Compilation Principle
编 译 原 理

第16讲：语义分析(4)

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DCS290, 4/28/2022

Review Questions

- SDD vs. SDT

  SDD = Syntax Directed Definitions, SDT = SD Translation Schemes

- What are S-SDD and L-SDD?

  S-SDD: synthesized-SDD (only syn attributes),

  L-SDD: left-attributed SDD (only left-to-right dependency).

- Why S-SDD is natural to be implemented in LR parsing?

  Syn attributes: evaluate parent after seeing all children (=reduce).

- Why L-SDD is not natural for LR parsing?

  Semantic actions can be in anywhere of the production body.

- At high level, why L-SDD can be implemented in LR?

  Left-attributed, the needed attribute values must be in the stack.

- Roughly, how do we modify L-SDD for LR parsing?

  Add non-terminal markers to make all actions at production end.

Overview of Symbol Table[符号表]

- **Symbol table** records info of each symbol name in a program[符号表记录每个符号的信息]
  - symbol = name = identifier
- Symbol table is created in the semantic analysis phase[语义分析阶段创建]
  - Because it is not until the semantic analysis phase that enough info is known about a name to describe it
- But, many compilers set up a table at lexical analysis time for the various variables in the program[词法分析阶段准备]
  - And fill in info about the symbol later during semantic analysis when more information about the variable is known
- Symbol table is used in code generation to output assembler directives of the appropriate size and type[后续代码生成阶段使用]

Binding[绑定]

- **Binding**: match identifier use with definition[使用-定义]
  - Definition: associating an *id* with a memory location
  - Hence, binding associates an *id* use with a location
  - Binding is an essential step before machine code generation
- If there are multiple definitions, which one to use?

```
void foo()
{
    char x;    /* allocated at mem[0x100] */
    ...
    {
        int x;  /* allocated at mem[0x200] */
        ...
    }
    x = x + 1; /* add mem[0x100],1 ? add mem[0x200],1 ? */
}
```

Scope[作用域]

- **Scope**: program region where a definition can be bound
  - Uses of identifier in the scope is bound to that definition
  - For C: auto/local, static, global
- Some properties of scopes
  - Use not in scope of any definition results in undefined error
  - Scopes for the same identifier can never overlap
    - There is at most one binding at any given time
- Two types: <u>static scoping</u> and <u>dynamic scoping</u>
  - Depending on how scopes are formed

Static Scoping[静态作用域]

- Scopes formed by where definitions are in program text[声明起作用的那段区域]
  - Also known as lexical scoping since related to program text C/C++, Java, Python, JavaScript[也叫词法作用域]
- Rule: bind to the closest enclosing definition

```
void foo()
{
    char x;
    ...
    {
        int x;
        ...
     }
    x = x + 1;
}
```

Dynamic Scoping[动态作用域]

- Scopes formed by when definitions happen during runtime[运行时决定]
  - Perl, Bash, LISP, Scheme
- Rule: bind to most recent definition in current execution

```
void foo()
{
   (1) char x;
   (2) if (...) {
   (3)      int x;
   (4)      ...
          }
   (5) x = x + 1;
 }
```

- Which *x*'s definition is the most recent?
  - Execution (a): ...(1)...(2)...(5)
  - Execution (b): ...(1)...(2)...(3)...(4)...(5)

Static vs. Dynamic Scoping[对比]

- Most languages that started with dynamic scoping (LISP, Scheme, Perl) added static scoping afterwards
- Why? With dynamic scoping ...
  - All bindings are done at execution time
  - Hard to figure out by eyeballing, for both compiler and human
- Pros of static scoping[静态的好处]
  - Static scoping leads to fewer programmer errors
    - Bindings readily apparent from lexical structure of code
  - Static scoping leads to more efficient code
    - Compiler can determine bindings at compile time
    - Compiler can translate identifier directly to memory location
    - Results in generation of efficient code
- We will discuss static scoping only

What is Symbol Table[符号表]

- **Symbol**: same thing as **identifier** (used interchangeably)
- **Symbol table**: a compiler data structure that tracks info about all program symbols
  - Each entry represents a definition of that identifier
  - Maintains list of definitions that reach current program point
  - List updated whenever scopes are entered or exited
  - Used to perform binding of identifier uses at current point
  - Built by either...
    - Traversing the parse tree in a separate pass after parsing
    - Using semantic actions as an integral part of parsing pass
- Usually discarded after generating executable binary
  - Machine code instructions no longer contain symbols
  - For use in debuggers, symbol tables may be included
    - To display symbol names instead of addresses in debuggers
    - For GCC, using ‘gcc -g ...” includes debug symbol tables

Maintaining Symbol Table[维护]

- Basic idea

  int x=0; ... void foo() { int x=0; ... x=x+1; } ... x=x+1 ...

  - Start processing *foo*:
    - Add definition of x, overriding old definition of x if any
  - After processing *foo*:
    - Remove definition of x, restoring old definition of x if any
- Operations
  - enter_scope() start a new scope
  - exit_scope() exit current scope

  - find_symbol(*x*) find the information about *x*
  - add_symbol(*x*) add a symbol *x* to the symbol table
  - check_symbol(*x*) true if *x* is defined in current scope

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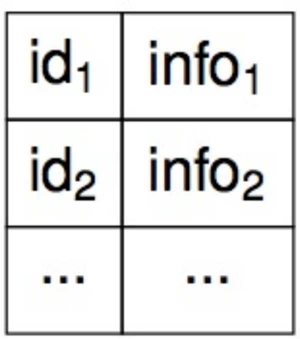
Symbol Table Structure[结构]

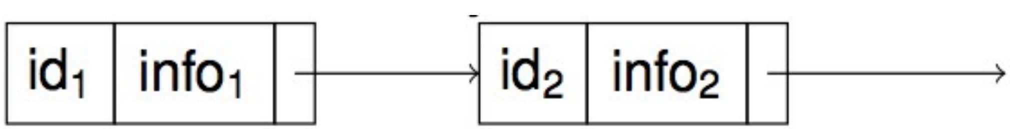
- Frontend time affected by symbol table access time[符号表访问时间影响编译前端性能]
  - Frontend: lexical, syntax, semantic analyses
  - Frequent searches on any large data structure is expensive
  - Symbol table design is important for compiler performance

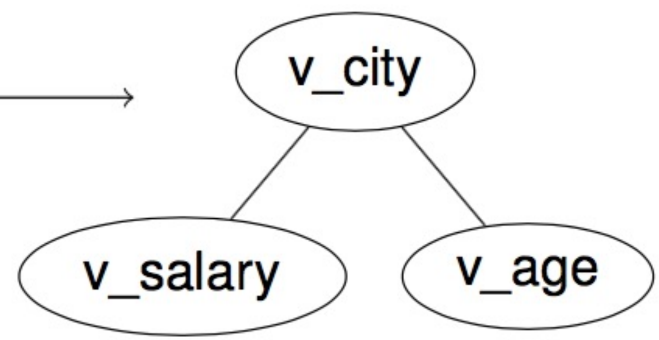
- What data structure to choose?[可选数据结构]
  - **List**[线性表]
  - **Binary tree**[二叉树]
  - **Hash table**[哈希表]
- Tradeoffs: time vs. space[空间和时间的权衡]
  - Let us first consider the organization w/o scope

Symbol Table Structure (cont.)

- **Array**: no space wasted, insert/delete: O(n), search: O(n)
- **Linked list**: extra pointer space, insert/delete: O(1), search: O(n)
  - Optimization: move recently used identifier to the head
  - Frequently used identifiers are found more quickly
- **Binary tree**: use more space than array/list
  - But insert/delete/search is O(log n) on balanced tree
  - In the worst case, tree may reduce to linked list
    - Then insert/delete/search becomes O(n)

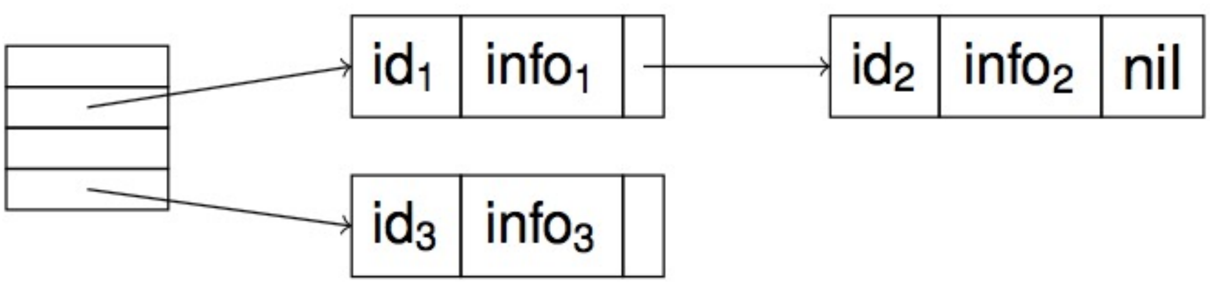






Symbol Table Structure (cont.)

- *hash(id_name)* → *index*[哈希表]
  - A hash function decides mapping from identifier to index
  - Conflicts resolved by chaining multiple IDs to same index
- Memory consumption from hash table (*N* << *M*)
  - M: the size of hash table
  - N: the number of stored identifiers
- But insert/delete/search in O(1) time
  - Can become O(n) with frequent conflicts and long chains
- Most compilers choose hash table for its quick access time



Adding Scope to Symbol Table[作用域]

- To handle multiple scopes in a program,[处理多个作用域]
  - Conceptually, need an individual table for each scope
    - In order to be able to enter and exit scopes
- Sometimes symbols in scope can be discarded on exit:

```
if (...) { int v; } /* block scope */
/* v is no longer valid */
```

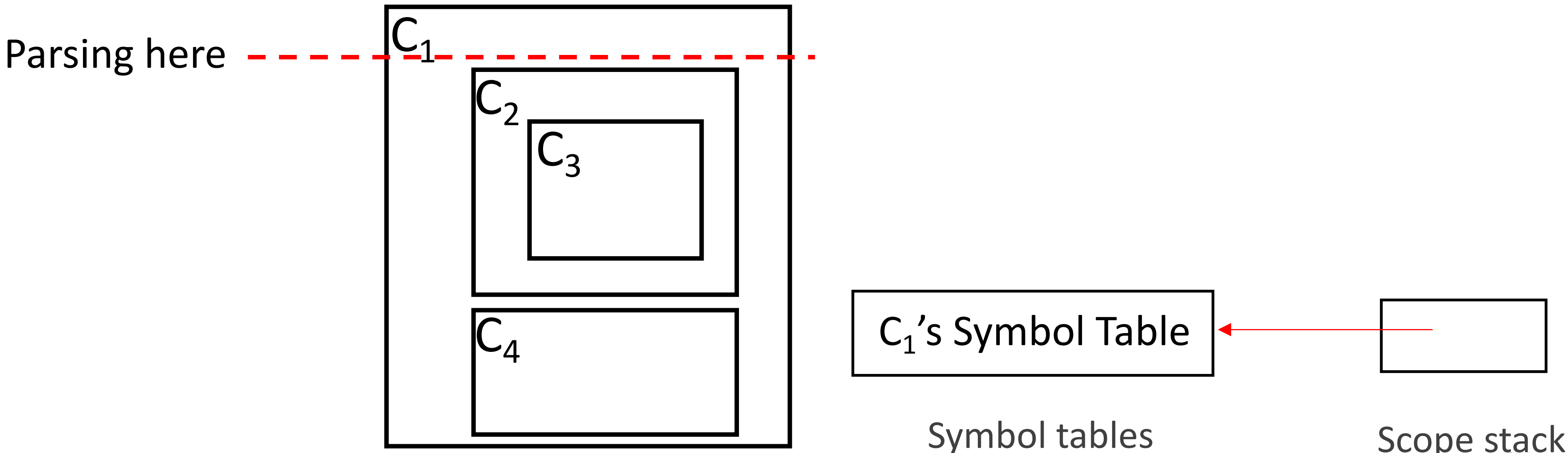
- Sometimes not:

```
class X { ... void foo() {...} ... } /* class scope */
/* foo() is no longer valid */
X v;
call v.foo(); /* v.foo() is still valid */
```

- How can scoping be enforced without discarding symbols?
  - Keep a *stack* of active scopes at a given point
  - Keep a *list* of all reachable scopes in the entire program

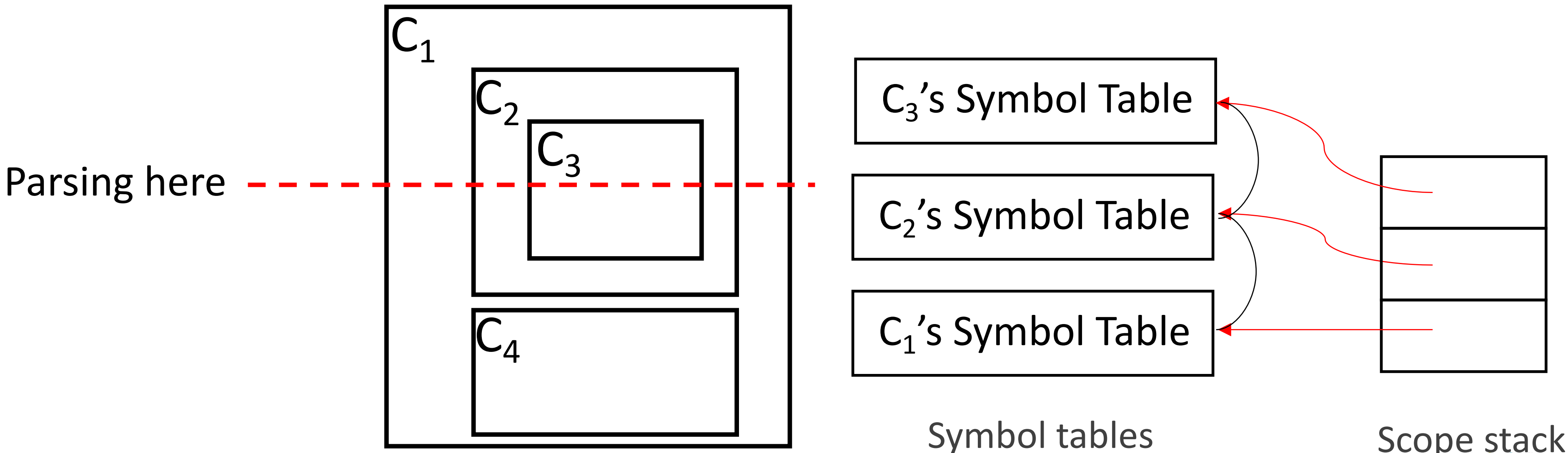
Handle Scopes with Stack

- Organize all symbol tables into a scope stack[作用域栈]
  - An individual symbol table for each scope
    - Scope is defined by nested lexical structure, e.g., {C_1 {C_2 {C_3}} {C_4}}
  - Stack holds one entry for each open scope
    - Innermost scope is stored at the top of the stack
- Stack push/pop happen when entering/exiting a scope



Handle Scopes with Stack (cont.)

- Operations
  - When entering a scope
    - Create a new symbol table to hold all variables declared in that scope
    - Push a pointer to the symbol table on the stack
  - Pop the pointer to the symbol table when exiting scope
  - Search from the top of the stack



Handle Scopes with Stack (cont.)

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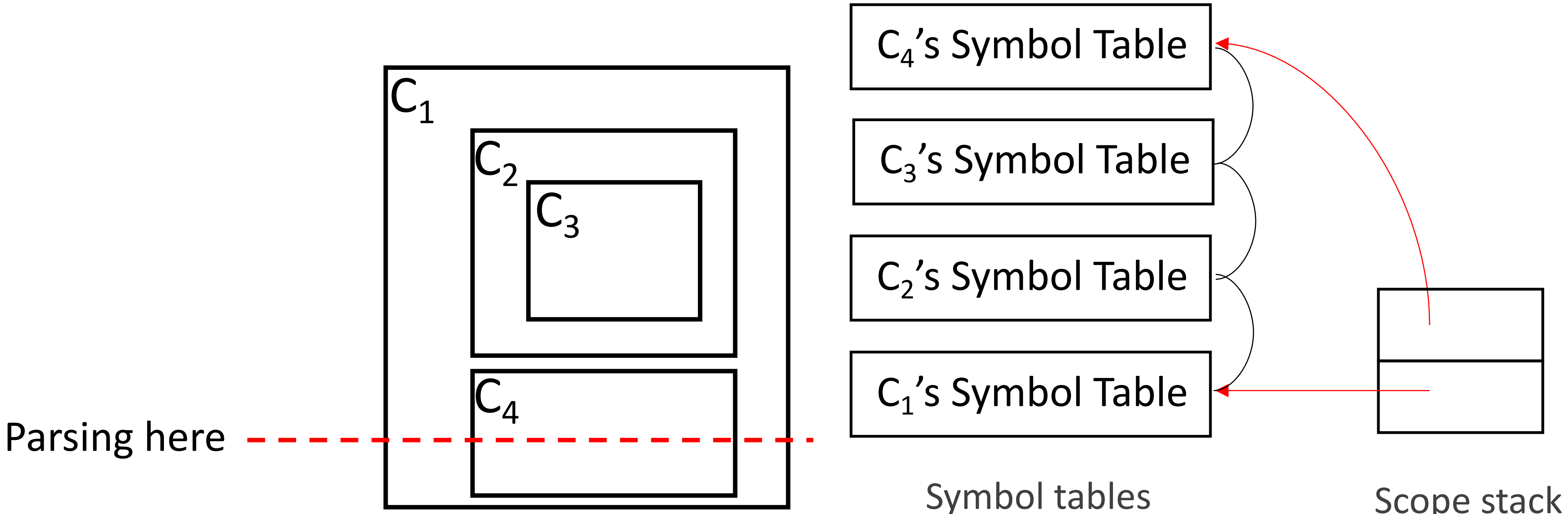
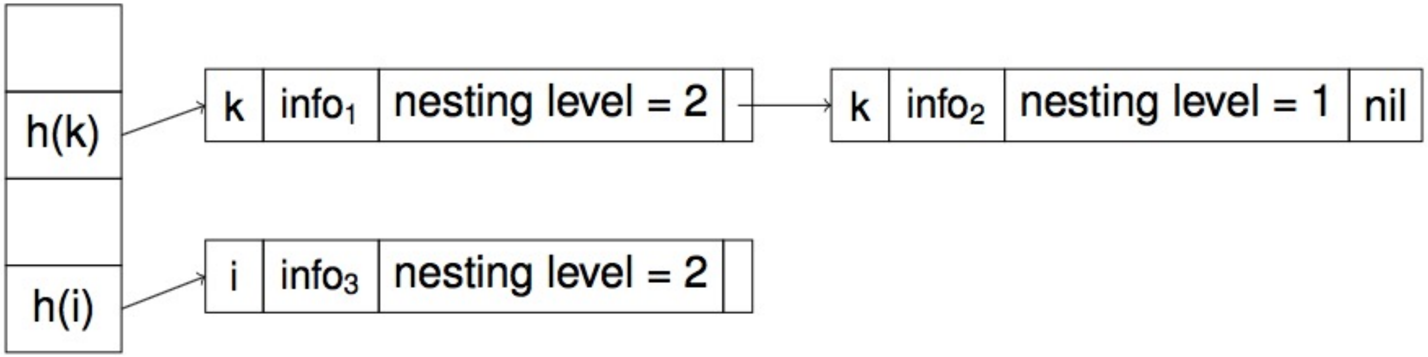


Handle Scopes using Chaining

- Cons of stacking symbol tables[栈方式的缺点]
  - Inefficient searching due to multiple hash table lookups
    - All global variables will be at the bottom of the stack
  - Inefficient use of memory due to multiple hash tables
    - Must size hash tables for max anticipated size of scope
- Solution: single symbol table for all scopes using chaining
  - Insert: insert *(ID, current nesting level)* at front of chain
  - Search: fetch ID at the front of chain
  - Delete: when exiting level *k*, remove all symbols with level *k*
    - For efficient deletion, IDs for each level maintained in a list



Handle Scopes using Chaining (cont.)

- Note: symbol table only maintains currently active scopes
  - All entries with the closing scope are deleted upon exiting
- Note: does not maintain list of all reachable scopes
  - Cannot refer back to old scopes that have been exited
  - Still useful for block scopes that are discarded on exit

- Usages
  - Unsuitable for class scopes (only block scopes)[✗]
  - Exiting scopes is slightly more expensive[✗]
    - Requires traversing the entire symbol table
  - Lookup requires only a single hash table access[✓]
  - Savings in memory due to single large hash table[✓]

Info Stored in Symbol Table

- Entry in symbol table
  - String: the name of identifier
  - Kind: function, variable, struct type, class type

string	kind	attributes

- Attributes vary with the kind of symbols
  - variable: type, address of variable
  - function: prototype, address of function body
  - struct type: field names, field types
  - class type: symbol table for class

Attribute List in Symbol Table

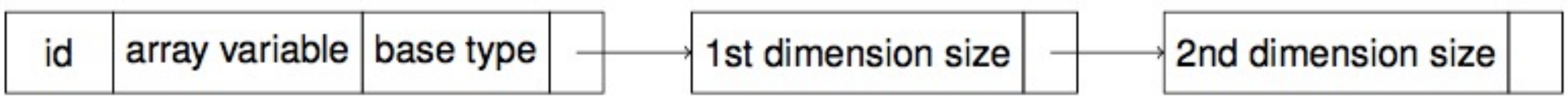
- Type info can be arbitrarily complicated
  - Type can be an array with multiple dimensions

    ```
    char arr[20][20];
    ```

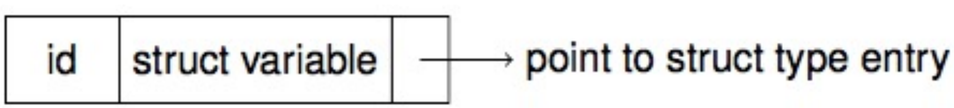
  - Type can be a struct with multiple fields

    ```
    struct Point {
            float x;
            float y;
        } point;
    ```

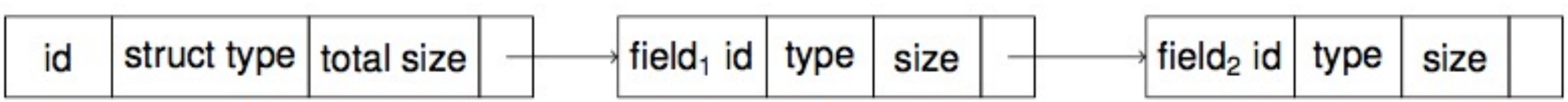
- Store all type info in an attribute list
  - Entry for an array variable with 2 dimensions



  - Entry for a struct variable



  - Entry for a struct type with 2 fields



Use Type Information[类型信息]

- Each variable or function entry contains type info
- Type info is used in later code generation stage[代码生成]
  - To calculate how much memory to alloc for a variable
  - To translate uses of variables to machine instructions
    - Should a '+' on variable be an integer or a floating point add?
    - Should a variable assignment be a 4 byte or 8 byte copy?
  - To translate calls to functions to machine instructions
    - What are the types of arguments passed to the function?
    - What is the type of value returned by the function?
- Also used in later code optimization stage[代码优化]
  - To help compiler understand semantics of program
- Also used in semantic analysis stage for ***Type Checking***
  - Uses types to check semantic correctness of program

Type and Type Checking

- **Type**: a set of values + a set of operations on these values
  - int/double: same memory storage
- **Type checking**: verifying type consistency across program[类型一致性检查]
  - A program is said to be type consistent if all operators are consistent with the operand value types
  - Much of what we do in semantic analysis is type checking
- Some type checking examples:
  - Given char *str = “Hello”;
    - str[2] is consistent: char* type allows [] operator
    - str/2 is not: char* type does not allow / operator
  - Given int pi = 3;
    - pi/2 is consistent: int type allows / operator
    - pi=3.14 is not: = operator not allowed on different types
      - Compiler must type convert implicitly to make it consistent

Static Type Checking[静态类型检查]

- Static type checking: at compile time[静态：编译时]
  - Infers program is type consistent through code analysis
    - Collect info via declarations and store in symbol table
    - Check the types involved in each operation
  - E.g., int a, b, c; a = b + c; can be proven type consistent because the addition of two *int*s is an *int*

- Difficult for a language to only do static type checking
  - Some type errors usually cannot be detected at compile time
    - E.g., a and b are of type *int*, a * b may not in the valid range of *int*
    - Typecasting can be pretty risky thing to do (Basically, typecast suspends type checking)
      - unsigned a; (int)a;

Dynamic Type Checking[动态检查]

- Dynamic type checking: at execution time[动态：执行时]
  - Type consistency by checking types of runtime values
  - Include type info for each data location at runtime
    - E.g., a variable of type double would contain both the actual double value and some kind of tag indicating "double type"
    - The execution of any operation begins by first checking these type tags
    - The operation is performed only if everything checks out (otherwise, a type error occurs and usually halts execution)
  - E.g., C++/Java downcasting to a subclass
    - Is `dynamic_cast<Child*>(parent);` type consistent?
  - Array bounds check:
    - Is `int A[10], i; … A[i] = i;` type consistent?
- Static type checking is always more desirable. Why?
  - Always good to catch more errors before runtime
  - Dynamic type checking carries runtime overhead

Static vs. Dynamic Typing[静态-动态]

- Static typing: C/C++, Java, …
  - Variables have static types → hold only one type of value
    - E.g. int x; → x can only hold ints
    - E.g. char *x; → x can only hold char pointers
  - How are types assigned to variables?
    - C/C++, Java: types are explicitly defined
    - int x; → explicit assignment of type int to x
- Pros / cons of static typing
  - More programmer effort
    - Programmer must adhere to strict type rules
    - Defining advanced types can be quite complex (e.g. classes)
  - Less program bugs and execution time
    - Thanks to static type checking

Static vs. Dynamic Typing (cont.)

- Dynamic Typing: Python, JavaScript, PHP, ...
  - Variables have dynamic types → can hold multiple types

```
var x; /* var declaration without a static type */
x = 1; /* now x holds an integer value */
x = "one"; /* now x holds a string value */
```

  - How are types assigned to variables?
    - Type is a runtime property → type tags stored with values
    - Dynamic type checking must be done during runtime
- Pros / cons of dynamic typing
  - Less programmer effort
    - Flexible type rule means program is more malleable
    - Absence of types / classes declarations means shorter code
    - Makes it suitable for scripting or prototyping languages
  - More program bugs and execution time
    - Due to dynamic type checking

Type System[类型系统]

- Static / dynamic typing are type systems
  - **Type System**: types + type rules of a language
- Static / dynamic type checking are methods
  - Methods to enforce the rules of the given type system
- Static type checking is not used exclusively for static typing
  - Static type checking also used for dynamic typing
  - If certain types can be inferred and checked at compile time
    - Can reduce dynamic type checks inserted into code
- Dynamic type checking is not used only for dynamic typing
  - Some features of statically typed languages require it
    - e.g. downcasting requires type check of object type tag

Type Systems: Soundness, Completeness

- Static type checking through inference
  - Inference: deducing a conclusion[结论] from a set of premises[前提]
  - What are the premises? Type rules in the type system
  - What is the conclusion? Accept / reject after applying rules
- A type system is said to be *Sound[可靠]* if:
  - Only correct programs are accepted
  - Flipside: all incorrect programs are rejected
- A type system is said to be *Complete[完备]* if:
  - All correct programs are accepted
  - Flipside: only incorrect programs are rejected
- A type system strives to be both sound and complete
  - The rules of inference (type rules) should reflect that

Rules of Inference

- What are rules of inference?
  - Inference rules have the form

    if Precondition is true, then Conclusion is true
  - Below concise notation used to express above statement

    $$\frac{\text{Precondition}}{\text{Conclusion}}$$
  - For example: Given E3 → E1 + E2, a rule may be:

    if E1, E2 are type consistent and int types (Precondition),
    then E3 is type consistent and is an int type (Conclusion)
- Recursive type checking via inference
  - Start from variable and constant types at bottom of tree
    - Serves as initial preconditions for the inference
  - Apply rules on operator nodes while working up the tree
    - Checks type consistency and assigns type to node

LLVM: Semantic Analysis

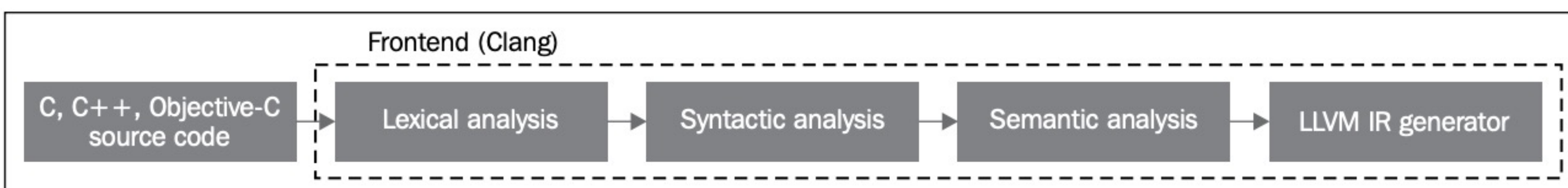
- Clang does not traverse the AST after parsing
  - Instead, it performs type checking on the fly, together with AST node generation

```
StmtResult Parser::ParseIfStatement(SourceLocation *TrailingElseLoc) {

    // perform semantic checking for the if statement, emitting diagnostics accordingly
    return Actions.ActOnIfStmt(IfLoc, IsConstexpr, InitStmt.get(), Cond,
                                ThenStmt.get(), ElseLoc, ElseStmt.get());
}
```

https://github.com/llvm-mirror/clang/blob/master/lib/Parse/ParseStmt.cpp
https://clang.llvm.org/doxygen/ParseAST_8cpp_source.html

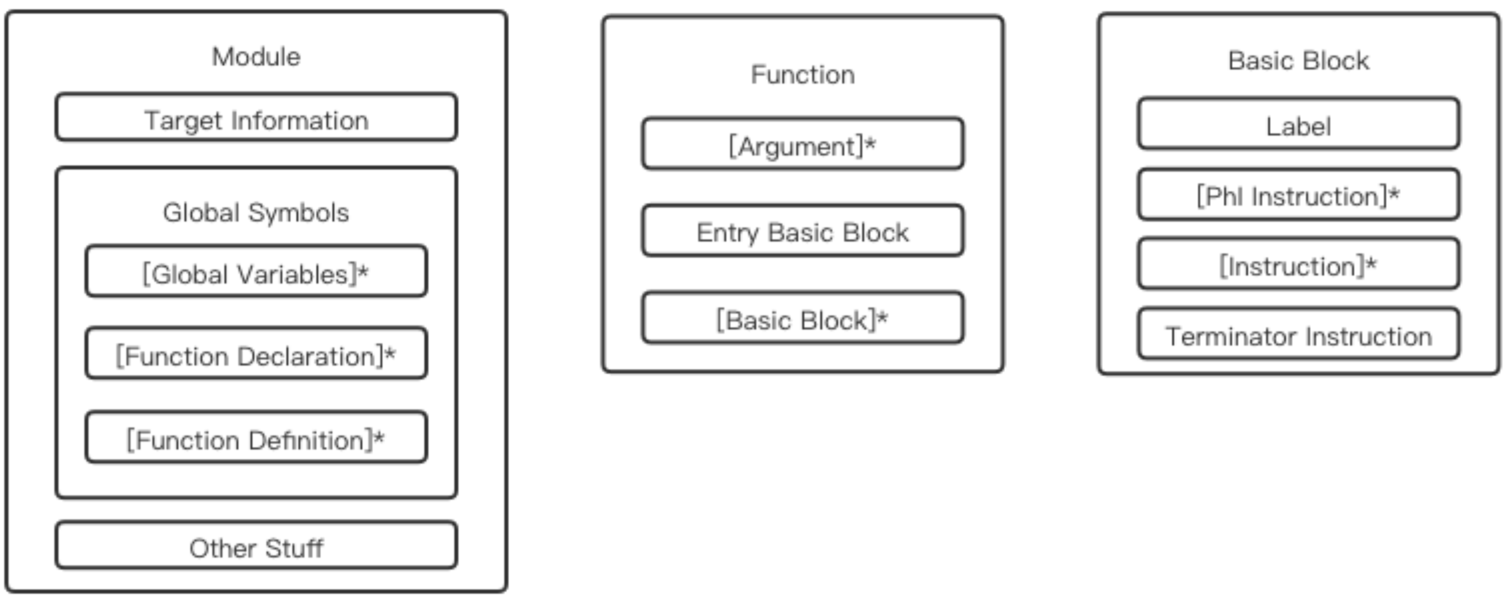
  - After the combined parsing and semantic analysis, the ParseAST function invokes the method HandleTranslationUnit to trigger any client that is interested in consuming the final AST.



Bruno Cardoso Lopes and Rafael Auler, Getting Started with LLVM Core Libraries

LLVM: Module

- The Module class represents the top level structure present in LLVM programs
  - An LLVM module is effectively either a translation unit of the original program or a combination of several translation units merged by the linker
  - The Module class keeps track of a list of Functions, a list of GlobalVariables, and a **SymbolTable**



https://releases.llvm.org/7.1.0/docs/ProgrammersManual.html#symboltable

LLVM: Symbol Table

- Public members of Module class
  - *SymbolTable *getSymbolTable()*
    - Return a reference to the SymbolTable for this Module
  - *Function *getOrInsertFunction(const std::string &Name, const FunctionType *T)*
    - Look up the specified function in the Module SymbolTable. If it does not exist, add an external declaration for the function and return it.
  - *std::string getTypeName(const Type *Ty)*
    - If there is at least one entry in the SymbolTable for the specified Type, return it. Otherwise return the empty string
  - *bool addTypeName(const std::string &Name, const Type *Ty)*
    - Insert an entry in the SymbolTable mapping Name to Ty. If there is already an entry for this name, true is returned and the SymbolTable is not modified.