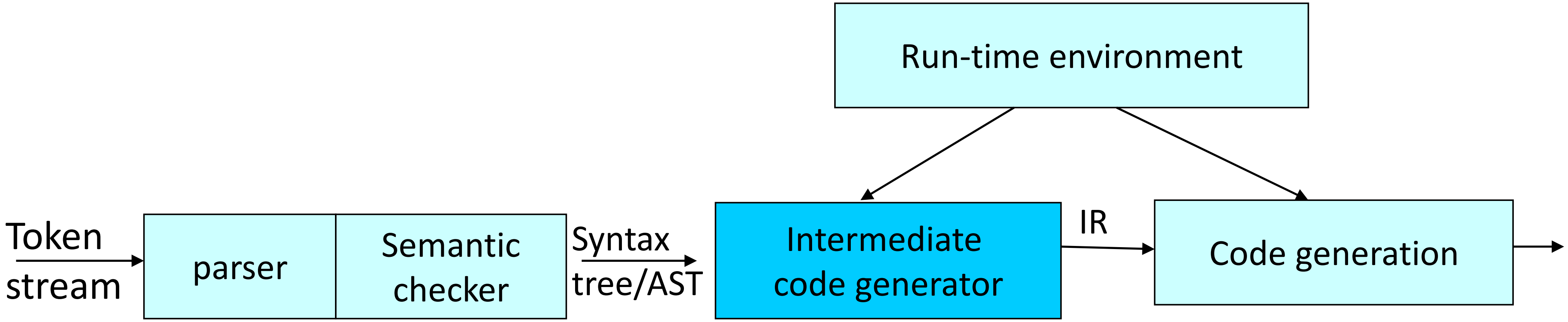
Intermediate Code Generation

- ***Intermediate codes*** are machine independent codes, but they are close to machine instructions
- The given program in a source language is converted to an **equivalent program** in an intermediate language by the intermediate code generator



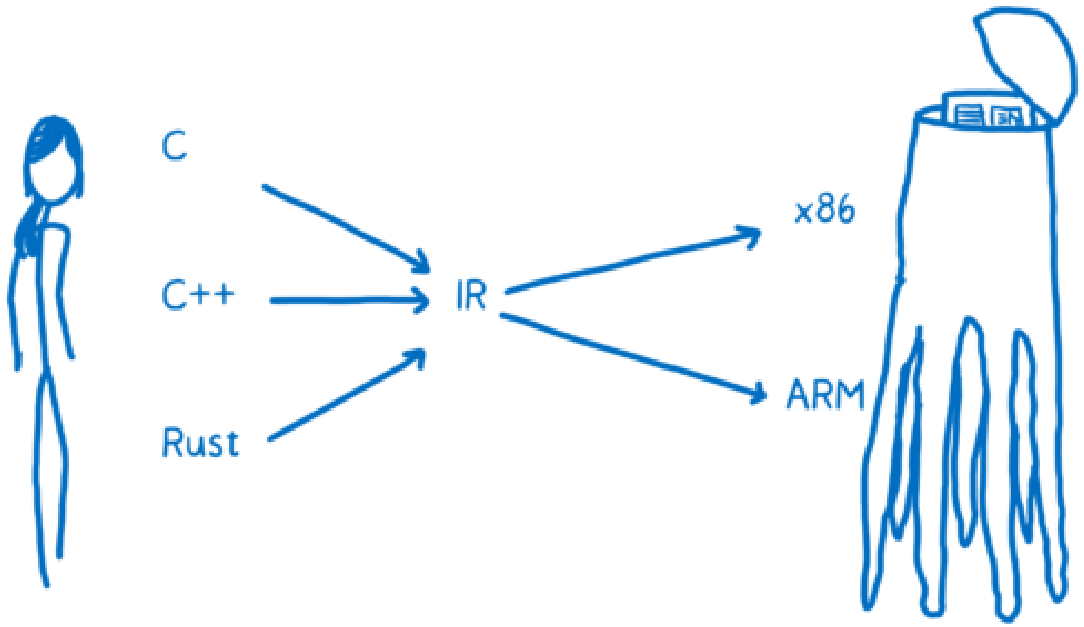
Basic Goals: Separation of Concerns

- Generate efficient code sequences for individual operations
- Keep it fast and simple: leave most optimizations to later phases
- Provide clean, easy-to-optimize code
- IR forms the basis for code optimization and target code generation

Intermediate language

- Goal: Translate AST to low-level machine-independent 3-address IR

- Two alternative ways:
  1. Bottom-up tree-walk on AST
  2. Syntax-Directed Translation



Three-Address Code (Quadraples)

- A quadraple is: `x := y op z`

  where x, y and z are names, constants or compiler-generated temporaries;

  op is any operator.

- But we may also use the following notation for quadraples (much better notation because it looks like a machine code instruction)

  ```
  op   x,y,z
  ```

  apply operator `op` to `y` and `z`, and store the result in `x`.

- We use the term "three-address code" because each statement usually contains three addresses (two for operands, one for the result).

Three-Address Statements

Binary Operator: `op result,y,z` or `result := y op z`

where `op` is a binary arithmetic or logical operator. This binary operator is applied to `y` and `z`, and the result of the operation is stored in `result`.

Ex:
```
add  a,b,c
addi a,b,c
gt   a,b,c
```

Unary Operator: `op result,,y` or `result := op y`

where `op` is a unary arithmetic or logical operator. This unary operator is applied to `y`, and the result of the operation is stored in `result`.

Ex:
```
uminus    a,,c
not       a,,c
inttoreal a,,c
```

Three-Address Statements (cont.)

Move Operator: `mov result,,y` or `result := y`

where the content of `y` is copied into `result`.

Ex:
```
mov   a,,c
movi  a,,c
movr  a,,c
```

Unconditional Jumps: `jmp ,,L` or `goto L`

We will jump to the three-address code with the label `L`, and the execution continues from that statement.

Ex:
```
jmp  ,,L1   // jump to L1
jmp  ,,7    // jump to the statement 7
```

Three-Address Statements (cont.)

Conditional Jumps: `jmp`***`relop`*** `y,z,L` or `if y` ***`relop`*** `z goto L`

We will jump to the three-address code with the label `L` if the result of `y relop z` is true, and the execution continues from that statement. If the result is false, the execution continues from the statement following this conditional jump statement.

Ex:

```
jmpgt  y,z,L1    // jump to L1 if y>z
jmpge  y,z,L1    // jump to L1 if y>=z
jmpeq  y,z,L1    // jump to L1 if y==z
jmpne  y,z,L1    // jump to L1 if y!=z
```

Our relational operator can also be a unary operator.

```
jmpnz  y,,L1     // jump to L1 if y is not zero
jmpz   y,,L1     // jump to L1 if y is zero
jmpt   y,,L1     // jump to L1 if y is true
jmpf   y,,L1     // jump to L1 if y is false
```

Three-Address Statements (cont.)

Procedure Parameters: `param x,,` or `param x`

Procedure Calls: `call p,n,` or `call p,n`

where `x` is an actual parameter, we invoke the procedure `p` with `n` parameters.

Ex: param x_1,,

… ➔ p(x_1,...,x_n)

param x_n,,

call p,n,

```
f(x+1,y) ➔  add   t1,x,1
            param t1,,
            param y,,
            call  f,2,
```

Three-Address Statements (cont.)

Indexed Assignments:

`move x,,y[i]` or `x := y[i]`

`move y[i],,x` or `y[i] := x`

Address and Pointer Assignments:

`moveaddr x,,y` or `x := &y`

`movecont x,,y` or `x := *y`

Bottom-up tree-walk on AST

```
expr( node )
    int result, t1, t2, t3;
    switch( type of node )
    {
    case TIMES:
        t1 = expr( left child of node );
        t2 = expr( right child of node );
        result = new_name();
        emit( mov, result, t1, t2 );
        break;
    case PLUS:
        t1 = expr( left child of node );
        t2 = expr( right child of node );
        result = new_name();
        emit( add, result, t1, t2);
        break;
    case ID:
        result = id.place;
        emit(“”)
        break;
    case NUM:
        result = node.val
        emit(“”)
        break;
    }
    return result;
```

Declarations

- A symbol table entry is created for every declared name
- Information includes name, type, relative address of storage, etc.
- Relative address consists of an offset:
  - Offset is from the base of the static data area for global
  - Offset is from the field for local data in an activation record for locals to procedures
- Types are assigned attributes type and width (size)
- Becomes more complex if we need to deal with nested procedures or records

Declarations

D→ T id ; D | ε

T→ B C | record '{' D '}'

B→ int | float

C→ ε | [num] C

How to compute types via SDT?

SDT for Declarations

D→ T id ; D | ε

T→ B C | record '{' D '}'

B→ int | float

C→ ε | [num] C

P→ {offset = 0; top =new ST();} D

D→ T id ; {top.enter(id.name, T.type, offset); offset = offset + T.width;} D_1

D→ ε

T→ B {C.t = B.type ; C.w = B.width; } C {T.type = C.type; T.width = C.width ;}

B→ int { B.type = integer; B.width = 4; }

B→ float { B.type = float; B.width = 8; }

C→ ε { C.type = C.t ; C.width = C.w; }

C→ [num] {C_1.t = C.t; C_1.w = C.w; } C_1 { C.type = array(num.val, C_1.type); C.width = num.val * C_1.width; }

T→ record '{' { STStack.push(top); top =new ST(top); Stack.push(offset); offset=0 }

D '}' {T.type = record(top); T.width =offset; offset=Stack.pop(); top=STStack.pop(); }

Syntax-Directed Translation into Three-Address Code

- Temporary names are created for the interior nodes of a syntax tree
- The synthesized attribute S.code represents the code for the production S
- The nonterminal E has attributes:
  - E.place is the name that holds the value of E
  - E.code is a sequence of three-address statements evaluating E
- The function newtemp() returns a distinct name
- The function newlabel() returns a distinct label

Statements

$S \rightarrow$ **id** $:= E$

$S \rightarrow \text{while } E \text{ do } S_1$

$S \rightarrow \text{if } E \text{ then } S_1 \text{ else } S_2$

$S \rightarrow S_1\ S_2$

$E \rightarrow E_1 * E_2$

$E \rightarrow E_1 + E_2$

$E \rightarrow -\ E_1$

$E \rightarrow (\ E_1\ )$

$E \rightarrow$ **id**

Syntax-Directed Translation into Three-Address Code

$S \rightarrow$ **id** := E { S.code = E.code || p = top.lookup(id.name);
if p != NULL then gen('mov' p ',,' E.place); else error ;}

$E \rightarrow E_1 + E_2$ { E.place = newtemp();
E.code = E_1.code || E_2.code || gen('add' E.place ','E_1.place ',' E_2.place) ; }

$E \rightarrow E_1 * E_2$ { E.place = newtemp();
E.code = E_1.code || E_2.code || gen('mult' E.place ',' E_1.place ',' E_2.place); }

$E \rightarrow - E_1$ { E.place = newtemp();
E.code = E_1.code || gen('uminus' E.place ',,' E_1.place); }

$E \rightarrow (E_1)$ { E.place = E_1.place;
E.code = E_1.code; }

$E \rightarrow$ **id** { p = top.lookup(id.name);
if p != NULL then E.place = **id**.place; else error;
E.code = "" // null }

Syntax-Directed Definitions (cont.)

$S \rightarrow$ if E then S_1 else S_2 S.else = newlabel();
S.after = newlabel();
S.code = E.code ||
gen('jmpf' E.place ',' S.else) || S_1.code ||
gen('jmp' ',' S.after) ||
gen(S.else ':") || S_2.code ||
gen(S.after ':")

$S \rightarrow S_1 S_2$ S_1.code || S_2.code

Syntax-Directed Definitions (cont.)

$S \rightarrow$ while E do S_1 S.begin = newlabel();

S.after = newlabel();

S.code = gen(S.begin ":") || E.code ||

gen('jmpf' E.place ',' S.after) || S_1.code ||

gen('jmp' ',' S.begin) ||

gen(S.after ':") }

Break and continue?

Syntax-Directed Definitions (cont.)

$S \to$ while E do S_1 $\quad$ S_1.inbegin = newlabel(); S.begin =S_1.inbegin

S_1.inafter = newlabel(); S.after = S_1.inafter

S.code = gen(S.begin ":") || E.code ||

gen('jmpf' E.place ',' S.after) || S_1.code ||

gen('jmp' ',' S.begin) ||

gen(S.after ':") }

$S \to S_1 S_2$ $\quad$ S_1.inbegin=S_2.inbegin=S.inbegin;

S_1.inafter=S_2.inafter=S.inafter;

S_1.code || S_2.code

$S \to$ break $\quad$ gen('jmp' S.inafter)

$S \to$ continue $\quad$ gen('jmp' S.inbegin)

Statements (cont.)

$D \rightarrow T\ id\ ;\ D\ |\ \varepsilon$

$T \rightarrow B\ C\ |\ record\ '\{'\ D\ '\}'$

$B \rightarrow int\ |\ float$

$C \rightarrow \varepsilon\ |\ [num]\ C$

$S \rightarrow$ **id** $:= E$

$S \rightarrow$ while E do S_1

$S \rightarrow$ if E then S_1 else S_2

$S \rightarrow S_1\ S_2$

$E \rightarrow E_1 * E_2$

$E \rightarrow E_1 + E_2$

$E \rightarrow -\ E_1$

$E \rightarrow (\ E_1\ )$

$E \rightarrow$ **id**

$S \rightarrow$ return E

$E \rightarrow$ id (AP)

$AP \rightarrow \varepsilon\ |\ E, AP$

Function definitions and function calls

$D \rightarrow$ fn T id $(FP)\ \{D; S\}$

$FP \rightarrow \varepsilon\ |\ T$ id, FP

Syntax-Directed Translation (cont.)

$D \rightarrow$ fn T id

(FP) '{ begin=newlabel(); gen(begin' :');

{ STStack.push(top); top =new ST(top); Stack.push(offset); offset=0 }

D ; S}' {offset=Stack.pop(); top=STStack.pop();

top.enter(id.name,T.type, FP.types, begin)}

$FP \rightarrow \varepsilon$ | T id, FP construct a list of types from FP

$S \rightarrow$ return E // introduced in runtime organization

$E \rightarrow$ id (AP) {p=top.lookup(id.name); AP.code||gen('call' p,n);}

$AP \rightarrow \varepsilon$

$AP \rightarrow E, AP_1$ {AP.code = E.code|| gen('param' E.place)|| AP_1.code}

Statements

$S \rightarrow \textbf{id} := E$

$S \rightarrow$ while E do S

$S \rightarrow$ if E then S else S

$E \rightarrow E * E$

$E \rightarrow E + E$

$E \rightarrow - E$

$E \rightarrow (E_1)$

$E \rightarrow \textbf{id}$

$S \rightarrow L := E$

$E \rightarrow L$

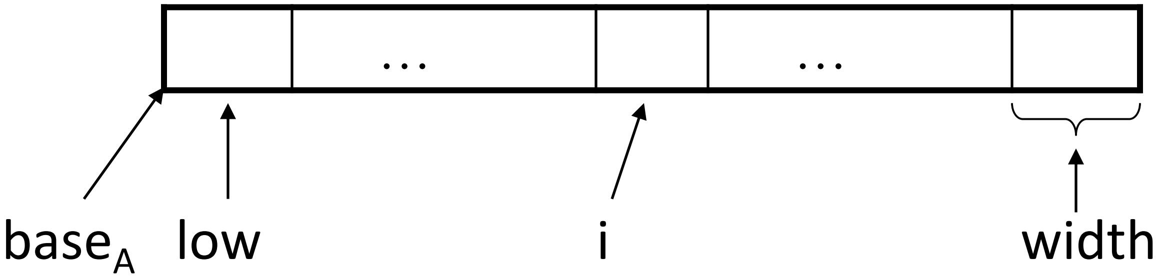
$L \rightarrow id\ [E]$

$L \rightarrow L\ [E]$

Arrays

- Elements of arrays can be accessed quickly if the elements are stored in a block of consecutive locations.

A one-dimensional array **A**:



base$_A$ is the address of the first location of the array A,

width is the width of each array element.

low is the index of the first array element

location of A[i] ➔ base$_A$+(i-low)*width

Arrays (cont.)

$\texttt{base}_A\texttt{+(i-low)*width}$

can be re-written as $\underbrace{\texttt{i*width}} + \underbrace{(\texttt{base}_A\texttt{-low*width})}$

should be computed at run-time can be computed at compile-time

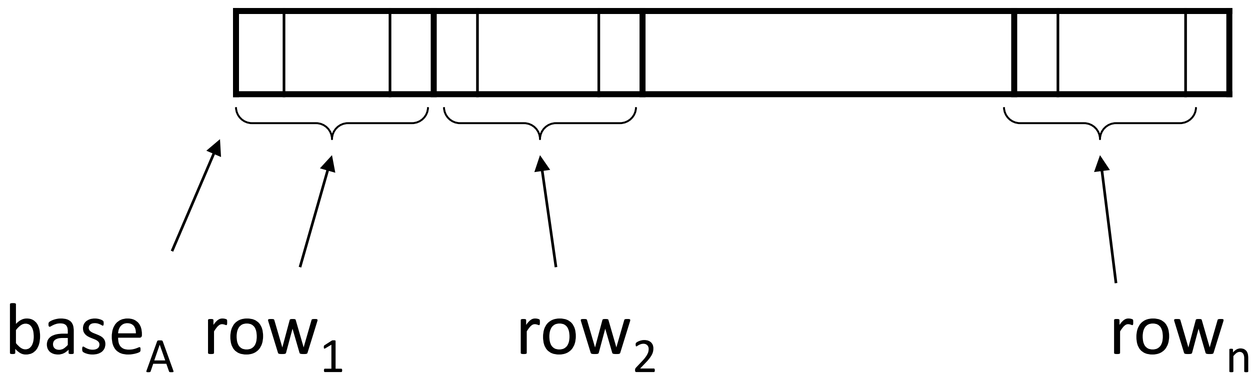
- So, the location of A[i] can be computed at the run-time by evaluating the formula i*width + c where c is ($base_A$-low*width) which is evaluated at compile-time.

- Intermediate code generator should produce the code to evaluate this formula i*width + c (one multiplication and one addition operation).

Two-Dimensional Arrays

- A two-dimensional array can be stored in
  - either **row-major** (*row-by-row*)
  - or **column-major** (*column-by-column*).
- Most of the programming languages use **row-major** method.

- Row-major representation of a two-dimensional array:



Two-Dimensional Arrays (cont.)

- The location of $A[i_1][i_2]$ is: $base_A + ((i_1\text{-}low_1)*n_2+i_2\text{-}low_2)*width$

  $base_A$ is the location of the array A.
  low_1 is the index of the first row
  low_2 is the index of the first column
  n_2 is the number of elements in each row
  width is the width of each array element

- Again, this formula can be re-written as

$$\underbrace{((i_1*n_2)+i_2)*width}_{\text{should be computed at run-time}} + \underbrace{(base_A-((low_1*n_2)+low_2)*width)}_{\text{can be computed at compile-time}}$$

should be computed at run-time can be computed at compile-time

Multi-Dimensional Arrays

- In general, the location of $A[i_1][i_2]\ldots[i_k]$ is

  $$((\ldots((i_1*n_2)+i_2)\ldots)*n_k+i_k)*width \;+\; (base_A-((\ldots((low_1*n_2)+low_2)\ldots)*n_k+low_k)*width)$$

- So, the intermediate code generator should produce the codes to evaluate the following formula (to find the location of $A[i_1][i_2]\ldots[i_k]$) :

$$((\ldots((i_1*n_2)+i_2)\ldots)*n_k+i_k)*width \;+ c$$

- To evaluate the $((\ldots((i_1*n_2)+i_2)\ldots)*n_k+i_k)*width$ portion of this formula, we can compute

$$i_1 * width * n_2*\ldots*n_k + \ldots + i_j * \underbrace{width * n_{j+1}*\ldots*n_k}_{} + \ldots + i_k*width$$

=width of the element at i_j-th DIM = C_1.width

C→ [num] {C_1.t = C.t; C_1.w = C.w; } C_1 { C.type = array(num.val, C_1.type); C.width = num.val * C_1.width; }

Syntax-Directed Translation into Three-Address Code

$S \rightarrow$ **id** := E { S.code = E.code || p = top.lookup(id.name);
if p != NULL then gen('mov' p ',' E.place); else error ; }

$E \rightarrow E_1 * E_2$ { E.place = newtemp();
E.code = E_1.code || E_2.code || gen('mult' E.place ',' E_1.place ',' E_2.place); }

$S \rightarrow$ L := E { S.code =E.code || gen('mov' L.array.base '[' L.place ']', , E.place); }

$E \rightarrow$ L { E.place = newtemp(); gen('mov' E.place, , L.array.base '[' L.place ']'); }

$L \rightarrow$ id [E] { L.code = E.code || L.array = top.lookup(id.name); L.type = L.array.type.elem;
L.place = newtemp(); gen('mult' L.place, E.place, L.type.width) ;}

$L \rightarrow L_1$ [E] { L.code = E.code || L1.type = L_1.array.type.elem;
L.place = newtemp(); t= newtemp();
gen('mult' t, E.place, L1.type.width);
gen('add' L.place, L_1.place, t); }

Boolean Expressions

$E \rightarrow E_1$ and E_2

{ E.code =$E_{1.}$code||$E_{2.}$code||E.place = newtemp(); gen('and' E.place ',' E_1.place ',' E_2.place; }

$E \rightarrow E_1$ or E_2

{E.code =$E_{1.}$code ||$E_{2.}$code|| E.place = newtemp(); gen('or' E.place ',' E_1.place ',' E_2.place}

$E \rightarrow$ not E_1

{E.code =$E_{1.}$code || E.place = newtemp(); gen('not' E.place ',,' E_1.place) }

$E \rightarrow E_1$ **relop** E_2

{E.code =$E_{1.}$code ||$E_{2.}$code|| E.place = newtemp(); gen(**relop**.code E.place ',' E_1.place ',' E_2.place) }

Three Address Codes - Example

```
x:=1;
y:=x+10;
while (x<y) {
   x:=x+1;
   if (x%2==1) then y:=y+1;
   else y:=y-2;
}
```

➔

```
01: mov   x,,1
02: add   t1,x,10
03: mov   y,,t1
04: lt    t2,x,y
05: jmpf  t2,,17
06: add   t3,x,1
07: mov   x,,t3
08: mod   t4,x,2
09: eq    t5,t4,1
10: jmpf  t5,,14
11: add   t6,y,1
12: mov   y,,t6
13: jmp   ,,16
14: sub   t7,y,2
15: mov   y,,t7
16: jmp   ,,4
17:
```

Classes

- Each class is regarded as a record
- All the non-static attributes are fields of the record
- All the static attributes are regarded as global variables/functions

Class C {	Record C {
int x;	int x;
fn T f(FP){	fn T f’(C& this, FP){
…	…
}	}
}	}
f(AP)	f’(this, AP)
c.f(AP)	f’(c,AP)
o.x	o.x
x	this.x

Inheritance

- How to handle methods may inherited from this parent classes?
- Naive approach: each class has its own Implementation?
- Better approach:
  - For each class, construct a method table including all the functions (pointers to entry points of functions) defined in this class as well as functions inherited from this parent classes
  - method table:
    1. Copy inherited methods
    2. Overwrite overridden methods
    3. Append its own methods
  - The record of the class includes all the data attributes defined in this class as well as inherited data attributes, in addition with a pointer to this method table

Exercise

Record {int x; float[3] y;} z; write ST?

D→ T id ; D | ε

T→ B C | record '{' D '}'

B→ int | float

C→ ε | [num] C

P→ {offset = 0; top =new ST();} D

D→ T id ; {top.enter(id.name, T.type, offset); offset = offset + T.width;} D_1

D→ ε

T→ B {C.t = B.type ; C.w = B.width; } C {T.type = C.type; T.width = C.width ;}

B→ int { B.type = integer; B.width = 4; }

B→ float { B.type = float; B.width = 8; }

C→ ε { C.type = C.t ; C.width = C.w; }

C→ [num] {C_1.t = C.t; C_1.w = C.w; } C_1 { C.type = array(num.val, C_1.type); C.width = num.val * C_1.width; }

T→ record '{' { STStack.push(top); top =new ST(top); Stack.push(offset); offset=0 }

D '}' {T.type = record(Top); T.width =offset; offset=Stack.pop(); top.STStack.pop(); }