or logical operation. Example: `Abs`, `UnaryMinus`, `Float`.
$\boxed{x := y}$	Copy statement.

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`.

Three-Address Code...

$\boxed{x := \text{ADDR}(y)}$ Address assignment. Set `x` to the address of `y`.

$\boxed{x := \text{IND}(y)}$ Indirect assignment. Set `x` to the value stored at the address in `y`.

$\boxed{\text{IND}(x) := y}$ Indirect assignment. Set the memory location pointed to by `x` to the value held by `y`.

Three-Address Code...

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

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

$$\begin{array}{llll}
\mathtt{t}_1 & := & \mathtt{a} \quad \textbf{mul} & 2 \\
\mathtt{t}_2 & := & \mathtt{a} \quad \textbf{mul} & 2 \\
\mathtt{t}_3 & := & \mathtt{t}_1 \quad \textbf{add} & \mathtt{t}_2 \\
\mathtt{b} & := & \mathtt{t}_3 &
\end{array}$$

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.

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.

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

Nr	Res	Op	Arg$_1$	Arg$_2$
(1)	$\mathtt{t}_1$	**mul**	a	2
(2)	$\mathtt{t}_2$	**mul**	a	2
(3)	$\mathtt{t}_3$	**add**	$\mathtt{t}_1$	$\mathtt{t}_2$
(4)	b	**assign**	$\mathtt{t}_3$	

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.

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

Nr	Op	Arg_1	Arg_2
(1)	**mul**	a	2
(2)	**mul**	a	2
(3)	**add**	(1)	(2)
(4)	**assign**	b	(3)

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.

Summary

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

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.

Homework

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.
```

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.

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.
```

Tree Code Example

`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`

`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.

`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.

`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.

`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.

`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.

```
record Index (BaseAddress,IndexExpr,ElementSize,ElementCou
```

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.

`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.

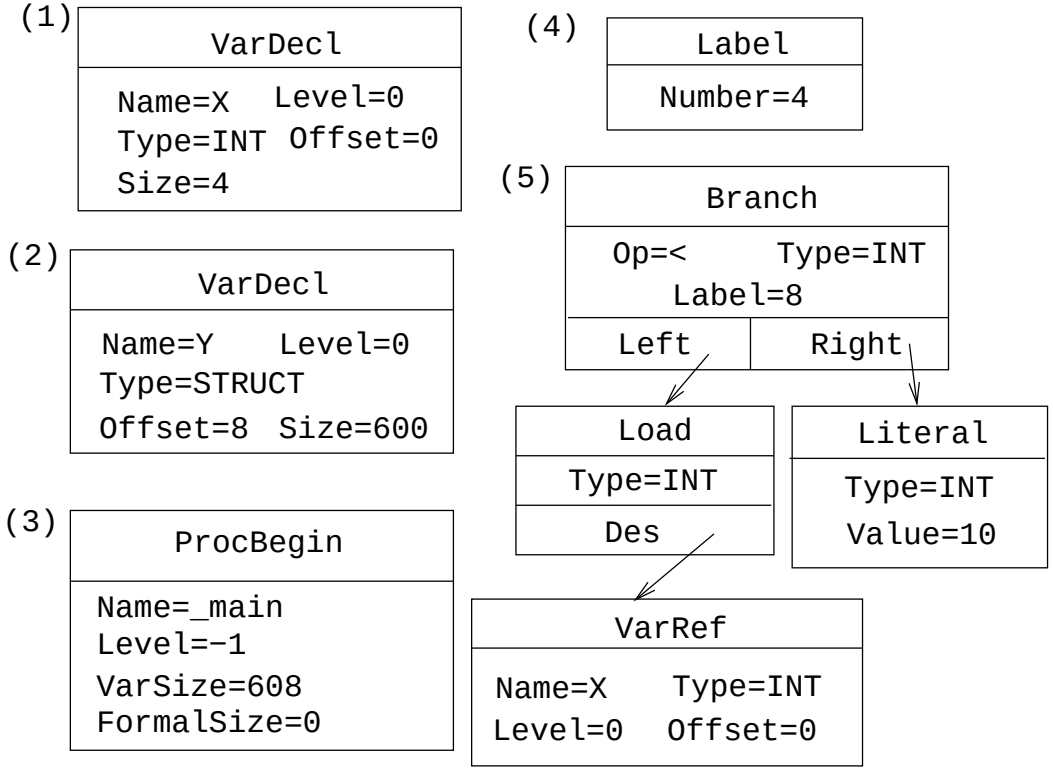
`record FormalRef(Type,Name,Level,Offset,Number,LineNo)`

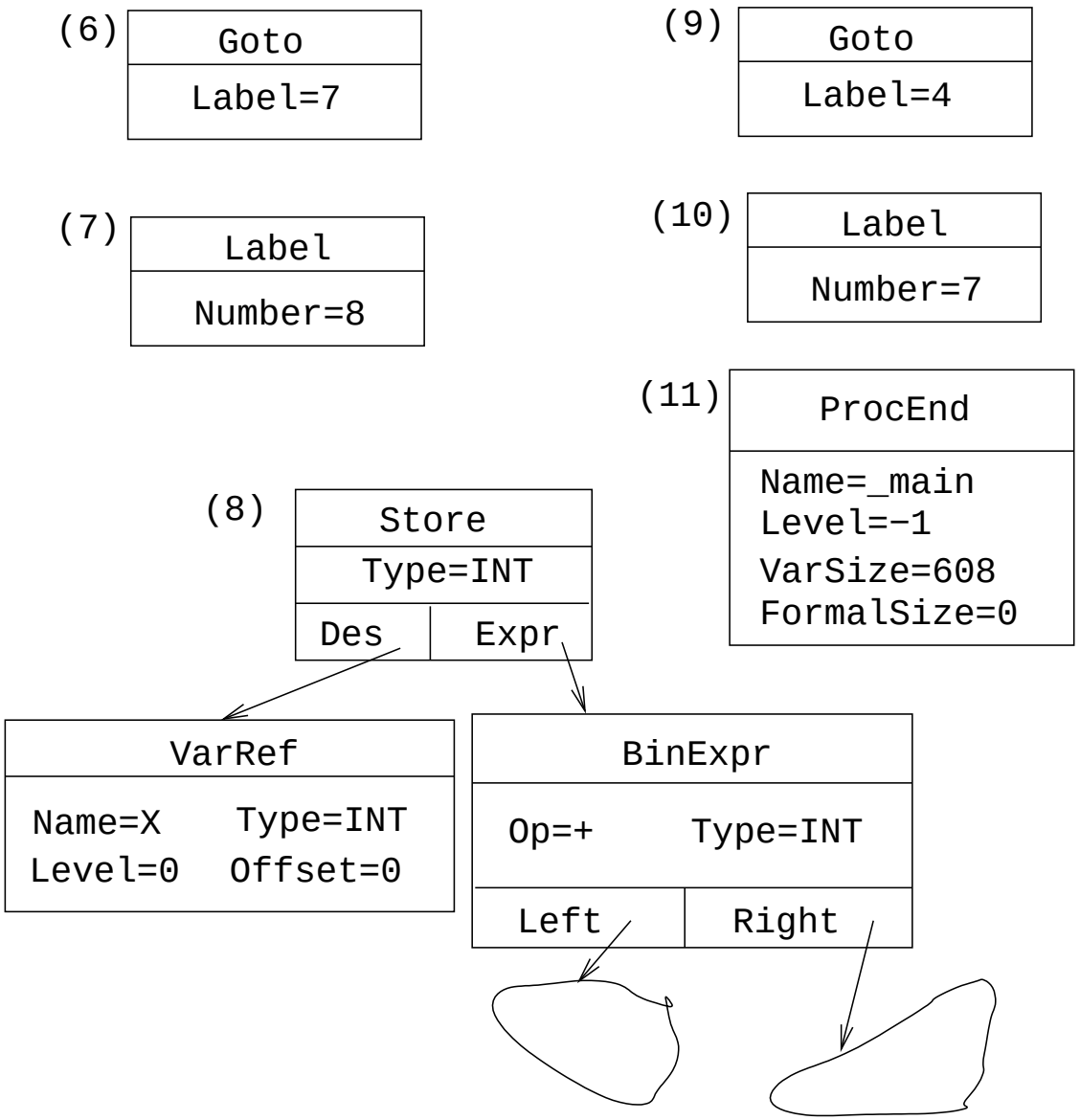
Reference to the value of a formal parameter. Similar to `VarRef`.

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.

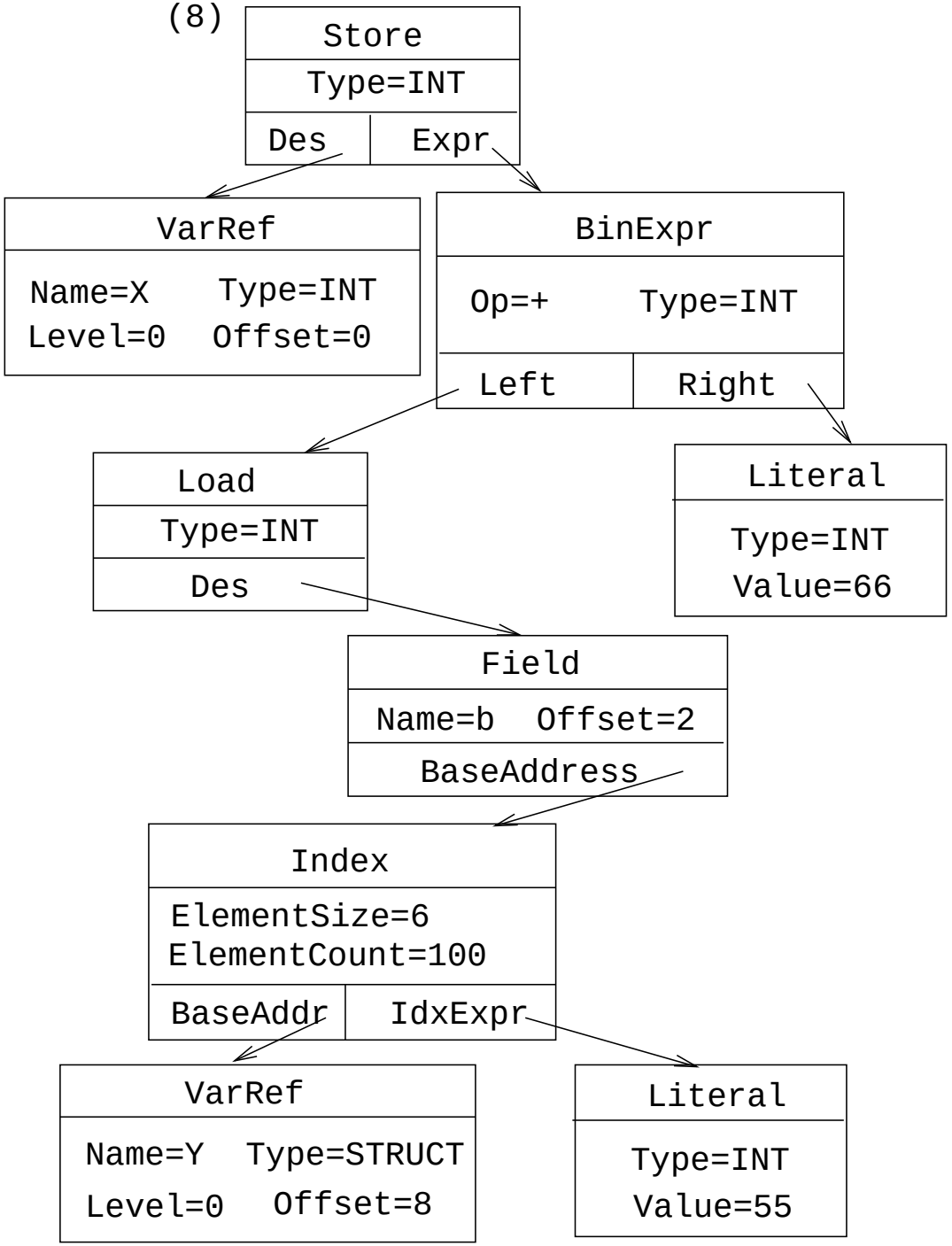
Children: None.

```
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.
```




(6)
Goto
Label=7
(9)
Goto
Label=4
(7)
Label
Number=8
(10)
Label
Number=7
(11)
ProcEnd
Name=_main
Level=−1
VarSize=608
FormalSize=0
(8)
Store
Type=INT
Des
Expr
VarRef
Name=X
Type=INT
Level=0
Offset=0
BinExpr
Op=+
Type=INT
Left
Right

(8)


Store
Type=INT
Des
Expr
VarRef
Name=X
Type=INT
Level=0
Offset=0
BinExpr
Op=+
Type=INT
Left
Right
Load
Type=INT
Des
Literal
Type=INT
Value=66
Field
Name=b
Offset=2
BaseAddress
Index
ElementSize=6
ElementCount=100
BaseAddr
IdxExpr
VarRef
Name=Y
Type=STRUCT
Level=0
Offset=8
Literal
Type=INT
Value=55

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

```
(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
```

```
Expr=
   [BinExpr]: Op='+':Type=INT
   Left=
      [Load]: Type=INT
         Des=
            [Field]: Name='b':Offset=2
               BaseAddress=
                  [Index]: ElementSize='6':ElementCount=1
                     BaseAddress=
                        [VarRef]: Name='Y':Type=STRUCT:
                                  Level=0:Offset=8
                     IndexExpr=
                        [Literal]: Type=INT:Value='55'
```