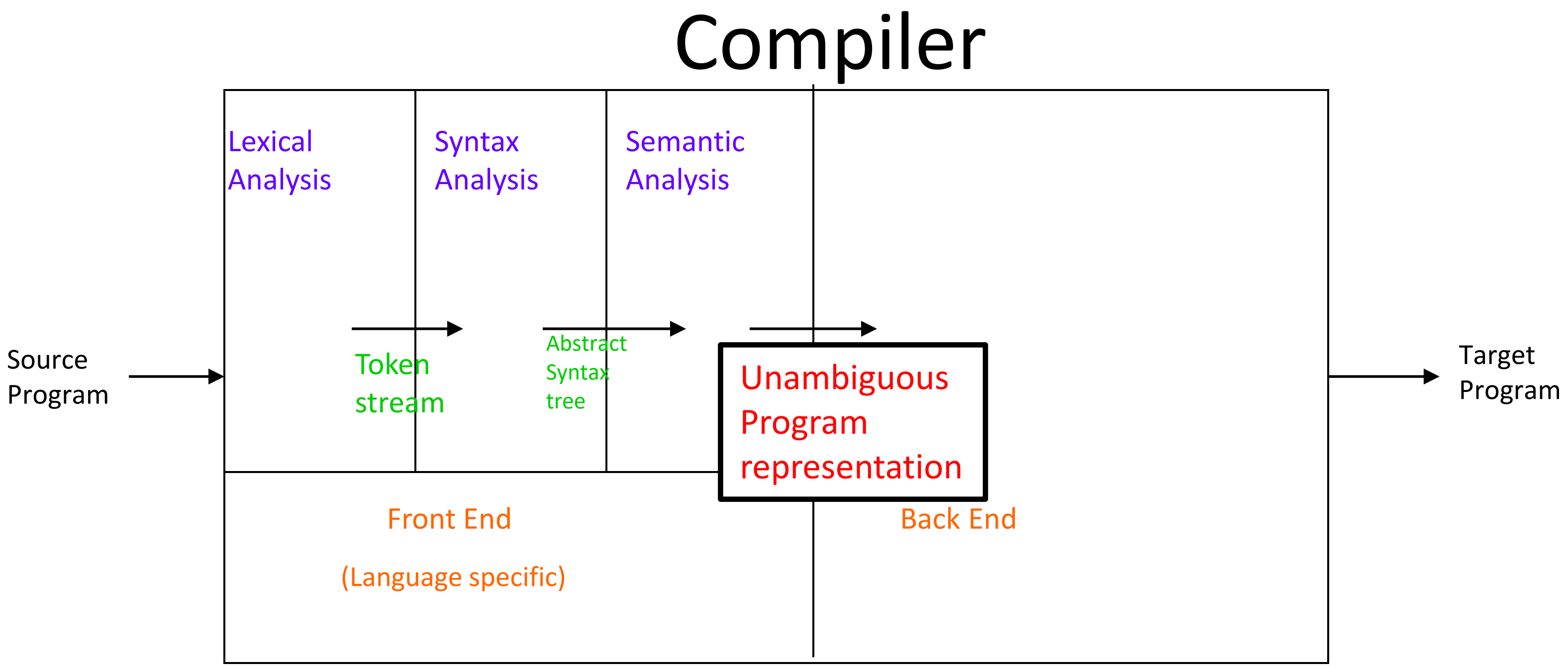
Compiler Design

I.R. and Symbol Tables

Amey Karkare
Department of Computer Science and Engineering
IIT Kanpur
karkare@iitk.ac.in

Principles of Compiler Design

Intermediate Representation



Intermediate Representation Design

- More of a wizardry rather than science
- Compiler commonly use 2-3 IRs
- HIR (high level IR) preserves loop structure and array bounds
- MIR (medium level IR) reflects range of features in a set of source languages
  - language independent
  - good for code generation for one or more architectures
  - appropriate for most optimizations
- LIR (low level IR) low level similar to the machines

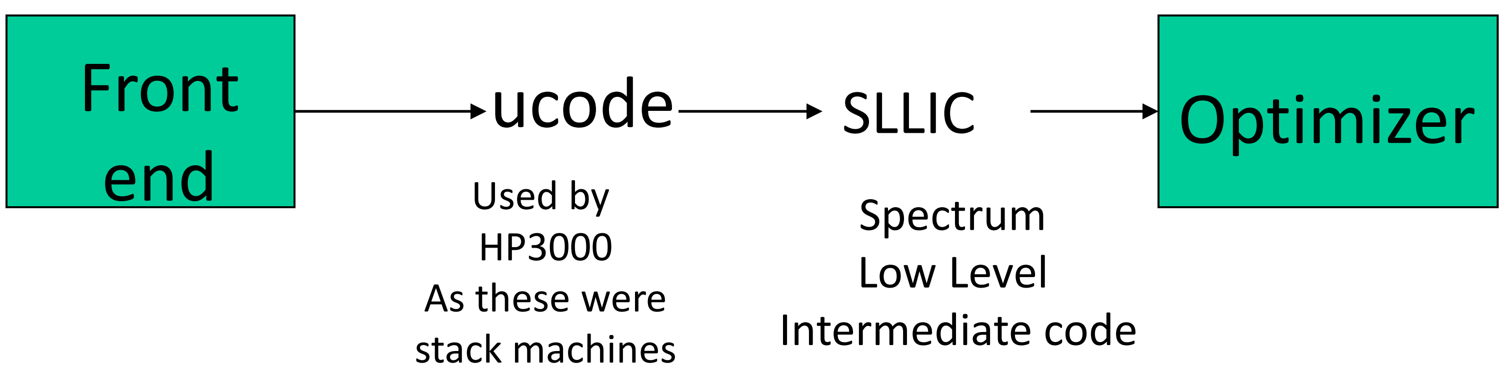
- Compiler writers have tried to define Universal IRs and have failed. (UNCOL in 1958)
- There is no standard Intermediate Representation. IR is a step in expressing a source program so that machine understands it
- As the translation takes place, IR is repeatedly analyzed and transformed
- Compiler users want analysis and translation to be fast and correct
- Compiler writers want optimizations to be simple to write, easy to understand and easy to extend
- IR should be simple and light weight while allowing easy expression of optimizations and transformations.

Issues in IR Design

- source language and target language
- porting cost or reuse of existing design
- whether appropriate for optimizations
- U-code IR used on PA-RISC and Mips. Suitable for expression evaluation on stacks but less suited for load-store architectures
- both compilers translate U-code to another form
  - HP translates to very low level representation
  - Mips translates to MIR and translates back to U-code for code generator

Issues in new IR Design

- how much machine dependent
- expressiveness: how many languages are covered
- appropriateness for code optimization
- appropriateness for code generation
- Use more than one IR (like in PA-RISC)



Issues in new IR Design …

- Use more than one IR for more than one optimization
- represent subscripts by list of subscripts: suitable for dependence analysis
- make addresses explicit in linearized form:
  - suitable for constant folding, strength reduction, loop invariant code motion, other basic optimizations

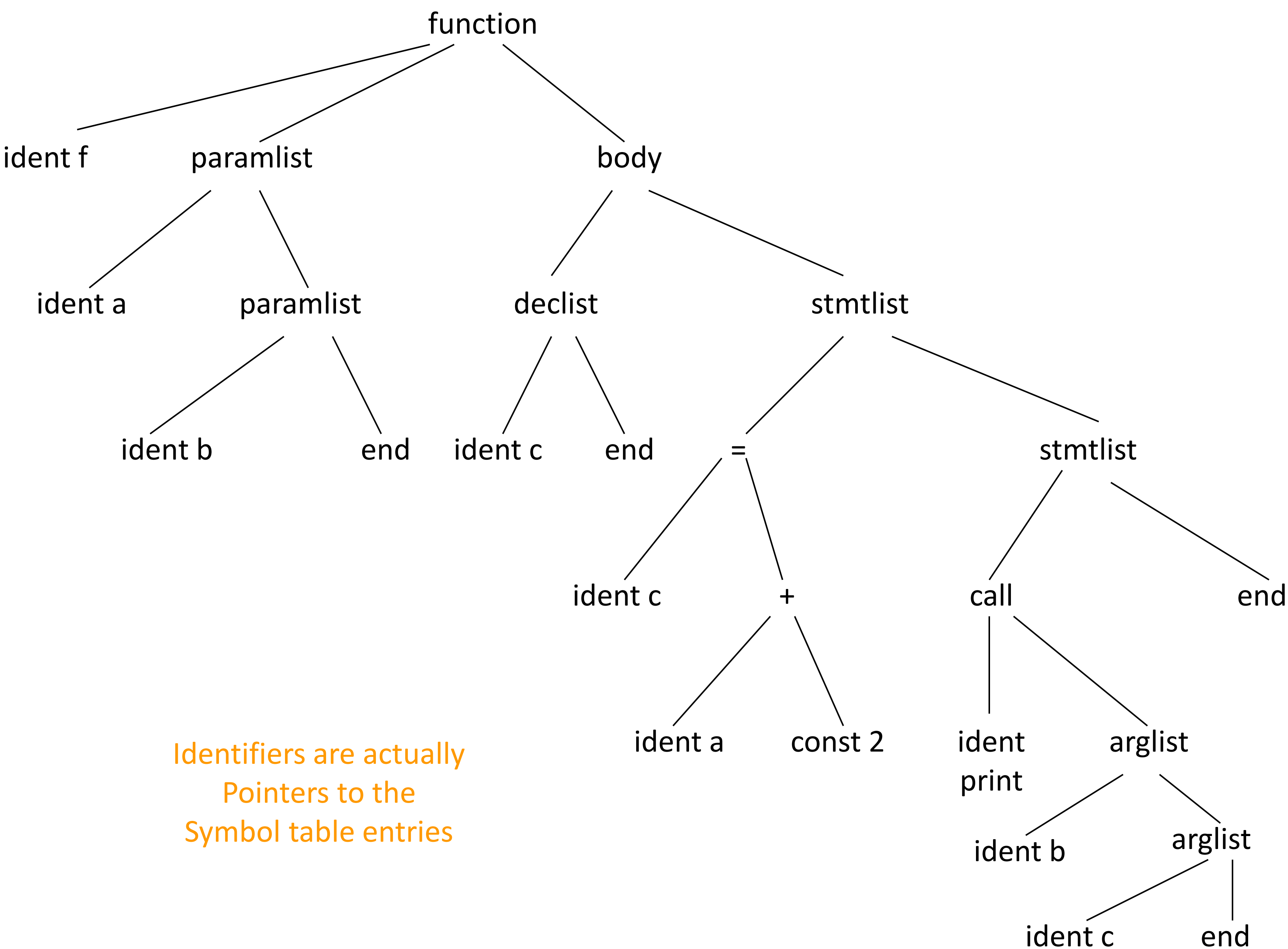
float a[10][20];
use a[i][j+2]

HIR	MIR	LIR
t1←a[i,j+2]	t1← j+2	r1← [fp-4]
	t2← i*20	r2← r1+2
	t3← t1+t2	r3← [fp-8]
	t4← 4*t3	r4← r3*20
	t5← addr a	r5← r4+r2
	t6← t4+t5	r6← 4*r5
	t7←*t6	r7←fp-216
		f1← [r7+r6]

High level IR

```
int f(int a, int b) {
    int c;
    c = a + 2;
    print(b, c);
}
```

- Abstract syntax tree
  - keeps enough information to reconstruct source form
  - keeps information about symbol table



Identifiers are actually
Pointers to the
Symbol table entries

- Medium level IR
  - reflects range of features in a set of source languages
  - language independent
  - good for code generation for a number of architectures
  - appropriate for most of the optimizations
  - normally three address code
- Low level IR
  - corresponds one to one to target machine instructions
  - architecture dependent
- Multi-level IR
  - has features of MIR and LIR
  - may also have some features of HIR

Three address code

- A linearized representation of a syntax tree where explicit names correspond to the interior nodes of the graph
- Sequence of statements of the general form

$$X := Y \text{ op } Z$$

  - X, Y or Z are names, constants or compiler generated temporaries
  - op stands for any operator such as a fixed- or floating-point arithmetic operator, or a logical operator
  - Extensions to handle arrays, function call

Three address code …

- Only one operator on the right-hand side is allowed
- Source expression like x + y * z might be translated into

  $t_1 := y * z$

  $t_2 := x + t_1$

  where t_1 and t_2 are compiler generated temporary names
- Unraveling of complicated arithmetic expressions and of control flow makes 3-address code desirable for code generation and optimization
- The use of names for intermediate values allows 3-address code to be easily rearranged

Three address instructions

- Assignment
  - x = y op z
  - x = op y
  - x = y
- Jump
  - goto L
  - if x relop y goto L
- Indexed assignment
  - x = y[i]
  - x[i] = y
- Function
  - param x
  - call p,n
  - return y
- Pointer
  - x = &y
  - x = *y
  - *x = y

Other IRs

- SSA: Single Static Assignment
- RTL: Register transfer language
- Stack machines: P-code
- CFG: Control Flow Graph
- Dominator Trees
- DJ-graph: dominator tree augmented with join edges
- PDG: Program Dependence Graph
- VDG: Value Dependence Graph
- GURRR: Global unified resource requirement representation. Combines PDG with resource requirements
- Java intermediate bytecodes
- The list goes on ......

Symbol Table

- Compiler uses symbol table to keep track of scope and binding information about names
- changes to table occur
  - if a new name is discovered
  - if new information about an existing name is discovered
- Symbol table must have mechanism to:
  - add new entries
  - find existing information efficiently

Symbol Table

- Two common mechanism:
  - linear lists
    - simple to implement, poor performance
  - hash tables
    - greater programming/space overhead, good performance
- Compiler should be able to grow symbol table dynamically
  - If size is fixed, it must be large enough for the largest program

Data Structures for Symbol Table

- List data structure
  - simplest to implement
  - use a single array to store names and information
  - search for a name is linear
  - entry and lookup are independent operations
  - cost of entry and search operations are very high, and lot of time goes into bookkeeping

- Hash table
  - The advantages are obvious

Symbol Table Entries

- each entry corresponds to a declaration of a name
- format need not be uniform because information depends upon the usage of the name
- each entry is a record consisting of consecutive words
  - If uniform records are desired, some entries may be kept outside the symbol table (e.g., variable length strings)

Symbol Table Entries

- information is entered into symbol table at various times
  - keywords are entered initially
  - identifier lexemes are entered by lexical analyzer
  - attribute values are filled in as information is available
- a name may denote several objects in the same block

  int x;

  struct x {float y, z; }

  - lexical analyzer returns the name itself and not pointer to symbol table entry
  - record in the symbol table is created when role of the name becomes clear
  - in this case two symbol table entries will be created

- attributes of a name are entered in response to declarations
- labels are often identified by colon (:)
- syntax of procedure/function specifies that certain identifiers are formals
- there is a distinction between token id, lexeme and attributes of the names
  - it is difficult to work with lexemes
  - if there is modest upper bound on length then lexemes can be stored in symbol table
  - if limit is large store lexemes separately

Storage Allocation Information

- information about storage locations is kept in the symbol table
  - if target is assembly code, then assembler can take care of storage for various names
- compiler needs to generate data definitions to be appended to assembly code
- if target is machine code, then compiler does the allocation
- for names, whose storage is allocated at runtime, no storage allocation is done
  - compiler plans out activation records

Representing Scope Information

- entries are declarations of names
- when a lookup is done, entry for appropriate declaration must be returned
- scope rules determine which entry is appropriate
- maintain separate table for each scope
- symbol table for a procedure or scope is compile time equivalent an activation record
- information about non local is found by scanning symbol table for the enclosing procedures
- symbol table can be attached to abstract syntax of the procedure (integrated into intermediate representation)

- most closely nested scope rule can be implemented in data structures discussed
  - give each procedure a unique number
  - blocks must also be numbered
  - procedure number is part of all local declarations
  - name is represented as a pair of number and name
- names are entered in symbol table in the order they occur
- most closely nested rule can be created in terms of following operations:
  - lookup: find the most recently created entry
  - insert: make a new entry
  - delete: remove the most recently created entry

Symbol table structure

- Assign variables to storage classes that prescribe scope, visibility, and lifetime
  - scope rules prescribe the symbol table structure
  - scope: unit of static program structure with one or more variable declarations
  - scope may be nested
    - Pascal: procedures are scoping units
    - C: blocks, functions, files are scoping units
- Visibility, lifetimes, global variables
- Automatic or stack storage
- Static variables

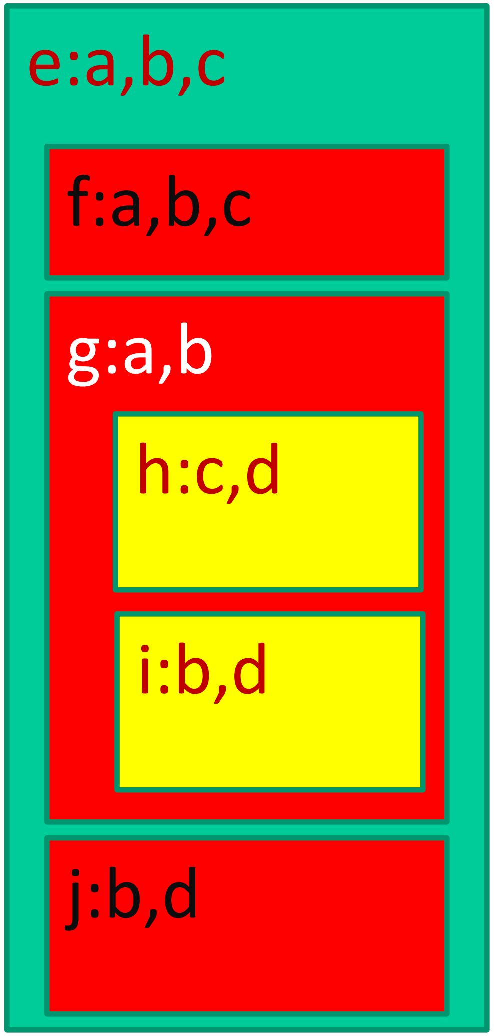
Symbol attributes and symbol table entries

- Symbols have associated attributes
- typical attributes are name, type, scope, size, addressing mode etc.
- a symbol table entry collects together attributes such that they can be easily set and retrieved
- example of typical names in symbol table

Name	Type
name	character string
class	enumeration
size	integer
type	enumeration

Nesting structure of an example Pascal program

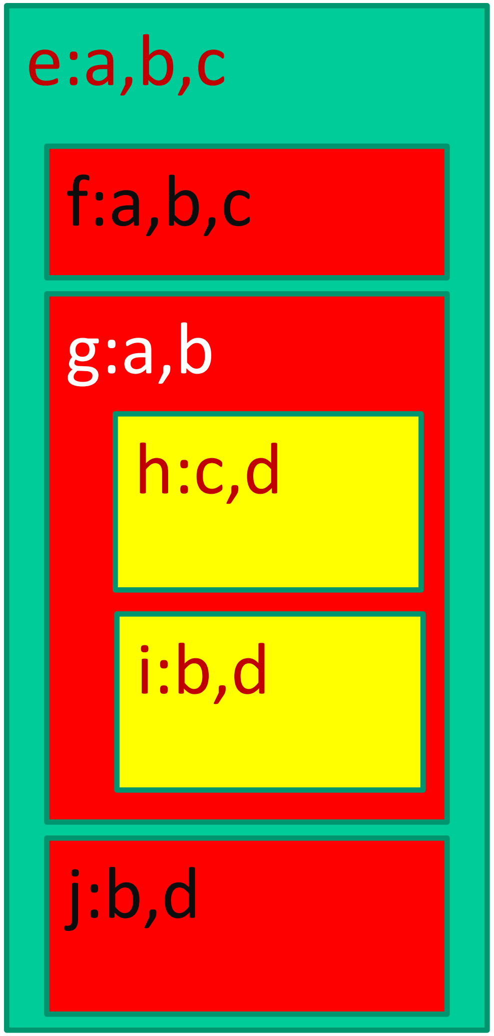
```
program e;
  var a, b, c: integer;

  procedure f;
    var a, b, c: integer;
    begin
      a := b+c
    end;

  procedure g;
    var a, b: integer;

      procedure h;
        var c, d: integer;
        begin
          c := a+d
        end;

      procedure i;
        var b, d: integer;
        begin
          b:= a+c
        end;
    begin
     ....
    end
  procedure j;
    var b, d: integer;
    begin
      b := a+d
    end;

begin
  a := b+c
end.
```

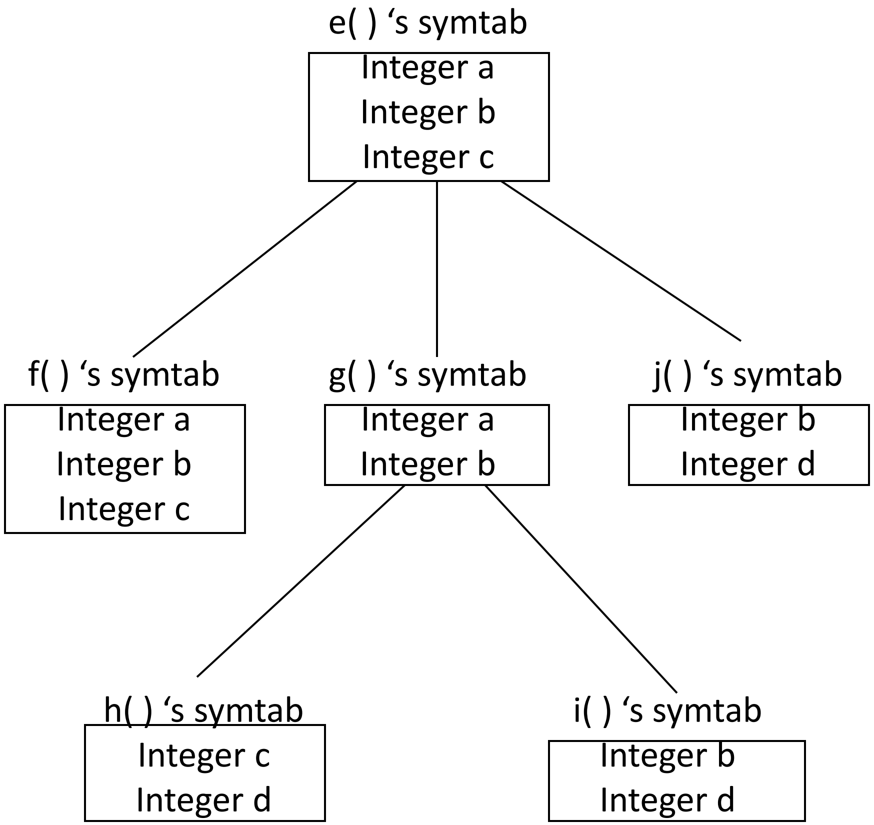


Global Symbol table structure

- scope and visibility rules determine the structure of global symbol table
- for Algol class of languages scoping rules structure the symbol table as tree of local tables
  - global scope as root
  - tables for nested scope as children of the table for the scope they are nested in

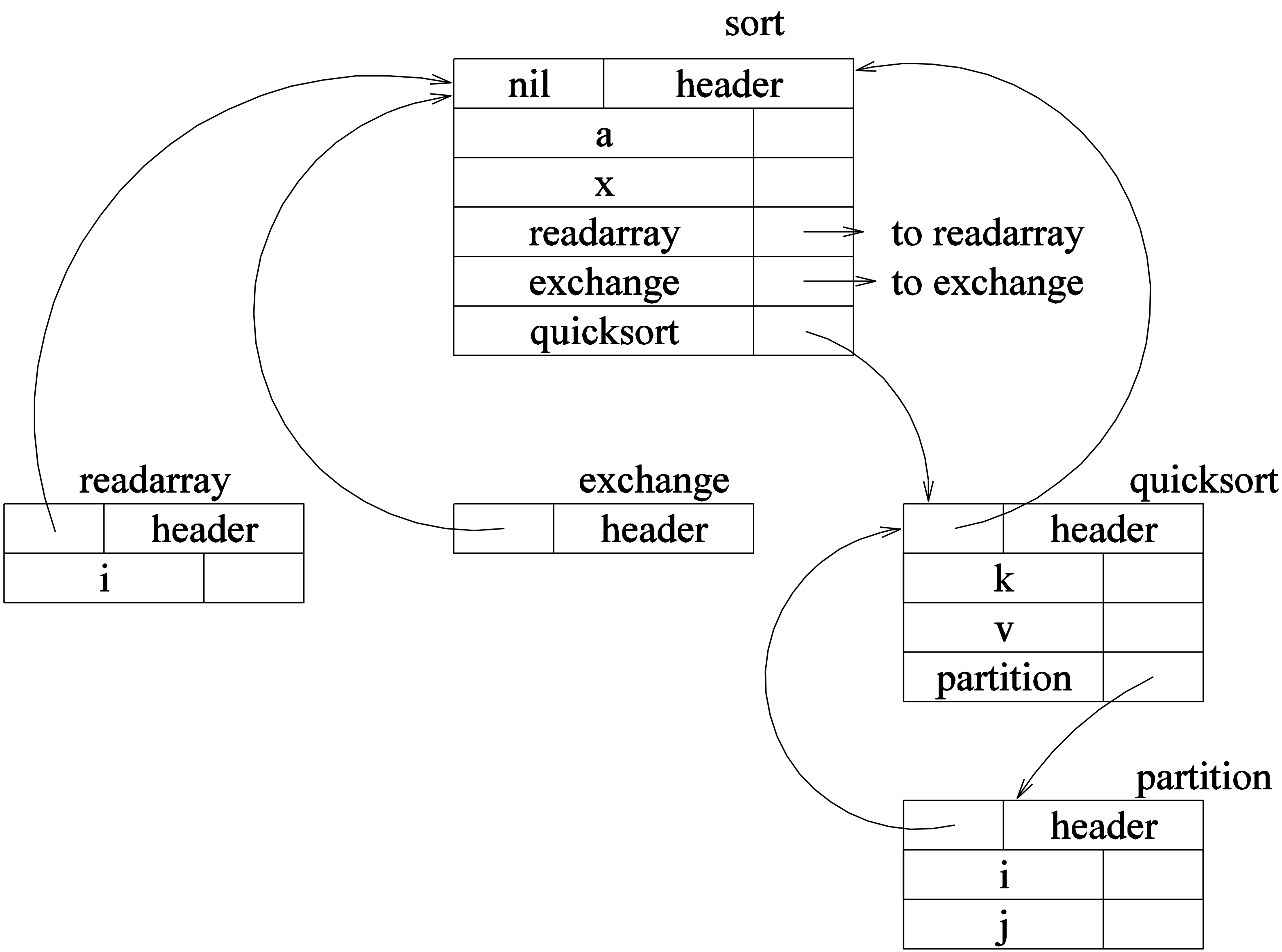
Global Symbol table structure





Example

```
program sort;
  var a : array[0..10] of integer;

    procedure readarray;
       var i :integer;
            :
    procedure exchange(i, j
                    :integer)
            :

procedure quicksort (m, n :integer);
       var i :integer;
     function partition (y, z
                    :integer) :integer;
          var i, j, x, v :integer;
               :
       i:= partition (m,n);
       quicksort (m,i-1);
       quicksort(i+1, n);
               :
begin{main}
     readarray;
     quicksort(1,9)
end.
```


sort
nil
header
a
x
readarray
exchange
quicksort
to readarray
to exchange
readarray
header
i
exchange
header
quicksort
header
k
v
partition
partition
header
i
j

Storage binding and symbolic registers

- Translates variable names into addresses
- This process must occur before or during code generation
- each variable is assigned an address or addressing method
- each variable is assigned an offset with respect to base which changes with every invocation
- variables fall in four classes: global, global static, stack, local (non-stack) static

- global/static: fixed relocatable address or offset with respect to base as global pointer
- stack variable: offset from stack/frame pointer
- allocate stack/global in registers
- registers are not indexable, therefore, arrays cannot be in registers
- assign symbolic registers to scalar variables
- used for graph coloring for global register allocation

a: global b: local c[0..9]: local

gp: global pointer fp: frame pointer

MIR	LIR	LIR
a ← a*2	r1 ← [gp+8]	s0 ← s0*2
	r2 ← r1*2	
	[gp+8] ← r2	
b ← a+c[1]	r3 ← [gp+8]	s1 ← [fp-28]
	r4 ← [fp-28]	s2 ← s0+s1
	r5 ← r3+r4	
	[fp-20]←r5	
	Names bound to locations	Names bound to symbolic registers

Local Variables in Frame

- assign to consecutive locations; allow enough space for each
  - may put word size object in half word boundaries
  - requires two half word loads
  - requires shift, or, and
- align on double word boundaries
  - wastes space
  - machine may allow small offsets

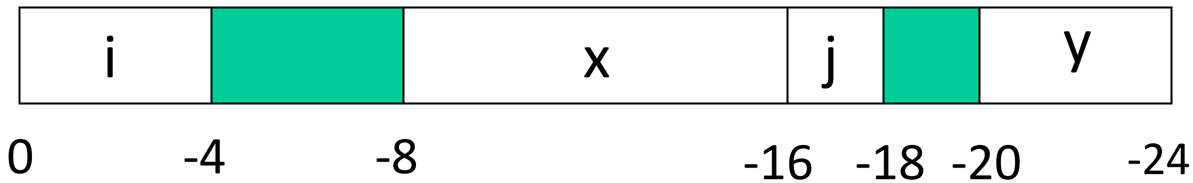
- sort variables by the alignment they need
- store largest variables first
  - automatically aligns all the variables
  - does not require padding
- store smallest variables first
  - requires more space (padding)
  - for large stack frame makes more variables accessible with small offsets

How to store large local data structures

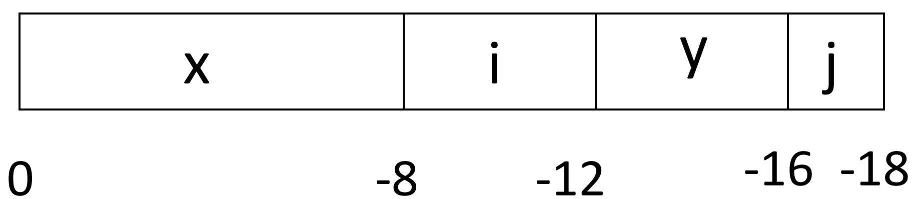
- Requires large space in local frames and therefore large offsets
- If large object is put near the boundary other objects require large offset either from fp (if put near beginning) or sp (if put near end)
- Allocate another base register to access large objects
- Allocate space in the middle or elsewhere; store pointer to these locations from at a small offset from fp
- Requires extra loads

```
int i;
double float x;
short int j;
float y;
```

Unsorted aligned



Sorted frames



Symbol Table Creation

Declarations

$P \rightarrow D$

$D \rightarrow D \; ; \; D$

$D \rightarrow id : T$

$T \rightarrow integer$

$T \rightarrow real$

Declarations

For each name create symbol table entry with information like type and relative address

P $\rightarrow$ {offset=0} D

D $\rightarrow$ D ; D

D $\rightarrow$ id : T

enter(id.name, T.type, offset);
offset = offset + T.width

T $\rightarrow$ integer

T.type = integer; T.width = 4

T $\rightarrow$ real

T.type = real; T.width = 8

Declarations …

$T \rightarrow$ array [num] of T_1

T.type = array(num.val, T_1.type)

T.width = num.val x T_1.width

$T \rightarrow \uparrow T_1$

T.type = pointer(T_1.type)

T.width = 4

Keeping track of local information

- when a nested procedure is seen, processing of declaration in enclosing procedure is temporarily suspended

- assume following language

  $P \rightarrow D$

  $D \rightarrow D\ ;D \mid id : T \mid proc\ id\ ;D\ ;\ S$

- a new symbol table is created when procedure declaration

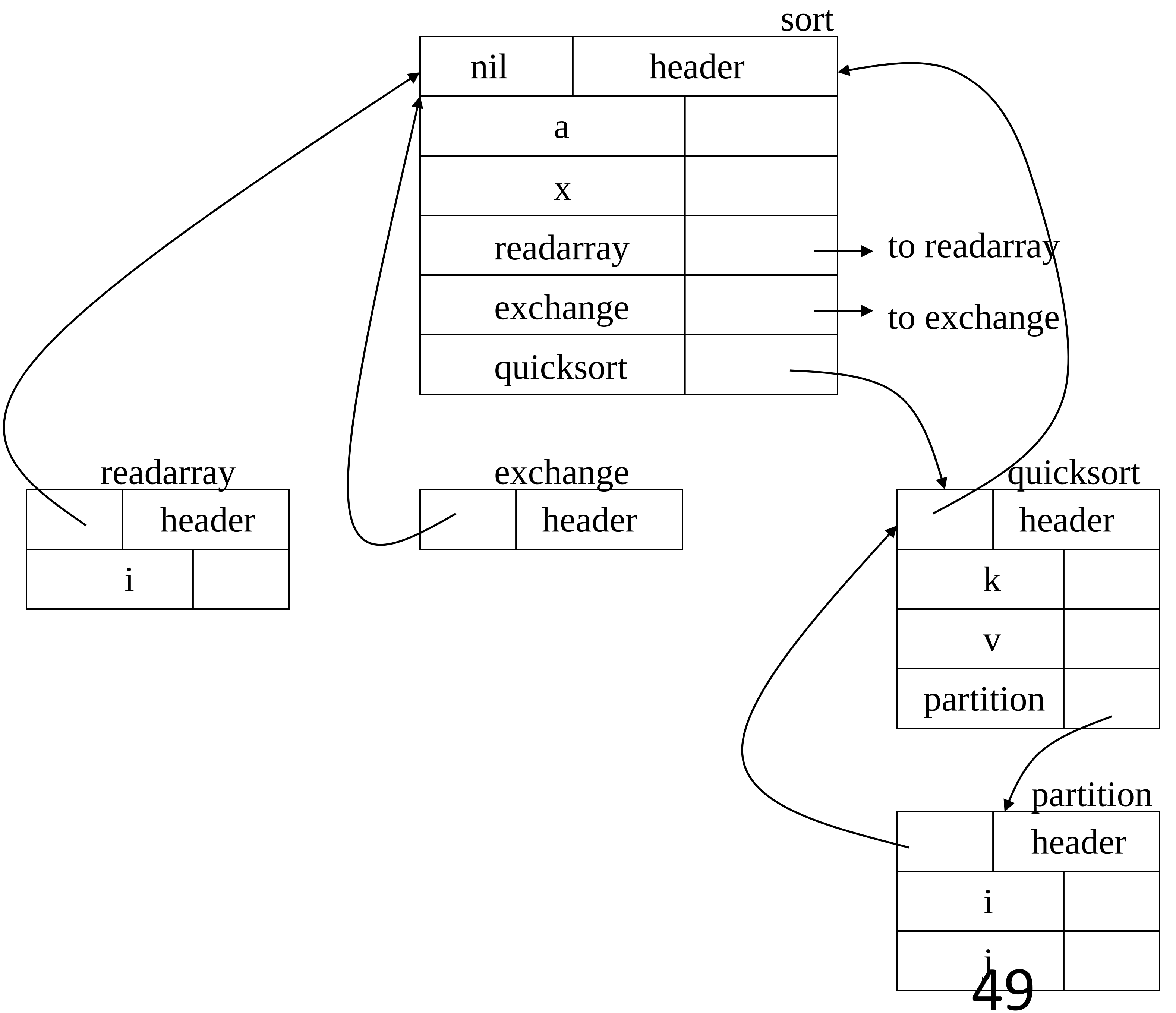
  $D \rightarrow proc\ id\ ;\ D_1\ ;\ S$ is seen

- entries for D_1 are created in the new symbol table

- the name represented by id is local to the enclosing procedure

Example

```
program sort;
    var a : array[1..n] of integer;
        x : integer;
    procedure readarray;
        var i : integer;
            ……
    procedure exchange(i,j:integers);
            ……
    procedure quicksort(m,n : integer);
        var k,v : integer;
            function partition(x,y:integer):integer;
                var i,j: integer;
                    ……
          ……
begin{main}
    ……
end.
```


sort
nil
header
a
x
readarray
exchange
quicksort
to readarray
to exchange
readarray
header
i
exchange
header
quicksort
header
k
v
partition
partition
header
i
j

Creating symbol table: Interface

- mktable (previous)

  create a new symbol table and return a pointer to the new table. The argument previous points to the enclosing procedure
- enter (table, name, type, offset)

  creates a new entry
- addwidth (table, width)

  records cumulative width of all the entries in a table
- enterproc (table, name, newtable)

  creates a new entry for procedure name. newtable points to the symbol table of the new procedure
- Maintain two stacks: (1) symbol tables and (2) offsets
- Standard stack operations: push, pop, top

Creating symbol table …

D $\rightarrow$ proc id;

{t = mktable(top(tblptr));
push(t, tblptr); push(0, offset)}

D_1; S

{t = top(tblptr);
addwidth(t, top(offset));
pop(tblptr); pop(offset);
enterproc(top(tblptr), id.name, t)}

D $\rightarrow$ id: T

{enter(top(tblptr), id.name, T.type, top(offset));
top(offset) = top (offset) + T.width}

Creating symbol table …

P →
{t=mktable(nil);
push(t,tblptr);
push(0,offset)}
D
{addwidth(top(tblptr),top(offset));
pop(tblptr); // save it somewhere!
pop(offset)}

D → D ; D

Field names in records

T → record

{t = mktable(nil);

push(t, tblptr); push(0, offset)}

D end

{T.type = record(top(tblptr));

T.width = top(offset);

pop(tblptr); pop(offset)}

Addressing Array Elements

- Arrays are stored in a block of consecutive locations
- assume width of each element is w
- ith element of array A begins in location

  base + (i - low) x w

  where base is relative address of A[low]
- the expression is equivalent to

  i x w + (base-low x w)

  ➔ i x w + const

2-dimensional array

- storage can be either row major or column major

- in case of 2-D array stored in row major form address of $A[i_1, i_2]$ can be calculated as

$$\text{base} + ((i_1 - low_1) \times n_2 + i_2 - low_2) \times w$$

where $n_2 = high_2 - low_2 + 1$

- rewriting the expression gives

$((i_1 \times n_2) + i_2) \times w + (\text{base} - ((low_1 \times n_2) + low_2) \times w)$

$\rightarrow ((i_1 \times n_2) + i_2) \times w + \text{constant}$

- this can be generalized for $A[i_1, i_2, \ldots, i_k]$

Example

- Let A be a 10x20 array, low indices at 1.

  therefore, $n_1 = 10$ and $n_2 = 20$

  and assume $w = 4$
- code to access A[y,z] is

  $t_1 = y * 20$

  $t_1 = t_1 + z$

  $t_2 = 4 * t_1$

  $t_3 = addr(A) - 84$ $\{((low_1 X n_2)+low_2)Xw)=(1*20+1)*4=84\}$

  $t_4 = t_2 + t_3$

  $x = t_4$