Compilation Principle
编 译 原 理

第14讲：语义分析(4)

张献伟

xianweiz.github.io

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Review Questions (1)

- How is Semantic Rules differing from Actions?

  Rules are used in SDD, actions are for SDT. Actions are specifically placed at somewhere of the production body.

- What is S-SDD?

  Synthesized-SDD, with only synthesized attributes.

- S-SDD is suitable for bottom-up or top-down parsing?

  Bottom-up. Natural to evaluate the parent after seeing all children.

- How to convert an S-SDD into SDT?

  Place each rule inside ‘{}’ at the end of production.

- If implementing the SDT of S-SDD in LR parsing, when to execute the actions?

  Along with reduction.

Review Questions (2)

A -> X Y Z	Y.*i* = f(Z.*z*, A.*s*)

- Is the SDD a L-SDD?

  NO. Z is right to Y, A.s is synthesized attribute.

- Why do we prefer to do semantic analysis during parsing?

  Skip parse-tree generation, saving time and memory.

- For S-SDD in LR-parsing, how to change parse stack?

  Save synthesized attributes into the stack, along with state/symbol.

- How to convert L-SDD into SDT?

  Inherited rules: place before the non-terminal; syn: production end.

- L-SDD can be implemented in LL- or LR-parsing?

  Both. LL: predictive, recursive-descent; LR

L-SDD in LL Parsing[非递归预测]

- Extend the parse stack to hold **actions** and certain **data items** needed for attribute evaluation[扩展语法分析栈]
  - Action-record[动作记录]: represent the actions to be executed
  - Synthesize-record[综合记录]: hold synthesized attributes for non-terminals
  - Typically, the data items are copies of attributes[属性备份]
- Manage attributes on the stack[管理属性信息]
  - The inherited attributes of a nonterminal A are placed in the <u>stack record</u> that represents that terminal[符号位放继承属性]
    - Action-record to evaluate these attributes are immediately <u>above</u> A
  - The synthesized attributes of a nonterminal A are placed in a separate synthesize-record that is immediately <u>below</u> A[综合属性另存放]

action	Code
A	Inh Attr.
A.syn	Syn Attr.

L-SDD in LL Parsing (cont.)

- Table-driven LL-parser
  - Mimics a leftmost derivation --> stack expansion

- A -> BC, suppose nonterminal C has an inherited attr C.*i*
  - C.*i* may depend not only on the inherited attr. of A, but on all the attrs of B
    - Extra care should be taken on the attribute values
  - Since SDD is L-attributed, surely that the values of the inherited attrs of A are available when A rises to stack top
    - Thus, available to be copied into C
  - A's synthesized attrs remain on the stack, below B and C when expansion happens

action	Code
A	Inh Attr.
A.syn	Syn Attr.

L-SDD in LL Parsing (cont.)

- A -> BC: C.*i* may depend not only on the inherited attr. of A, but on all the attrs of B
  - Thus, need to process B completely before C.*i* can be evaluated
  - Save temporary copies of all attrs needed by evaluate C.*i* in the action-record that evaluates C.*i*; otherwise, when the parser replaces A on top of the stack by BC, the inherited attrs of A will be gone, along with its stack record
  - 变量展开时（i.e., 变量本身的记录出栈时），若其含有集成属性，则要将集成属性复制给后面的动作记录
  - 综合记录出栈时，要将综合属性值复制给后面的动作记录

action	Code
A	
A.syn	

Example

(1) T -> F { T'.*inh* = F.*val* } T' { T.*val* = T'.*syn* }

(2) T' -> * F { T_1'.*inh* = T'.*inh* x F.*val* } T_1' { T'.*syn* = T_1'.*syn* }

(3) T' -> ε { T'.*syn* = T'.*inh* }
(4) F -> digit { F.*val* = digit.*lexval* }

Three kinds of symbols:
1) Terminal
2) Non-terminal
3) Action symbol

(1) T -> F { a_1 } T' { a_2 } (2) T' -> * F { a_3 } T_1' { a_4 } (3) T' -> ε { a_5 } (4) F -> digit { a_6 }	a_1: T'.*inh* = F.*val* a_2: T.*val* = T'.*syn* a_3: T_1'.*inh* = T'.*inh* x F.*val* a_4: T'.*syn* = T_1'.*syn* a_5: T'.*syn* = T'.*inh* a_6: F.*val* = digit.*lexval*

Example (cont.)

(1) T -> F { a_1 } T' { a_2 }	a_1: T'.*inh* = F.*val*
	a_2: T.*val* = T'.*syn*
(2) T' -> * F { a_3 } T_1' { a_4 }	a_3: T_1'.*inh* = T'.*inh* x F.*val*
	a_4: T'.*syn* = T_1'.*syn*
(3) T' -> ε { a_5 }	a_5: T'.*syn* = T'.*inh*
(4) F -> digit { a_6 }	a_6: F.*val* = digit.*lexval*

Input: 3 * 5

Stack top 'digit' matches the input '3'
- pop 'digit', but value copy is needed

a_6: stack[top-1].*val* = stack[top].*d_lexval*

digit	{ a_6 }	Fsyn	{ a_1 }	T'	T'syn	{ a_2 }	Tsyn	$
lexv=3	d_lexv=3	val =3	val=3	inh	val		val	

完整步骤见👉： MOOC:语法制导翻译-3

L-SDD in LR Parsing

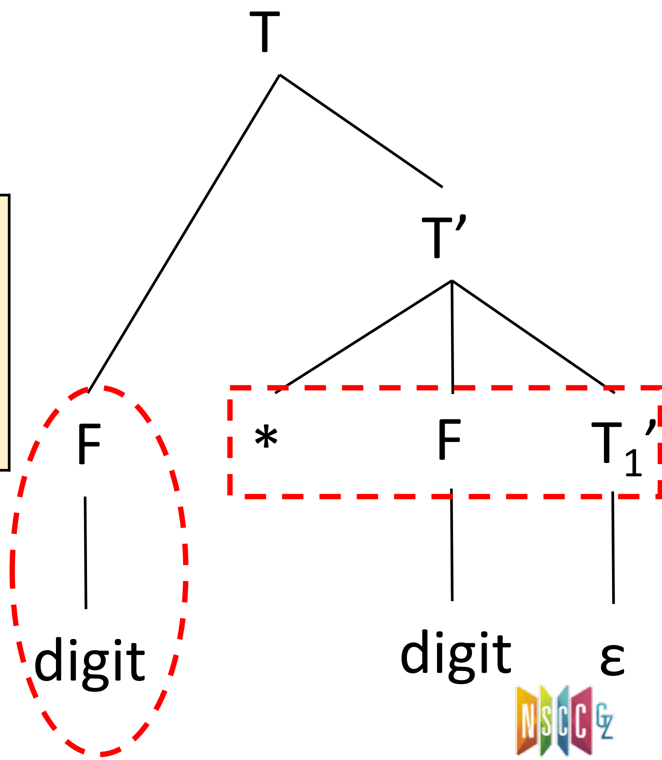
- What we already learnt
  - LR > LL, w.r.t parsing power
    - We can do bottom-up every translation that we can do top-down
  - S-attributed SDD can be implemented in bottom-up way
    - All semantic actions are at the end of productions, i.e., triggered in reduce
- For L-attributed SDD on an LL grammar, can it be implemented during bottom-up parsing?
  - Problem: semantic actions can be in anywhere of the production body

(1) T -> F { T'.*inh* = F.*val* } T' { T.*val* = T'.*syn* }
(2) T' -> * F { T_1'.*inh* = T'.*inh* x F.*val* } T_1' { T'.*syn* = T_1'.*syn* }
(3) T' -> ε { T'.*syn* = T'.*inh* }
(4) F -> digit { F.*val* = digit.*lexval* }

The Problem

- It is not natural to evaluate inherited attributes
  - Example: how to get T'.*inh*
- Claim: inherited attributes are on the stack
  - Left attributes guarantee they've already been computed
  - But computed by previous productions – deep in the stack
- Solution
  - **Hack the stack to dig out those values**

(1) T -> F { T'.*inh* = F.*val* } T' { T.*val* = T'.*syn* }
(2) T' -> * F { T_1'.*inh* = T'.*inh* x F.*val* } T_1' { T'.*syn* = T_1'.*syn* }
(3) T' -> ε { T'.*syn* = T'.*inh* }
(4) F -> digit { F.*val* = digit.*lexval* }



Marker

- Given the following SDD, where $|\alpha| \neq |\beta|$

  A -> X α { Y.*in* = X.*s* } Y | X β { Y.*in* = X.*s* } Y

  Y -> γ { Y.*s* = f(Y.*in*) }

- Problem: cannot generate stack location for Y.*in*
  - Because X.*s* is at different relative stack locations from Y

- Solution: insert markers M_1, M_2 right before Y

  A -> X α M_1 Y | X β M_2 Y

  Y -> γ { Y.*s* = f(stack[top - $|\gamma|$].*s*) } // Y.*s* = M_1.*s* or Y.*s* = M_2.*s*

  M_1 -> ε { M_1.*s* = stack[top - $|\alpha|$].*s* } // M_1.*s* = X.*s*

  M_2 -> ε { M_2.*s* = stack[top - $|\beta|$].*s* } // M_2.*s* = X.*s*

Modify Grammar with Marker

- Given an L-SDD on an LL grammar, we can adapt the grammar to compute the same SDD during an LR parse
  - Introduce into the grammar a **marker nonterminal**[标记非终结符] in place of each embedded action
    - Each such place gets a distinct marker, and there is one production for any marker M, M -> ε [空产生式]
  - Modify the action a if marker nonterminal M replaces it in some production A -> α { a } β, and associate with M -> ε an action a' that
    - Copies, as inherited attrs of M, any attrs of A or symbols of α that action a needs (e.g., M.*i* = A.*i*)
    - Computes attrs in the same way as a, but makes those attrs be synthesized attrs of M (e,.g., M.*s* = f(M.*i*))

A -> { B.*i* = f(A.*i*); } B C

A -> M B C
M -> ε { M.*i* = A.*i*; M.*s* = f(M.*i*); }

Example

(1) T -> F { T'.*inh* = F.*val* } T' { T.*val* = T'.*syn* }
(2) T' -> * F { T_1'.*inh* = T'.*inh* x F.*val* } T_1' { T'.*syn* = T_1'.*syn* }
(3) T' -> ε { T'.*syn* = T'.*inh* }
(4) F -> digit { F.*val* = digit.*lexval* }

(1) T -> F **M** T' { T.*val* = T'.*syn* }
  M -> ε { M.i = F.val; M.s = M.i }
(2) T' -> * F **N** T_1' { T'.*syn* = T_1'.*syn* }
  N -> ε { N.i1 = T'.inh; N.i2 = F.val; N.s = N.i1 x N.i2 }
(3) T' -> ε { T'.*syn* = T'.*inh* }
(4) F -> digit { F.*val* = digit.*lexval* }

Stack Manipulation[栈操作]

(1) T -> F { T'.*inh* = F.*val* } T' { T.*val* = T'.*syn* }
(2) T' -> * F { T_1'.*inh* = T'.*inh* x F.*val* } T_1' { T'.*syn* = T_1'.*syn* }
(3) T' -> ε { T'.*syn* = T'.*inh* }
(4) F -> digit { F.*val* = digit.*lexval* }

(1) T -> F **M** T' { T.*val* = T'.*syn* }
M -> ε { M.i = F.val; M.s = M.i }
(2) T' -> * F **N** T_1' { T'.*syn* = T_1'.*syn* }
N -> ε { N.i1 = T'.inh; N.i2 = F.val; N.s = N.i1 x N.i2 }
(3) T' -> ε { T'.*syn* = T'.*inh* }
(4) F -> digit { F.*val* = digit.*lexval* }

(1) T -> F **M** T' { stack[top-2].*val* = stack[top].*syn*; top = top - 2; }
M -> ε { stack[top+1].*T'inh* = stack[top].*val*; top = top + 1; }
(2) T' -> * F **N** T_1' { stack[top-3].*syn* = stack[top].*syn*; top = top -3; }
N -> ε { stack[top+1].*T'inh* = stack[top-2].*T'inh* x stack[top].*val*; top = top + 1; }
(3) T' -> ε { stack[top+1].*syn* = stack[top].T'*inh*; top = top + 1; }
(4) F -> digit { stack[top].*val* = stack[top].*lexval*; }

完整步骤见👉： MOOC:语法制导翻译-3

Semantic Analysis (4)

Symbol Table

Compilation Phases [编译阶段]

- Lexical analysis[词法分析]
  - Source code → tokens
  - Detects inputs with illegal tokens
  - Is the input program lexically well-formed?
- Syntax analysis[语法分析]
  - Tokens → parse tree or abstract syntax tree (AST)
  - Detects inputs with incorrect structure
  - Is the input program syntactically well-formed?
- Semantic analysis[语义分析]
  - AST → (modified) AST + **symbol table**
  - Detects semantic errors (errors in meaning)
  - Does the input program has a well-defined meaning?

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Overview of Symbol Table

- **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]

Variable[程序变量]

- What are **variables** in a program?
  - Variables are the names you give to computer memory locations which are used to store values in a computer program
  - Retrieve and update the variables using the names
- Variable **declaration** and **definition**[声明和定义]
  - Declaration: informs the compiler type and name of a variable[类型和名字]
  - Definition: to assign a memory[内存空间分配]
    - Once we assign or initialized a value compiler allocates the memory

```
int X, Y;               /* Declaration of X and Y */
int M = 0, N = -1; /* Declaration and definition of X and Y */
X = 7;                  /* Defining X */
/* In the end Y is still not defined */
```

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Example

```c
1 #include <stdio.h>
2
3 int g_val;
4
5 int main() {
6     int l_val;
7     static int s_val;
8
9     printf("g_val=%d, l_val=%d, s_val=%d\n", g_val, l_val, s_val);
10
11     return 0;
12 }
```

```
[xianwei@test>]$ gcc -Wall -g -o testc testc.c
testc.c:9:52: warning: variable 'l_val' is uninitialized when used here [-Wuninitialized]
   printf("g_val=%d, l_val=%d, s_val=%d\n", g_val, l_val, s_val);
                                                   ^~~~~

testc.c:6:13: note: initialize the variable 'l_val' to silence this warning
   int l_val;
            ^
             = 0
1 warning generated.
[xianwei@test>]$ ./testc
g_val=0, l_val=282353718, s_val=0
[xianwei@test>]$ ./testc
g_val=0, l_val=142671926, s_val=0
[xianwei@test>]$ ./testc
g_val=0, l_val=227987510, s_val=0
```

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 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[一个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

- 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
- For this class, 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; ... void foo() { int x; ... 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 nested 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