Compilation Principle
编 译 原 理

第15讲：语义分析(5)

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Review Questions (1)

- 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.

- For L-SDD in LL parsing, how to extend the parse stack?

  Action record – symbol (inh) – synthesized record (syn).

- For L-SDD in LL parsing, we add data-items?

  When popping symbol or syn-record, attr values should be copied.

Review Questions (2)

- 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.

- What is symbol table?

  A structure to record info of each symbol name in a program.

- Is the symbol table deleted after semantic analysis?

  NO. Symbol table is still needed by code generation.

- Why static scoping is better than dynamic?

  Fewer programmer errors, more efficient code.

Maintaining Symbol Table[维护]

- Basic idea

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

  - Before 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

Symbol Table Structure[结构]

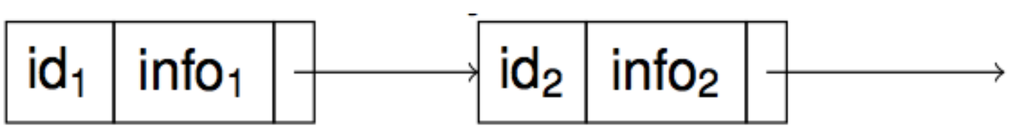
- Frontend time affected by symbol table access time[符号表访问时间影响编译前端性能]
  - Frontend: lexical, syntax, semantic analyses
  - Frequent searches on any large data structure is expensive
  - Symbol table design is important for compiler performance

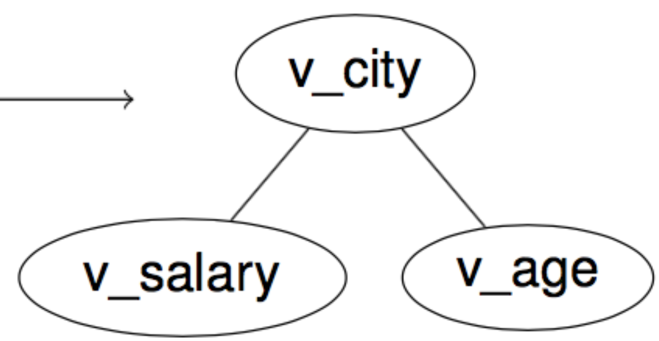
- What data structure to choose?[可选数据结构]
  - **List**[线性表]
  - **Binary tree**[二叉树]
  - **Hash table**[哈希表]
- Tradeoffs: time vs. space[空间和时间的权衡]
  - Let us first consider the organization w/o scope

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)

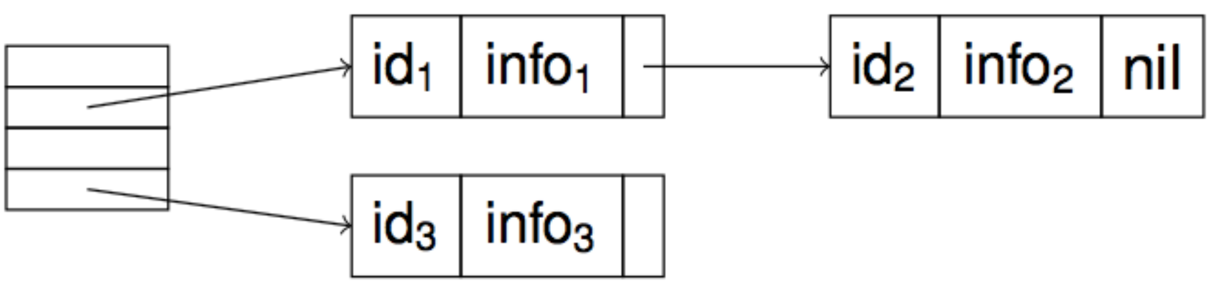
id_1	$info_1$
id_2	$info_2$
...	...





Hash Table[哈希表]

- *hash(id_name) → index*
  - 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

- 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 */
```

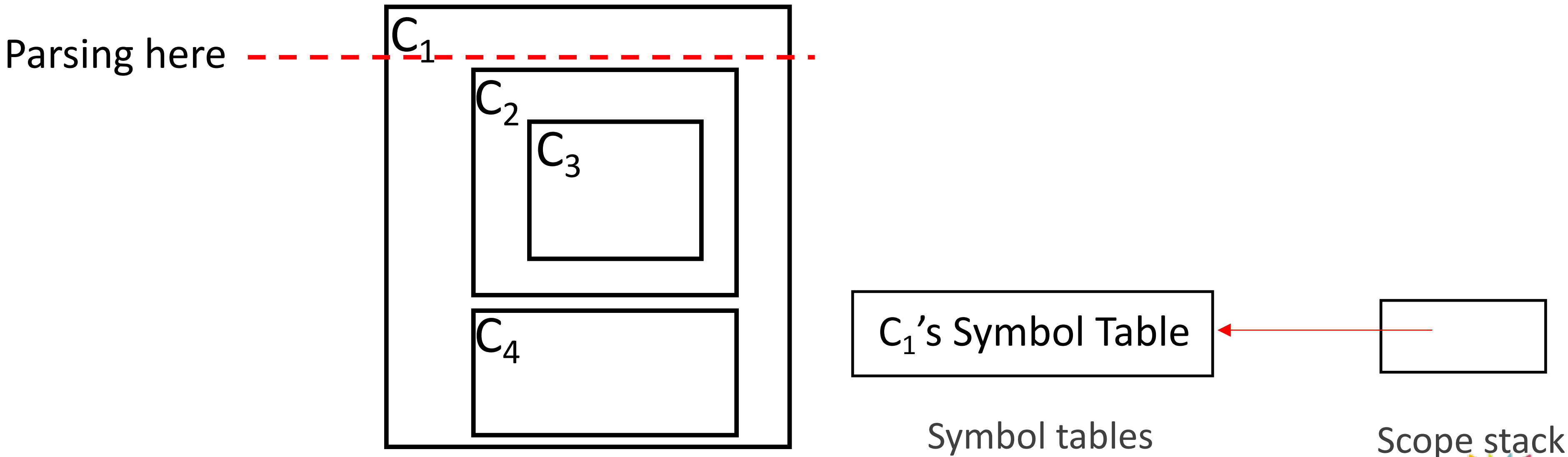
- Sometimes not:

```
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

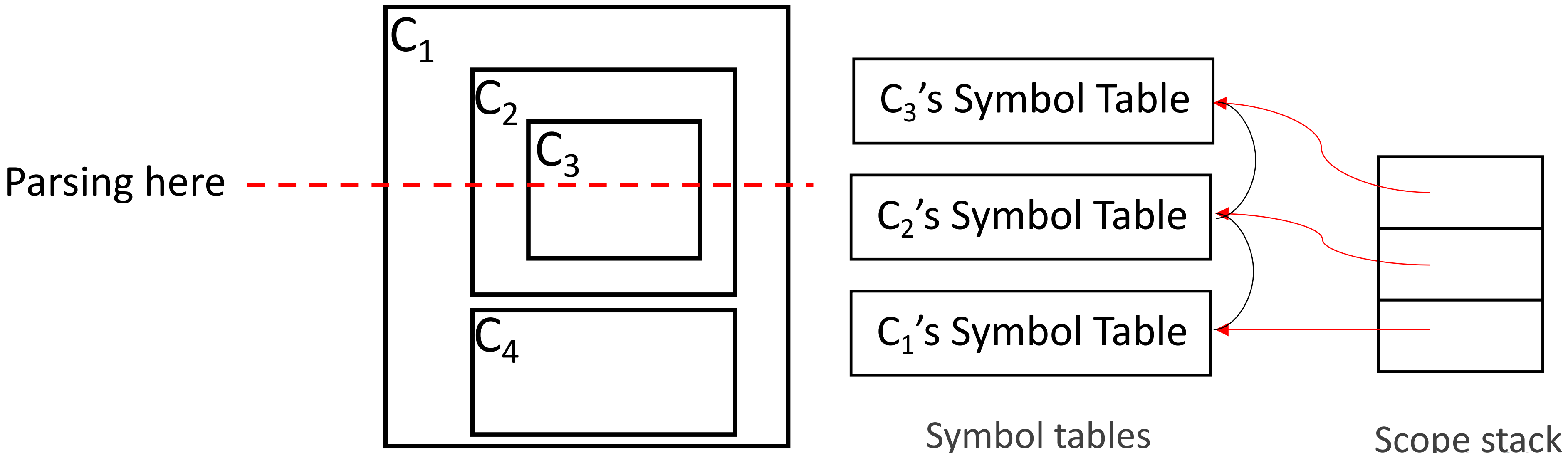
Handle Scopes with Stack

- 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



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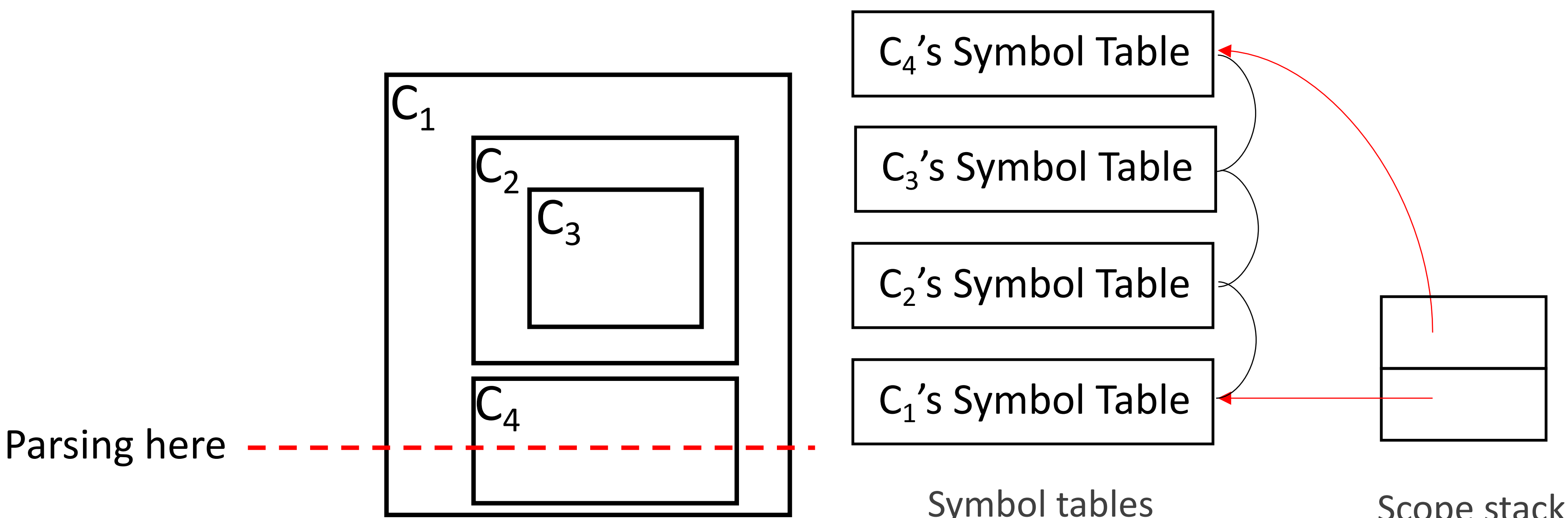
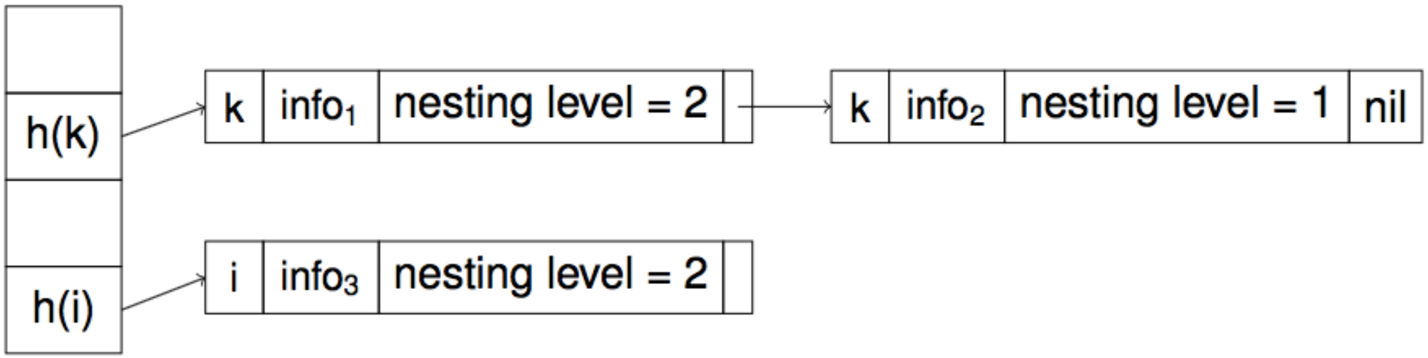


Handle Scopes using Chaining

- 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: <u>single symbol table for all scopes</u> 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

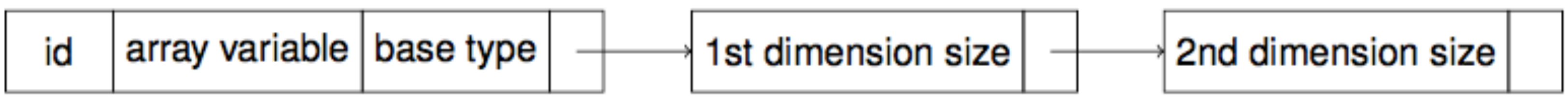
- Type info can be arbitrarily complicated
  - Type can be an array with multiple dimensions

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

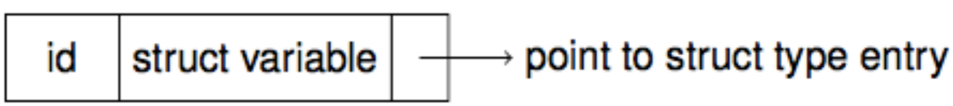
  - Type can be a struct with multiple fields

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

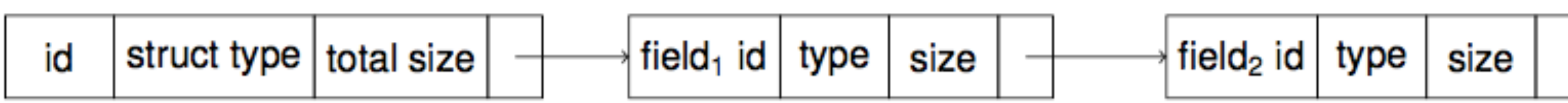
- Store all type info in an attribute list
  - Entry for an array variable with 2 dimensions



  - 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 allot 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

Semantic Analysis (5)

Type Checking

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 desirable to catch more errors before runtime
  - Dynamic type checking carriers runtime overhead

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Static vs. Dynamic Typing[静态-动态]

- Static typing: C/C++, Java, …
  - Variables have static types → holds 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 Systems[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

考核要求

- 编译原理
  - 课堂参与（10%）- 点名、提问、测试
  - 课程作业 （20%）- 4次左右，理论
  - 期中考查 （10%）- 课下习题
  - 期末考试 （60%）- 闭卷

- 编译器构造实验
  - Project 1（25%）- Lexical Analysis
  - Project 2（25%）- Syntax Analysis
  - Project 3（25%）- Semantic Analysis
  - Project 4（25%）- Code Generation

平时成绩（12%）
- Project 1（22%）
- Project 2（22%）
- Project 3（22%）
- Project 4（22%）