编译原理
Complier Principles

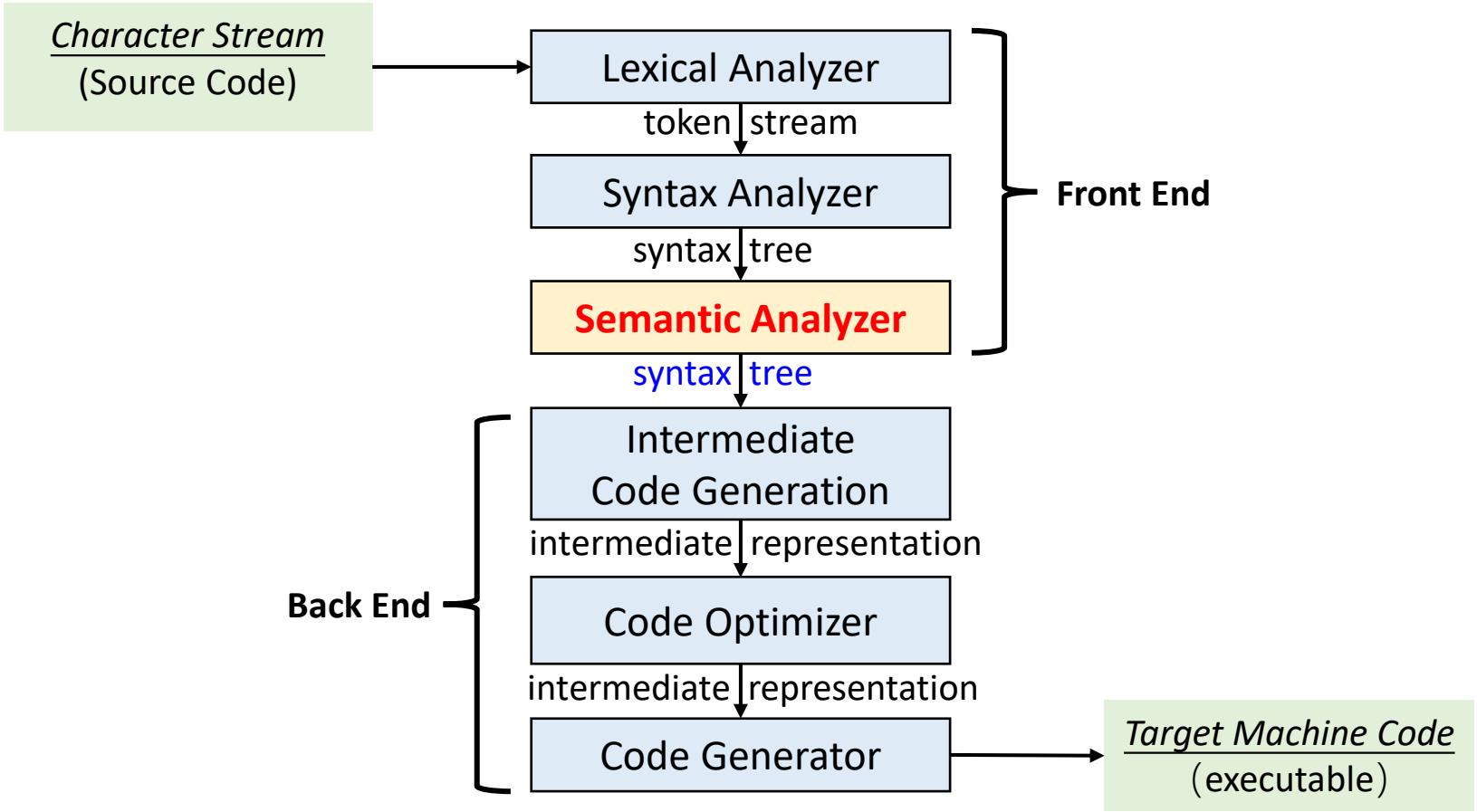
Lecture 6
Semantic Analysis: Intro & SDD & SDT

赵帅

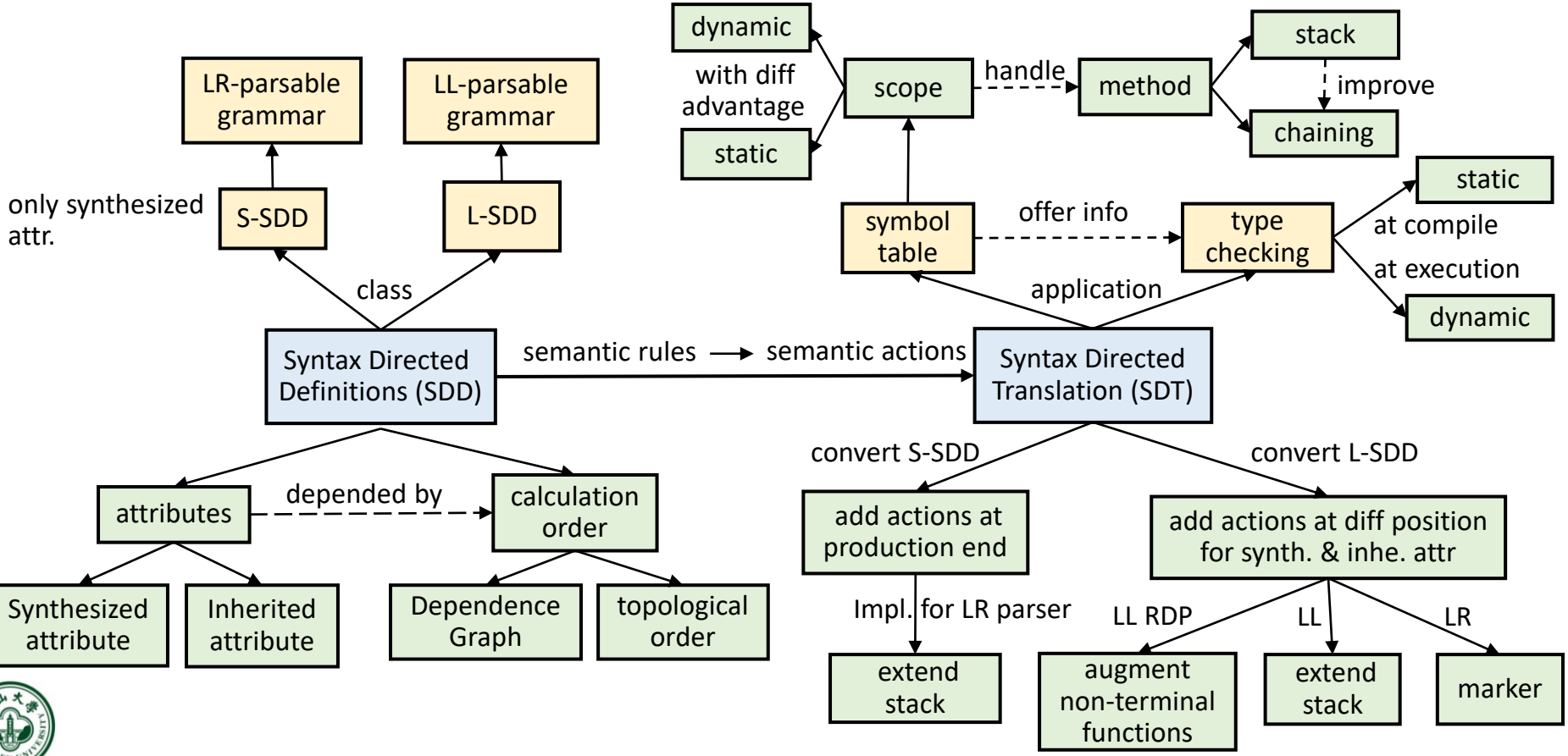
计算机学院

中山大学

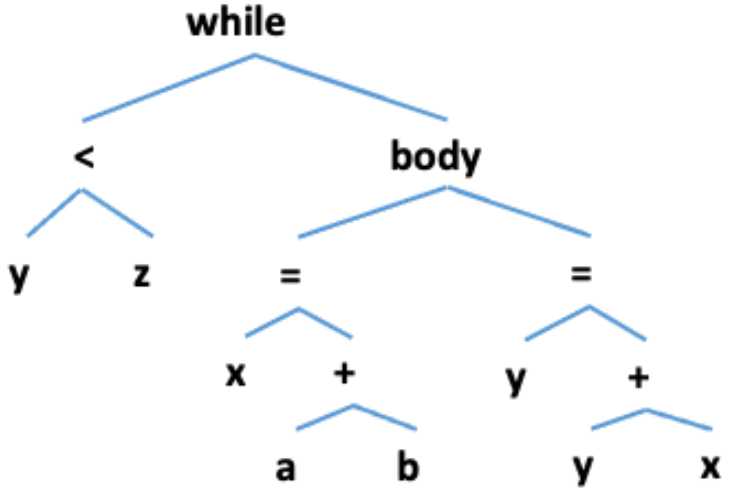
Compilation Phases[编译阶段]



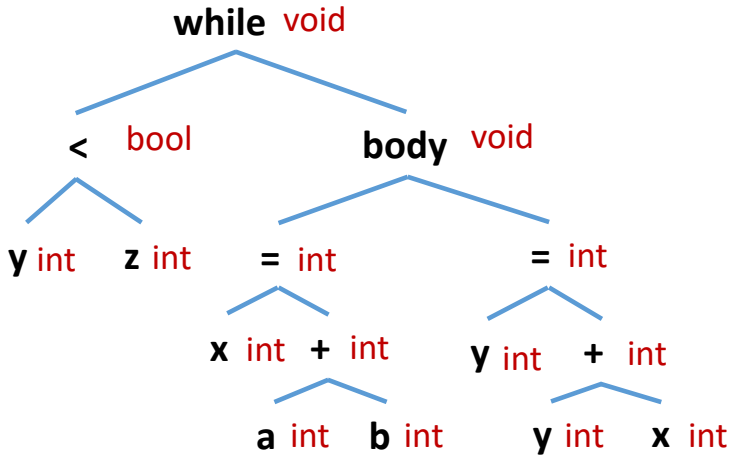
Content


LR-parsable grammar
LL-parsable grammar
only synthesized attr.
S-SDD
L-SDD
class
Syntax Directed Definitions (SDD)
semantic rules
semantic actions
Syntax Directed Translation (SDT)
attributes
depended by
calculation order
Synthesized attribute
Inherited attribute
Dependence Graph
topological order
dynamic
with diff advantage
static
scope
handle
method
stack
improve
chaining
symbol table
offer info
type checking
static
at compile
at execution
dynamic
application
convert S-SDD
convert L-SDD
add actions at production end
add actions at diff position for synth. & inhe. attr
Impl. for LR parser
LL RDP
LL
LR
extend stack
augment non-terminal functions
extend stack
marker

Compilation Phases[编译阶段]



Abstract Syntax Tree(AST)



Annotated AST/Decorated AST
[带标注的抽象语法树]

Why Semantic Analysis? [语义分析]

- Because programs use symbols (a.k.a. identifiers)
  - Identifiers require **context** to figure out the meaning
- Consider the English sentence: "He ate it"
  - This sentence is syntactically correct
  - But it makes sense only in the context of a previous sentence: "Sam bought a pizza." (what if "Sam bought a car."?)
- **Semantic analysis**
  - Associates identifiers with objects they refer to[关联]
    - "He" --> "Sam"
    - "it" --> "pizza"
  - Checks whether identifiers are used correctly[检查]
    - "He" and "it" refer to some object: def-use check
    - "it" is a type of object that can be eaten: type check

Why Semantic Analysis?

- Semantic of a language is more difficult to describe than syntax [语义比语法更难描述]
  - Syntax: describes the proper form of the programs [仅形式]
  - Semantics: defines the meaning of programs (i.e., what each program does when it executes) [到意义]
- Context cannot be analyzed using a CFG parser[CFG不能分析上下文信息]
  - Associating IDs with objects require expressing the pattern:

    {wcw | w ∈ (a|b)*}
    - The first w represents the definition of an ID
    - The c represents arbitrary intervening code
    - The second w represents the use of the ID

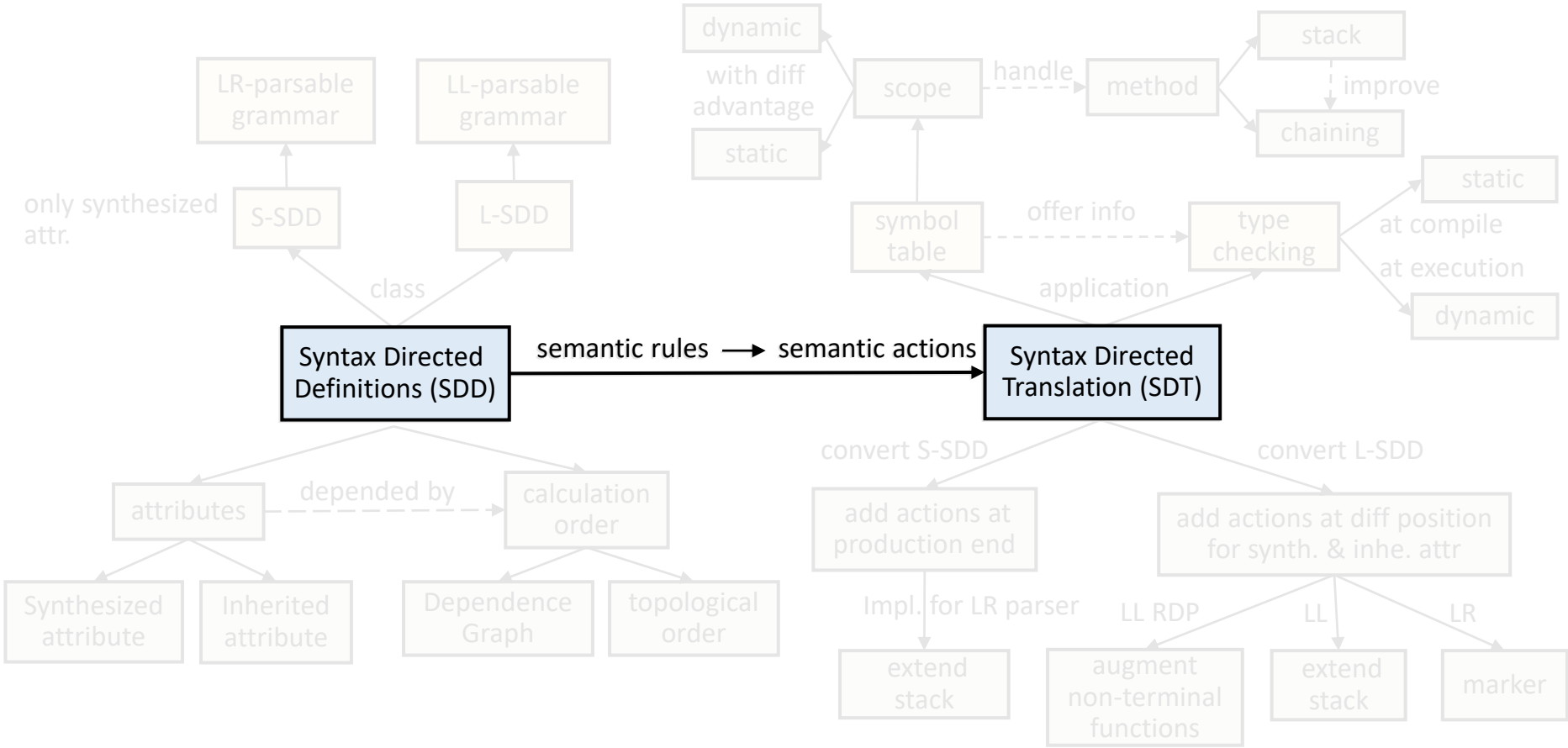
Semantic Analysis

- Deeper check into the source program[对程序进一步分析]
  - Last stage of the front end[前端最后阶段]
  - Compiler's last chance to reject incorrect programs[最后拒绝机会]
  - Verify properties that aren't caught in earlier phases
    - Variables declaration before use [先声明后使用]
    - Type consistency when using IDs [变量类型一致]
    - Correct expressions types [表达式类型]
- Gather useful info about program for later phases[收集后续信息]
  - Determine what variables are meant by each identifier
  - Build an internal representation of inheritance hierarchies
  - Count how many variables are in scope at each point

Semantic Analysis: Implementation

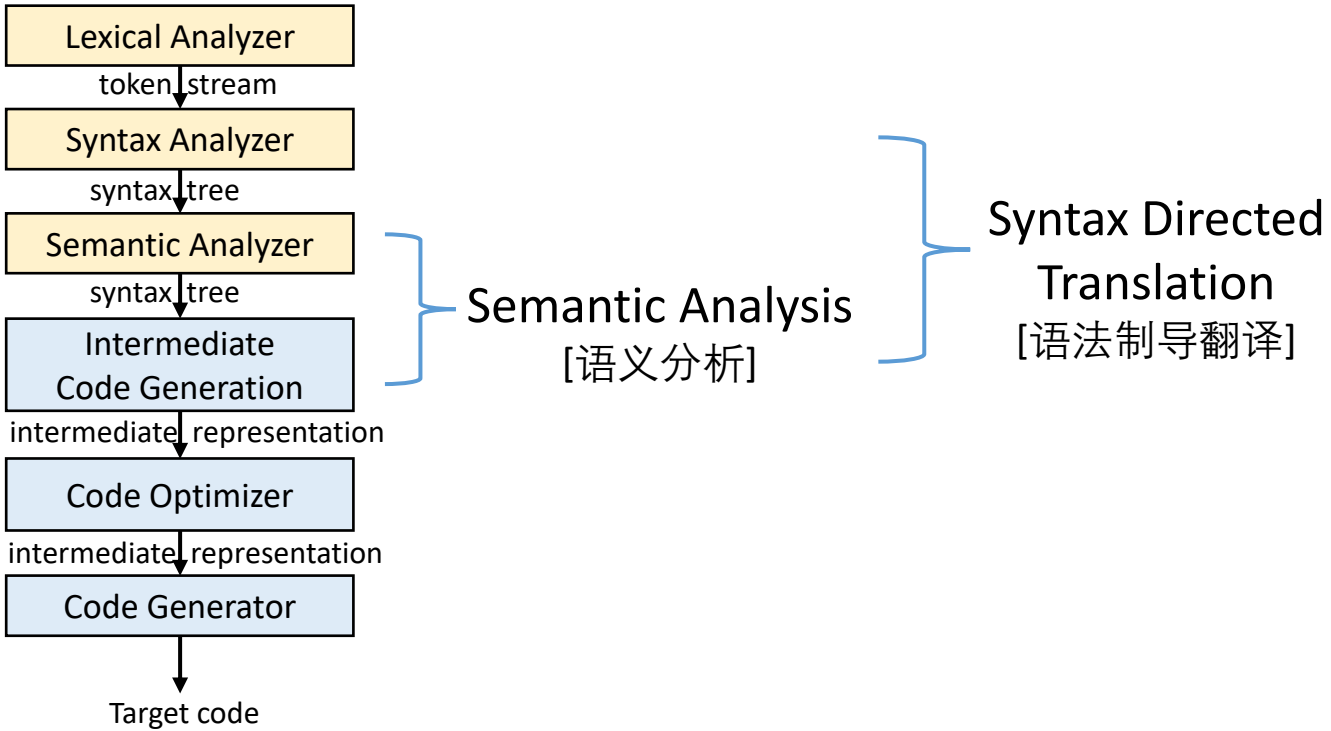
- Attribute grammars[属性文法]
  - One-pass compilation
    - Semantic analysis is done along with parsing
  - Augment rules to do checking during parsing
  - The approach suggested in the Compilers book
- AST walk[语法树遍历]
  - Two-pass compilation
    - First pass digests the syntax and builds a parse tree
    - The second pass traverses the tree to verify that the program respects all semantic rules
  - Strict phase separation of Syntax Analysis and Semantic Analysis

Content


dynamic
with diff advantage
static
scope
handle
method
stack
improve
chaining
LR-parsable grammar
LL-parsable grammar
only synthesized attr.
S-SDD
L-SDD
class
symbol table
offer info
type checking
static
at compile
at execution
dynamic
application
Syntax Directed Definitions (SDD)
semantic rules
semantic actions
Syntax Directed Translation (SDT)
attributes
depended by
calculation order
Synthesized attribute
Inherited attribute
Dependence Graph
topological order
convert S-SDD
convert L-SDD
add actions at production end
add actions at diff position for synth. & inhe. attr
Impl. for LR parser
LL RDP
LL
LR
extend stack
augment non-terminal functions
extend stack
marker

Syntax Directed Translation

- **Syntax Directed Translation**[语法制导翻译]



Syntax Directed Translation[语法制导翻译]

- **Translate based on the program's grammar structure**[语法结构]
  - Syntactic structure: structure of a program given by grammar[文法]
  - The parsing process and parse trees are used to direct semantic analysis and the translation of the program, i.e., **CFG-driven translation**[CFG驱动的翻译]

- How? Augment the grammar used in parser[对语法的进一步加强]:
  - Attach **semantic attributes**[语义属性] to each grammar symbol
    - The attributes describe the symbol properties [符号特征]
    - An attribute has a name and an associated value: a string, a number, a type, a memory location, an assigned register…
  - For each grammar production, give **semantic rules or actions**[语义规则或动作]
    - The actions describe how to **compute the attribute values** associated with each symbol in a production

Attributes[语义属性]

- **Attributes can represent anything depending on the task**[属性可以表示任意含义]
  - If computing expression: a number (value of expression)
  - If building AST: a pointer (pointer to AST for expression)
  - If generating code: a string (assembly code for expression)
  - If type checking: a type (type for expression)

- Attributes are associated directly with the grammar symbols

- Format: **X.a** (X is a symbol, a is one of its attributes)

SDD & SDT

Associating semantic rules with grammar rules (productions) involves two concepts:

- **Syntax Directed Definitions (SDD)** [语法制导定义]
- **Syntax Directed Translation scheme (SDT)** [语法制导翻译方案]

Syntax Directed Definitions (SDD)

- **Syntax Directed Definitions (SDD)** [语法制导定义]
  - A syntax-directed definition (SDD) is a context-free grammar(CFG) together with attributes and rules
  - Add Attributes + semantic rules[语义规则] in CFG
  - A generalization of CFG
    - Attributes for grammar symbols [文法符号和语义属性关联]
    - Semantic rules for productions [产生式和语义规则关联]

Productions	Attributes	Semantic rules
E -> E1 + E2	E.val; E1.val; E2.val	E.val = E1.val + E2.val
E -> id	E.val; id.lexval	E.val = id.lexval

Syntax Directed Translation (SDT)

- **Syntax Directed Translation scheme (SDT)** [语法制导翻译方案]
  - SDT is a CFG with program fragments embedded in the right part of the production, and these program fragments are called **semantic actions**.
  - Attributes + semantic actions[语义动作]
  - Example actions for computing the value of an expression

```
E -> E1 + E2 {E.val = E1.val + E2.val}
E -> id {E.val = id.lexval}
...
```

The position of a semantic action in a production determines the execution point of the action

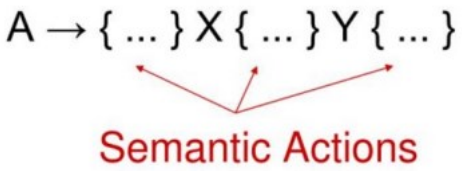
SDD v.s. SDT

- SDD[语法制导定义]: 是CFG的推广，翻译的高层次规则说明
  - A CFG grammar together with attributes and semantic rules
    - A subset of them are also called attribute grammars[属性文法]
  - Semantic rules imply no order to attribute evaluation
- SDT[语法制导翻译方案]: SDD的补充，具体翻译实施方案
  - An executable specification of the SDD
    - Program fragments are attached to different points in production rules
  - The execution order is important

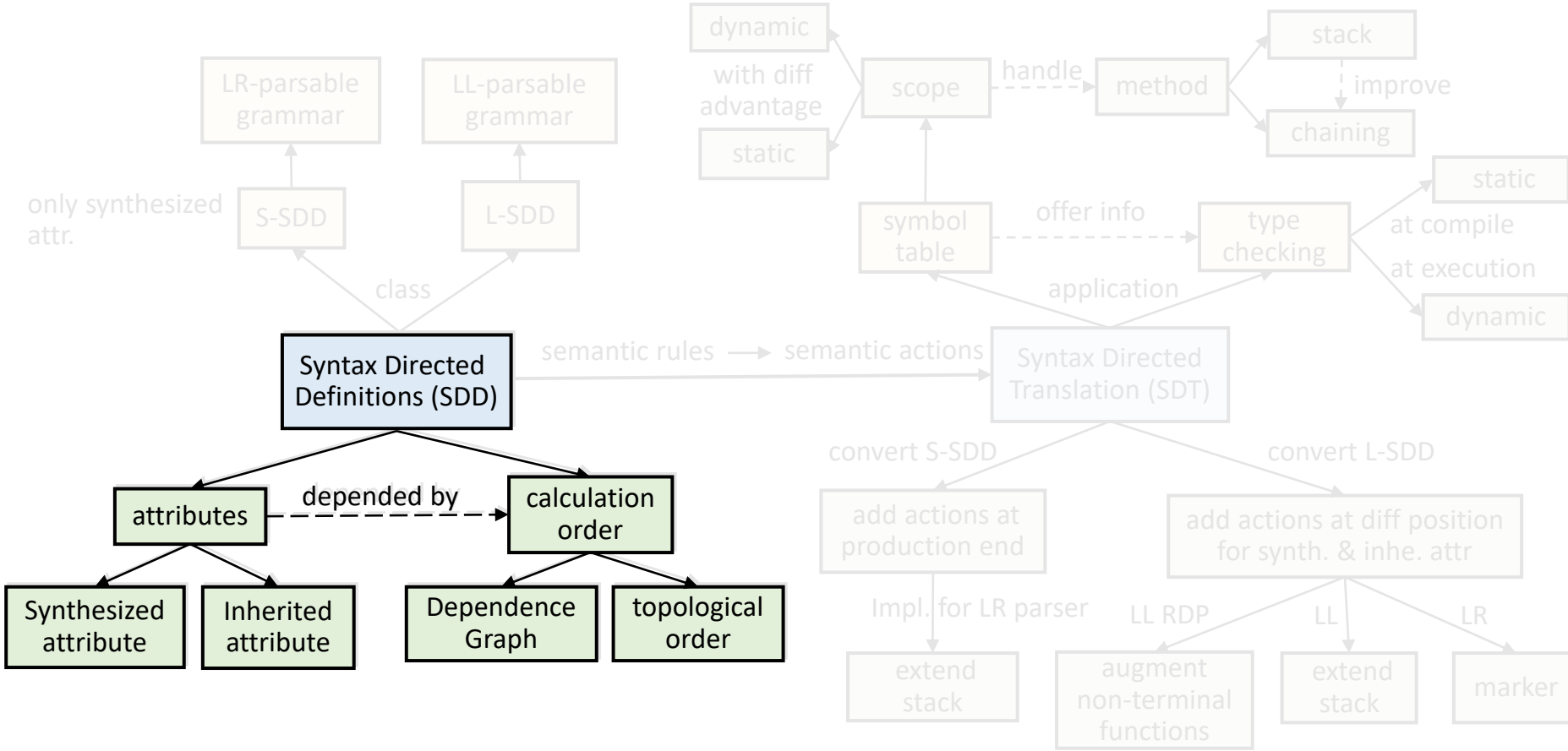
Grammar	SDD	SDT
D -> TL T -> int T -> float L -> L_1, id	L.inh = T.type T.type = int T.type = float L1.inh = L.inh	D ->T {L.inh = T.type} L T -> int {T.type = int} T -> float {T.type = float} L -> {L1.inh = L.inh} L_1, id

SDD v.s. SDT

- Syntax: A -> α $\{action_1\}$ β $\{action_2\}$ γ …
- Actions are executed "**at that point**" in the RHS
  - $action_1$ executes after α has been produced but before β
  - $action_2$ executes after α, $action_1$, β but before γ
- Semantic rule v.s. Action[语义规则 vs. 语义动作]
  - Semantic rules are not associated with locations in RHS
    - SDD doesn't impose any order other than dependences
  - Location of action in RHS specifies when it should occur
    - SDT specifies the execution order and time of each action



Content


Syntax Directed Definitions (SDD)
attributes
depended by
calculation order
Synthesized attribute
Inherited attribute
Dependence Graph
topological order
class
S-SDD
L-SDD
only synthesized attr.
LR-parsable grammar
LL-parsable grammar
semantic rules
semantic actions
Syntax Directed Translation (SDT)
application
symbol table
offer info
type checking
dynamic
with diff advantage
static
scope
handle
method
stack
improve
chaining
static
at compile
at execution
dynamic
convert S-SDD
convert L-SDD
add actions at production end
add actions at diff position for synth. & inhe. attr
Impl. for LR parser
LL RDP
LL
LR
extend stack
augment non-terminal functions
extend stack
marker

Syntax Directed Definitions (SDD)

- SDD是CFG的增广
  - Grammar symbols together with semantic attributes
  - Productions associated with a set of semantic rules to compute the value of an expression

- SDD has two types of attributes [文法符号的两种属性]
  - **Synthesized attribute** [综合属性]
  - **Inherited attribute** [继承属性]

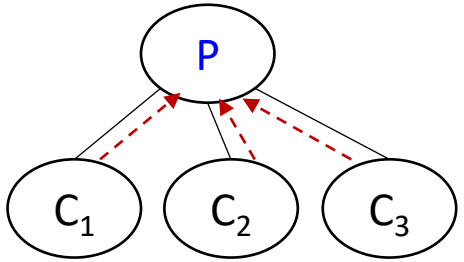
Syntax Directed Definitions (SDD)

- **Synthesized attribute**[综合属性]
  - Defined by a semantic rule associated with the production at N
    - The production must have A as its head (i.e., A -> …)
  - A synthesized attribute of node N is defined only by attributes of **N's children** and **N itself**[子节点或自身]

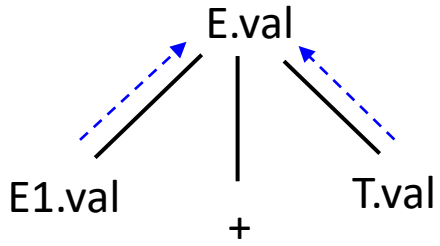
- **Inherited attribute**[继承属性]
  - Defined by a semantic rule associated with the production at the parent of N
    - The production must have A as a symbol in its body (i.e., … -> …A…)
  - An inherited attributed of node N is defined only by attribute values at N's parent, N itself, and N's siblings[父节点、自身或兄弟节点]

Synthesized Attribute[综合属性]

- Synthesized attribute for non-terminal A of parse-tree node N[非终结符的综合属性]
  - Only defined by N's children and N itself
    - Passed up the tree
    - P.syn_attr = f(P.attrs, C_1.attrs, C_2.attrs, C_3.attrs)
  - Example



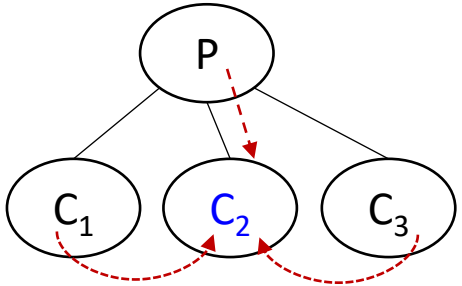
Productions	Semantic rules
E -> E1 + T	*E.val = E1.val + T.val*



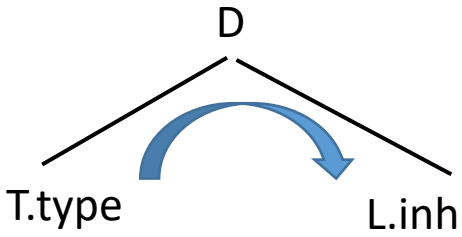
- Terminals **CAN** have synthesized attributes[终结符可以具有综合属性]
  - Lexical values supplied by the lexical analysis
  - Thus, no semantic rules in SDD for terminals

Inherited Attribute[继承属性]

- Inherited attribute for non-terminal A of parse-tree node N[非终结符继承属性]
  - Only defined by N's parent, N's siblings and N itself
    - Passed down a parse tree
    - C_2.inh_attr = f(P.attrs, C_1.attrs, C_2.attrs, C_3.attrs)
  - Example



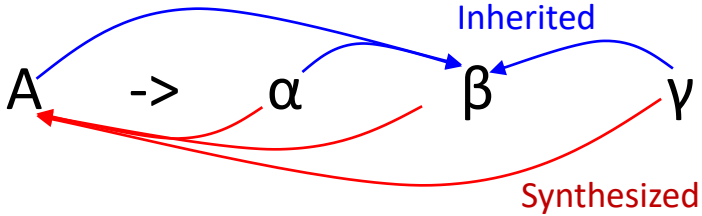
Productions	Semantic rules
D -> T L	*L.inh = T.type*



- Terminals **CANNOT** have inherited attributes[终结符无继承属性]
  - Only synthesized attributes from lexical analysis

SDD[语法制导定义]

- Attribute dependencies in a production rule[产生式中的属性依赖]



- SDD has rule of the form for each grammar production
  - b = f(A.attrs, α.attrs, β.attrs, γ.attrs)
- b is either an attribute in LHS (an attribute of A)
  - In which case b is a **synthesized** attribute
  - Why? From A's perspective α, β, γ are children
- Or, b is an attribute in RHS (e.g., of β)
  - In which case b is an inherited attribute
  - Why? From β's perspective A, α, γ are parent or siblings

Example: Synthesized attribute

Attribute grammar for simple integer arithmetic expression

Grammar rule	Semantic Rules
$E \rightarrow E_1 + T$	$E.val = E_1.val + T.val$
$E \rightarrow T$	$E.val = T.val$
$T \rightarrow T_1 * F$	$T.val = T_1.val * F.val$
$T \rightarrow F$	$T.val = F.val$
$F \rightarrow (E)$	$F.val = E.val$
$F \rightarrow dight$	$F.val = dight.val$

The *val* attribute is synthesized

Example: Inherited Attribute

Attribute grammar for variable

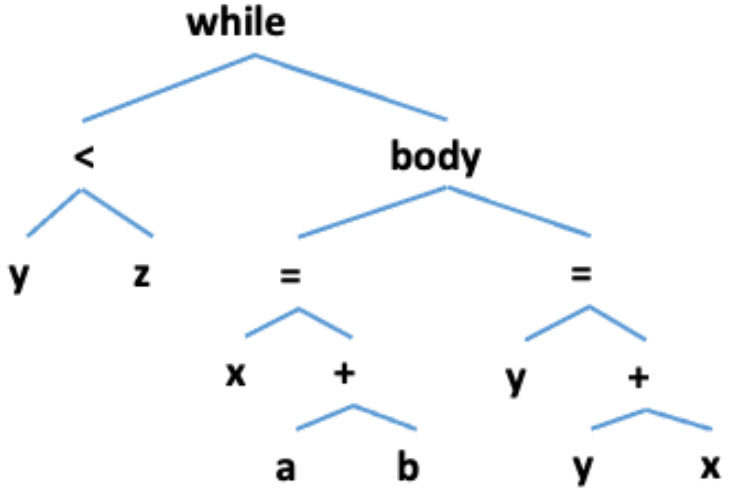
Grammar rule	Semantic Rules
decl -> type varlist	varlist.dtype = type.dtype
type -> int	type.dtype = integer
type -> float	type.dtype = real
varlist1 -> id, varlist2	id.dtype = varlist1.dtype
varlist -> id	varlist2.dtype = varlist1.dtype
	id.dtype = varlist.dtype

The *dtype* attribute is inherited

The Concepts

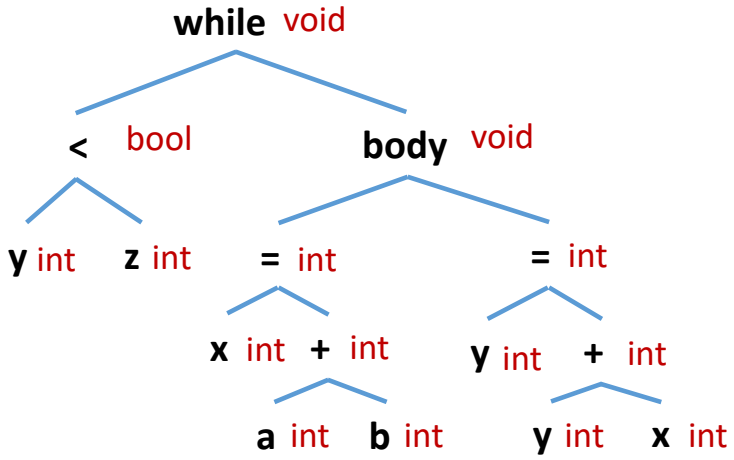
- Side effect[副作用]
  - 一般属性值计算（基于属性值或常量进行的）之外的功能
  - 例如：code generation, print results, modify symbol table …
- Attribute grammar[属性文法]
  - 一个没有副作用的SDD
  - The rules define the value of an attribute purely in terms of the value of other attributes and constants[属性文法的规则仅仅通过其他属性值和常量来定义一个属性值]
- Annotated parse-tree[标注分析树]
  - 每个节点都带有属性值的分析树
    - A parse tree showing the value(s) of its attribute(s)
  - a.k.a., attribute parse tree[属性分析树]

Compilation Phases[编译阶段]



Abstract Syntax Tree(AST)

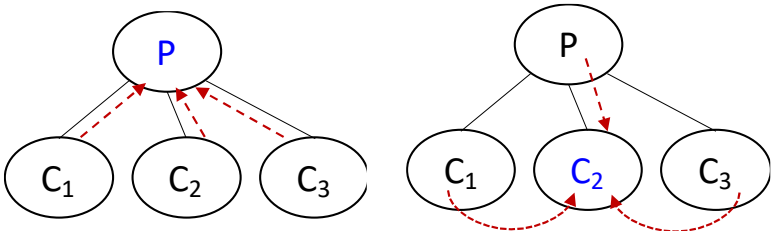
A very simple illustrative case!



Annotated AST/Decorated AST
[带标注的抽象语法树]

Semantic Analysis Revisit

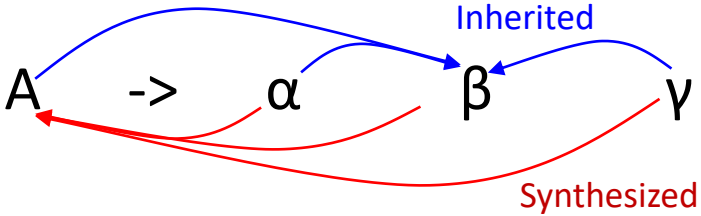
- **SDD** (Syntax-directed definition)
  - CFG + attributes for each symbol + semantic rules ***for*** each production
- **SDT** (Syntax-directed definition)
  - CFG + attributes for each symbol + {semantic actions} ***in*** each production
- Synthesized attribute
  - Terminals **CAN** have synthesized attributes
- Inherited Attribute
  - Terminals **CANNOT** have inherited attributes



Grammar	SDD (rules)	SDT (actions)
D -> TL	L.inh = T.type	D ->T {L.inh = T.type} L
T -> int	T.type = int	T -> int {T.type = int}
T -> float	T.type = float	T -> float {T.type = float}
L -> L_1, id	L1.inh = L.inh	L -> {L1.inh = L.inh} L_1, id

Dependence Graph[依赖图]

- Dependence relationship[依赖关系]
  - Before evaluating an attribute at a node of a parse tree, we must evaluate all attributes it depends on



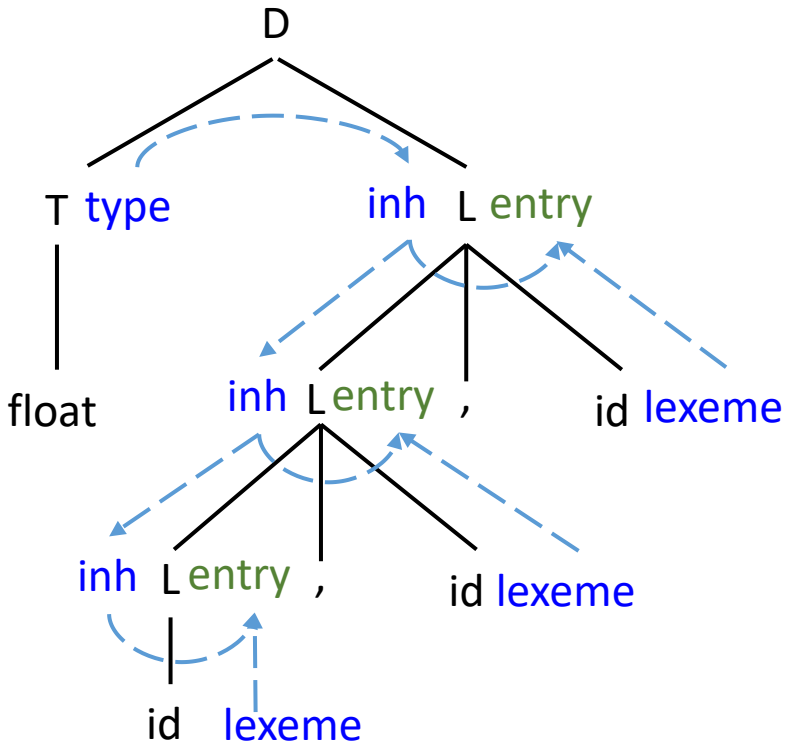
- **Dependency graph**[依赖图]
  - While the annotated parse tree shows the values of attributes, a dependency graph helps determine how those values can be computed[决定属性值计算]
  - Depicts the flow of information among the attribute instances in a particular parse tree[描绘了分析树的属性信息流]
    - Edges are dependence relationships between attributes
    - For each parse-tree node X, there's a graph node for each attr of X
    - If X.a depends on Y.b, then there's one directed edge from X.a to Y.b

Example: Dependency Graph

SDD:

Productions	Semantic rules
D -> T L	L.inh = T.type
T -> int	T.Type = int
T -> float	T.Type = float
L -> L_1, id	L1.inh = L.inh
	addtype(id.entry,L.inh)
L-> id	addtype(id.entry,L.inh)

Input:
float a, b, c



'entry' is dummy attribute for the addtype()

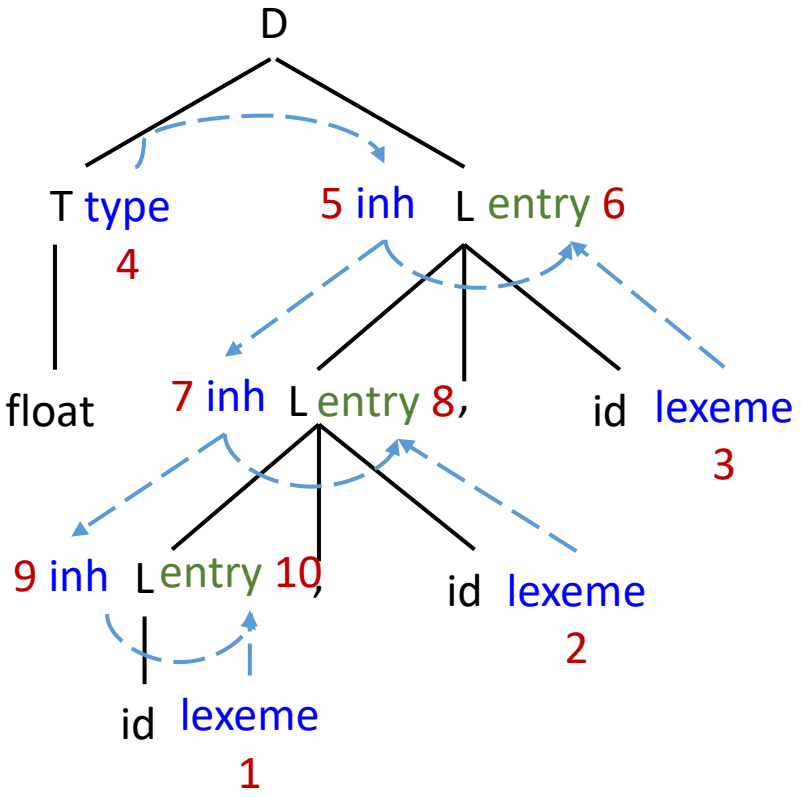
Evaluation Order[属性值计算顺序]

- Ordering the evaluation of attributes[计算顺序]
  - Dependency graph characterizes possible orders in which we can evaluate the attributes at the various nodes of a parse-tree[依赖图描述了属性计算顺序]
- If the graph has an edge from node M to node N, then the attribute associated with M must be evaluated before N[用图的边来确定计算顺序]
  - Thus, the only allowable orders of evaluation are those sequences of nodes N_1, N_2, …, N_k such that if there is an edge from N_i to N_j and $i < j$
  - This order embeds a directed graph into a linear order, called a **topological sort**[拓扑排序] of the graph
    - If there's any cycle in the graph, then there are no topological sorts, i.e., no way to evaluate the SDD on this parse tree
    - If there are no cycles, then there is always at least one topological sort

Example: Evaluation Order

SDD:

Productions	Semantic rules
D -> T L	L.inh = T.type
T -> int	T.type= int
T -> float	T.type= float
L -> L_1, id	L1.inh=L.inh
	addtype(id.entry,L.inh)
L-> id	addtype(id.entry,L.inh)



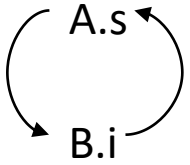
Input:
float a,b,c

Topological sort:
1, 2, 3, 4, 5, 6, 7, 8, 9, 10

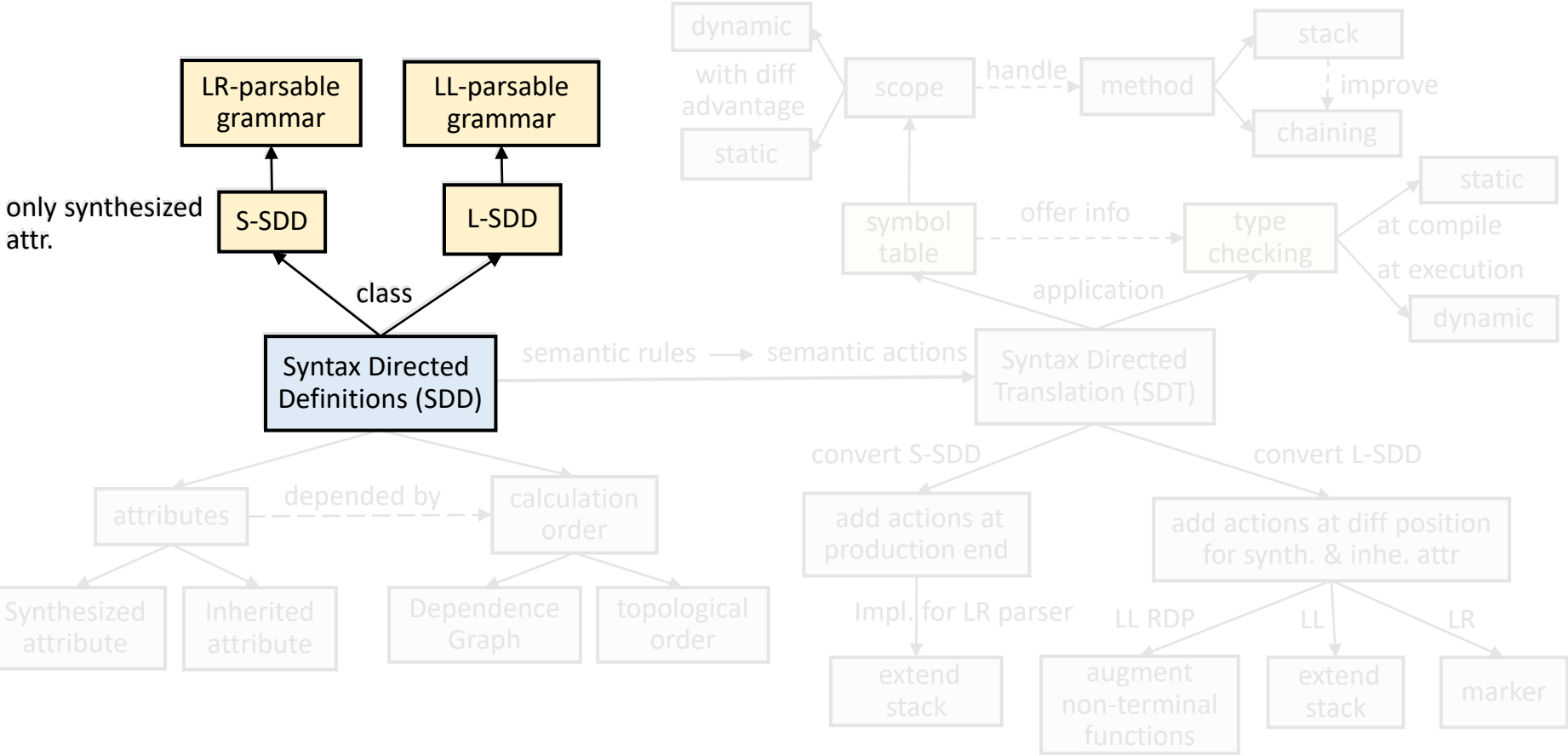
Evaluation Order (cont.)

- Before evaluating an attribute at a node of a parse tree, we must evaluate all attributes it depends on [依赖关系]
  - Synthesized: evaluate children first, then the node itself
  - Inherited: evaluate parent and dependent siblings first, then the node itself
  - For SDD's with both inherited and synthesized attributes, there's no guarantee that there is even one evaluation order
- Difficult to check circularities in a dependency graph
  - But, there are **subclasses of SDD's** that guarantee an evaluation order
    - Such classes do not permit graphs with cycles

Production	Semantic Rules
A-> B	A.s=B.i; B.i= A.s + 1;



Content


LR-parsable grammar
LL-parsable grammar
only synthesized attr.
S-SDD
L-SDD
class
Syntax Directed Definitions (SDD)
semantic rules
semantic actions
Syntax Directed Translation (SDT)
attributes
depended by
calculation order
Synthesized attribute
Inherited attribute
Dependence Graph
topological order
dynamic
with diff advantage
static
scope
handle
method
stack
improve
chaining
symbol table
offer info
type checking
static
at compile
at execution
dynamic
application
convert S-SDD
convert L-SDD
add actions at production end
add actions at diff position for synth. & inhe. attr
Impl. for LR parser
LL RDP
LL
LR
extend stack
augment non-terminal functions
extend stack
marker

S-Attributed Definitions[S-属性定义]

- An SDD is **S-attributed** if every attribute is synthesized[只具有综合属性]

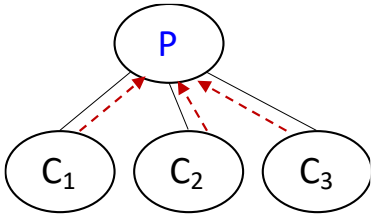
- If an SDD is S-attributed (S-SDD)
  - Can evaluate its attributes in any bottom-up order of the nodes of the parse-tree[自底向上的顺序计算属性值]
  - Can be implemented during bottom-up parsing[与自底向上的语法分析同时进行]

Productions	Semantic rules
(1)L-> E	print(E.val)
(2)E-> E_1+ T	E.val = E_1.val+T.val
(3)E-> T	E.val =T.val
(4)T-> T_1* F	T.val= T_1.valxF.val
(5)T-> F	T.val=F.val
(6)F-> (E)	F.val=E.val
(7)F-> digit	F.val=digit.lexval

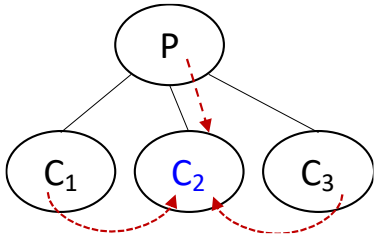
L-Attributed Definitions[L-属性定义]

- An SDD is **L-attributed** (L-SDD) if
  - Between the attributes associated with a production body, dependency graph edges can only go from left to right [依赖图的边只能从左到右]
  - Each attribute can be either **synthesized,** or **inherited** with the rules that suppose $A \rightarrow X_1X_2...X_{i-1}X_i$, the inherited attribute $X_i.a$ only depends on:
    1. Inherited attributes associated with A [A的继承属性, Why?]
    2. Either syn or inh attributes of $X_1, X_2, ..., X_{i-1}$ located to the left of X_i [X_i的之前符号的综合/继承属性]
    3. Either syn or inh attributes of X_i itself, but no cycles formed by the attributes of this X_i [X_i的综合/继承属性 (不能出现环形依赖)]
  - L-SDD是对S-SDD的拓展, Can be implemented during top-down/bottom-up parsing [L属性的语义分析可在LL/LR分析中完成]

L-Attributed Definitions (cont.)



综合属性



继承属性

S-SDD or L-SDD?

Productions	Semantic rules
A -> BC	A.s = B.b B.i = f(C.c, A.s)

Not S-SDD: B.i is inh

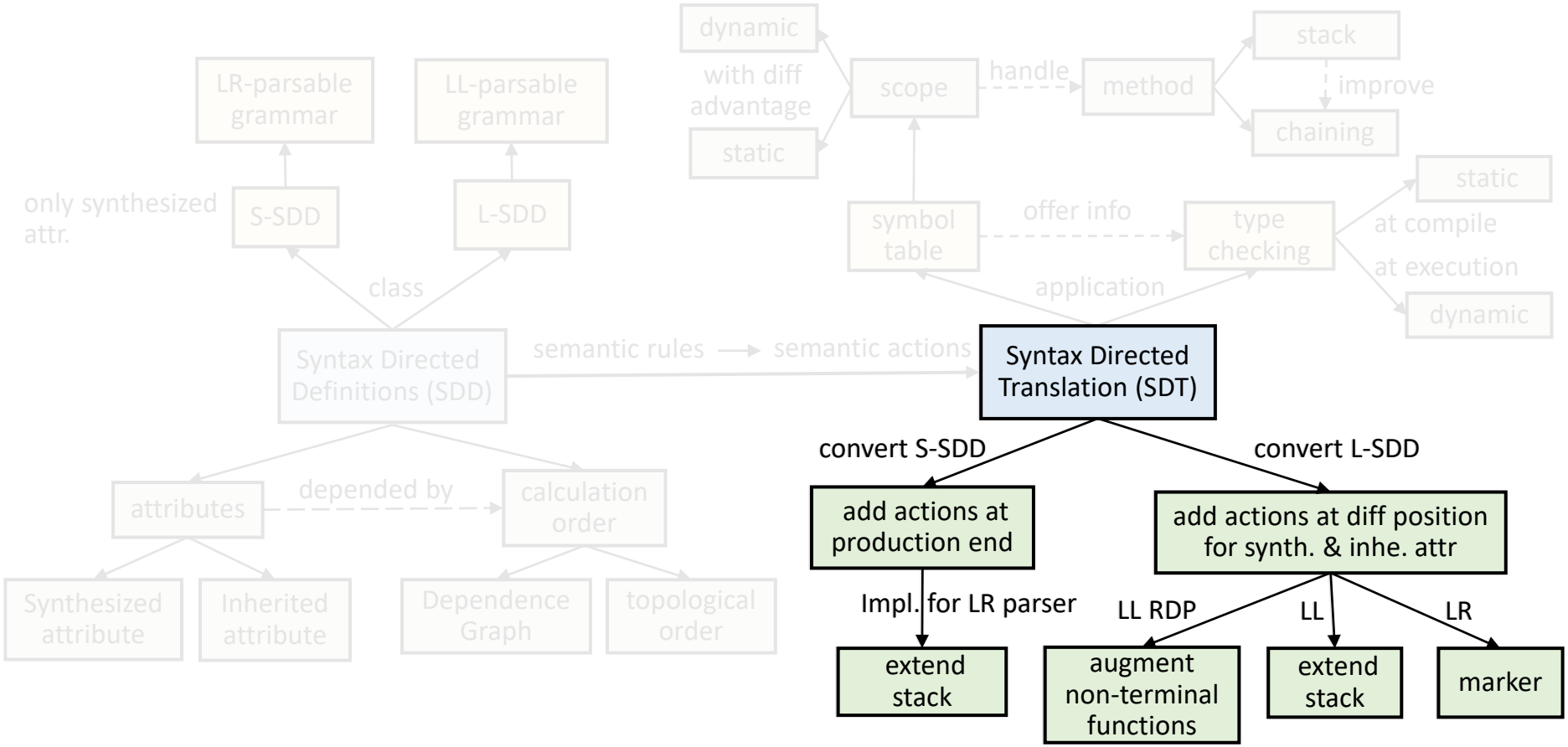
[S属性文法中不会出现继承属性]

Not L-SDD: A.s is syn arrt, C is right to B

[L属性文法中, 继承属性 (B.I)不会依赖综合属性(A.s)]

[L属性文法中, RHS不会出现从右到左的依赖关系]

Content


dynamic
with diff advantage
static
scope
handle
method
stack
improve
chaining
LR-parsable grammar
LL-parsable grammar
only synthesized attr.
S-SDD
L-SDD
symbol table
offer info
type checking
static
at compile
at execution
dynamic
class
application
Syntax Directed Definitions (SDD)
semantic rules
semantic actions
Syntax Directed Translation (SDT)
convert S-SDD
convert L-SDD
attributes
depended by
calculation order
add actions at production end
add actions at diff position for synth. & inhe. attr
Synthesized attribute
Inherited attribute
Dependence Graph
topological order
Impl. for LR parser
LL RDP
LL
LR
extend stack
augment non-terminal functions
extend stack
marker

Implementation[实现]

- SDT (executable SDD) can be implemented in two ways
  - **Using a parse tree or AST**[基于预先构建的分析树]
    - First build a parse tree, and then apply rules or actions at each node while traversing the tree
    - All SDDs (without cycles) and SDTs can be implemented since the tree can be traversed freely, implements any ordering
  - **During parsing**, without building a parse tree[语法分析过程中]
    - Apply rules or actions at each production while parsing
    - Only a subset of SDDs and SDTs can be implemented
    - Evaluation ordering restricted to parser derivation order

Implementation[实现]

- Two important classes of SDD's[两个关键子类]
  - SDD is S-attributed, the underlying grammar is LR-parsable
  - SDD is *L-attributed*, the underlying grammar is LL-parsable

- For both classes, semantic rules in an SDD can be converted into an SDT with actions that are executed at the right time[允许SDD到SDT的转换]
  - During parsing, an action in a production body is executed as soon as all the grammar symbols to the left of the action have been matched

Implement S-SDD

- Convert S-attributed SDD to SDT[SDD到SDT的转换]
  - Place each action at the end of the production[将每个语义动作都放在产生式的最后]
  - SDTs with all actions at the right ends of the production bodies are called **Postfix SDT** [后缀/尾部SDT]

S-SDD

Productions	Semantic rules
(1)L-> E	*print(E.val)*
(2)E-> E_1+ T	*E.val= E_1.val+T.val*
(3)E-> T	*E.val=T.val*
(4)T-> T_1 F*	*T.val= T_1.valxF.val*
(5)T-> F	*T.val=F.val*
(6)F-> (E)	*F.val=E.val*
(7)F-> digit	*F.val=digit.lexval*

SDT

CFG with actions
(1)L-> E {print(E.val)}
(2)E-> E_1+ T {E.val= E_1.val+T.val}
(3)E-> T {E.val=T.val}
(4)T-> T_1 F {T.val= T_1.valxF.val }*
(5)T-> F {T.val=F.val}
(6)F-> (E) {F.val=E.val}
(7)F-> digit {F.val=digit.lexval}

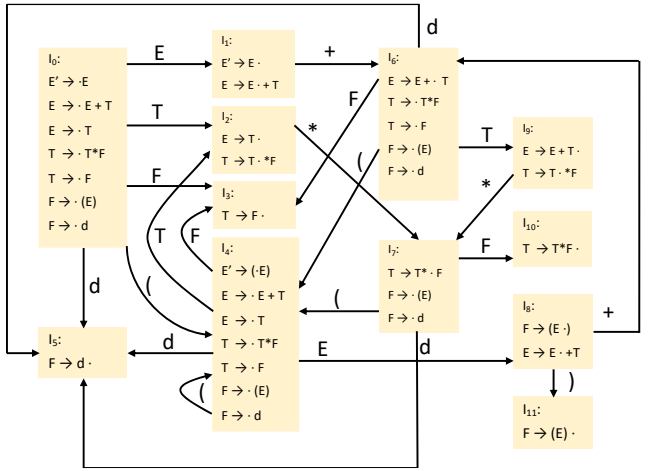
Implement S-SDD (cont.)

- If the underlying grammar of S-SDD is LR parsable
  - Then the SDT can be implemented during LR parsing
- Implement the converted SDT by reduction[借助归约实现]
  - Executing the action along with the reduction of LHS <- RHS

SDT

CFG with actions
(1)L-> E {print(E.val)}
(2)E-> E_1+ T {E.val = E_1.val+T.val}
(3)E-> T {E.val = T.val}
(4)T-> T_1 F {T.val = T_1.valxF.val }*
(5)T-> F {T.val = F.val}
(6)F-> (E) {F.val = E.val}
(7)F-> digit {F.val = digit.lexval}

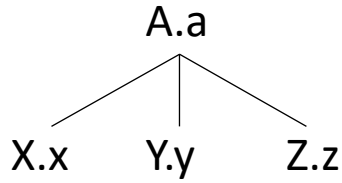
SLR Automaton



Extend LR Parse Stack[扩展分析栈]

- Save synthesized attributes into the stack[栈中额外存放综合属性值]
  - Place the attributes along with the grammar symbols (or LR states that associated with these symbols) in records on stack
  - If there are multiple attributes
    - Make the records large enough or by putting pointers to records on the stack [栈记录足够大，或栈记录中存放指针]

- Example: A -> XYZ
  - x, y, z are attributes of X, Y, Z respectively
  - After the action, A and its attributes are at the top (i.e., m-2)



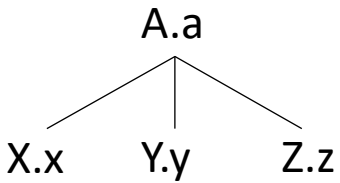
State:	S_0	…	S_{m-2}	S_{m-1}	S_m	state ->	S_0 …	S_{m-2}
Symbol:	$	…	X	Y	Z	Symbol ->	$ …	A
Attribute:	-	…	X.x	Y.y	Z.z	Attribute ->	- …	A.a
					top			top

Stack Manipulation[栈操作]

- Rewrite the actions to manipulate the parser stack
  - The manipulation can be done automatically by the parser

stack[top-2].symbol= A
stack[top-2].val = f(stack[top-2].val, stack[top-1].val, stack[top].val)top = top-2

A -> XYZ {A.a= f(X.x,Y.y,Z.z)}



State:	S_0	…	S_{m-2}	S_{m-1}	S_m
Symbol:	$	…	X	Y	Z
Attribute:	-	…	X.x	Y.y	Z.z
					top

state ->	S_0	…	S_{m-2}
Symbol ->	$	…	A
Attribute ->	-	…	A.a
			top

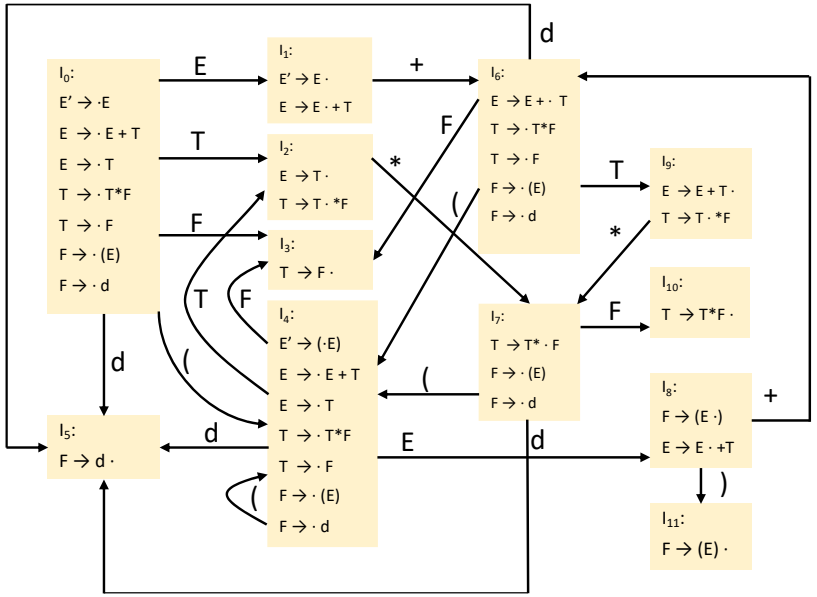
Example

- **Rewrite the actions to manipulate the parser stack**
  - The manipulation can be done automatically by the parser

Productions	Semantic rules	Semantic Actions
(1)L-> E	print(E.val)	{print(stack[top].val);}
(2)E-> E_1+ T	E.val= E_1.val+T.val	{ stack[top-2].val= stack[top-2].val + stack[top].val; top = top-2;}
(3)E-> T	E.val=T.val	
(4)T-> T_1* F	T.val= T_1.val*F.val	{stack[top-2].val= stack[top-2].val * stack[top].val; top = top-2;}
(5)T-> F	T.val=F.val	
(6)F-> (E)	F.val=E.val	{stack[top-2].val= (stack[top-1].val); top = top-2;}
(7)F-> digit	F.val=digit.lexval	

Example

Productions	Semantic Actions
(1)L-> E	*{ print(stack[top].val);}*
(2)E-> E1+ T	*{ stack[top-2].val=stack[top-2].val + stack[top].val; top = top-2;}*
(3)E-> T	
(4)T-> T_1 F*	*{ stack[top-2].val=stack[top-2].val * stack[top].val; top = top-2;}*
(5)T-> F	
(6)F-> (E)	*{ stack[top-2].val= stack[top-1].val; top = top-2;}*
(7)F-> digit	



Input: 3*5+4

state -> S_0 S_2 S_7 S_{10}
Symbol -> $ T * F
Attribute -> - 3 - 5 (top)

state -> S_0 S_n
Symbol -> $ T
Attribute -> - 15 (top)

Example

Input: 3*5+4

Productions
(1)L-> E n (2)E-> E1+ T (3)E-> T (4)T-> T_1* F (5)T-> F (6)F-> (E) (7)F-> digit

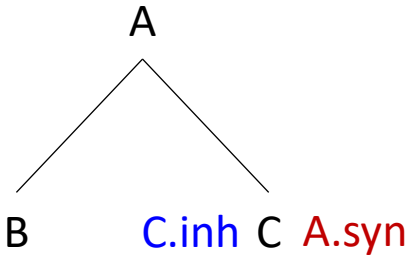
Step	States (Illustrative)	Attributes	Input	Code	Output
1	$	$	**3 * 5 + 4 n $**		
2	$ 3	$ 3	*** 5 + 4 n $**	--	F → **digit**
3	$ F	$ 3	*** 5 + 4 n $**	--	T → F
4	$ T	$ 3	*** 5 + 4 n $**		
5	$ T *	$ 3 *	**5 + 4 n $**		
6	$ T * 5	$ 3 * 5	**+ 4 n $**	--	F → **digit**
7	$ T * F	$ 3 * 5	**+ 4 n $**	3 * 5	T → T * F
8	$ T	$ 15	**+ 4 n $**	--	E → T
9	$ E	$ 15	**+ 4 n $**		
10	$ E +	$ 15 +	**4 n $**		
11	$ E + 4	$ 15 + 4	**n $**	--	F → **digit**
12	$ E + F	$ 15 + 4	**n $**	--	T → F
13	$ E + T	$ 15 + 4	**n $**	15 + 4	E → E **+** T
14	$ E	$ 19	**n $**		
15	$ E **n**	$ 19 **n**	**$**	print(19)	L → E **n**
16	$ L	$ 19	**$**	accept	

Implement L-SDD

- We have examined **S-SDD** -> **SDT** -> **implementation**
  - S-SDD can be converted to SDT with actions at production ends
  - The SDT can be parsed and translated by bottom-up, as long as the underlying grammar is LR-parsable
- What about the more-general **L-attributed SDD**?
  - Rule for turning L-SDD into an SDT
    1. Embed the action that computes the inherited attributes for a nonterminal A immediately **before the occurrence** of A in the production body
    2. Place the actions that compute a synthesized attribute for the LHS **at the end** of the production body

Example

- **A -> B** {C.inh} **C** {A.syn}
  - C的继承属性: 在C之前
  - A的综合属性: 在RHS末尾



Productions	Semantic rules
(1)T-> FT'	T'.inh = F.val T.val = T'.syn
(2)T'-> *FT_1'	T_1'.inh = T'.int * F.val T'.syn = T_1'.syn
(3)T'-> ε	T'.syn = T'.inh
(4)F-> digit	F.val = digit.lexval

SDT

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

Implement L-SDD

- If the underlying grammar is LL-parsable, then the SDT of L-SDD can be implemented during LL or LR parsing [若文法是LL可解析的，则可在LL或LR语法分析过程中实现]
- Semantic translation during **parsing**
  - An **LL** recursive-descent parser[递归下降的LL分析]
    - Augment non-terminal functions to both parsing and attributes handling
  - An **LL** predictive parser[非递归的LL预测分析]
    - Extend the parse stack to hold actions and certain data items needed for attribute evaluation
  - An **LR** parser[LR分析]
    - Rewrite grammars to involve marker
- **For the top-down ones, we need to eliminate left recursion first!**

Eliminating left recursion

- A motivating example: a simple case
  - Trick: treating actions as terminals if they **do not calculate** any attributes.

$E \overset{*}{\Rightarrow} E+T+T+T\ldots$

$A \rightarrow A\alpha \mid \beta \quad \Rightarrow \quad A \rightarrow \beta A';\ A' \rightarrow \alpha A' \mid \varepsilon$

$$E \rightarrow E + T \qquad E \rightarrow T$$

$$E \rightarrow T\ R \qquad R \rightarrow + T\ R \mid \varepsilon$$

$$E \rightarrow E + T\ \{\ \text{print('+')}\ \} \qquad E \rightarrow T$$

a single terminal

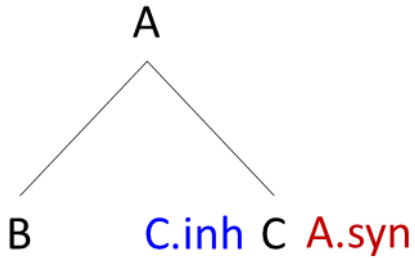
$$E \rightarrow T\ R \qquad R \rightarrow + T\ \{\ \text{print('+')}\ \}\ R \qquad R \rightarrow \varepsilon$$

Semantic Analysis Revisit

- Implementing L-SDD: top-down/bottom-up
  - L-SDD -> SDT:
    1. Embed the action that computes the inherited attributes for a nonterminal A immediately **before the occurrence** of A in the production body
    2. Place the actions that compute a synthesized attribute for the LHS **at the end** of the production body

A -> B {C.inh} **C** {A.syn}

- C的继承属性: 在C之前
- A的综合属性: 在RHS末尾



- **Eliminating left recursion!**

Eliminating left recursion

- A more complex case

$E \rightarrow E_1 + T \quad \{ E.val = E_1.val + T.val; \}$
$E \rightarrow E_1 - T \quad \{ E.val = E_1.val - T.val; \}$
$E \rightarrow T \quad \{ E.val = T.val; \}$
$T \rightarrow (E) \quad \{ T.val = E.val; \}$
$T \rightarrow num \quad \{ T.val = num.val; \}$

$E \rightarrow T\ R$
$R \rightarrow +\ T\ R_1$
$R \rightarrow -\ T\ R_1$
$R \rightarrow \varepsilon$
$T \rightarrow (\ E\ )$
$T \rightarrow num$

$A \rightarrow A\alpha \mid \beta$

⇩

$A \rightarrow \beta A';$
$A' \rightarrow \alpha A' \mid \varepsilon$

$E \rightarrow T \ \{ R.i = T.val; \}\ R \ \{ E.val = R.s; \}$
$R \rightarrow +\ T \ \{ R_1.i = R.i + T.val; \}\ R_1 \ \{ R.s = R_1.s; \}$
$R \rightarrow -\ T \ \{ R_1.i = R.i - T.val; \}\ R_1 \ \{ R.s = R_1.s; \}$
$R \rightarrow \varepsilon \ \{ R.s = R.i; \}$
$T \rightarrow (\ E\ ) \ \{ T.val = E.val; \}$
$T \rightarrow num \ \{ T.val = num.val; \}$

解决左递归斩断了产生式 (及actions)
$E \rightarrow E_1 + T \Rightarrow E \rightarrow TR \quad R \rightarrow +TR \quad R \rightarrow \varepsilon$

用新引入的R，传递属性值，实现计算
R.i (属性传递) R.s (属性返回)

通过R-> ε，将计算结果传回

Eliminating left recursion

E → T { R.i = T.val; } R { E.val = R.s; }

R → + T { R_1.i = R.i + T.val; } R_1 { R.s = R_1.s; }

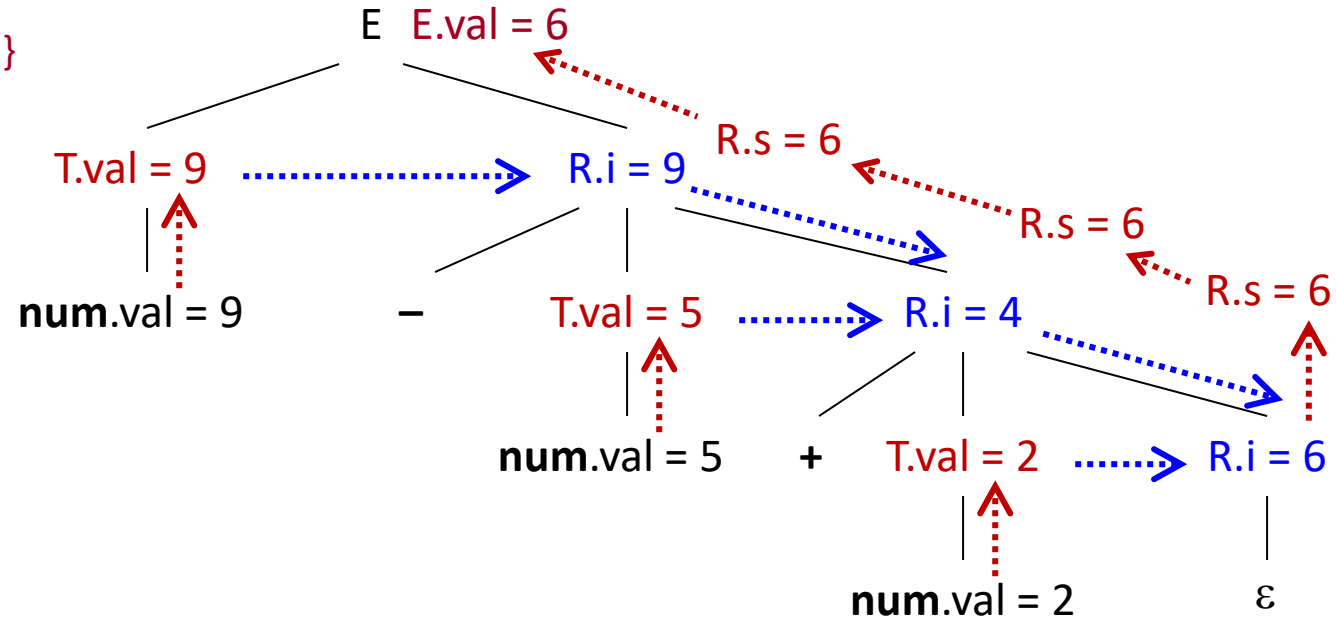
R → – T { R_1.i = R.i – T.val; } R_1 { R.s = R_1.s; }

R → ε { R.s = R.i; }

T → (E) { T.val = E.val; }

T → **num** { T.val = **num**.val; }

Input: **9 – 5 + 2**



Eliminating left recursion

- General rules
  - Only available for S-SDD (postfix translation schemes), a subset of L-SDD

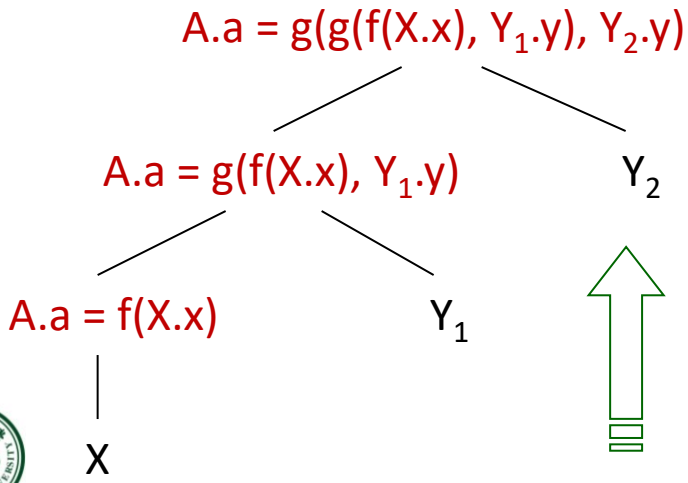
$A \rightarrow A_1\ Y\ \{ A.a = g(A_1.a, Y.y) \}$

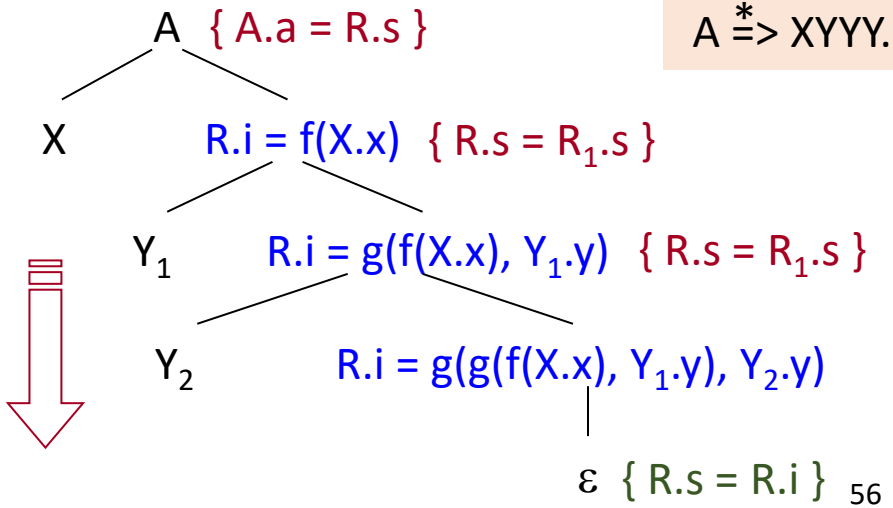
$A \rightarrow X\ \{ A.a = f(X.x) \}$

$A \rightarrow X\ \{ R.i = f(X.x) \}\ R\ \{ A.a = R.s \}$

$R \rightarrow Y\ \{ R_1.i = g(R.i, Y.y) \}\ R_1\ \{ R.s = R_1.s \}$

$R \rightarrow \varepsilon\ \{ R.s = R.i \}$





$A \overset{*}{\Rightarrow} XYYY...$

Semantic Analysis Revisit

- Evaluation order -> DAG -> topological sort -> circle is NOT allowed
- SDD Subsets without circle: **S-SDD** and **L-SDD**
  - **S-SDD:** Synthesized attributes only
  - **L-SDD**: Synthesized and Inherited attributes ($A \rightarrow X_1X_2...X_{i-1}X_i$)
    - X_i.inh can depend on: (i) A.inh, (ii) X_j.attr, $j<i$, (iii) X_i.attr with **no circles**
- Implementation:
  - Based on parser tree or AST
    - Any computation order without dependency circles
  - Along with Parser
    - Strictly follows the parsing order: Top-down or Bottom-up

L-SDD **S/L-SDD**

Semantic Analysis Revisit

- Implementing S-SDD: bottom-up
  - S-SDD -> SDT: Place each action at the end of the production
  - Slack manuscription: enable automation

S-SDD

Productions	Semantic rules
(1)L-> E	print(E.val)
(2)E-> E_1+ T	E.val= E_1.val+T.val
(3)E-> T	E.val=T.val
(4)T-> T_1* F	T.val= T_1.valxF.val
(5)T-> F	T.val=F.val
(6)F-> (E)	F.val=E.val
(7)F-> digit	F.val=digit.lexval

SDT

CFG with actions
(1)L-> E {print(E.val)}
(2)E-> E_1+ T {E.val= E_1.val+T.val}
(3)E-> T {E.val=T.val}
(4)T-> T_1* F {T.val= T_1.valxF.val }
(5)T-> F {T.val=F.val}
(6)F-> (E) {F.val=E.val}
(7)F-> digit {F.val=digit.lexval}

- Example: A -> XYZ
  - x, y, z are attributes of X, Y, Z respectively
  - After the action, A and its attributes are at the top (i.e., m-2)

State:	S_0	…	S_{m-2}	S_{m-1}	S_m
Symbol:	$	…	X	Y	Z
Attribute:	-	…	X.x	Y.y	Z.z
					top

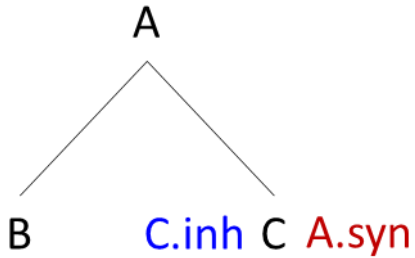
state ->	S_0	…	S_{m-2}
Symbol ->	$	…	A
Attribute ->	-	…	A.a
			top

Semantic Analysis Revisit

- Implementing L-SDD: top-down/bottom-up
  - L-SDD -> SDT:
    1. Embed the action that computes the inherited attributes for a nonterminal A immediately **before the occurrence** of A in the production body
    2. Place the actions that compute a synthesized attribute for the LHS **at the end** of the production body

A -> B {C.inh} **C** {A.syn}

- C的继承属性: 在C之前
- A的综合属性: 在RHS末尾



- **Eliminating left recursion!**

Eliminating left recursion

- A more complex case

$E \rightarrow E_1 + T \quad \{ E.val = E_1.val + T.val; \}$
$E \rightarrow E_1 - T \quad \{ E.val = E_1.val - T.val; \}$
$E \rightarrow T \quad \{ E.val = T.val; \}$
$T \rightarrow (E) \quad \{ T.val = E.val; \}$
$T \rightarrow num \quad \{ T.val = num.val; \}$

$E \rightarrow T\ R$
$R \rightarrow +\ T\ R_1$
$R \rightarrow -\ T\ R_1$
$R \rightarrow \varepsilon$
$T \rightarrow (\ E\ )$
$T \rightarrow num$

$A \rightarrow A\alpha \mid \beta$

⇩

$A \rightarrow \beta A';$
$A' \rightarrow \alpha A' \mid \varepsilon$

$E \rightarrow T \ \{ R.i = T.val; \}\ R \ \{ E.val = R.s; \}$
$R \rightarrow +\ T \ \{ R_1.i = R.i + T.val; \}\ R_1 \ \{ R.s = R_1.s; \}$
$R \rightarrow -\ T \ \{ R_1.i = R.i - T.val; \}\ R_1 \ \{ R.s = R_1.s; \}$
$R \rightarrow \varepsilon \ \{ R.s = R.i; \}$
$T \rightarrow (\ E\ ) \ \{ T.val = E.val; \}$
$T \rightarrow num \ \{ T.val = num.val; \}$

解决左递归斩断了产生式 (及actions)
$E \rightarrow E_1 + T \Rightarrow E \rightarrow TR \quad R \rightarrow +TR \quad R \rightarrow \varepsilon$

用新引入的R，传递属性值，实现计算
R.i (属性传递) R.s (属性返回)

通过R-> ε，将计算结果传回

Eliminating left recursion

- General rules
  - Only available for S-SDD (postfix translation schemes), a subset of L-SDD

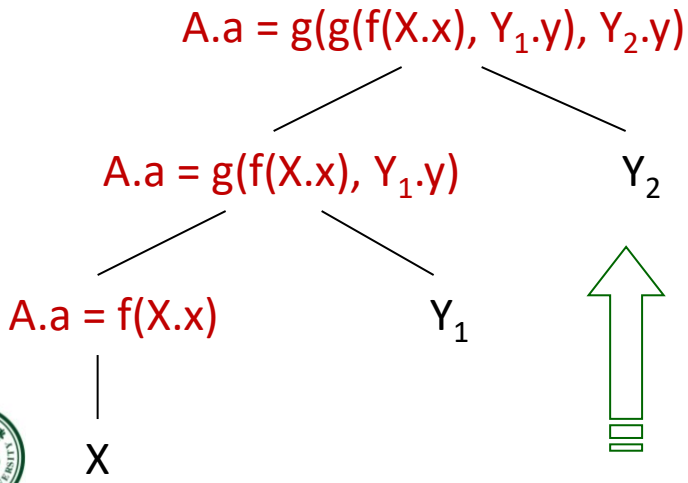
$A \rightarrow A_1\ Y\ \{ A.a = g(A_1.a, Y.y) \}$

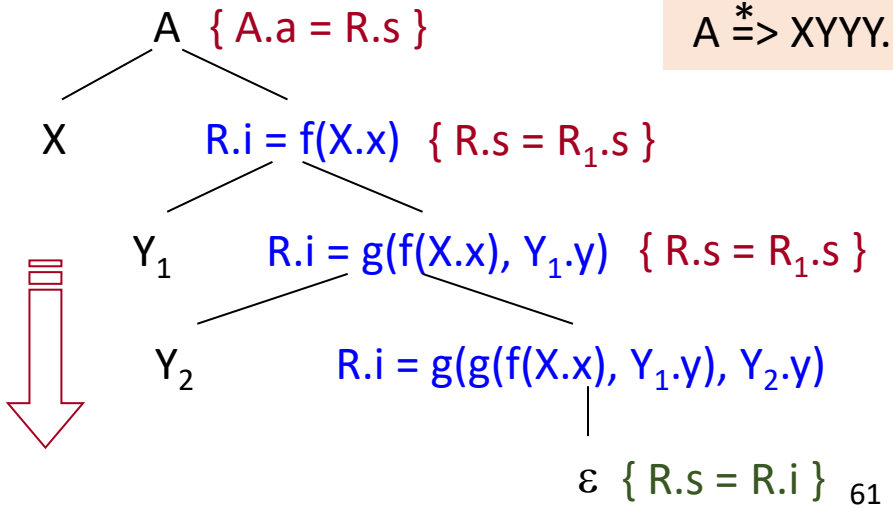
$A \rightarrow X\ \{ A.a = f(X.x) \}$

$A \rightarrow X\ \{ R.i = f(X.x) \}\ R\ \{ A.a = R.s \}$

$R \rightarrow Y\ \{ R_1.i = g(R.i, Y.y) \}\ R_1\ \{ R.s = R_1.s \}$

$R \rightarrow \varepsilon\ \{ R.s = R.i \}$





$A \overset{*}{\Rightarrow} XYYY...$

L-SDD in Recursive Decent Parsing

- A recursive-descent parser has a function A for each nonterminal A [递归预测分析方法]
  - Non-terminal expansion implemented by a function call
    - (Recursive) calls to functions for non-terminals in RHS
- Synthesized attributes: evaluate at end of function[综合属性: 最后计算]
  - All calls for RHS would have done by then
- Inherited attributes: pass as argument to function[继承属性: 参数传递]
  - Values may come from parent or siblings
  - L-attributed guarantees they have been computed (can only come from already computed portion of RHS)

It becomes clearer here that the inherited attributes of symbols at RHS cannot depend on the synthesized attribute of the LHS

Example

- **Function arguments and return**[参数和返回值]
  - Inherited: arguments
  - Synthesized: return

Augmentation:

- Use local variables[增加局部变量]
- Embed semantic actions[嵌入语义动作]

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

```
T'.syn T'(token, T'.inh) {
  if token = "*", then{
        getnext(token);
        F.val = F(token);
        T1'.inh = T'.inh * F.val
        getnext(token);
        T1'.syn = T1'(token, T1'.inh);
        T'.syn = T1'.syn
        return T'.syn
    } else if token = "$", then {
        T'.syn = T'.inh;
        return T'.syn;
    } else
        Error;
}
```

D: F.val -> T_1'.inh -> T_1'.syn

L-SDD in LL Parsing[非递归预测]

- **Extend the 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]

Action	Code
A	Inh Attr.
A.syn	Syn Attr.

- Manage attributes on the stack[管理属性信息]
  - The inherited attributes of a nonterminal A are placed in the stack that represents that terminal[A的继承属性直接放在符号位]
    - Action-record to evaluate these attributes are immediately above A
  - The synthesized attributes of a nonterminal A are placed in a separate synthesize-record that is immediately below A[A的综合属性另存放在A后]

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 A.i, but on all attrs of B
  - As an L-SDD, it ensures A.i are available when A is on the stack top
    - Thus, available to be copied into C
  - A's synthesized attrs A.s remain on the stack, below B and C when expansion happens

Action	Code
A	Inh Attr.
A.syn	Syn Attr.

Action	Code
B	Inh Attr.
B.syn	Syn Attr.
C	Inh Attr.
C.syn	Syn Attr.
A.syn	Syn Attr.

L-SDD in LL Parsing (cont.)

- A-> BC: C.i may depend not only on the inherited attr A.I, 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 C.i in the action-record that evaluates C.i;
  - Otherwise, when the parser replaces A on top of the stack by BC, the A.i will be gone, along with its stack record

1. 左部展开时（i.e., 左部符号本身的记录出栈时），若其含有继承属性，则要将继承属性复制给后面的动作记录
2. 综合属性出栈时，要将综合属性值复制给后面的动作记录

Action	Code
B	Inh Attr.
B.syn	Syn Attr.
C	Inh Attr.
C.syn	Syn Attr.
A.syn	Syn Attr.

Example

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

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

(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 = T1' .syn
(3)T'-> Ɛ {a_5}	a_5: T'.syn = T'.inh
(4)F-> digit {a_6}	a_6: F.val = digit.lexval

Example (cont.)

Input: 3*5

Stack top ‘digit’ matches the input ‘3’

- pop ‘digit’, but value copy is needed

(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 = T1’ .syn
(3)T’-> Ɛ $\{a_5\}$	a_5:T’.syn = T’.inh
(4)F-> digit $\{a_6\}$	a_6:F.val = digit.lexval

T -> F $\{a_1\}$ T’ $\{a_2\}$

F -> digit $\{a_6\}$

a6: stack[top-1].val= stack[top].d_lexval

digit	$\{a_6\}$	F’syn	$\{a_1\}$	T’	T’syn	$\{a_2\}$	Tsyn	$
lexv=3	d_lexv=3	val=3	val=3	inh	val		val	

L-SDD in LR Parsing

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

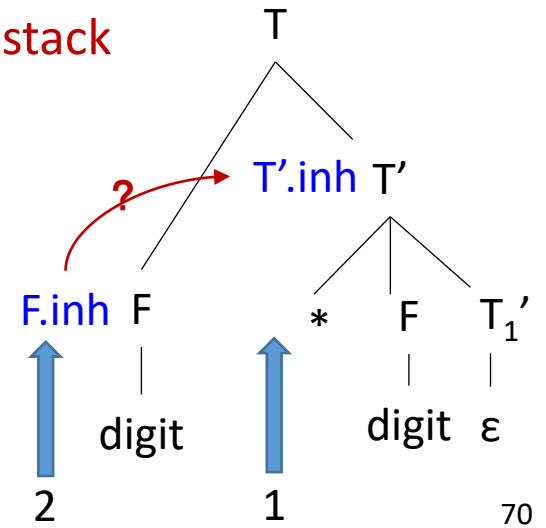
- What we already learnt
  - LR > LL, w.r.t parsing power
    - We can do bottom-up if we can do top-down
  - S-attributed SDD can be implemented in bottom-up way
    - All semantic actions are at the end of productions, i.e., triggered in reduce
- For L-SDD on an LL grammar, can it be implemented during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

Action	Code
B	Inh Attr.
B.syn	Syn Attr.
C	Inh Attr.
C.syn	Syn Attr.
A.syn	Syn Attr.

L-SDD in LR - The Problem

- It is not natural to evaluate inherited attributes
  - Example: how to get T'.inh
- Claims: inherited attributes are on the stack
  - L-SDD 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'.int x F.val} T_1' {T'.syn = T_1'.syn}
(3) T'-> ε {T'.syn = T'.inh }
(4) F -> digit {F.val = digit.lexval }



L-SDD in LR - Marker

- Given the following SDD, where $|\alpha| \neq |\beta|$
  - A-> Xα {Y.in= X.s} Y | Xβ {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 locations** from Y in the stack
- Solution: insert markers M_1, M_2 right before Y
  - A-> X α M_1 Y | X β M_2 Y
  - M_1-> ε {M_1.s= stack[top-$|\alpha|$].s} // M1.s= X.s
  - M_2-> ε {M_2.s= stack[top-$|\beta|$].s} // M2.s= X.s
  - Y -> γ {Y.s= f(stack[top-$|\gamma|$].s) } // Y.s= M1.s or Y.s= M2.s
- Marker: a non-terminal marking a location that is the same with the symbol that has an inherited attribute
  - Always produces ε since it is only a placeholder for an action

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
  - Put a marker non-terminal[标记非终结符] in the place of each embedded action
    - Each of such places gets a distinct marker, say M, where M -> ε [空产生式]
  - Modify the action {a} if marker M replaces it in some production A->α {a} β, and associate with M -> ε an action {a'} that
    1. Copies, as inherited attrs of M, any attrs of A or symbols of α that action {a} needs (e.g., M.i=A.i)[M的继承属性为{a}的输入]
    2. Compute sattrs in the same way as {a}, but makes those attrs be synthesized attrs of M (e.g., M.s= f(M.i)) [M的综合属性为{a}中的输出]

A -> {B.i= f(A.i)} BC

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

Example

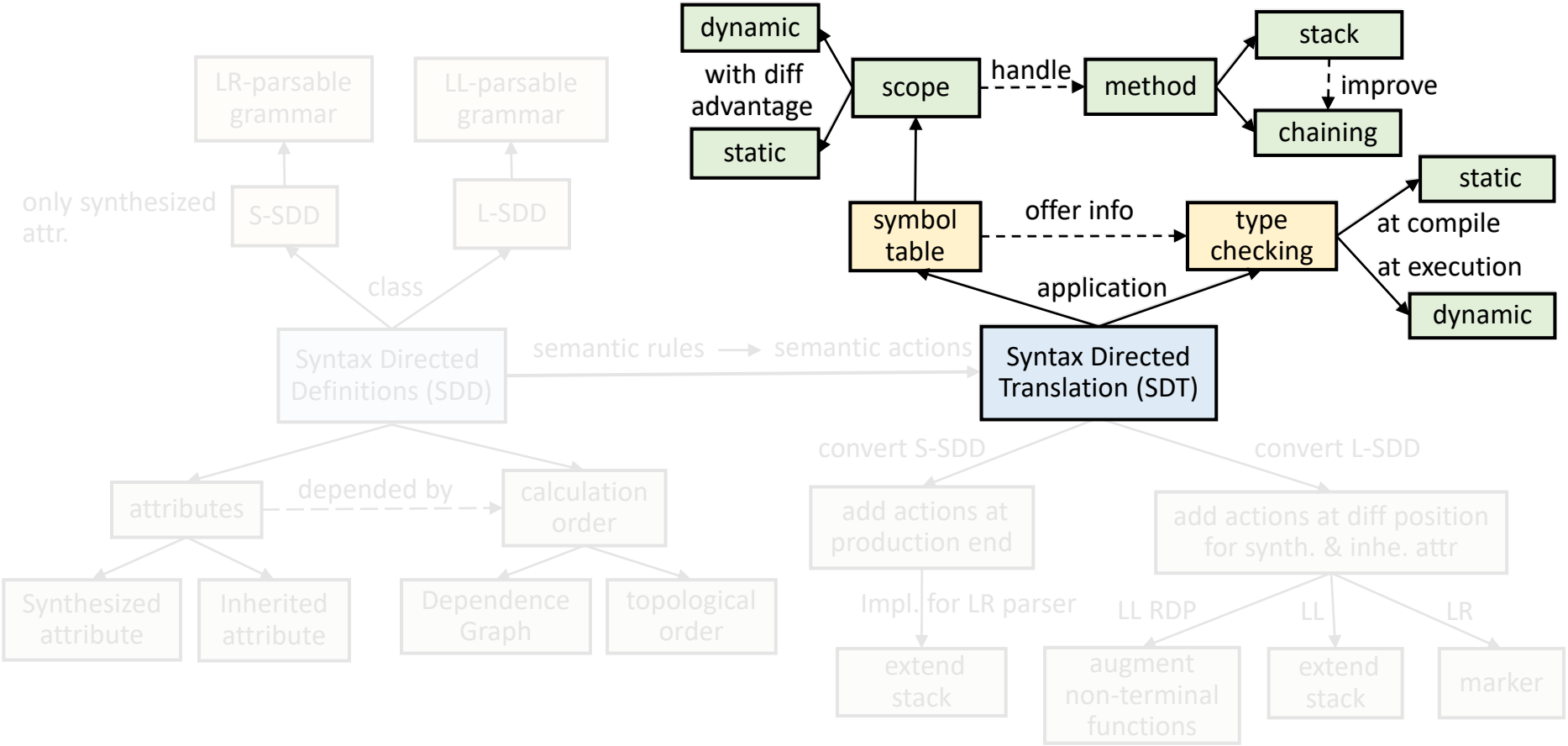
(1)T -> F {T'.inh = F.val} **T'** *{T.val = T'.syn}*
*(2) T' -> *F {T_1'.inh = T'.int * F.val}* T_1' *{T'.syn = T_1'.syn}*
(3) T' -> ε {T'.syn = T'.inh }
(4) F -> digit {F.val = digit.lexval }

(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 * N.i2 }
(3) T'-> ε {T'.syn = T'.inh }
(4) F-> digit {F.val = digit.lexval }

A -> {B.i= f(A.i)} BC

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

Content


dynamic
with diff advantage
static
scope
handle
method
stack
improve
chaining
symbol table
offer info
type checking
static
at compile
at execution
dynamic
application
Syntax Directed Translation (SDT)
semantic rules
semantic actions
Syntax Directed Definitions (SDD)
class
LR-parsable grammar
LL-parsable grammar
only synthesized attr.
S-SDD
L-SDD
attributes
depended by
calculation order
Synthesized attribute
Inherited attribute
Dependence Graph
topological order
convert S-SDD
convert L-SDD
add actions at production end
add actions at diff position for synth. & inhe. attr
Impl. for LR parser
LL RDP
LL
LR
extend stack
augment non-terminal functions
extend stack
marker

Overview of Symbol Table [符号表]

- **Symbol table** records the information 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**: matching identifier use with definition[使用-定义]
  - Definition: associating an id with a memory 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 Java: private, global, static, etc...
- 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: static scoping and dynamic scoping [静态/动态作用域]
  - 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
    - Can determine bindings at compile time – allow code optimization

What is Symbol Table[符号表]

- **Symbol**: same thing as identifier (used interchangeably)
- **Symbol table**: a data structure that tracks info about all symbols
  - Each entry represents a definition of that identifier[标识符的定义]
  - Maintains definitions that reach current program point[当前作用域中的定义]
  - List updated whenever scopes are entered or exited [随作用域改变而更新]
  - Used to perform binding of identifier uses [用于绑定变量定义与使用]
    - Traversing the parse tree in a separate pass after parsing [单独扫描语法树]
    - Using semantic actions as an integral part of parsing pass [或与语法分析同时]
  - 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

Symbol Table Structure [结构]

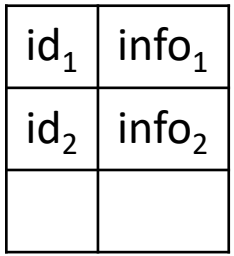
- Front-end time is affected by symbol table access time[符号表访问时间影响编译前端性能]
  - Front-end: lexical, syntax, semantic analysis
  - Frequent searches on any large data structure is expensive
  - Symbol table design is important for compiler performance

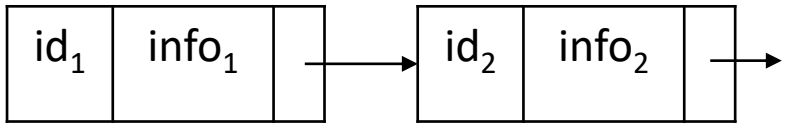
- What data structure to choose? [可选数据结构]
  - List[线性表]
  - Binary tree[二叉树]
  - Hash table[哈希表]

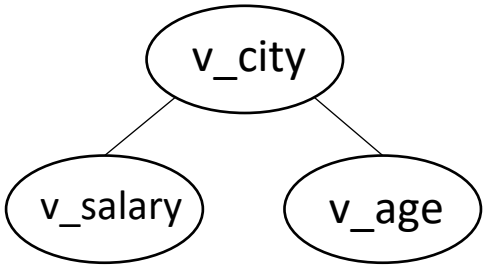
- Tradeoffs: time vs. space[空间和时间的权衡]
  - Let us first consider the organization without scope

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(logn) on balanced tree
  - In the worst case, tree may reduce to linked list
    - Then insert/delete/search becomes O(n)

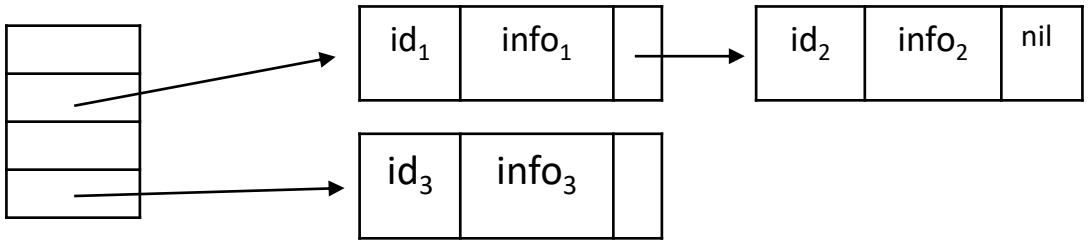






Symbol Table Structure (cont.)

- **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 */
```

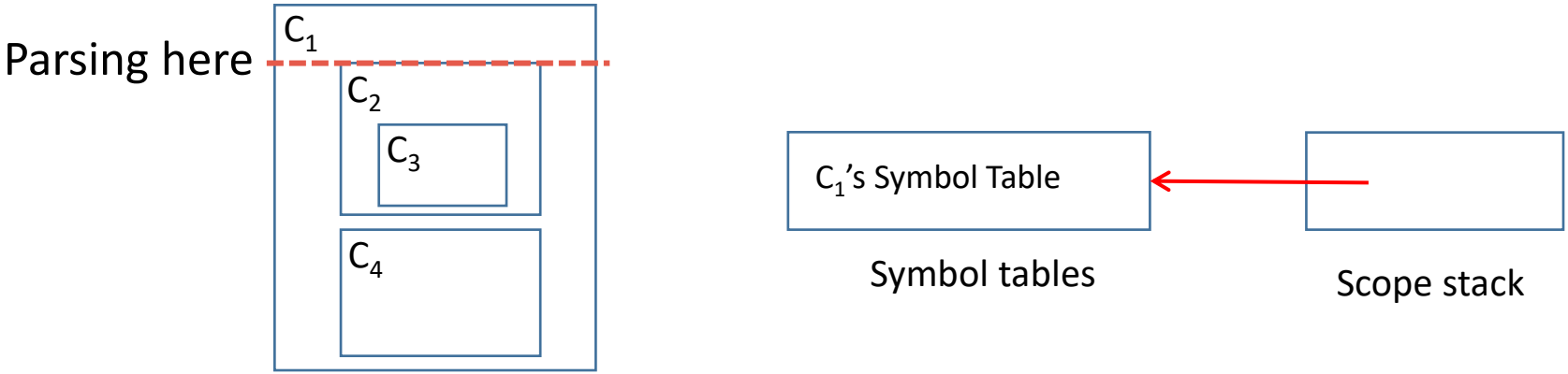
  - Sometimes not:

```
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

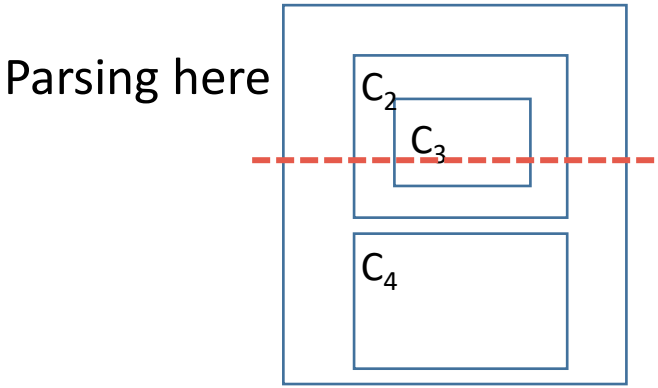
Handle Scopes with Stack

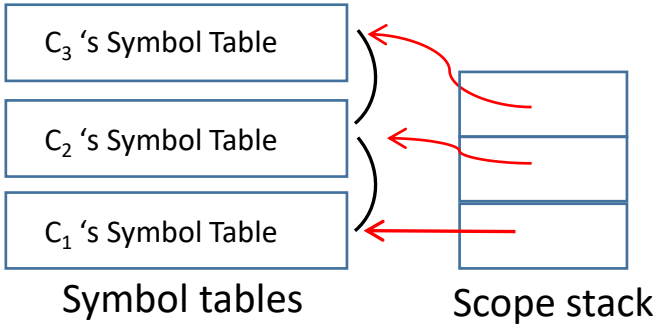
- Organize all symbol tables into **a scope stack**[作用域栈]
  - An individual symbol table for each scope
    - Scope is defined by nested lexical structure, e.g., { C_1 {C_2 {C_3}} {C_4} }
  - Stack holds one entry for each open scope
    - Inner-most scope is stored at the top of the stack
- Stack **push/pop**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



Handle Scopes with Stack (cont.)

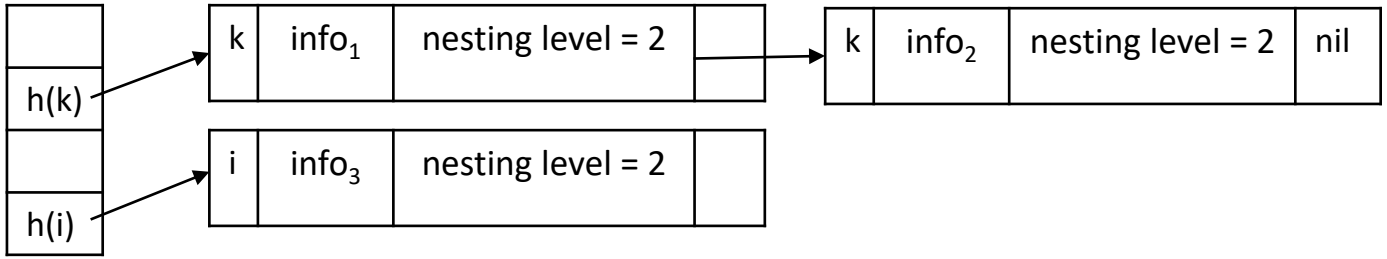
- Operations:
  - When entering a scope
    - Create a new symbol table to hold all variables declared in that scope
    - Push a pointer to the symbol table on the stack
  - Pop the pointer to the symbol table when exiting scope
  - Search from the top of the stack





Handle Scopes 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
- 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 are maintained in a list



Info Stored in Symbol Table

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

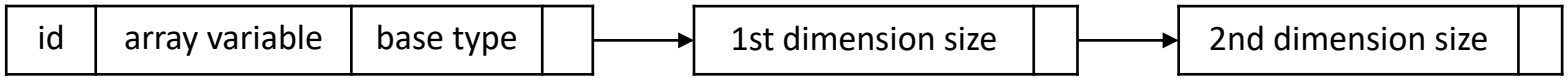
Attribute List in Symbol Table

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

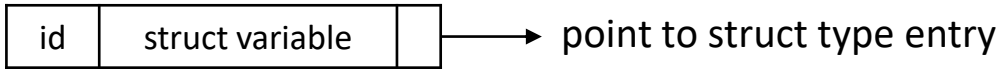
    char arr[20][20];
  - Type can be a struct with multiple fields

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

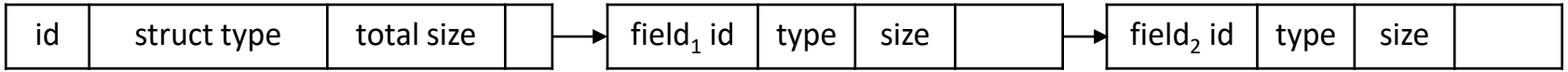
- Store all type info in an attribute list
  - Entry for an array variable with 2 dimensions



  - 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
    - Should a variable assignment be a 4 byte or 8 byte copy?
  - To translate uses of variables to machine instructions
    - Should a '+' on variable be an integer or a floating point add?
  - To translate calls to functions to machine instructions
    - What are the types of arguments and return value of 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 and a set of operations on these values
- **Type checking**: verifying type consistency across program
  - A program is 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
  - Infers[推断] whether the program is type consistent through code analysis
    - Collect info via declarations that 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 *ints* is still 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 a 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
  - 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
  - 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 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[可塑性强]
    - Absence of types declarations means shorter code
    - Suitable for scripting or prototyping languages
  - More program bugs and execution time
    - Due to dynamic type checking

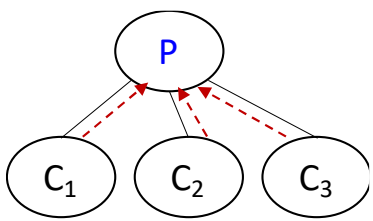
Type System[类型系统]

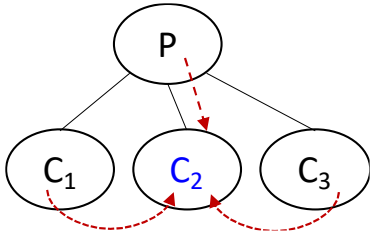
- **Static/dynamic typing** are type systems
  - Type System: types and type rules of a language
- **Static/dynamic type checking** are methods
  - Methods to enforce the rules of the given type system

- Static type checking is not used only for static typing
  - Also used for dynamic typing if types can be inferred at compile time
- Dynamic type checking is not used only for dynamic typing
  - Some features of statically typed languages require it
    - e.g., downcasting[父类向子类的强制类型转换]

Short Summary

- SDD & SDT
- Synthesized & inherited attribute
  - Evaluation order – DAG & topological order



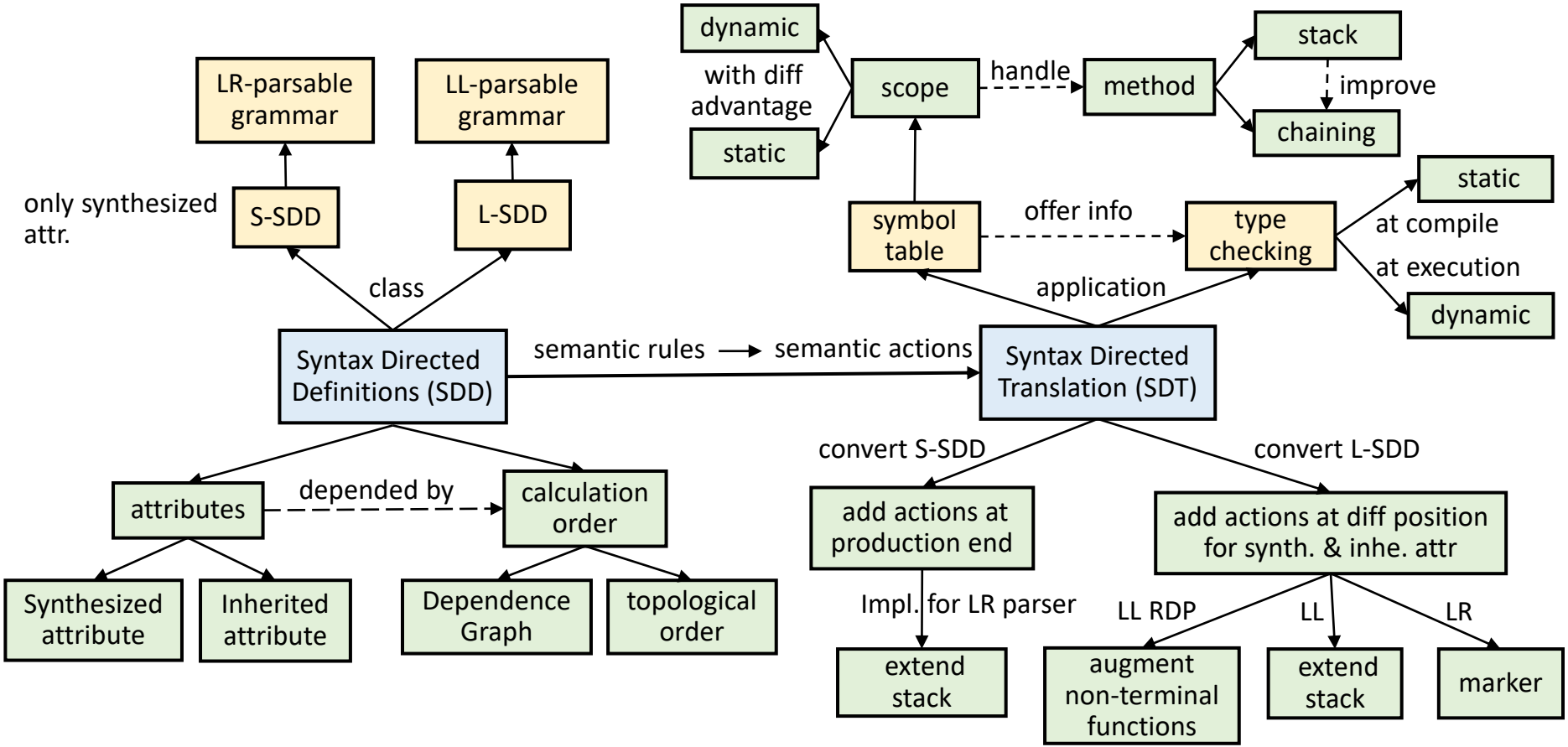


- S-SDD & L-SDD
- S-SDD -> SDT -> Implementation
  - (LR only) Postfix SDT -> stack extension -> stack manipulation
- L-SDD -> SDT -> Implementation
  - LL: Eliminate left recursion
    - RDP: inherited attributes (arguments) and synthesized attributes (return values)
    - Predictive Parsing: stack extension (action and synthesized records)
  - LR: Marker -> postfix SDT -> stack extension -> stack manipulation

Summary

- Static and Dynamic Scoping
  - Pros of **static**: fewer errors + more efficient
- Symbol and Symbol Table
  - Structuring: array, list, binary tree, **hash table**
  - Trade-off between time and space
- Scope handling
  - Stack: Inefficient searching and use of memory
  - So **chaining** is introduced
- Static and dynamic typing and type checking
  - Static: less bugs and execution time, but more effort
  - Dynamic: less effort, but more bugs and execution time
  - Static ones are more desirable, but is often insufficient, e.g., downcasting

Content


LR-parsable grammar
LL-parsable grammar
only synthesized attr.
S-SDD
L-SDD
class
Syntax Directed Definitions (SDD)
semantic rules
semantic actions
Syntax Directed Translation (SDT)
attributes
depended by
calculation order
Synthesized attribute
Inherited attribute
Dependence Graph
topological order
dynamic
with diff advantage
static
scope
handle
method
stack
improve
chaining
symbol table
offer info
type checking
static
at compile
at execution
dynamic
application
convert S-SDD
convert L-SDD
add actions at production end
add actions at diff position for synth. & inhe. attr
Impl. for LR parser
LL RDP
LL
LR
extend stack
augment non-terminal functions
extend stack
marker

Further Reading

- Dragon Book, 2nd Edition
  - Comprehensive Reading:
    - Section 5.1-5.3 on introduction to syntax-directed translation.
    - Section 5.4-5.5 on the implementation of translation schemes in top-down and bottom-up LR parsing.