Type Checking

CIS*4650 Compilers

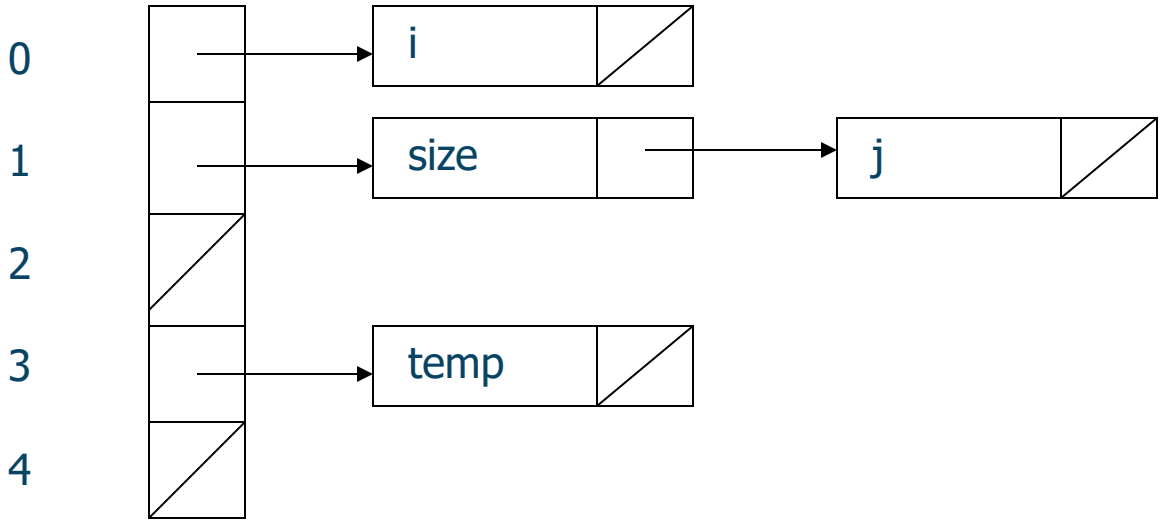
(Winter 2025)

Symbol Table

- Keep information associated with identifiers: constants, data types, variables, and functions
- Major operations:
  - Insert: store information from name declarations
  - Lookup: retrieve information associated with names
  - Delete: remove information from the view when the corresponding declaration is out of scope
- Usually implemented as hash tables. Why?

Hash Table

- Hash function: map a key to an address among the available buckets
  - Collisions: multiple keys mapped to the same address



Declarations

Constant: `const int SIZE = 199;`

Type:
```
struct Entry {
    char * name;
    int count;
    struct Entry * next;
};
typedef struct Entry * EntryPtr;
```

Variable:
```
int a, b[100];
struct Entry c;
EntryPtr d;
```

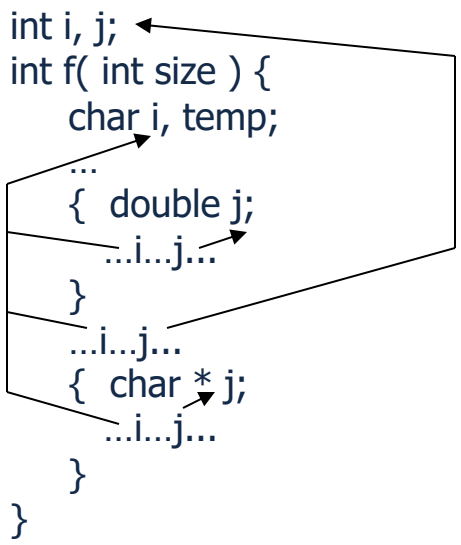
Function/procedure: see the example in slide 6 for an illustration

Name Bindings

- Constant declaration: associate values to names
- Type declaration: bind names to newly constructed types
- Variable declaration: bind names to scopes as well as data types
- Function declaration: bind names to modular language constructs

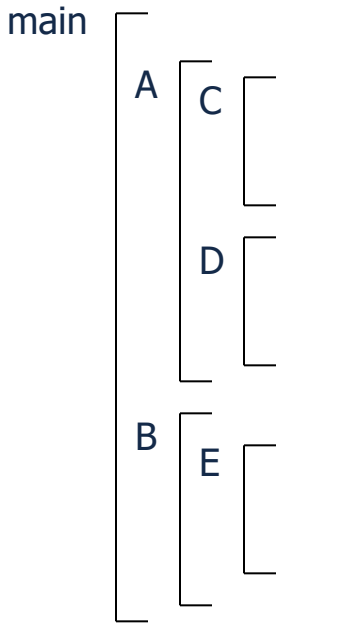
Scope Rules

- Declaration before use: facilitate one-pass processing
- Most closely nested rule for block structures: prefer the declaration in the most closely nested block to the reference.

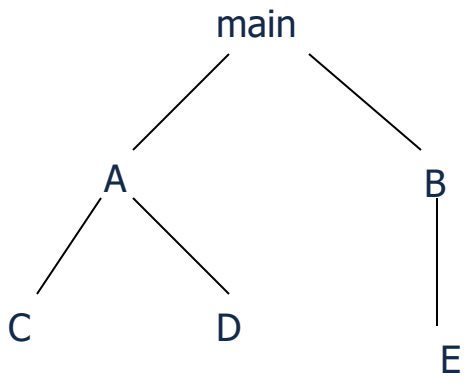



```
1     int i, j;
2     int f( int size ) {
3        char i, temp;
4        ...
5        {  double j;
6           ...i...j...
7        }
8        ...i...j...
9        {  char * j;
10          ...i...j...
11       }
12    }
```

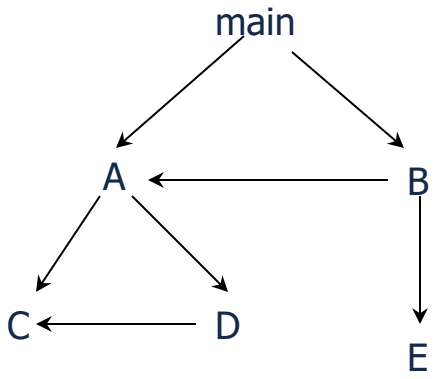
Block Structure in Pascal



Program Structure



Tree Structure

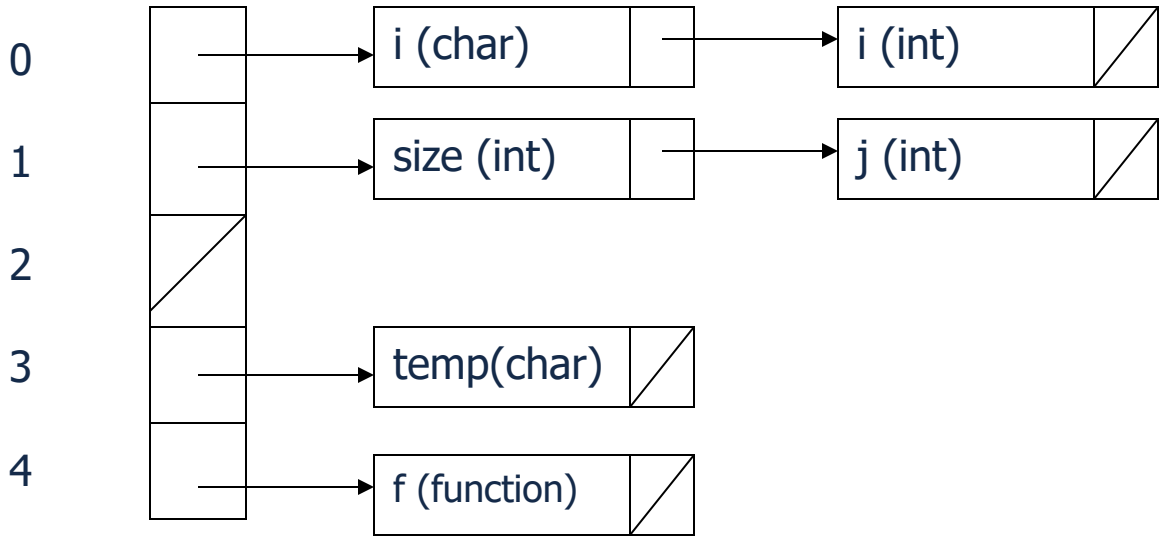


Call Graph

Implementing Nested Scopes

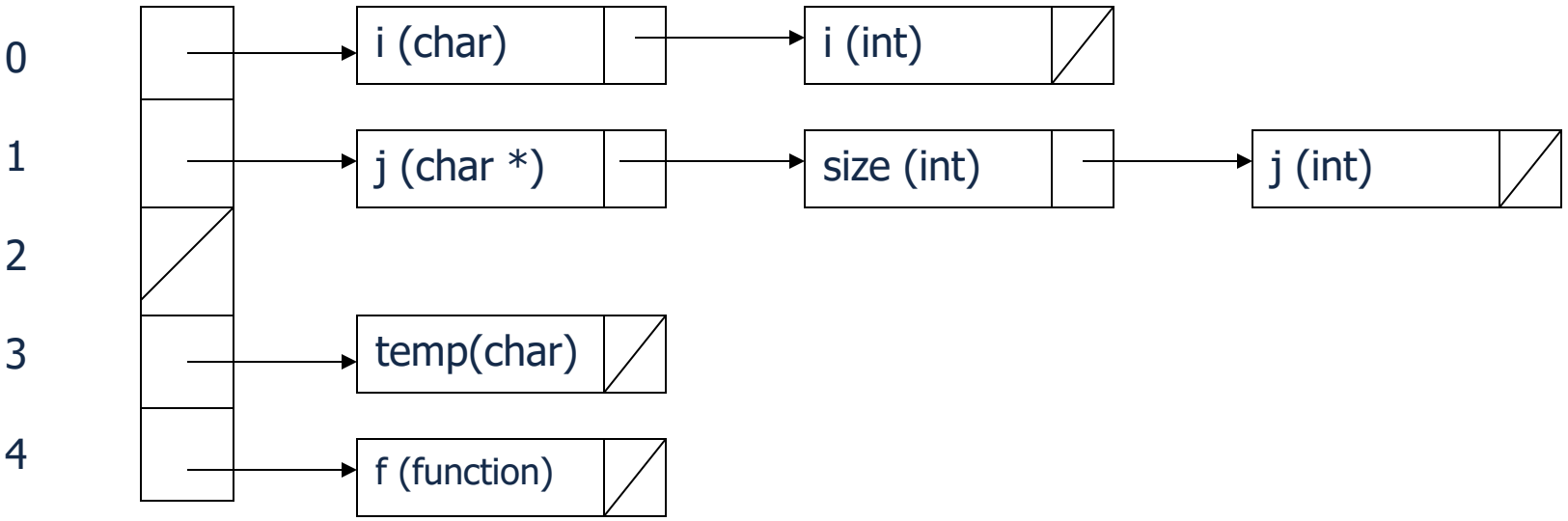
- Insert shouldn't overwrite existing names; just temporally hide irrelevant information

- After processing the declarations of function f



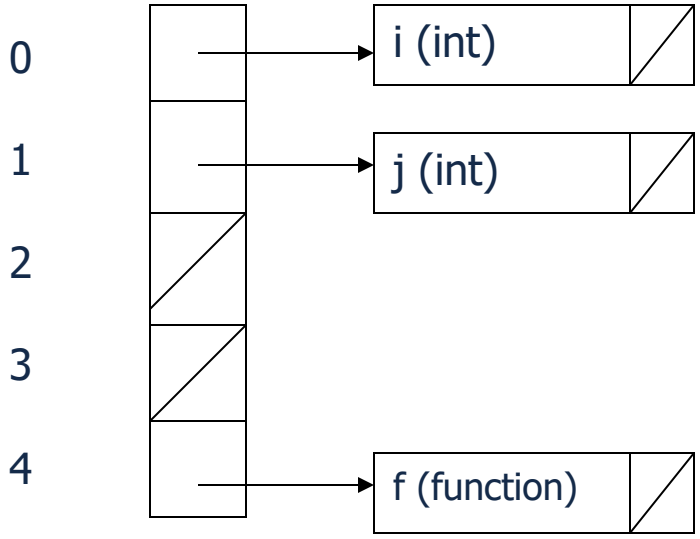
Implementing Nested Scopes

- After processing the declarations of the second nested block within the body of function f



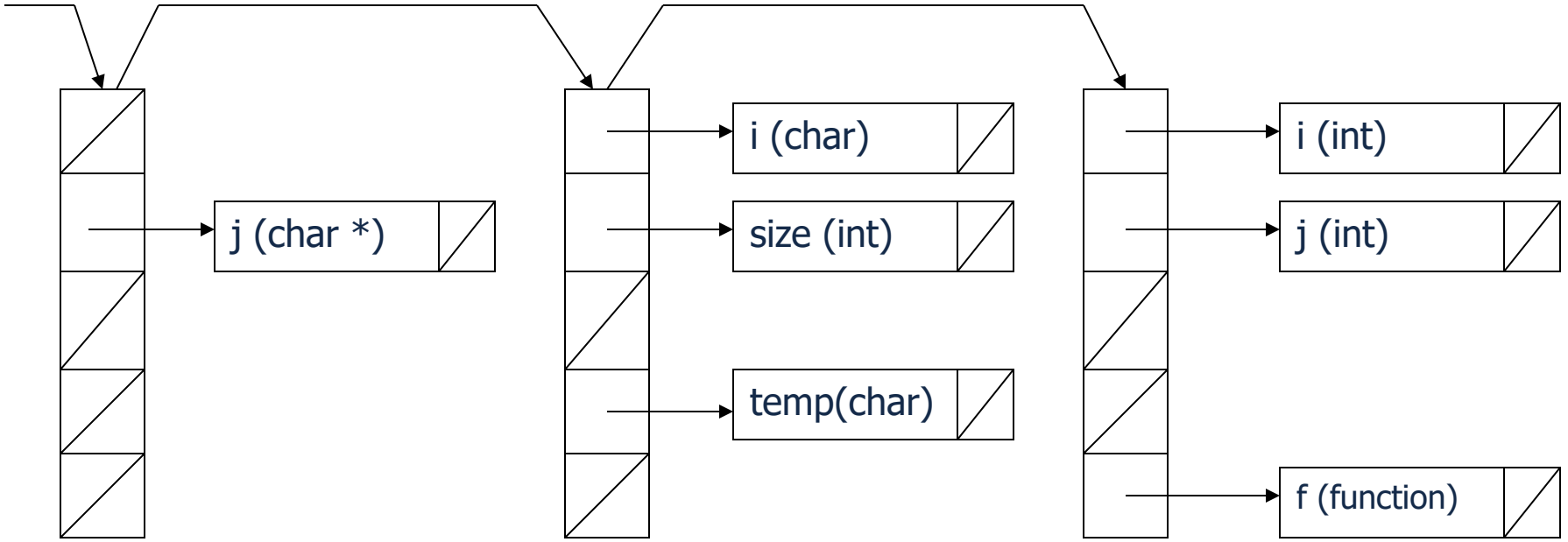
Implementing Nested Scopes

- After exiting the body of function f and deleting its declarations



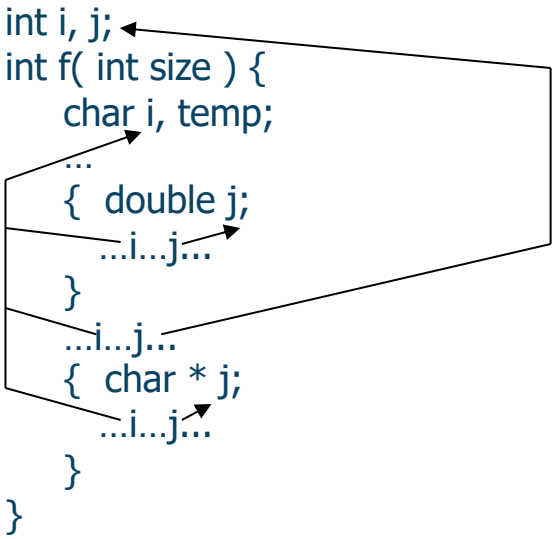
Implementing Nested Scopes

- Use multiply linked hash tables so that deletion can be done easily



Displaying Symbol Tables

- Table content changes as we enter a scope, and as a result, it's better to show the nested scoping structures and display the content just before we leave each scope.




```
Entering the global scope:
    Entering the scope for function f:
        Entering a new block:
            j: double
        Leaving the block
        Entering a new block:
            j: char *
        Leaving the block
        size: int
        i: char
        temp: char
    Leaving the function scope
    i: int
    j: int
    f: (int) -> int
Leaving the global scope
```

Interacting Declarations

- The same name can't be re-declared in the same scope
  - Solution: perform a lookup before each insert

    e.g., typedef int i;
    int i;

- Indirect recursions: use function prototype

```
void f( void ) {
   ... g()...
}

void g( void ) {
   ... f() ...
}
```

```
void g( void );      /* function prototype */

void f( void ) {
   ... g()...
}

void g( void ) {
   ... f() ...
}
```

Type Checking

- Declarations provide the initial type definitions
- Type checking: use type information to ensure that all constructs are valid under the type rules
  - For example, boolean variables can't be added and integer variables can be or'ed
- Type inference: compute and maintain type information
  - Given the data types of operands, determine the data types of expressions
- Error Recovery: if component types are not compatible, report errors and infer the right types for expressions

Type Checking

- Static type checking: performed at compilation time
  - Variables are declared
  - Rules for type compatibility

- Dynamic type checking: performed at execution time
  - Array: range is often known at run time
  - Reference

- All type checks can be done dynamically, but static checking is preferred where possible.

Type Expressions

<var-decls> -> <var-decls> ; <var-decl> | <var-decl>

<var-decl> -> id : <type-exp>

<type-exp> -> <simple-type> | <structured-type>

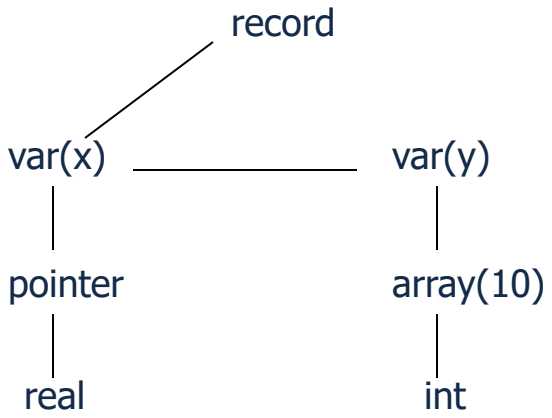
<simple-type> -> int | bool | real | char | void

<structured-type> -> array [num] of <type-exp> |
record <var-decls> end |
union <var-decls> end |
pointer to <type-exp> |
proc(<type-exps>) : type-exp

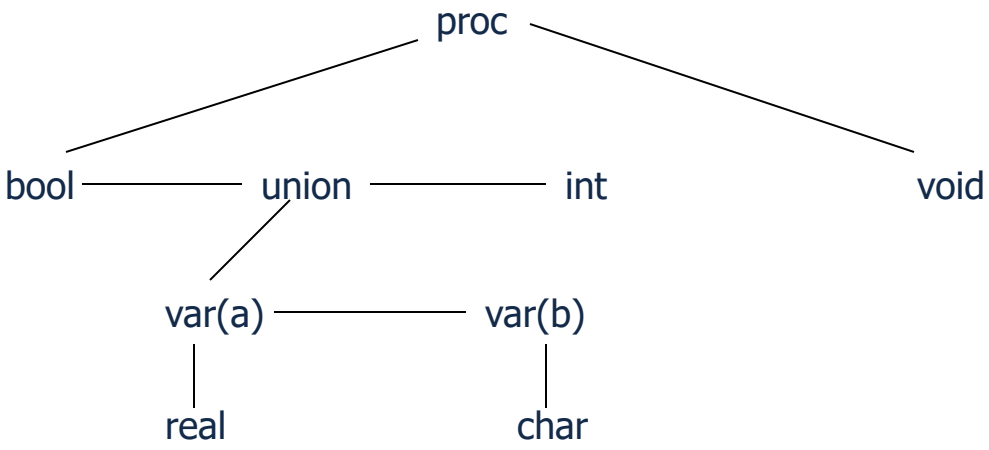
<type-exps> -> <type-exps> , <type-exp> | <type-exp>

Type as Syntax Tree

```
record
    x: pointer to real;
    y: array [10] of int
end
```



proc(bool, union a: real; b: char end, int): void



Type Equivalence

- Structural equivalence: iff two types have the same structure (syntax tree)

- Name equivalence: iff two types are the same simple type or are the same type name

```
e.g.,   t1 = int;          // t1 and t2 are not equivalent since they are
        t2 = int;          // different names
```

- Declaration equivalence: also called aliases
  - Implementation: introduce base type in addition to associated type

```
e.g.,   t1 = array [10] of int;     // t1 and t2 are not equivalent
        t2 = array [10] of int;     // t1 and t3 are equivalent
        t3 = t1                     // t2 and t3 are not equivalent
```

Type Declarations

<var-decls> -> <var-decls> ; <var-decl> | <var-decl>
<var-decl> -> id : <simple-type-exp>

<type-decls> -> <type-decls> ; <type-decl> | <type-decl>
<type-decl> -> id = <type-exp>

<type-exp> -> <simple-type-exp> | <structured-type>
<simple-type-exp> -> <simple-type> | id
<simple-type> -> int | bool | real | char | void
<structured-type> -> array [num] of <simple-type-exp> |
record <var-decls> end |
union <var-decls> end |
pointer to <simple-type-exp> |
proc(<type-exps>) : simple-type-exp

<type-exps> -> <type-exps> , <simple-type-exp> | <simple-type-exp>

Type Checking Example

<program> -> <var-decls> ; <stmts>

<var-decls> -> <var-decls> ; <var-decl> | <var-decl>

<var-decl> -> id : <type-exp>

<type-exp> -> int | bool | array [num] of <type-exp>

<stmts> -> <stmts> ; <stmt> | <stmt>

<stmt> -> if <exp> then <stmt> | id := <exp>

<exp> -> <exp> + <exp> | <exp> or <exp> | <exp> [<exp>] |
num | id | true | false

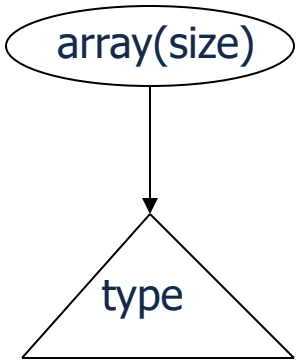
Type Checking Example

Grammar Rule	Semantic Rule
<var-decl> -> id : <type-exp>	insert(id.name, type-exp.type)
<type-exp> -> int	type-exp.type = integer
<type-exp> -> bool	type-exp.type = boolean
<type-exp$_1$> -> array [num] of <type-exp$_2$>	type-exp$_1$.type = makeTypeNode(array, num.size, type-exp$_2$.type)
<stmt$_1$> -> if <exp> then <stmt$_2$>	**if not** typeEqual(exp.type, boolean) **then** type-error(stmt$_1$) // type-check stmt$_2$
<stmt> -> id := <exp>	**if not** (typeEqual(lookup(id.name), exp-type) **then** type-error(stmt) stmt.type = lookup(id.name)
<exp$_1$> -> <exp$_2$> + <exp$_3$>	**if not** (typeEqual(exp$_2$.type, integer) **and** typeEqual(exp$_3$.type, integer)) **then** type-error(exp$_1$) exp$_1$.type = integer
<exp$_1$> -> <exp$_2$> **or** <exp$_3$>	**if not** (typeEqual(exp$_2$.type, boolean) **and** typeEqual(exp$_3$.type, boolean)) **then** type-error(exp$_1$) exp$_1$.type = boolean

Type Checking Example

Grammar Rule	Semantic Rule
$<exp_1>$ -> $<exp_2>$ [$<exp_3>$]	**if** isArrayType(exp_2.type) **and** typeEqual(exp_3.type, integer) **then** exp_1.type = exp_2.type.child1 **else** type-error(exp_1)
<exp> -> num	exp.type = integer
<exp> -> id	exp.type = lookup(id.name)
<exp> -> true	exp.type = boolean
<exp> -> false	exp.type = boolean

makeTypeNode(array, size, type)



Type Checking for Function Calls/Returns

- For a function definition, the return expression has to match the return type:

```
void foo(void) {
    int x;
    return x;
}
```

- For a function call, the number and types of its arguments must match the parameters of a function header:

```
void foo(void) {
}
```

```
void main(void) {
    int x;
    if (x) output(foo())
    else output(x, foo());
}
```

Special Cases for Checkpoint Two

- For a function, variables declared in the parameter list and immediately inside the body should belong to the same scope
  - Suggestion: use (level + 1) for "size" and after entering the block, increment "level" and then use "level" for "i" and "temp"

```
/* size, i, and temp at the same level */
int f(int size) {
    char i, temp;
    …
}
```

- For the two predefined functions "int input(void)" and "void output(int)", you may report "undefined" errors when they are used in a program
  - Suggestion: add their definitions to the symbol table at the very start

Special Cases for Checkpoint Two

- Since C- doesn't allow type definitions, we may have to support structural equivalence for arrays. To simplify the task, we only allow an array variable to match a parameter in a function call such as "sort(x, 0, 9)" in the program:

```
int x[10];

void sort(int a[], int low, int high) {
   …
}

void main(void) {
  …
  sort(x, 0, 9);
  …
}
```

Tips for the Implementation

- A new visitor class "SemanticAnalyzer.java" that maintains the symbol table and performs type checking:

- Symbol table structure:

```
HashMap<String, ArrayList<NodeType>> table;
// Initialized in the related constructor
// Accessed by the utility methods for "insert",
   "lookup", and "delete" operations
```

- "visit" methods that traverse the syntax trees in the post-order:

```
// Display the entry and exit points for the
   scoping structures: global, function, and
   blocks
// Add name-def pairs to "table" for "Dec" nodes
// Do type-checking for "Exp" nodes
```

Tips for the Implementation

- A new class "NodeType.java" that stores type-related information:

```
// Contains instance variables: "String name",
   "Dec def", "int level", and a constructor
```

- Add a new attribute "Dec dtype" in "Exp.java" so that it can be shared by all the descendent classes:

```
// dtype is essentially a reference to a "Dec"
   node that helps us find the type information
```

- Add boolean methods such as "isInteger(Dec dtype)" in SemanticAnalyzer.java to simplify the code for type checking:

```
// Given "int x[10]", "x[2]" is an integer, and
   given "int input(void)", "input()" is an integer
```

Tips for the Implementation

- Semantically speaking, "void x" and "void y[10]" are not meaningful and thus should be reported as errors:

```
// For error recovery, we can change "void" to
   "int" for the related declarations
```

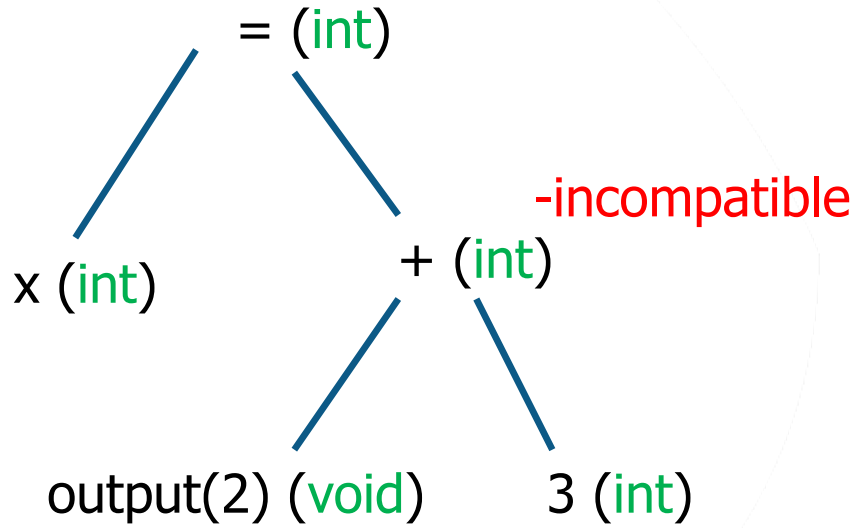
- On the other hand, "void output(int)" is perfectly fine and "output(3)" will be the "void" type:

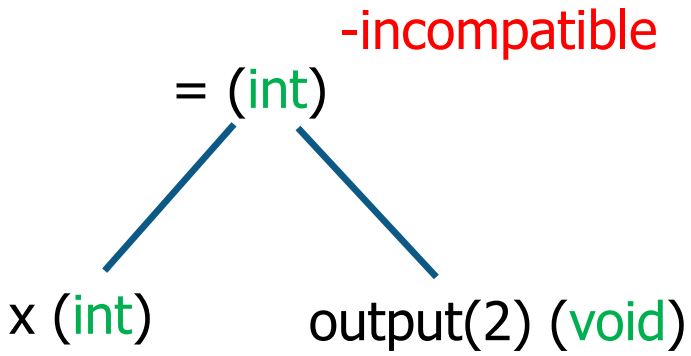
```
// For the type checking of OpExp or AssignExp,
   both children should have compatible types.
   Otherwise, report errors, and do type inference
   and error recovery by creating a suitable
   declaration and assigning it to the "dtype"
   of related OpExp and AssignExp
```

Type Checking Example for C-

```
int x;
void output(int x) {...}

x = output(2) + 3;
x = output(2);
```





Tips for the Implementation

- For Checkpoint One and Two, you are asked to implement "-a" and "-s" options on the command line in CM.java:

```
// When "-a" is specified, we will do parsing
   and save the syntax tree to an output file if
   the program runs to completion.
   For example, if the input is "gcd.cm", the output
   will be "gcd.abs" that is stored in the same
   folder for the input file

// When "-s" is specified, we will do both parsing
   and semantic analysis, and save the symbol table
   to an output file such as "gcd.sym" if the
   program runs to completion.  If there are syntactic
   errors, the program will terminate right after
   parsing since it's not meaningful to do semantic
   analysis for partially built syntax trees.
```

Tips for the Implementation

- Semantic analysis is only meaningful for a valid syntax tree; otherwise, the compilation process should stop. Similarly, code generation is only useful when there are no semantic errors; otherwise, the compilation process should stop as well.
  - To keep track of the parsing status, we can include a static Boolean variable in the *.cup file so that its value can be set when an error has occurred.
  - To keep track of the status for semantic analysis, we can include a static Boolean variable in the visitor class "SemanticAnalyzer.java".
- In addition, we should check if the "main" function is available in the source file and whether it is the last function defined since any C- program should have this function at the end of the file.

Type Conversion and Coercion

- Allow arithmetic expressions of mixed data types
  - e.g., 2.1 + 3
- Compatibility: integer $\subseteq$ float $\subseteq$ double
- Conversion: converting a data type explicitly
  - e.g., 2.1 + float(3)
- Coercision: converting a data type implicitly
  - Similar solution applies to subclasses in object-oriented languages (so-called subtype principle)