中山大學
SUN YAT-SEN UNIVERSITY

国家超级计算广州中心
NATIONAL SUPERCOMPUTER CENTER IN GUANGZHOU

Compilation Principle
编 译 原 理

第13讲：语义分析(1)

张献伟

xianweiz.github.io

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Quiz Questions

- Q1: main differences between LL(k) and LR(k)?

  LL(k): top-down, leftmost derivation; LR(k): bottom-up, reverse of rightmost derivation.

- Q2: for the grammar, get FIRST(*S*) and FIRST(*A*).

  FIRST(*S*) = {a}, FIRST(*A*) = {a}

  S → AB | a
  A → a
  B → b

- Q3: is the grammar a LL(1)?

  NO. One-lookahead of *S* is *a*, failing to distinguish the two rules.

- Q4: augment the grammar, and get the initial state (S_0).

  { S' → .S, S → .AB, S → .a, A → .a }

- Q5: LR(0), SLR(1), LR(1), LALR(1), what are the differences?

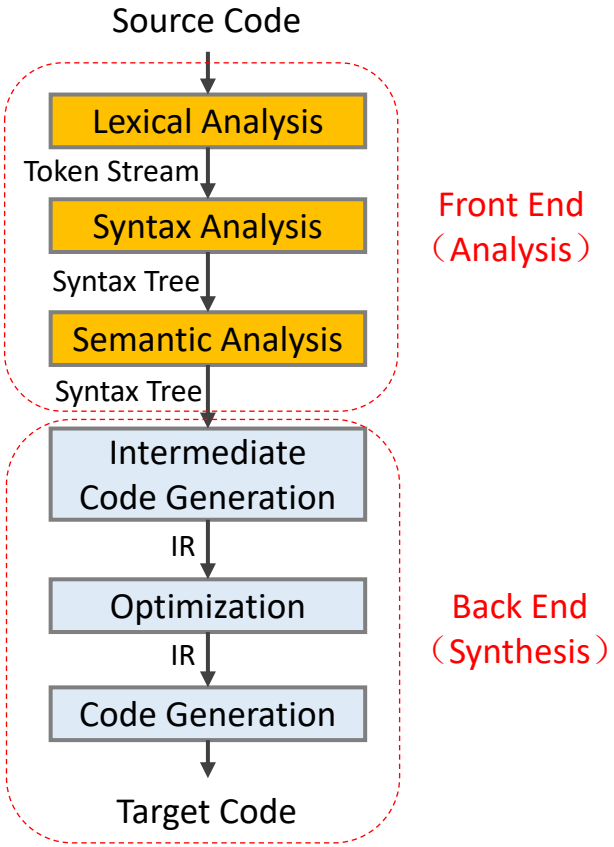
  LR(0): no lookahead, aggressive reduce

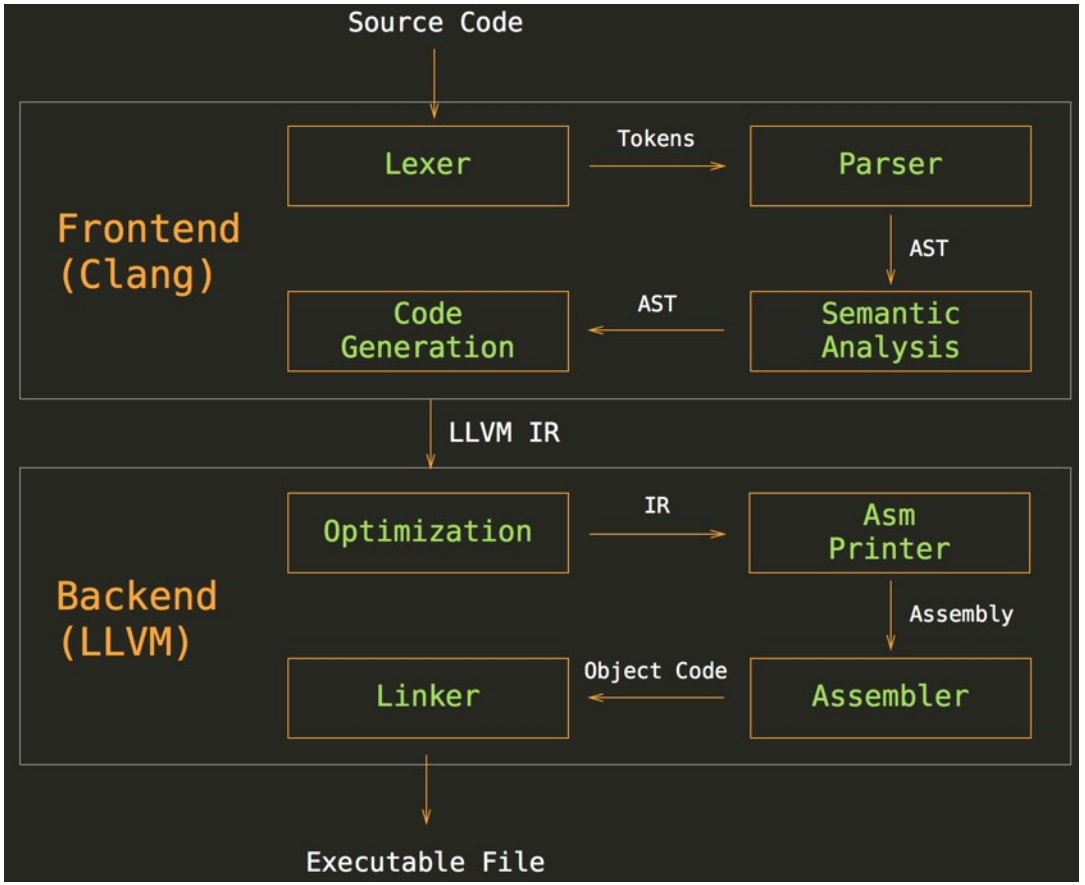
  SLR(1): one lookahead, reduce using FOLLOW

  LR(1): one lookahead, reduce using specified terminals

  LALR(1): a compromise of LR(1) and LR(0)/SLR(1)

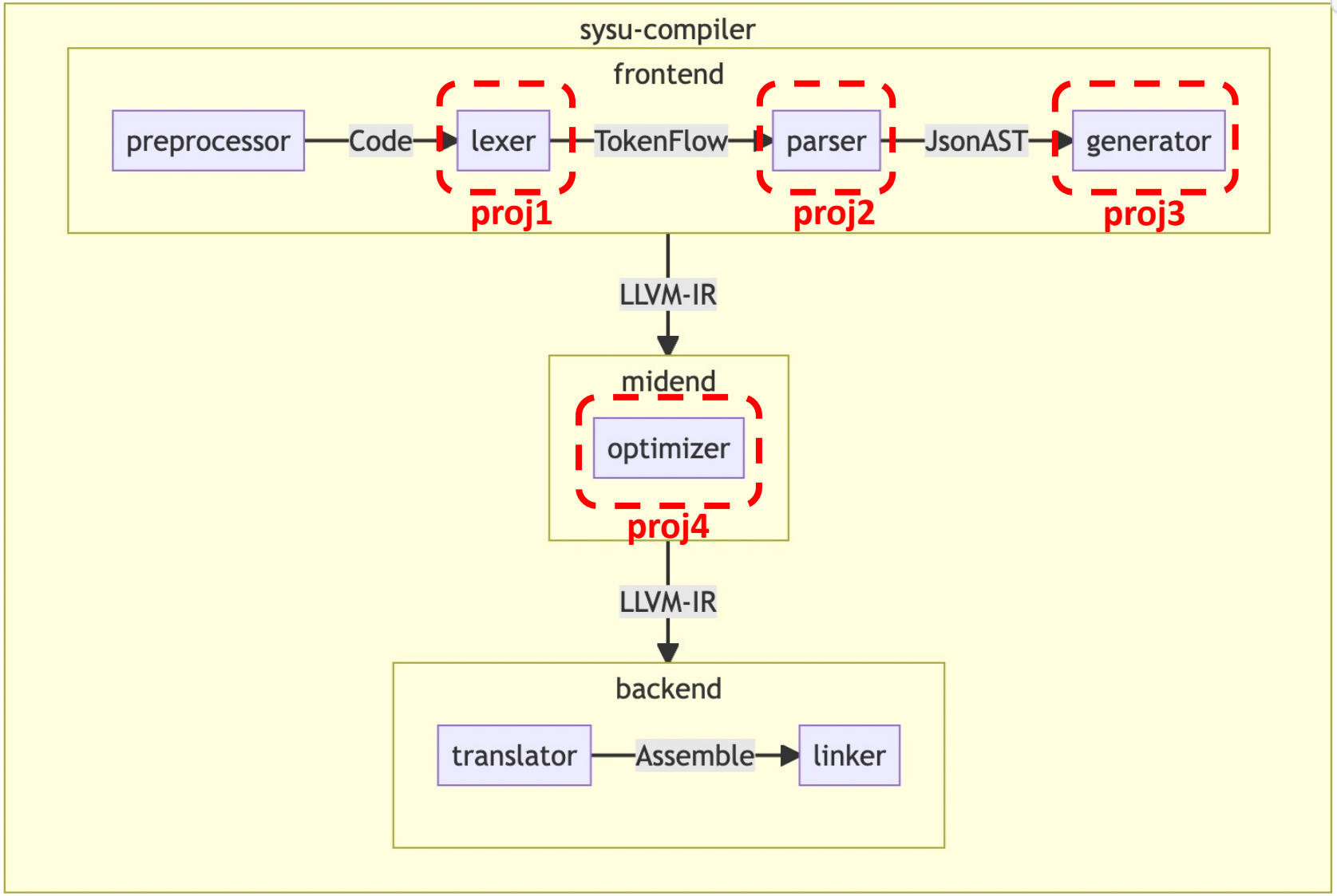
Compilation Phases[编译阶段]

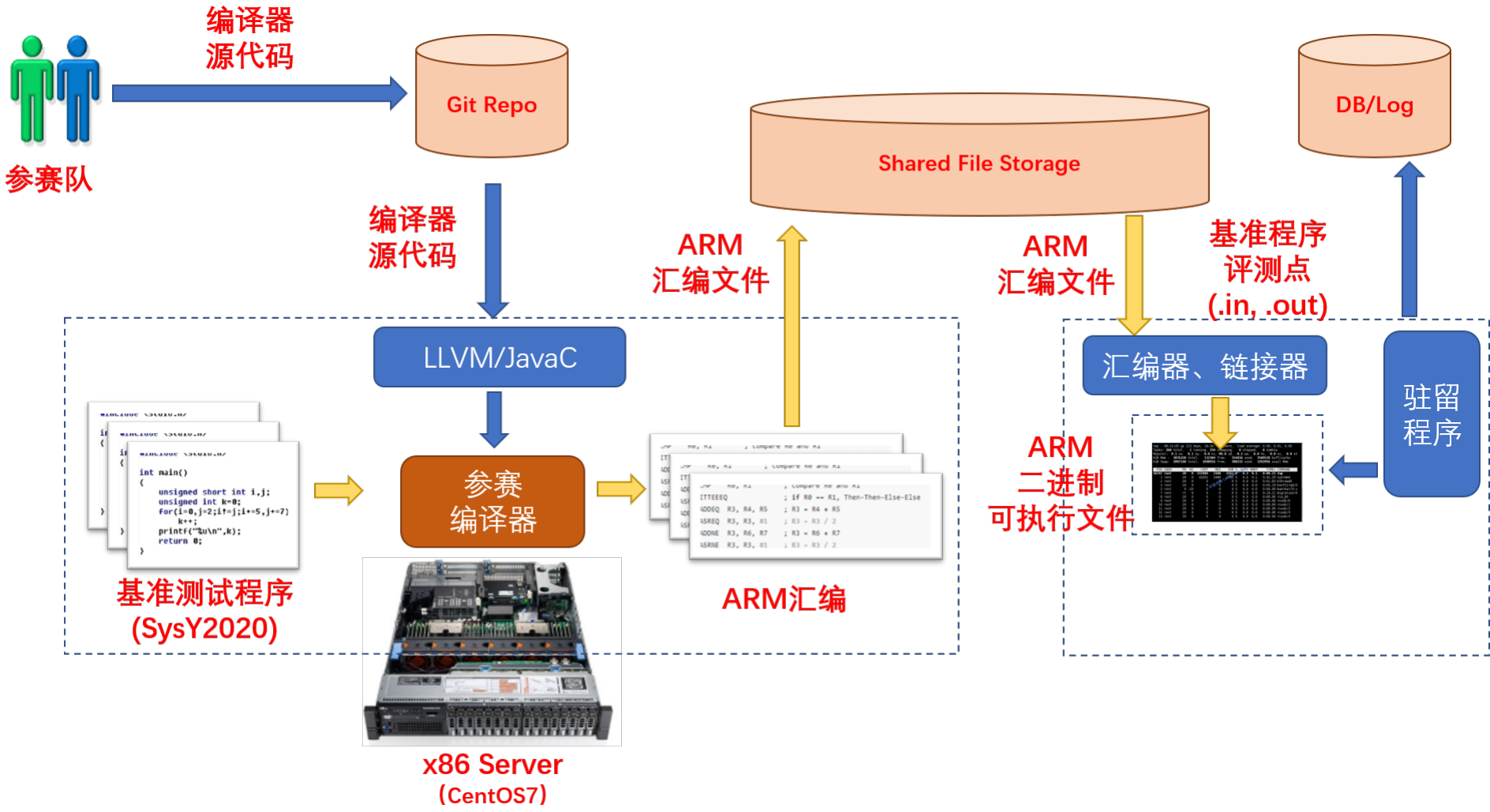




https://lowlevelbits.org/bitcode-demystified/

Compilation Phases (cont.)




编译器
源代码
Git Repo
参赛队
Shared File Storage
DB/Log
编译器
源代码
ARM
汇编文件
ARM
汇编文件
基准程序
评测点
(.in, .out)
LLVM/JavaC
汇编器、链接器
驻留
程序
参赛
编译器
ARM
二进制
可执行文件
基准测试程序
(SysY2020)
ARM汇编
x86 Server
(CentOS7)

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 (cont.)

- Semantics of a language is much 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 what the programs means (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 to objects require expressing the pattern:

    $\{wcw \mid w \in (a|b)^*\}$

    - The first w represents the definition of a 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 are declared before they're used[先声明后使用]
    - Type consistency when using IDs[变量类型一致]
    - Expressions have the right 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
  - …

Example

```
#include <iostream>

using namespace std;

//Derived class
class Child : public Base {
  string myInteger;

  void doSomething() {
    int x[] = {0, 1, 2, 3, 4};
    int z = 'a';
    x[5] = myInteger * y * z;
  }

  void doSomething() {
  }

  int getSum(int n) {
    return doSomething() + n;
  }
};
```

base class not defined

array index out of bounds (runtime)

1) **y variable not declared**

2) cannot multiply a string

cannot redefine functions

cannot add void to int

no main() function

https://web.stanford.edu/class/archive/cs/cs143/cs143.1128/lectures/08/Slides08.pdf

Example (cont.)

```
test.cpp:6:22: error: expected class name
class Child : public Base {
                     ^
test.cpp:15:8: error: class member cannot be redeclared
  void doSomething() {
       ^
test.cpp:9:8: note: previous definition is here
  void doSomething() {
       ^
test.cpp:12:24: error: use of undeclared identifier 'y'
    x[5] = myInteger * y * z;
                       ^
test.cpp:19:26: error: invalid operands to binary expression ('void' and 'int')
    return doSomething() + n;
           ~~~~~~~~~~~~~ ^ ~
4 errors generated.
```

```
#include <iostream>

using namespace std;

//Derived class
class Child : public Base {
  string myInteger;

  void doSomething() {
    int x[] = {0, 1, 2, 3, 4};
    int z = 'a';
    x[5] = myInteger * y * z;
  }

  void doSomething() {
  }

  int getSum(int n) {
    return doSomething() + n;
  }
};
```

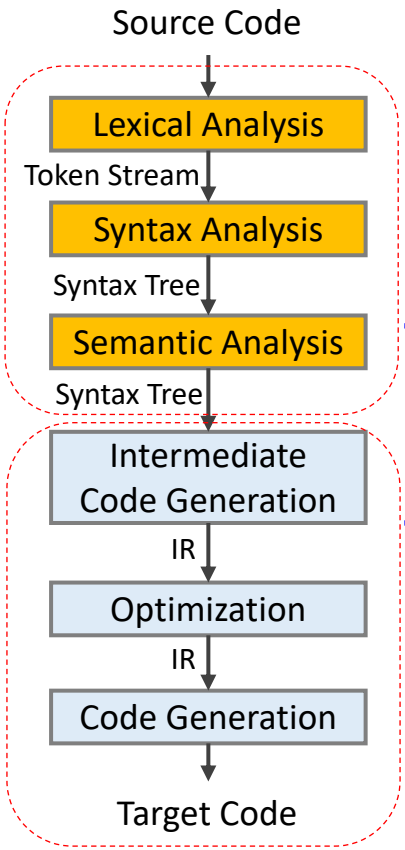

```
test.cpp:6:27: error: expected class-name before '{' token
    6 | class Child : public Base {
      |                           ^
test.cpp:15:8: error: 'void Child::doSomething()' cannot be overloaded with 'void Child::doSomething()'
   15 |   void doSomething() {
      |        ^~~~~~~~~~~
test.cpp:9:8: note: previous declaration 'void Child::doSomething()'
    9 |   void doSomething() {
      |        ^~~~~~~~~~~
test.cpp: In member function 'void Child::doSomething()':
test.cpp:12:24: error: 'y' was not declared in this scope
   12 |     x[5] = myInteger * y * z;
      |                        ^
test.cpp: In member function 'int Child::getSum(int)':
test.cpp:19:26: error: invalid operands of types 'void' and 'int' to binary 'operator+'
   19 |     return doSomething() + n;
      |            ~~~~~~~~~~~~~ ^ ~
      |                          |   |
      |                         void int
```

Semantic Analysis: Implementation

- Attribute grammars[属性文法]
  - One-pass compilation
    - Semantic analysis is done right in the middle of parsing
  - Augment rules to do checking during parsing
  - 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

Syntax Directed Translation[语法制导翻译]



Semantic Translation
(语义翻译)

Syntax Directed Translation
(语法制导翻译)

Syntax Directed Translation[语法制导翻译]

- To translate based on the program's syntactic structure[语法结构]
  - Syntactic structure: structure of a program given by grammar
  - 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:
  - Attach **semantic attributes**[语义属性] to each grammar symbol
    - The attributes describe the symbol properties
    - 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)*
- Format: *X.a* (*X* is a symbol, *a* is one of its attributes)
- For Project 2 – Syntax Analysis
  - Semantic attributes
    - *Name*, *type*
  - Semantic actions

```
CompUnit: FuncDef {
  auto inner = stak.back();
  stak.pop_back();
  stak.push_back(llvm::json::Object{{"kind", "TranslationUnitDecl"},
                                    {"inner", llvm::json::Array{inner}}});
}
```

How to Specify Syntax Directed Translation

- **Syntax Directed Definitions** (SDD)[语法制导定义]
  - Attributes + semantic rules[语义规则]for computing them
    - 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]
  - Example rules for computing the value of an expression

    E -> E_1 + E_2 RULE: {E.val = E_1.val + E_2.val}

    E -> id RULE: {E.val = id.lexval}
- **Syntax Directed Translation scheme** (SDT)[语法制导翻译方案]
  - Attributes + semantic actions[语义动作] for computing them
  - Example actions for computing the value of an expression

    E -> E_1 + E_2 {E.val = E_1.val + E_2.val}

    E -> id {E.val = id.lexval}

SDD vs. SDT

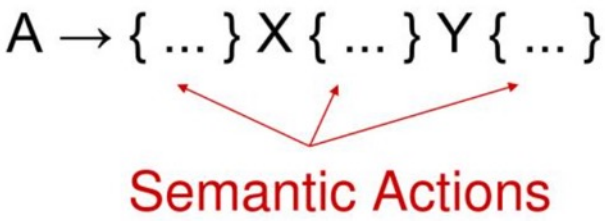
- SDD[语法制导定义]: 是CFG的推广，翻译的高层次规则说明
  - A CFG grammar together with attributes and semantic rules
    - A subset of them are also called **attribute grammars**[属性文法]
      - No side effects, i.e., rules are strictly local to each production
  - Semantic rules imply no order to attribute evaluation
- SDT[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
    - Fragments of programs are attached to different points in the production rules
  - The order of execution is important

Grammar	SDD	SDT
D -> T L	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	L_1.*inh* = L.*inh*	L -> { L_1.*inh* = L.*inh* }L_1, id

SDD vs. SDT (cont.)

- 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 vs. 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



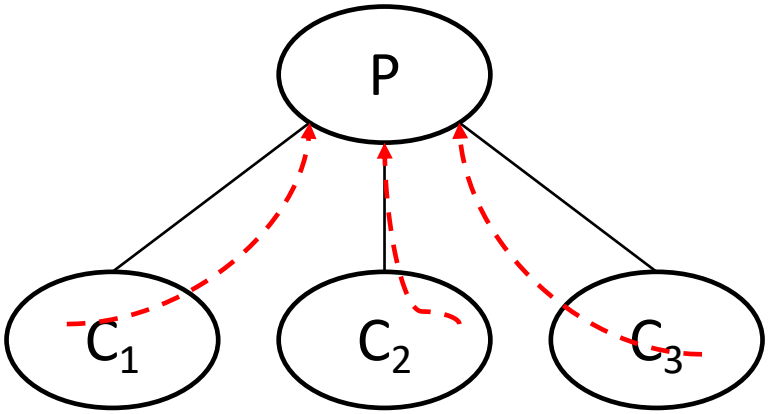
SDD[语法制导定义]

- SDD has two types of attributes[两种属性]
  - For a non-terminal *A* at a parse-tree node *N*

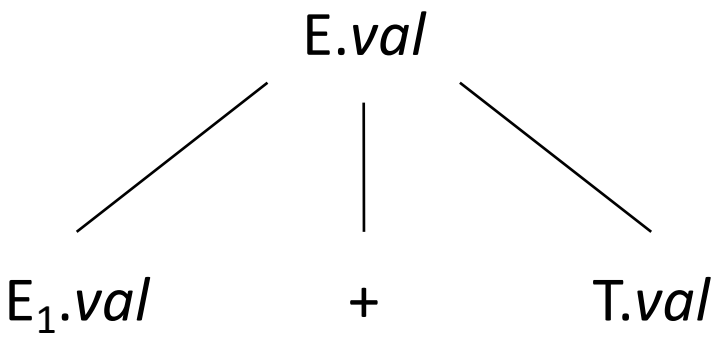
- **Synthesized attribute**[综合属性]
  - Defined by a semantic rule associated with the production at *N*
    - The production must have *A* as its head (i.e., A -> …)
  - A synthesized attribute of node *N* is defined only by attribute values at *N*'s children and *N* itself[子节点或自身]
- **Inherited attribute**[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 at 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)
- Terminals can have synthesized attributes[终结符综合属性]
  - Lexical values supplied by the lexical analysis
  - Thus, no semantic rules in SDD for terminals

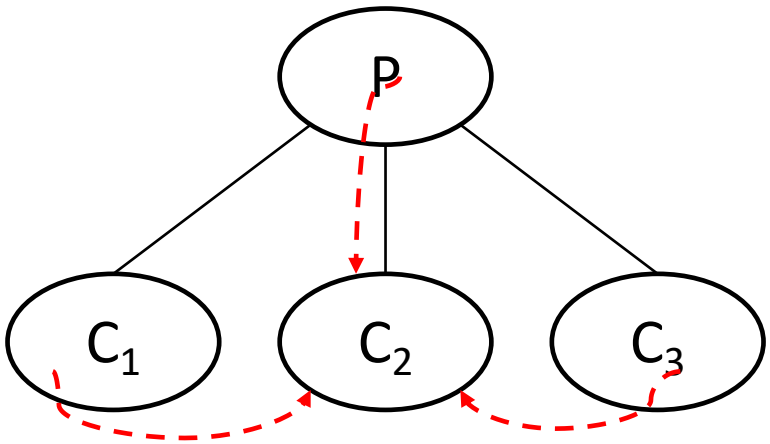


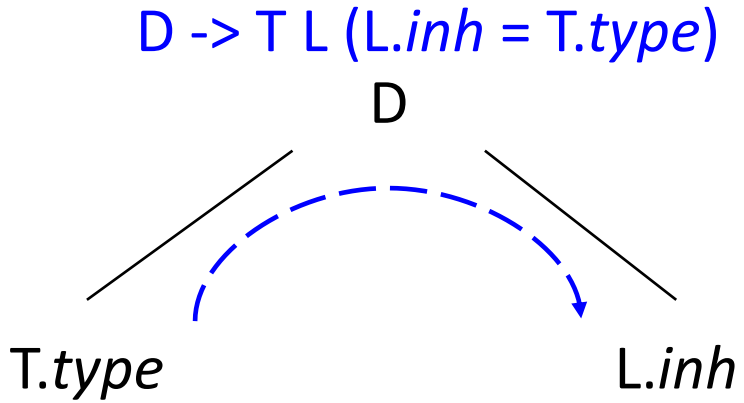
E.*val* = E_1.*val* + T.*val*



Inherited Attribute[继承属性]

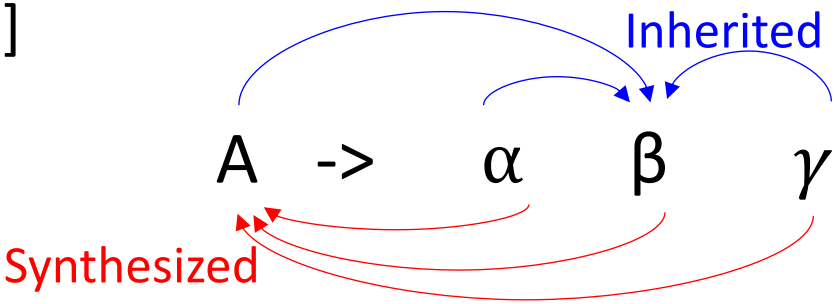
- Inherited attribute for non-terminal *A* of parse-tree node *N*[非终结符继承属性]
  - Only defined by *N*'s parent, *N*'s siblings and *N* itself
    - Passed down a parse tree
  - C_2.inh_attr = f(P.attrs, C_1.attrs, C_2.attrs, C_3.attrs)
- Terminals cannot have inherited attributes[终结符无继承属性]
  - Only synthesized 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[综合]

SDD:

Production Rules	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.*val* x F.*val*
(5) T -> F	T.*val* = F.*val*
(6) F -> (E)	F.*val* = E.*val*
(7) F -> digit	F.*val* = digit.*lexval*

Each non-terminal has a single synthesized attribute val
Terminal *digit* has a synthesized attribute lexval

Arithmetic expressions with + and *

(1) Print the numerical value of the entire expression
(2) Compute value of summation
(3) Value copy
(4) Compute value of multiplication
(5) Value copy
(6) Value copy