北京大学计算机学院

2026 年春季学期　　《编译原理(实验班)》

第四讲　语义分析（基础版）

Semantic Analysis

主要内容

- 语义分析的作用
- 语义分析的规约
- 语义分析的手动实现

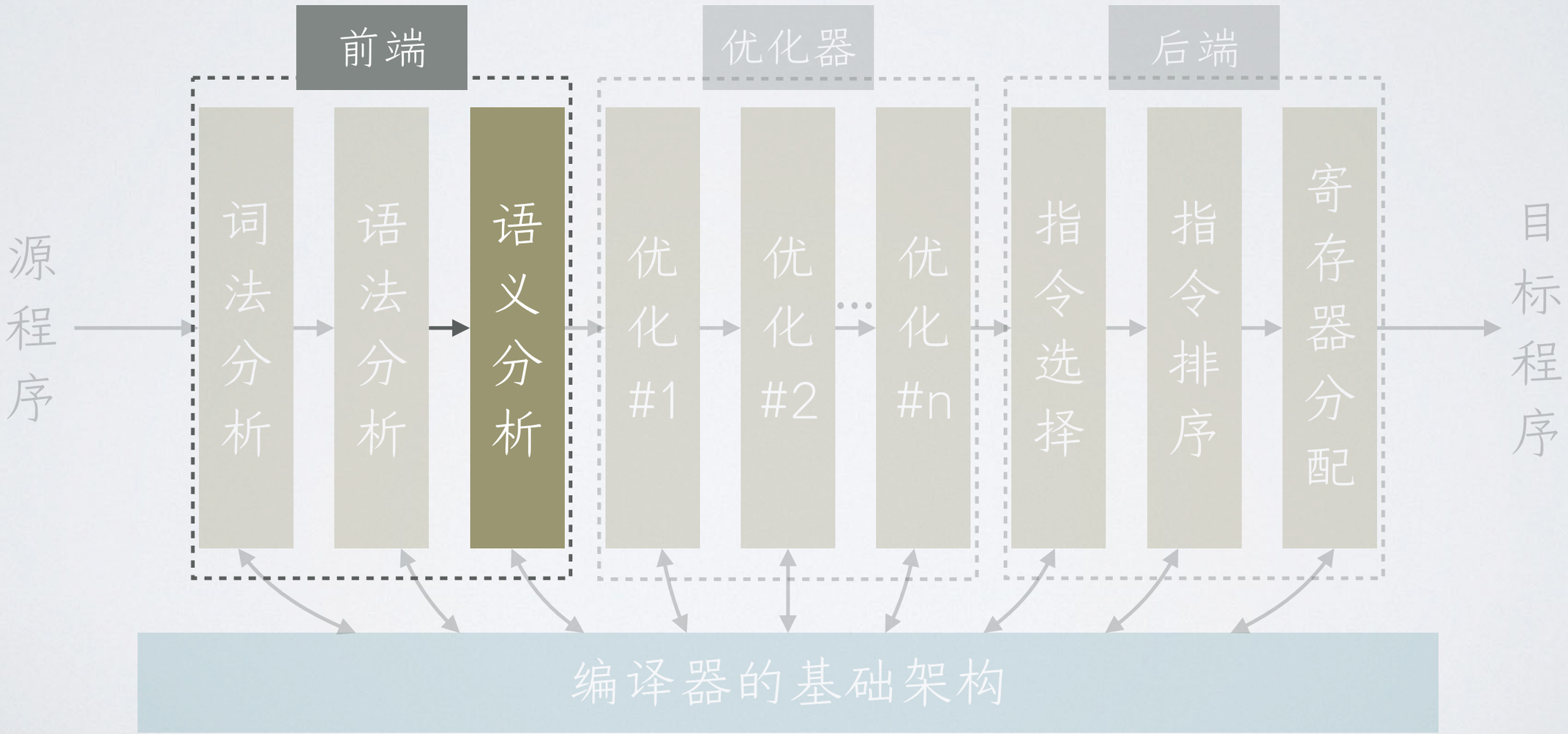
- 对应龙书章节：第 5 章

主要内容

- **语义分析的作用**
- 语义分析的规约
- 语义分析的手动实现

语义分析的作用

- 基于语法分析树，提取程序的核心语义
- 语义分析在不同场景下可以指不同的工作，但通常包括**翻译到中间表示**、**类型检查**、**解释执行**等



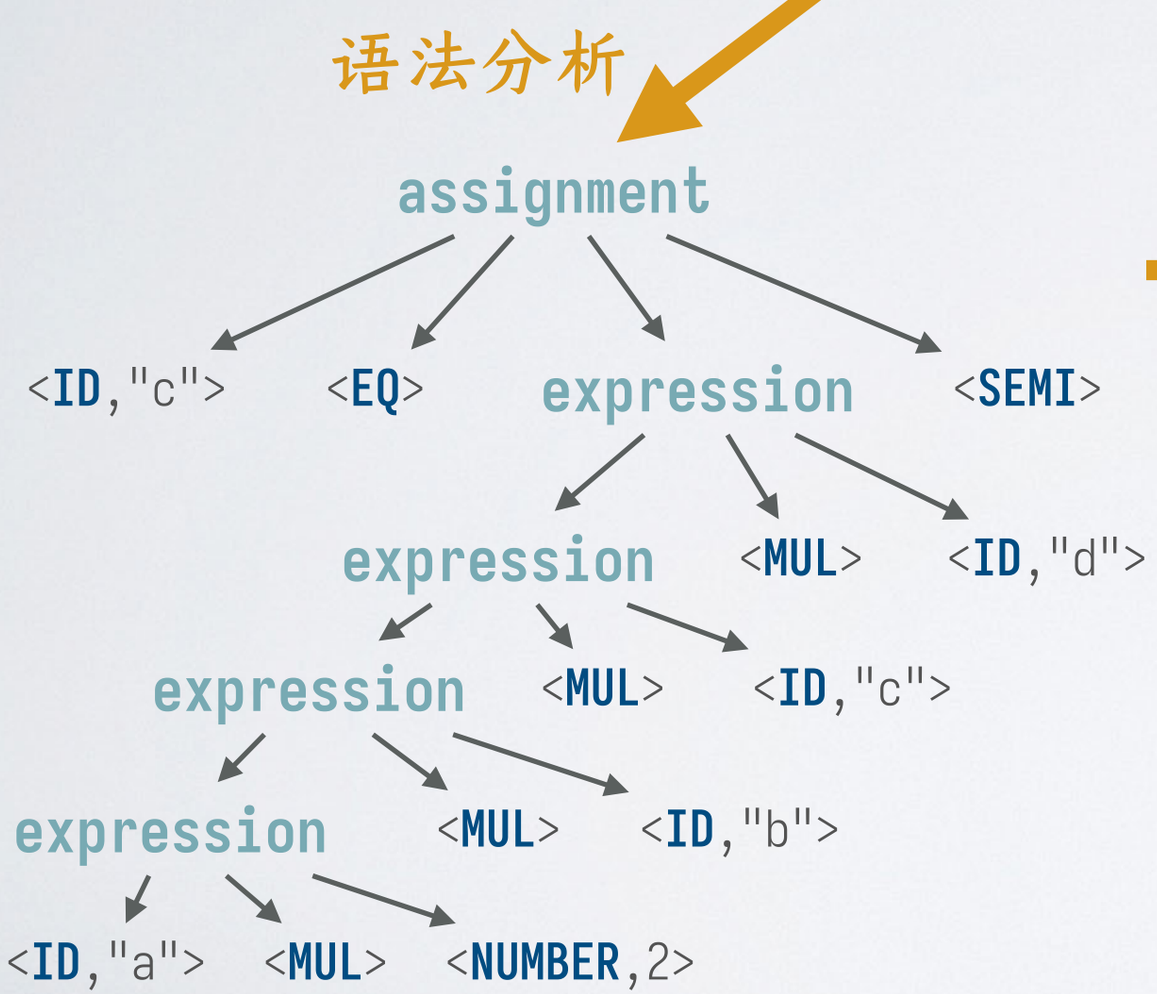
语义分析示例：翻译到中间表示

```
c = a * 2 * b * c * d;
```

词法分析

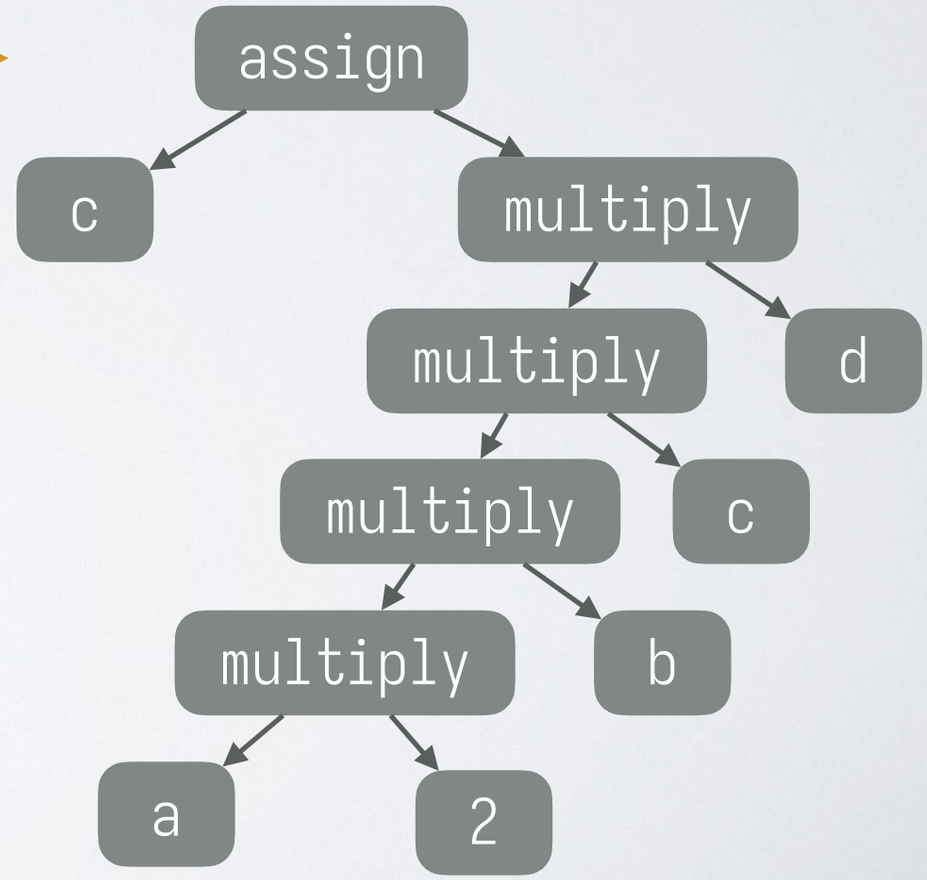
<ID,"c"> <EQ> <ID,"a"> <MUL> <NUMBER,2> <MUL> <ID,"b"> <MUL> <ID,"c"> <MUL> <ID,"d"> <SEMI>

语法分析



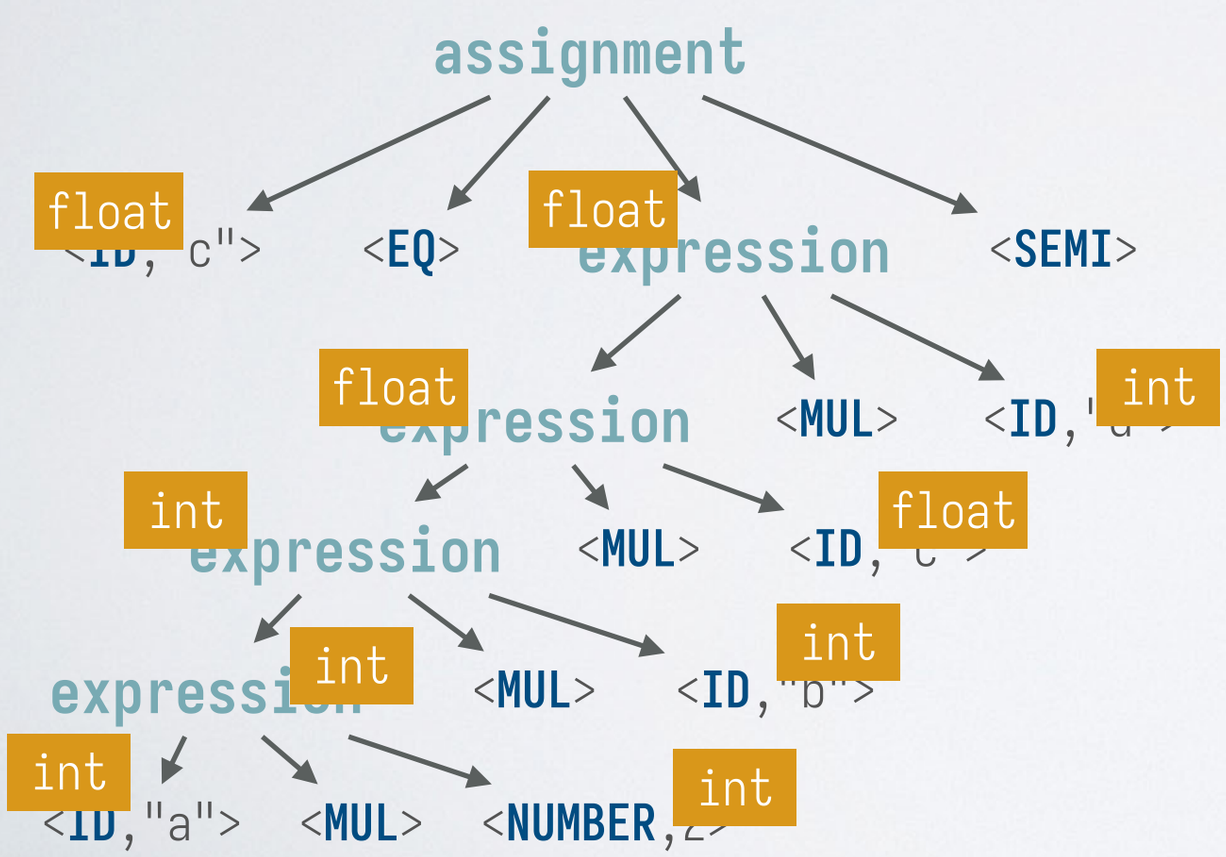
语义分析

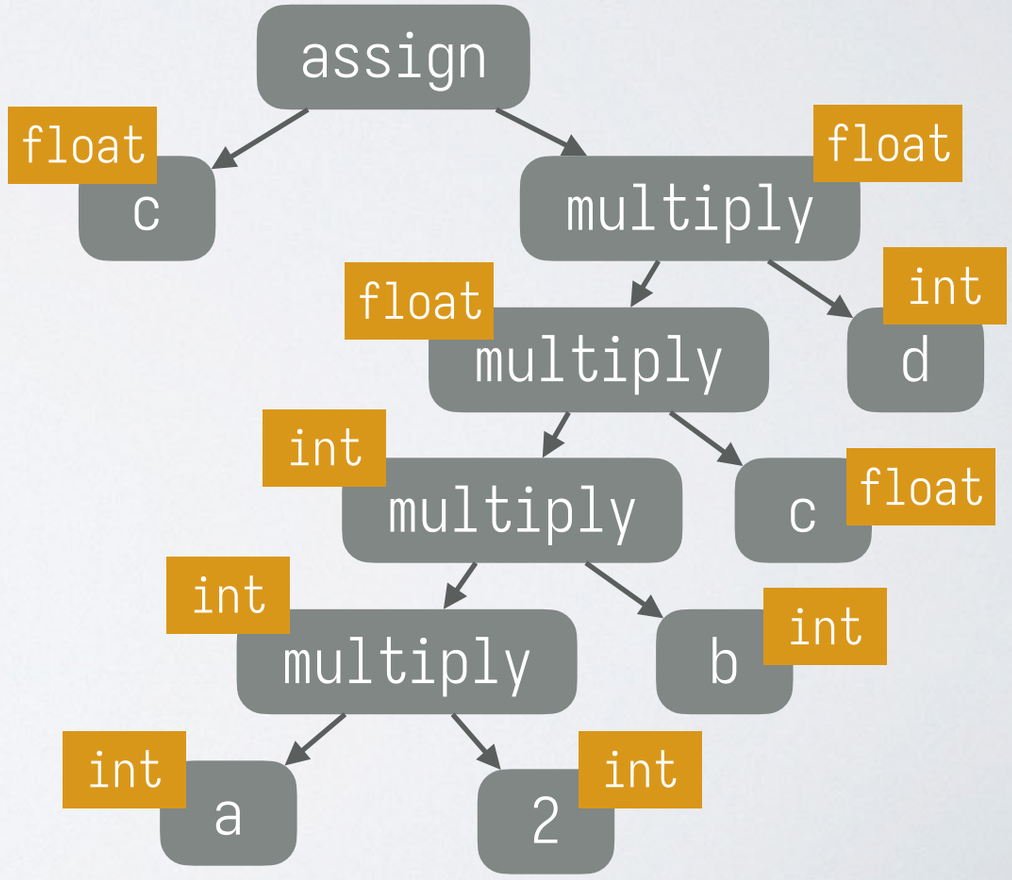
抽象语法树



语义分析示例：类型检查

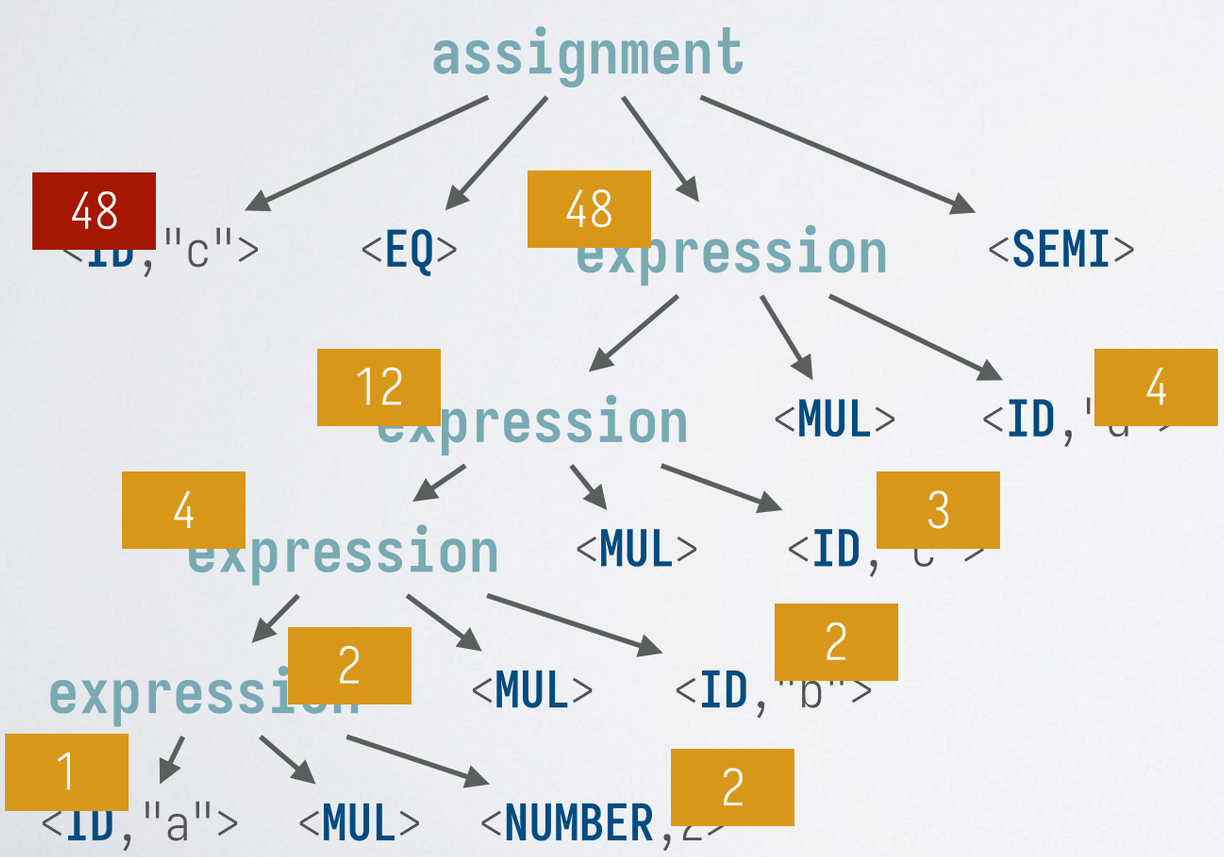
- 分析**名字**和**表达式**的类型，确保在上下文中的使用是合法的
- 避免运行时类型检查的开销
- 可以在语法分析树或抽象语法树上进行

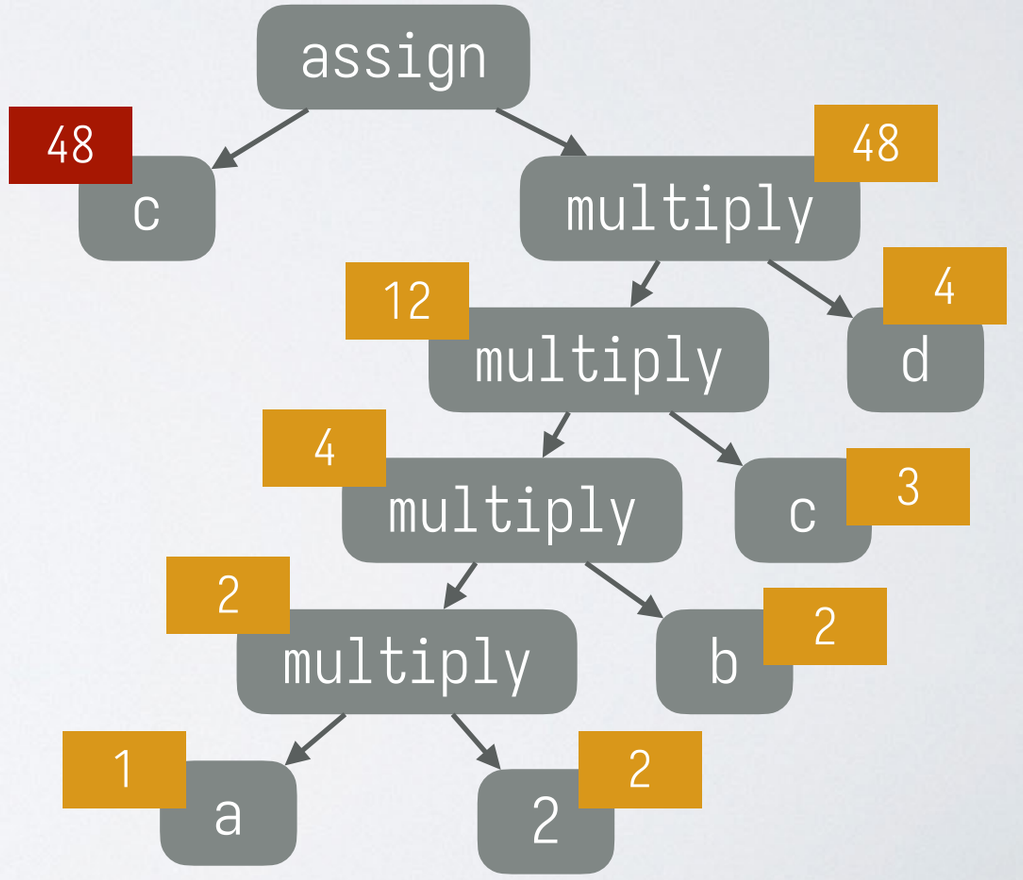




语义分析示例：解释执行

- **解释器**：不生成目标程序，而是直接计算源程序的执行结果
- 比如：对表达式，需要计算其值；对赋值语句，需要完成赋值操作
- 与类型检查类似，可以在语法分析树或抽象语法树上进行



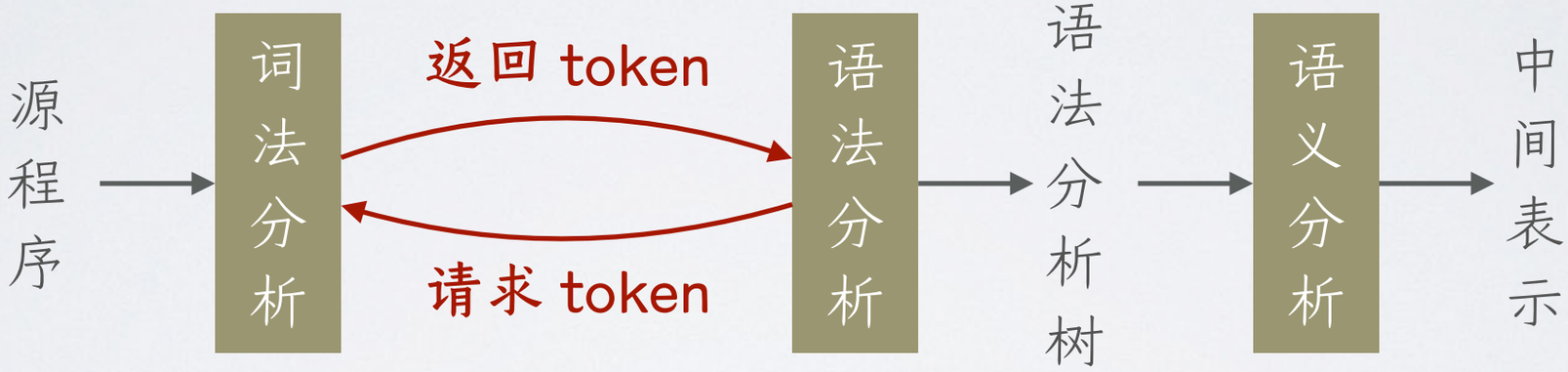


语义分析的工作

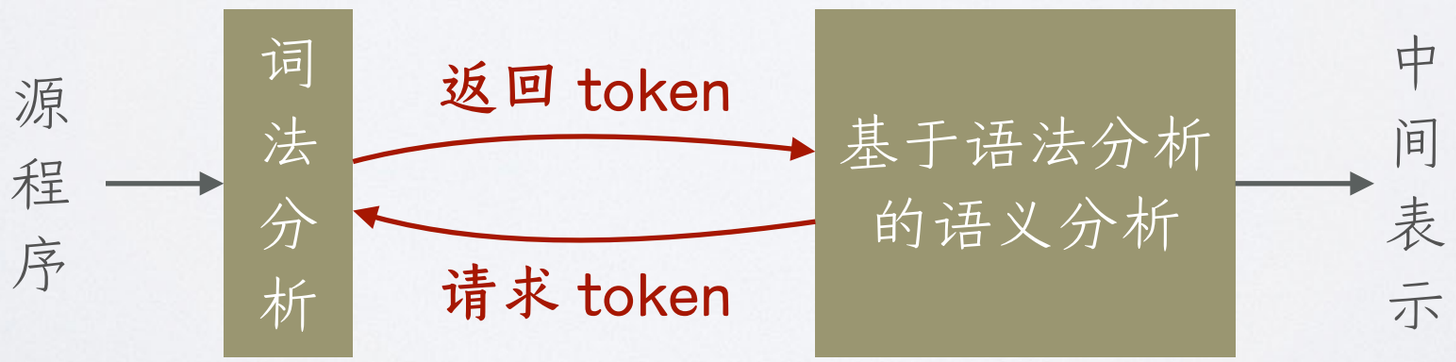
- 为**翻译到目标程序**或**直接进行解释执行**做准备
- 获取程序在语法之外的各种**上下文有关信息**
  - x 中存储了什么种类的值?
  - x 需要多大的存储空间?
  - 如果名字 x 是一个函数，它的参数和返回值是什么?
  - x 中存储的值的生命周期有多久?
  - x 应该被谁、在何时进行空间分配和初始化?
  - ……
- **上下文有关分析(context-sensitive analysis)**
  - 回顾: 语法分析中使用上下文无关文法

语义分析的工作

- 与优化器中的分析不同，语义分析主要关注**翻译到中间表示**
  - 也被称为**语义推敲(semantic elaboration)**
- 可以独立于语法分析进行实现



- 也可以与语法分析同步进行



主要内容

- 语义分析的作用
- **语义分析的规约**
- 语义分析的手动实现

回顾：词法分析的规约

- 使用一系列的正则表达式，标明它们每个对应的 token 类别

token 类别	正则表达式
IF	`if`
WHILE	`while`
ID	`[A-Za-z_]([A-Za-z_0-9])*`
NUMBER	`[+-]?([0-9])+`
LPAREN	`(`
NEQ	`!=`

- 每个正则表达式 r 表示了符号表 Σ 上的一个语言 $L(r)$
- 语法分析的规约需要描述**由 token 组成的语言**

回顾：语法分析的规约

- 使用上下文无关文法，其**终结符号**为词法分析所得的 token，其**非终结符号**为语言的语法变量

$$
\begin{aligned}
Expr &::= Expr \texttt{ + } Term \\
&\mid Expr \texttt{ - } Term \\
&\mid Term \\
Term &::= Term \texttt{ * } Factor \\
&\mid Term \texttt{ / } Factor \\
&\mid Factor \\
Factor &::= \texttt{(} Expr \texttt{)} \\
&\mid \texttt{ID} \mid \texttt{INT}
\end{aligned}
$$

$$
\begin{aligned}
Stmt &::= \texttt{\{ } Block \texttt{ \}} \\
&\mid \texttt{ID = } Expr \texttt{ ;} \\
&\mid \texttt{if (} Expr \texttt{)} Stmt \texttt{ else } Stmt \\
&\mid \texttt{while (} BDisj \texttt{)} Stmt \\
&\mid \texttt{return } Expr \texttt{ ;} \\
Block &::= \epsilon \\
&\mid Stmt\ Block
\end{aligned}
$$

- 每个文法 $G[S]$ 表示了一个终结符号串的语言 $L(G)$，其中的每个符号串 w 可以由**初始符号** S 通过**产生规则**推导而出（$S \Rightarrow^* w$）

- 语义分析的规约需要**针对 $L(G)$ 来分析和提取语义信息**

使用上下文有关文法作为规约？

- **问题：是否可以使用上下文有关文法描述语义分析？**
  - 允许产生规则 $\alpha \to \beta$ 的左侧长度大于 1，但要求 $|\alpha| \le |\beta|$

- 考虑语言 $\{\mathrm{a}^n \mathrm{b}^n \mathrm{c}^n \mid n \ge 1\}$
  - 可以把 a 想象成函数定义
  - 把 b 和 c 想象成两处函数调用
  - 右侧的上下文有关文法描述了该语言
  - **但是挺麻烦的，尤其考虑各种复杂语言特性**

[1]	$S \to \mathrm{a}BC$
[2]	$S \to \mathrm{a}SBC$
[3]	$CB \to BC$
[4]	$\mathrm{a}B \to \mathrm{ab}$
[5]	$\mathrm{b}B \to \mathrm{bb}$
[6]	$\mathrm{b}C \to \mathrm{bc}$
[7]	$\mathrm{c}C \to \mathrm{cc}$

- **观察：**检查一个串是否形如 $\mathrm{a}^n \mathrm{b}^n \mathrm{c}^n$ 是容易的
  - 编译器只要在语法分析树上能进行「检查」即可

属性文法（Attribute Grammar）

- **属性文法 = 上下文无关文法 + 属性计算规则**
  - 也被称为**语法制导定义**(Syntax-Directed Definition，SDD)
- 属性与**非终结符号**相关联
  - 用 X.a 表示语法分析树中某个 X 结点的 a 属性值
- 属性计算规则与**产生规则**相关联
  - 每条产生规则可以有多条计算规则，用来处理不同的属性
  - 计算规则可以使用产生规则中涉及的非终结符号的属性
- 从**语法分析树**的视角来看，属性文法规定了一个内部结点及其孩子结点的属性之间的关系

属性文法示例：四则运算表达式

- 文法 $G = (V_T, V_N, Expr, P)$ 表示四则运算表达式，其中

$$V_T = \{+, -, *, /, (,), \texttt{INT}\},\ V_N = \{Expr, Term, Factor\}$$

$$
\begin{aligned}
Expr &::= Expr + Term \\
&\mid Expr - Term \\
&\mid Term \\
Term &::= Term * Factor \\
&\mid Term / Factor \\
&\mid Factor \\
Factor &::= (Expr) \\
&\mid \texttt{INT}
\end{aligned}
$$

用下标区分相同符号的不同结点

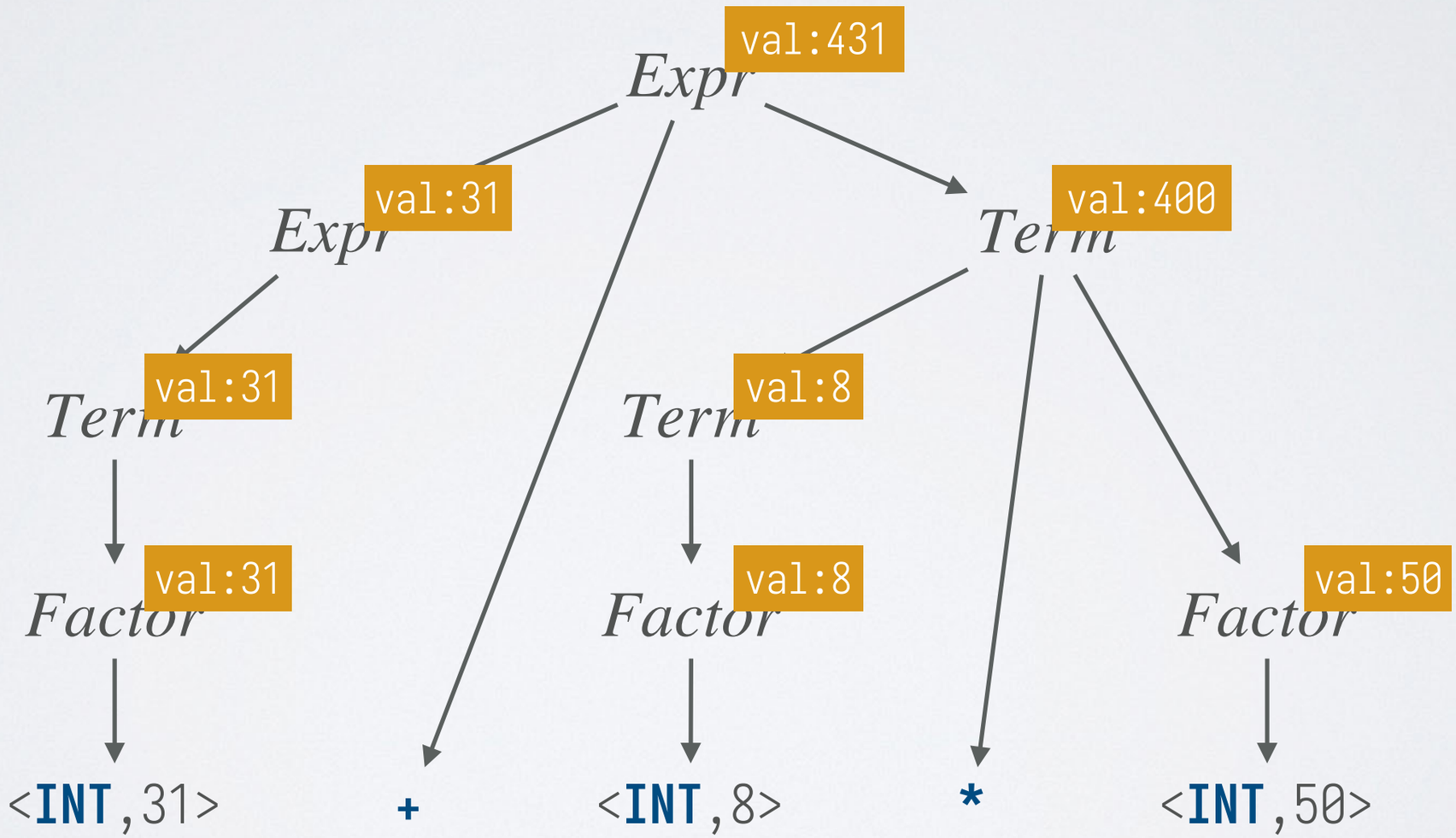
属性 val 记录表达式的求值结果

产生规则	属性计算规则
$Expr \to Expr_1 + Term$	$Expr.\texttt{val} = Expr_1.\texttt{val} + Term.\texttt{val}$
$Expr \to Expr_1 - Term$	$Expr.\texttt{val} = Expr_1.\texttt{val} - Term.\texttt{val}$
$Expr \to Term$	$Expr.\texttt{val} = Term.\texttt{val}$
$Term \to Term_1 * Factor$	$Term.\texttt{val} = Term_1.\texttt{val} \times Factor.\texttt{val}$
$Term \to Term_1 / Factor$	$Term.\texttt{val} = Term_1.\texttt{val} \div Factor.\texttt{val}$
$Term \to Factor$	$Term.\texttt{val} = Factor.\texttt{val}$
$Factor \to (Expr)$	$Factor.\texttt{val} = Expr.\texttt{val}$
$Factor \to \texttt{INT}$	$Factor.\texttt{val} = \texttt{INT}.\texttt{intval}$

INT 词法单元附带属性 intval 表示其值

属性文法示例：四则运算表达式

```
31 + 8 * 50
```



属性文法示例：有符号二进制数

- 文法 $G = (V_T, V_N, Number, P)$ 表示有符号二进制数，其中 $V_T = \{+, -, 0, 1\}$, $V_N = \{Number, Sign, List, Bit\}$

$$
\begin{aligned}
Number &::= Sign\ List \\
Sign &::= + \\
&\mid\ - \\
List &::= Bit \\
&\mid\ List\ Bit \\
Bit &::= 0 \\
&\mid\ 1
\end{aligned}
$$

属性文法示例：有符号二进制数

- 文法 $G = (V_T, V_N, Number, P)$ 表示有符号二进制数，其中 $V_T = \{+, -, 0, 1\}$，$V_N = \{Number, Sign, List, Bit\}$

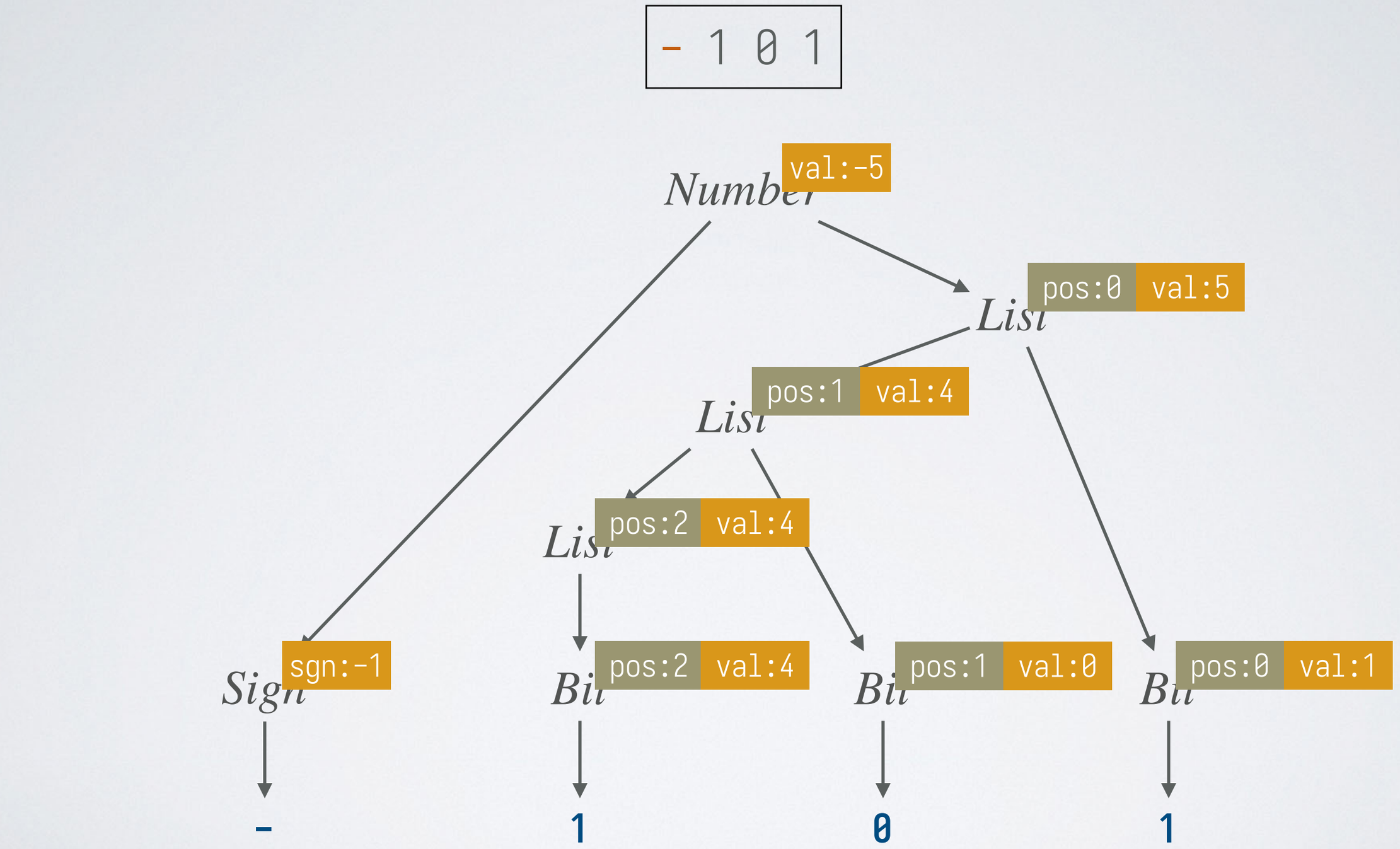
产生规则	属性计算规则
$Number \rightarrow Sign\ List$	$Number.\mathtt{val} = Sign.\mathtt{sgn} \times List.\mathtt{val}$ $List.\mathtt{pos} = 0$
$Sign \rightarrow +$	$Sign.\mathtt{sgn} = 1$
$Sign \rightarrow -$	$Sign.\mathtt{sgn} = -1$
$List \rightarrow Bit$	$List.\mathtt{val} = Bit.\mathtt{val}$ $Bit.\mathtt{pos} = List.\mathtt{pos}$
$List \rightarrow List_1\ Bit$	$List.\mathtt{val} = List_1.\mathtt{val} + Bit.\mathtt{val}$ $List_1.\mathtt{pos} = List.\mathtt{pos} + 1$ $Bit.\mathtt{pos} = List.\mathtt{pos}$
$Bit \rightarrow 0$	$Bit.\mathtt{val} = 0$
$Bit \rightarrow 1$	$Bit.\mathtt{val} = 2^{Bit.\mathtt{pos}}$

属性 val 记录对应的整数值

属性 sgn 记录正负符号值

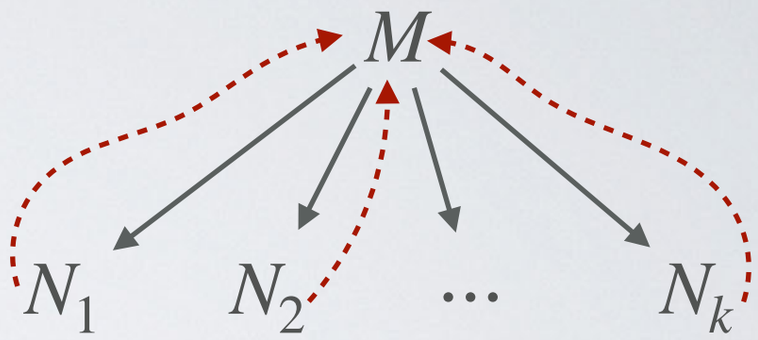
属性 pos 记录二进制位所在位置（最低位的位置为 0）

属性文法示例：有符号二进制数

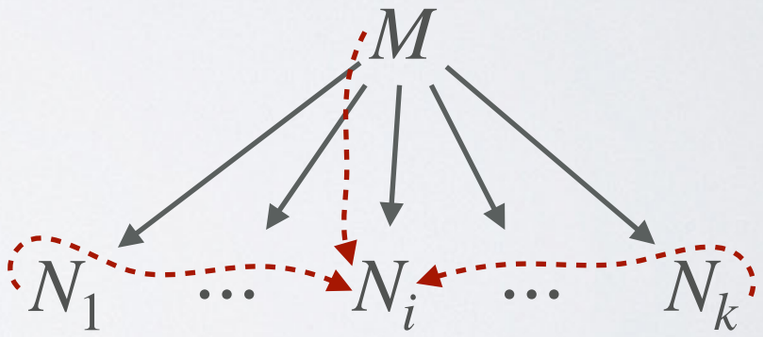


综合属性和继承属性

- **综合属性**(synthesized attribute)
  - 信息流向自底向上
  - 结点 M 的一个综合属性可以通过 M 自身和它的孩子结点 $N_1, N_2, \ldots, N_k$ 的属性来定义



- **继承属性**(inherited attribute)
  - 信息流向自顶向下
  - 结点 N_i 的一个继承属性可以通过 N_i 自身、它的 parent 结点 M 以及它的 sibling 结点 $N_1, \ldots, N_{i-1}, N_{i+1}, \ldots, N_k$ 的属性来定义



综合属性示例

产生规则	属性计算规则
$Expr \rightarrow Expr_1 + Term$	$Expr.\texttt{val} = Expr_1.\texttt{val} + Term.\texttt{val}$
$Expr \rightarrow Expr_1 - Term$	$Expr.\texttt{val} = Expr_1.\texttt{val} - Term.\texttt{val}$
$Expr \rightarrow Term$	$Expr.\texttt{val} = Term.\texttt{val}$
$Term \rightarrow Term_1 * Factor$	$Term.\texttt{val} = Term_1.\texttt{val} \times Factor.\texttt{val}$
$Term \rightarrow Term_1 / Factor$	$Term.\texttt{val} = Term_1.\texttt{val} \div Factor.\texttt{val}$
$Term \rightarrow Factor$	$Term.\texttt{val} = Factor.\texttt{val}$
$Factor \rightarrow (\ Expr\ )$	$Factor.\texttt{val} = Expr.\texttt{val}$
$Factor \rightarrow \texttt{INT}$	$Factor.\texttt{val} = \texttt{INT}.\texttt{intval}$

Expr、*Term*、*Factor* 的属性 val 都是综合属性

- 通常表现为产生规则**左侧**的属性由**右侧**符号的属性计算得出

继承属性示例

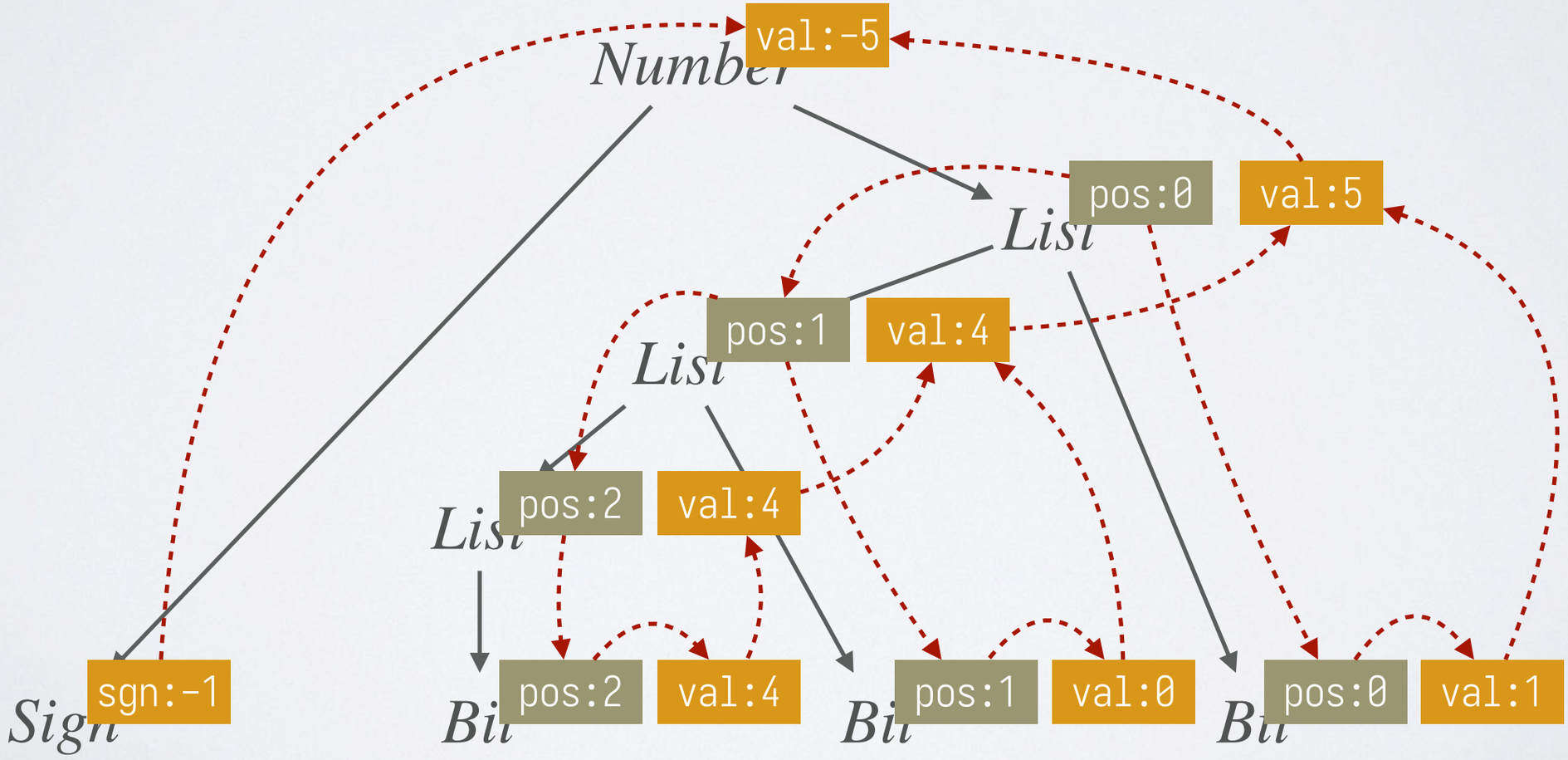
产生规则	属性计算规则
$Number \rightarrow Sign\ List$	$Number.\mathtt{val} = Sign.\mathtt{sgn} \times List.\mathtt{val}$ $List.\mathtt{pos} = 0$
$Sign \rightarrow +$	$Sign.\mathtt{sgn} = 1$
$Sign \rightarrow -$	$Sign.\mathtt{sgn} = -1$
$List \rightarrow Bit$	$List.\mathtt{val} = Bit.\mathtt{val}$ $Bit.\mathtt{pos} = List.\mathtt{pos}$
$List \rightarrow List_1\ Bit$	$List.\mathtt{val} = List_1.\mathtt{val} + Bit.\mathtt{val}$ $List_1.\mathtt{pos} = List.\mathtt{pos} + 1$ $Bit.\mathtt{pos} = List.\mathtt{pos}$
$Bit \rightarrow 0$	$Bit.\mathtt{val} = 0$
$Bit \rightarrow 1$	$Bit.\mathtt{val} = 2^{Bit.\mathtt{pos}}$

List、*Bit* 的属性 pos 记录二进制位所在位置，它们都是继承属性

- 通常表现为产生规则**右侧**符号的属性由**左侧**的属性计算得出

属性计算顺序

- **问题：属性之间可能依赖，如何确定一个计算顺序？**
- 以语法分析树中的所有属性为结点，用有向边 $c \to d$ 表示计算属性 d 的值需要用到属性 c 的值，建立属性依赖图
- 若依赖图中无环，则可以按照**拓扑序**进行计算



属性计算顺序：有环的情况

- 存在环的属性依赖关系在一些场景中是有意义的

$$
\begin{aligned}
Loop &::= \texttt{repeat INT do } Stmt \\
Stmt &::= \epsilon \\
&\quad\mid \texttt{cnt += INT ; } Stmt
\end{aligned}
$$

- 考虑上面的文法，它表示了一个操作变量 cnt 的简单循环
  - 例如：程序 repeat 10 do cnt += 50; 执行结束后 cnt 的值为 500
- **问题：如何设计属性文法对这个循环语言进行解释求值？**
  - 用属性 cnt_init 记录语句执行前 cnt 的值
  - 用属性 cnt_final 记录语句执行后 cnt 的值
  - **循环需要反复进行计算，必然导致属性间的依赖**

属性计算顺序：有环的情况

- 如果一个属性依赖的某个属性被更新了，那么它也需要更新

产生规则	属性计算规则

$Loop \rightarrow$ repeat INT do $Stmt$	$Loop$.cnt_init $= 0$
	$Loop$.loop_number $=$ INT.intval
	if $Loop$.loop_number > 0 then
	$Stmt$.cnt_init $= Loop$.cnt_init
	$Loop$.cnt_init $= Stmt$.cnt_final
	$Loop$.loop_number $= Loop$.loop_number $- 1$
	else
	$Loop$.cnt_final $= Loop$.cnt_init

$Stmt \rightarrow \epsilon$	$Stmt$.cnt_final $= Stmt$.cnt_init
$Stmt \rightarrow$ cnt += INT ; $Stmt_1$	$Stmt_1$.cnt_init $= Stmt$.cnt_init $+$ INT.intval $Stmt$.cnt_final $= Stmt_1$.cnt_final

在一轮循环中，需要先执行一遍循环体($Stmt$)，通过继承属性传递 cnt 的值

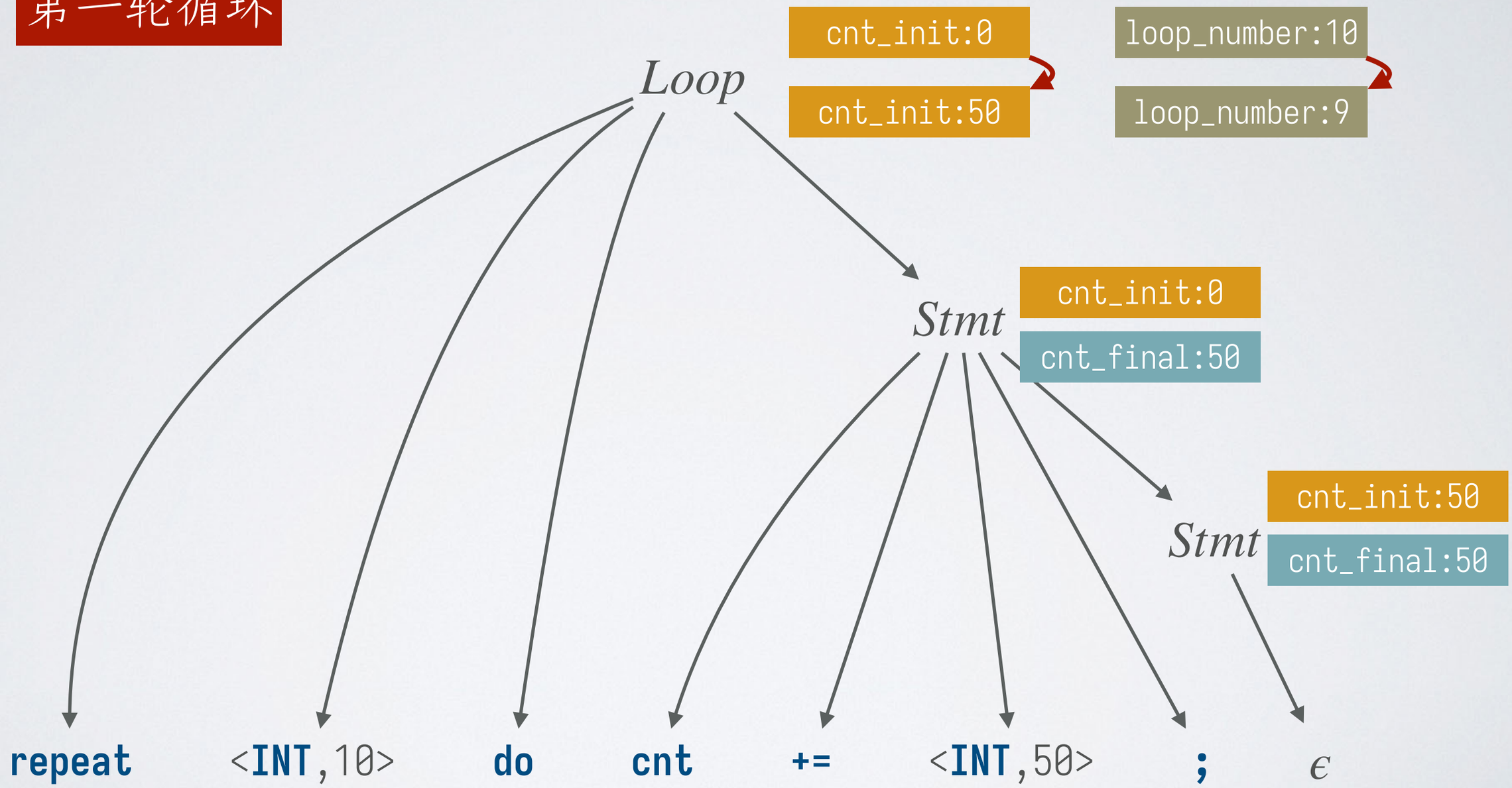
循环体执行结束后，更新 cnt 的值并准备进入下一轮循环

更新循环计数器，完成一轮循环

循环体中的语句依次对 cnt 的值进行更新

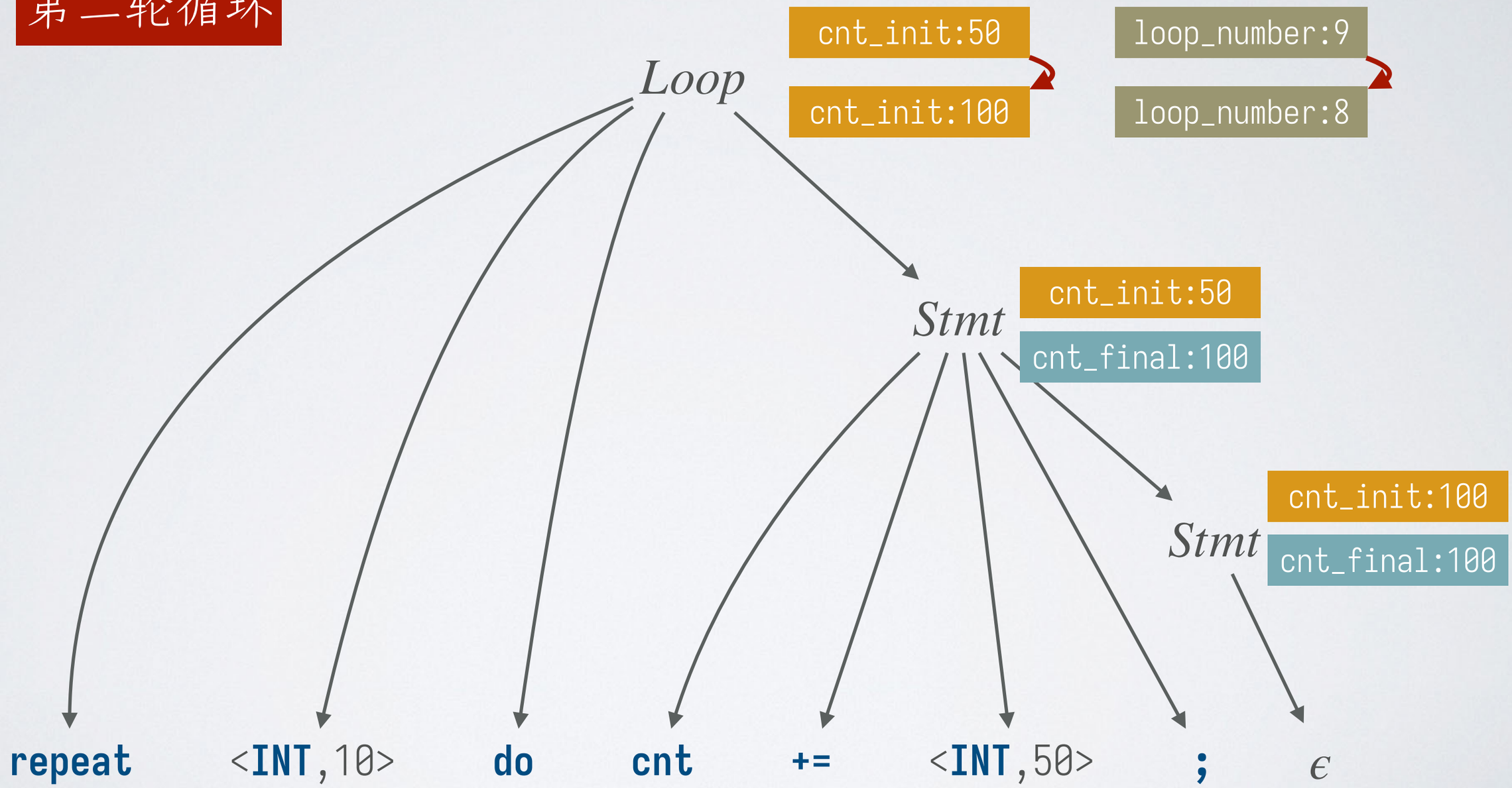
属性计算顺序：有环的情况

第一轮循环



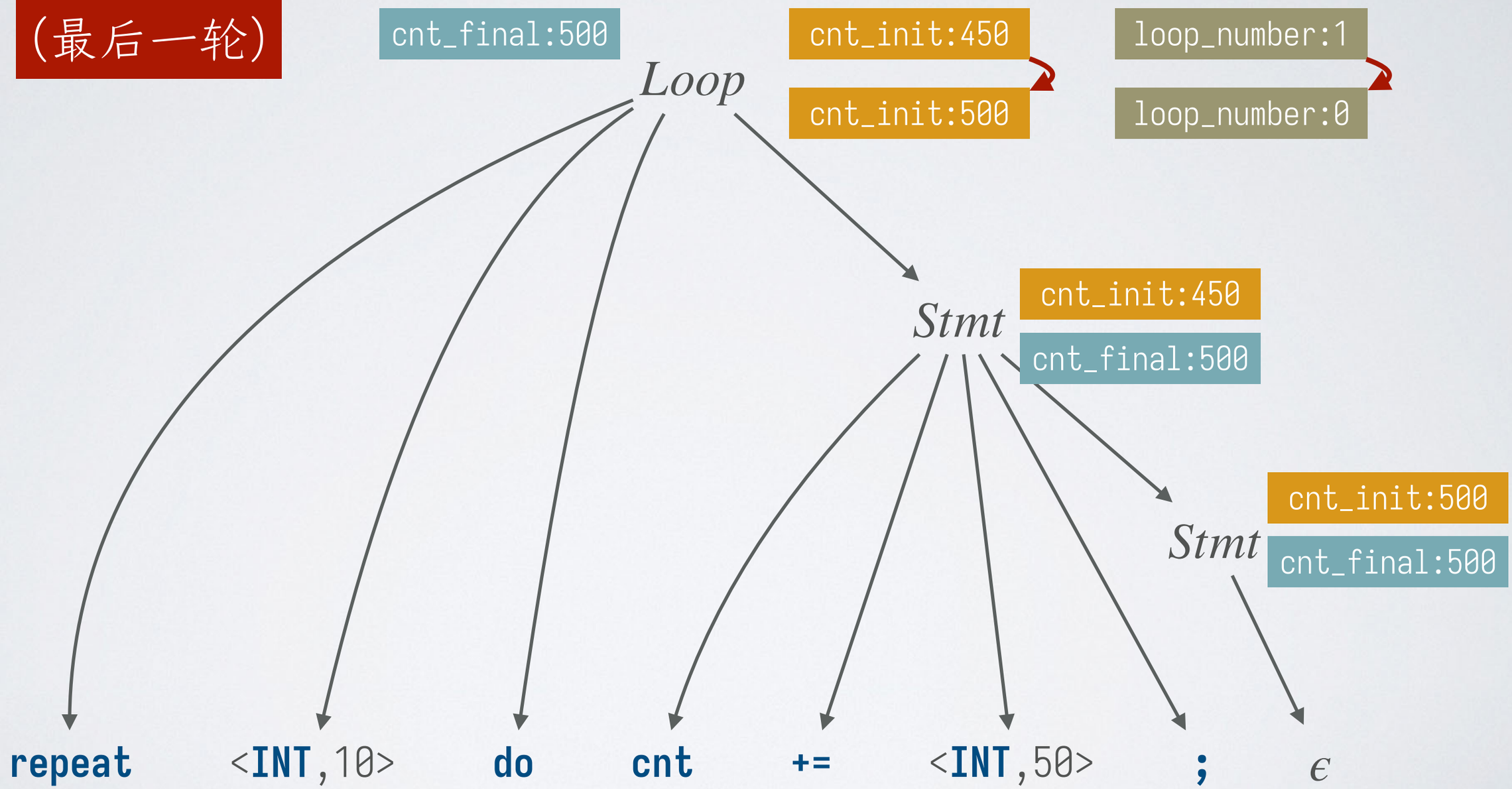
属性计算顺序：有环的情况

第二轮循环



属性计算顺序：有环的情况

第十轮循环
(最后一轮)



属性计算顺序：无环的情况

- 给定一个属性文法，很难判定是否存在一棵语法分析树对应的属性依赖图包含环
- 特定类型的属性文法一定不包含环，且有固定的计算顺序
  - **S 属性**的文法(或 S 属性的 SDD)
  - **L 属性**的文法(或 L 属性的 SDD)
- **这些类型的属性文法具备的优势：**
  - 可以不用构造完整的语法分析树
  - 进而可以和语法分析同步进行

S 属性的文法

- **每个属性都是综合属性**
  - 在语法分析树上，属性的信息流向是自底向上
  - 在属性依赖图上，通过 M 的孩子结点的属性值来计算 M 的属性值
- 例如：前面的四则运算表达式文法
- 容易结合自顶向下的语法分析进行实现

L 属性的文法

- 每个属性可以是
  - 综合属性
  - 继承属性，但是产生规则 $A \to X_1 X_2 \ldots X_k$，某个 X_i 的继承属性只依赖于 **X_i 的左边 $(X_1, X_2, \ldots, X_{i-1})$ 的属性**，以及 **A 的继承属性**
- 在语法分析树上：
  - 综合属性的信息流向自底向上
  - 继承属性的信息流向自顶向下、自左向右
- 例如：前面的有符号二进制数文法
- 容易结合自顶向下的语法分析进行实现

L 属性的文法示例

$$
\begin{aligned}
Expr &::= Term\ Expr' \\
Expr' &::= +\ Term\ Expr' \\
&\mid\ -\ Term\ Expr' \\
&\mid\ \epsilon \\
Term &::= Factor\ Term' \\
Term' &::= *\ Factor\ Term' \\
&\mid\ /\ Factor\ Term' \\
&\mid\ \epsilon \\
Factor &::= (\ Expr\ ) \\
&\mid\ \texttt{INT}
\end{aligned}
$$

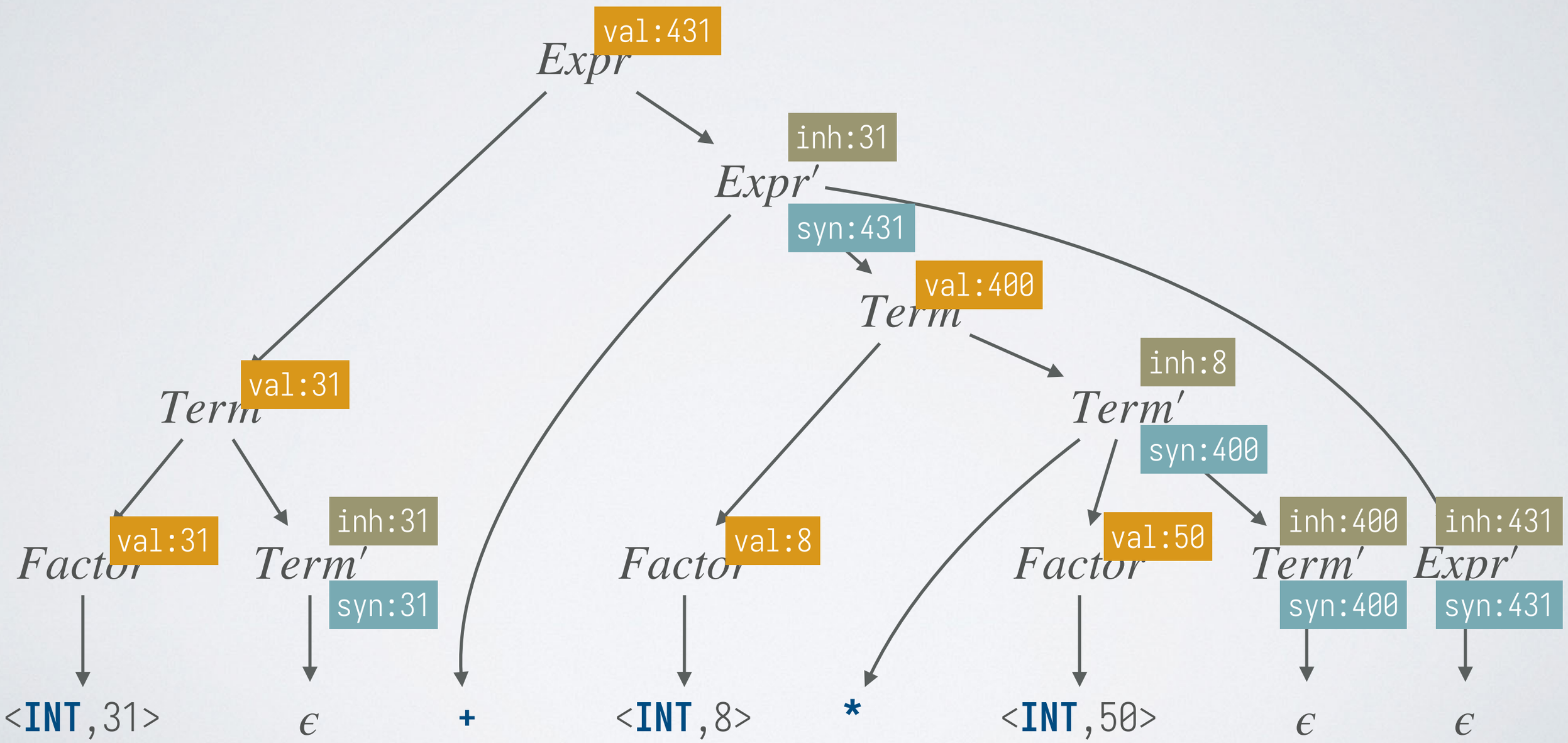
继承属性 inh 记录左侧已经计算的值

综合属性 syn 记录在 inh 基础上计算的值

产生规则	属性计算规则
$Expr \to Term\ Expr'$	$Expr'.\texttt{inh} = Term.\texttt{val}$ $Expr.\texttt{val} = Expr'.\texttt{syn}$
$Expr' \to +\ Term\ Expr'_1$	$Expr'_1.\texttt{inh} = Expr'.\texttt{inh} + Term.\texttt{val}$ $Expr'.\texttt{syn} = Expr'_1.\texttt{syn}$
$Expr' \to \epsilon$	$Expr'.\texttt{syn} = Expr'.\texttt{inh}$
$Term \to Factor\ Term'$	$Term'.\texttt{inh} = Factor.\texttt{val}$ $Term.\texttt{val} = Term'.\texttt{syn}$
$Term' \to *\ Factor\ Term'_1$	$Term'_1.\texttt{inh} = Term'.\texttt{inh} \times Factor.\texttt{val}$ $Term'.\texttt{syn} = Term'_1.\texttt{syn}$
$Term' \to \epsilon$	$Term'.\texttt{syn} = Term'.\texttt{inh}$
$Factor \to (\ Expr\ )$	$Factor.\texttt{val} = Expr.\texttt{val}$
$Factor \to \texttt{INT}$	$Factor.\texttt{val} = \texttt{INT}.\texttt{intval}$

L 属性的文法示例

31 + 8 * 50



属性文法应用：翻译到中间表示

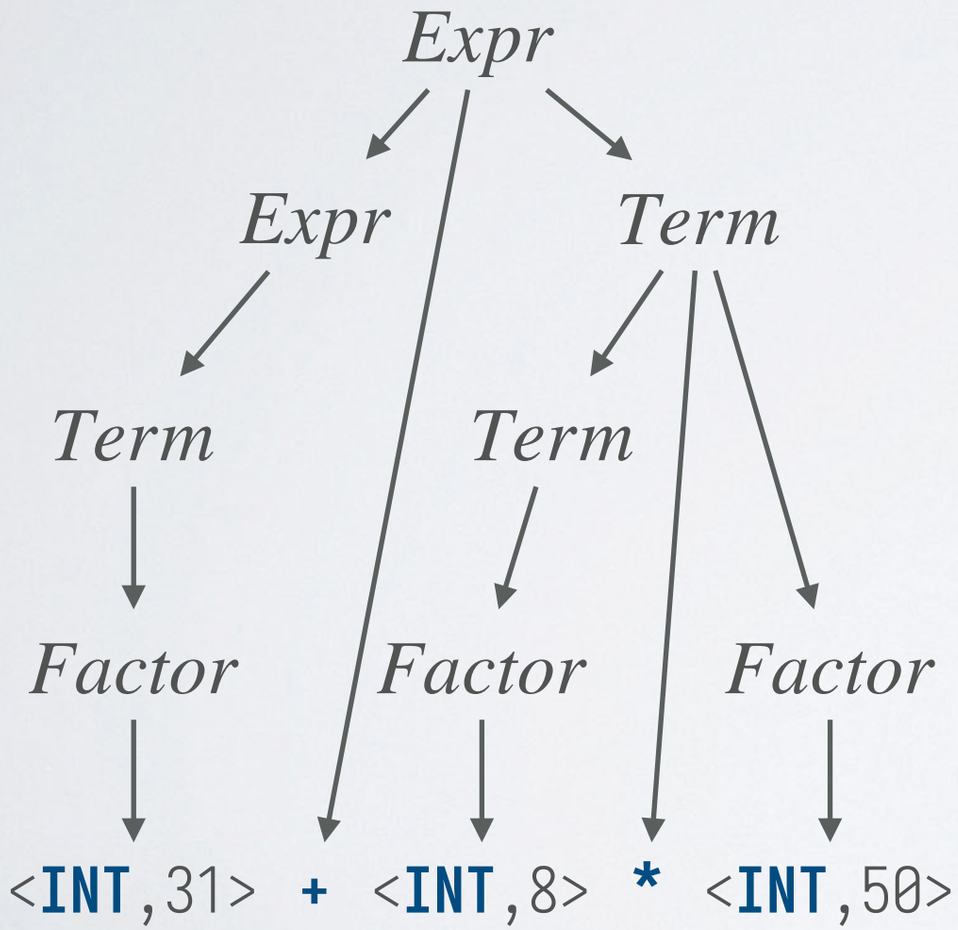
- **抽象语法树(Abstract Syntax Tree，AST)**
- 一种四则运算表达式 AST 的定义：

$$E ::= \texttt{add}(E, E) \mid \texttt{sub}(E, E) \mid \texttt{mul}(E, E) \mid \texttt{div}(E, E) \mid \texttt{intv}(i)$$

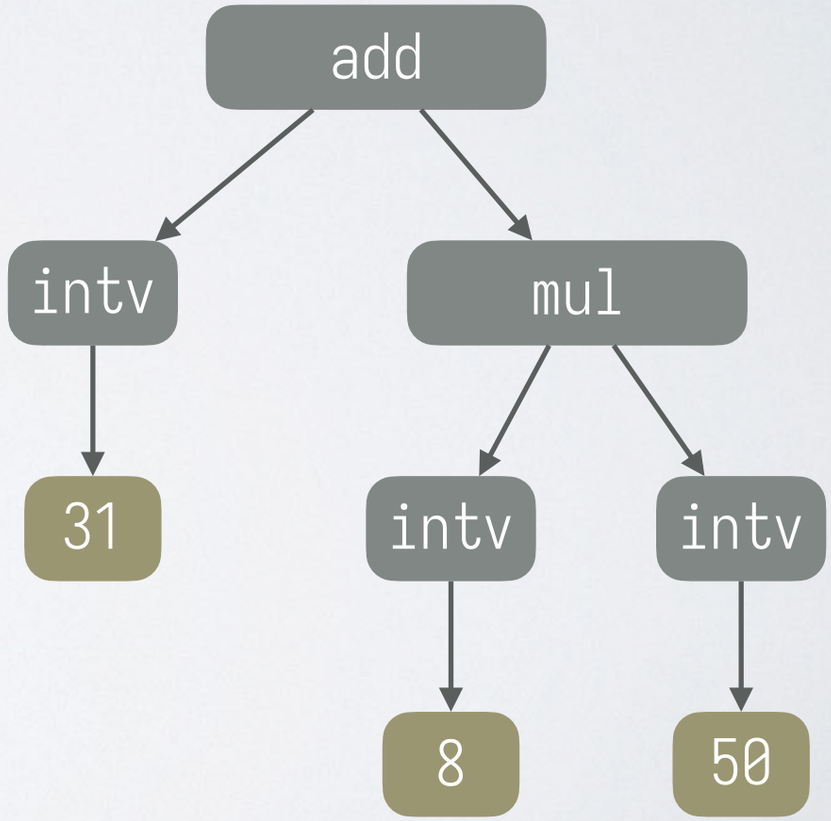
产生规则	属性计算规则
$Expr \rightarrow Expr_1 + Term$	$Expr.\texttt{ast} = \texttt{add}(Expr_1.\texttt{ast}, Term.\texttt{ast})$
$Expr \rightarrow Expr_1 - Term$	$Expr.\texttt{ast} = \texttt{sub}(Expr_1.\texttt{ast}, Term.\texttt{ast})$
$Expr \rightarrow Term$	$Expr.\texttt{ast} = Term.\texttt{ast}$
$Term \rightarrow Term_1 * Factor$	$Term.\texttt{ast} = \texttt{mul}(Term_1.\texttt{ast}, Factor.\texttt{ast})$
$Term \rightarrow Term_1 / Factor$	$Term.\texttt{ast} = \texttt{div}(Term_1.\texttt{ast}, Factor.\texttt{ast})$
$Term \rightarrow Factor$	$Term.\texttt{ast} = Factor.\texttt{ast}$
$Factor \rightarrow (Expr)$	$Factor.\texttt{ast} = Expr.\texttt{ast}$
$Factor \rightarrow \texttt{INT}$	$Factor.\texttt{ast} = \texttt{intv}(\texttt{INT}.\texttt{intval})$

属性文法应用：翻译到中间表示

```
31 + 8 * 50
```




```
add(intv(31), mul(intv(8), intv(50)))
```



属性文法应用：类型检查

- **通过文法属性记录程序结构的类型信息**
- 检查四则运算表达式计算结果的类型，其中考虑整数和浮点数两种基本类型：$Factor ::= (\ Expr\ ) \mid \texttt{INT} \mid \texttt{FLOAT}$

产生规则	属性计算规则
$Expr \rightarrow Expr_1 + Term$	$Expr.\texttt{type} = \mathcal{F}_+(Expr_1.\texttt{type}, Term.\texttt{type})$
$Expr \rightarrow Expr_1 - Term$	$Expr.\texttt{type} = \mathcal{F}_-(Expr_1.\texttt{type}, Term.\texttt{type})$
$Expr \rightarrow Term$	$Expr.\texttt{type} = Term.\texttt{type}$
$Term \rightarrow Term_1 * Factor$	$Term.\texttt{type} = \mathcal{F}_\times(Term_1.\texttt{type}, Factor.\texttt{type})$
$Term \rightarrow Term_1 / Factor$	$Term.\texttt{type} = \mathcal{F}_\div(Term_1.\texttt{type}, Factor.\texttt{type})$
$Term \rightarrow Factor$	$Term.\texttt{type} = Factor.\texttt{type}$
$Factor \rightarrow (\ Expr\ )$	$Factor.\texttt{type} = Expr.\texttt{type}$
$Factor \rightarrow \texttt{INT}$	$Factor.\texttt{type} = \texttt{int}$
$Factor \rightarrow \texttt{FLOAT}$	$Factor.\texttt{type} = \texttt{float}$

由编程语言规定的类型计算规则

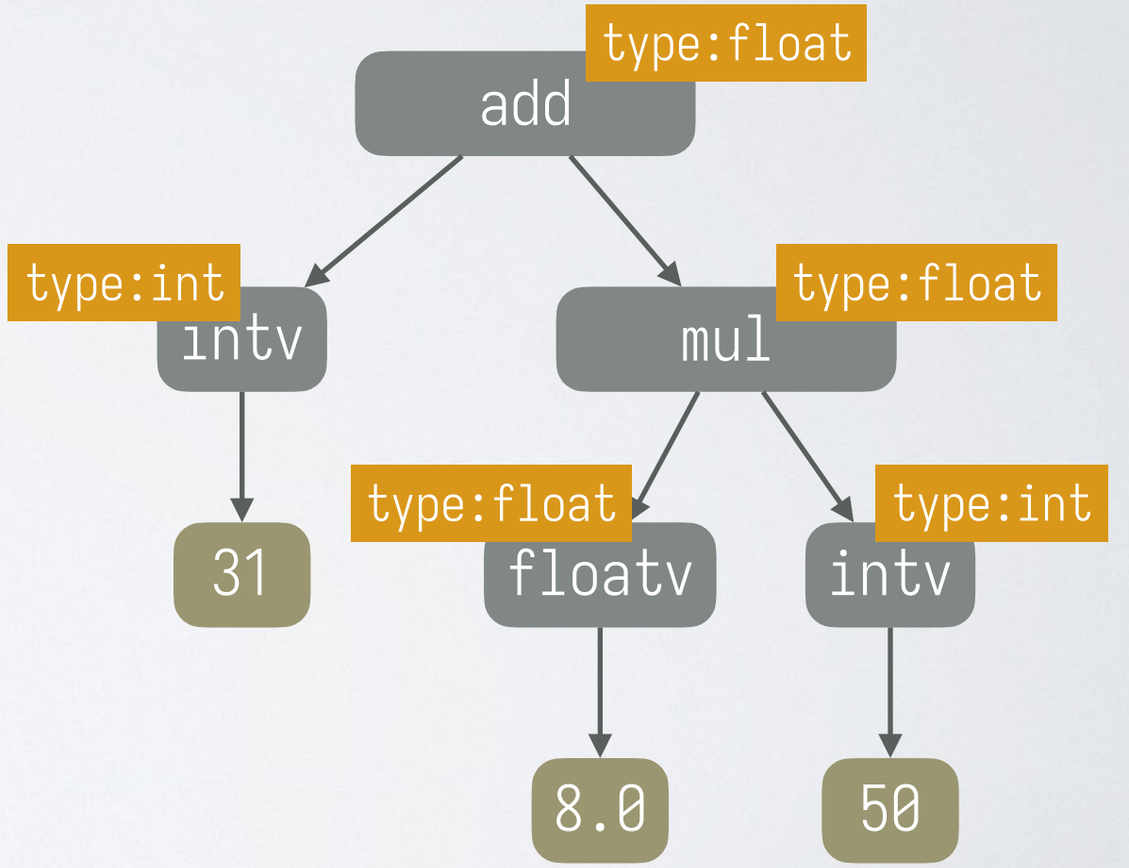
$\mathcal{F}_+$	int	float
int	int	float
float	float	float

属性文法应用：类型检查

- 也可以定义为**抽象语法树**(AST)上的属性文法

$$E ::= \texttt{add}(E,E) \mid \texttt{sub}(E,E) \mid \texttt{mul}(E,E) \mid \texttt{div}(E,E) \mid \texttt{intv}(i) \mid \texttt{floatv}(f)$$

产生规则	属性计算规则
$E \to \texttt{add}(E_1, E_2)$	$E.\texttt{type} = \mathscr{F}_{+}(E_1.\texttt{type}, E_2.\texttt{type})$
$E \to \texttt{sub}(E_1, E_2)$	$E.\texttt{type} = \mathscr{F}_{-}(E_1.\texttt{type}, E_2.\texttt{type})$
$E \to \texttt{mul}(E_1, E_2)$	$E.\texttt{type} = \mathscr{F}_{\times}(E_1.\texttt{type}, E_2.\texttt{type})$
$E \to \texttt{div}(E_1, E_2)$	$E.\texttt{type} = \mathscr{F}_{\div}(E_1.\texttt{type}, E_2.\texttt{type})$
$E \to \texttt{intv}(i)$	$E.\texttt{type} = \texttt{int}$
$E \to \texttt{floatv}(f)$	$E.\texttt{type} = \texttt{float}$



属性文法应用：解释执行

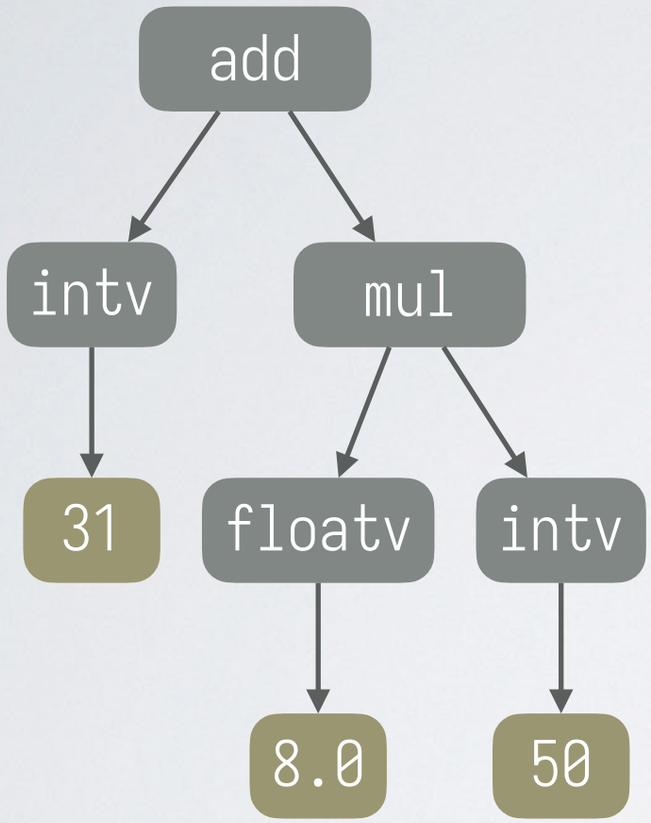
- 前面的简单循环的解释执行是通过存在依赖环的文法实现的
- 也可以通过属性文法定义一个**小步(small-step)运算**
  - 比如计算四则运算表达式(AST)一步运算后的结果表达式(AST)

$$E ::= \texttt{add}(E,E) \mid \texttt{sub}(E,E) \mid \texttt{mul}(E,E) \mid \texttt{div}(E,E) \mid \texttt{intv}(i) \mid \texttt{floatv}(f)$$

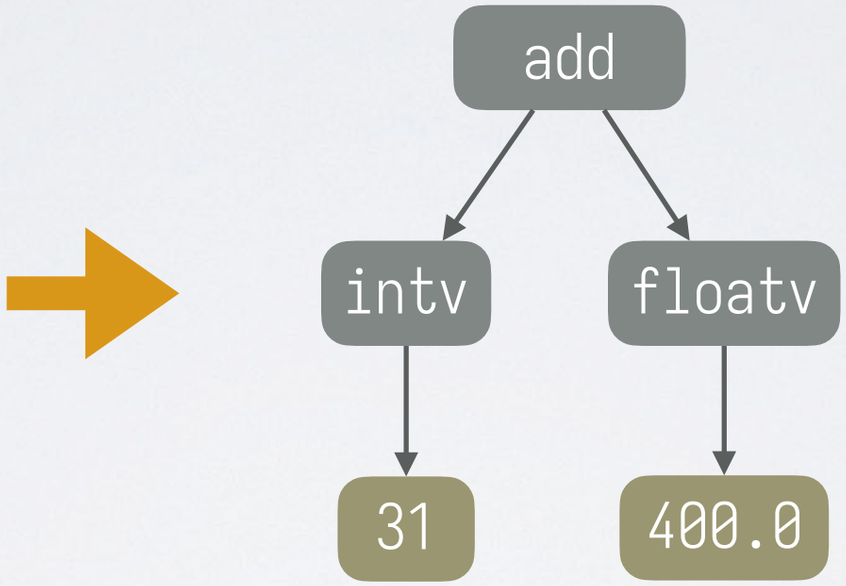
产生规则	属性计算规则
$E \to \texttt{add}(E_1, E_2)$	$E.\texttt{next} = \mathscr{C}_+(E_1, E_2)$
$E \to \texttt{sub}(E_1, E_2)$	$E.\texttt{next} = \mathscr{C}_-(E_1, E_2)$
$E \to \texttt{mul}(E_1, E_2)$	$E.\texttt{next} = \mathscr{C}_\times(E_1, E_2)$
$E \to \texttt{div}(E_1, E_2)$	$E.\texttt{next} = \mathscr{C}_\div(E_1, E_2)$
$E \to \texttt{intv}(i)$	$E.\texttt{next} = i$
$E \to \texttt{floatv}(f)$	$E.\texttt{next} = f$

$\mathscr{C}_+(E_1, E_2) =$
  if E_1 is not a value yet then
    $\texttt{add}(E_1.\texttt{next}, E_2)$
  else if E_2 is not a value yet then
    $\texttt{add}(E_1, E_2.\texttt{next})$
  else
    if both E_1 and E_2 are intv then
      $\texttt{intv}(E_1.\texttt{next} + E_2.\texttt{next})$
    else
      $\texttt{floatv}(E_1.\texttt{next} + E_2.\texttt{next})$

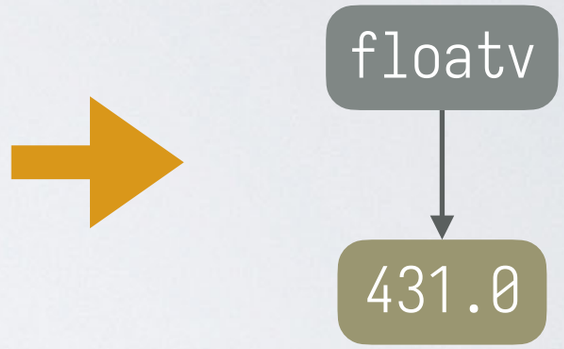
属性文法应用：解释执行




```
add(
    intv(31),
    mul(floatv(8.0), intv(50))
  )
```




```
add(
    intv(31),
    floatv(400.0)
  )
```



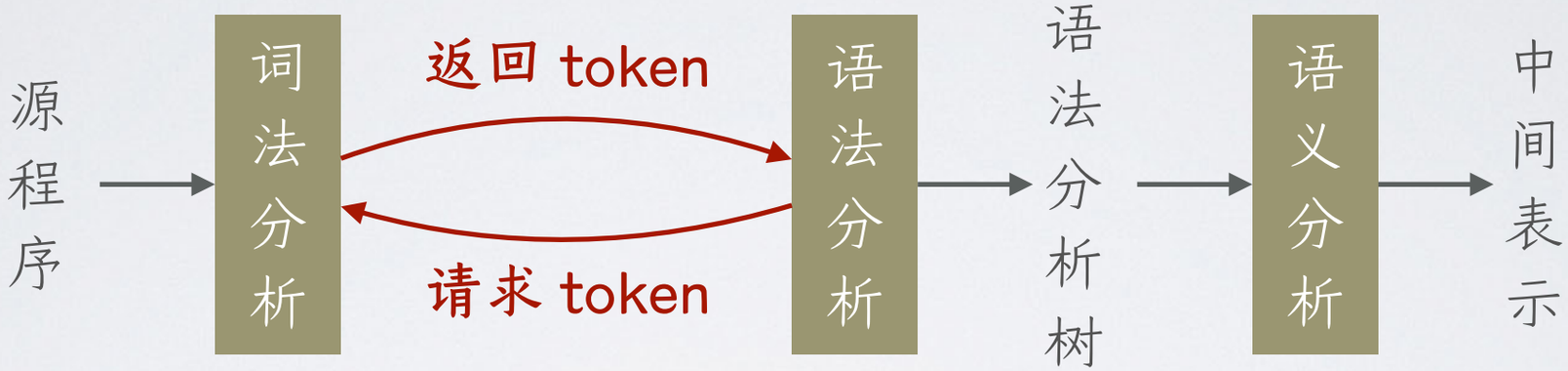

```
floatv(431.0)
```

主要内容

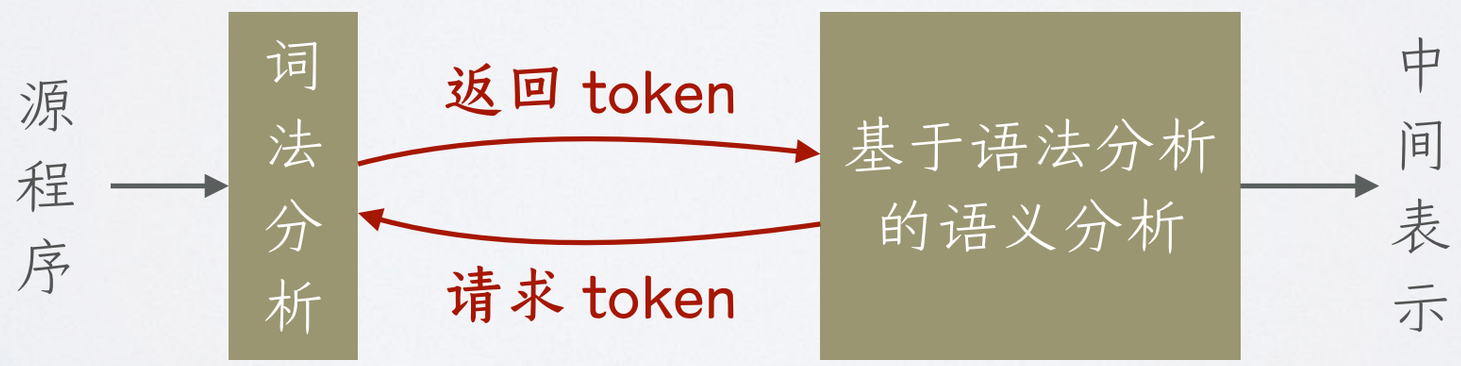
- 语义分析的作用
- 语义分析的规约
- **语义分析的手动实现**

基于语法分析的实现

- 如果分开实现语法和语义分析，后者可以通过遍历语法分析树来实现(通常可以使用深度优先遍历)



- 本部分侧重如何实现语法、语义分析的同步进行



回顾：自顶向下的语法分析

- **递归下降分析**
  - 为每个非终结符号实现一个递归过程
  - 该过程通过「向前看」符号确定产生规则

$$
\begin{array}{ll}
 & S' \to S\ \texttt{EOF} \\
[1] & S \to \epsilon \\
[2] & S \to [\ S\ ]\ S
\end{array}
$$

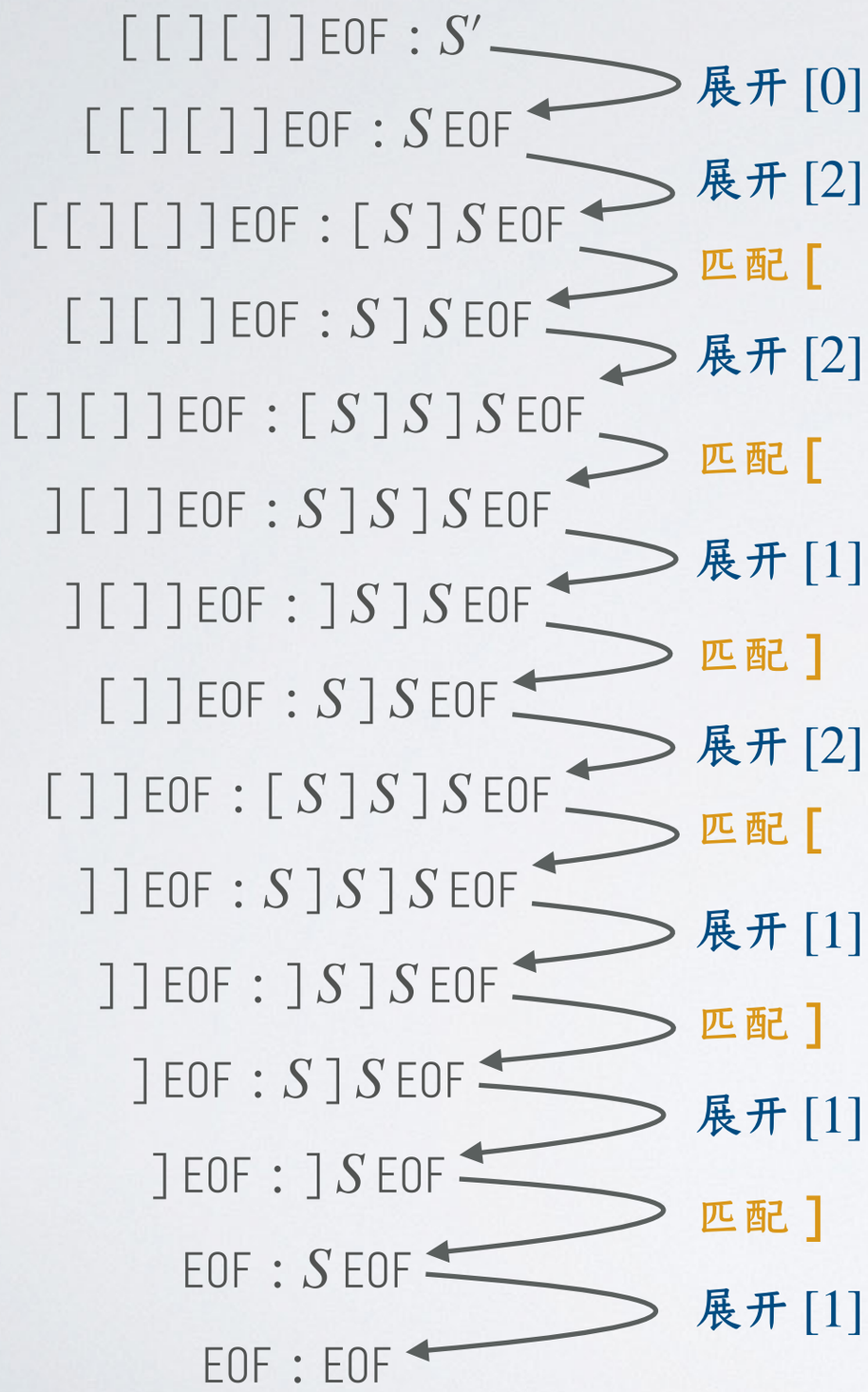
$$\text{FIRST}(S) = \{[, \epsilon\}$$

$$\text{FOLLOW}(S) = \{\texttt{EOF},]\}$$

```
S'() {
  if (token == LSQUARE ||
      token == EOF) {
    if (S()) {
      if (token == EOF) {
        return true;
      }
    }
  }
  return false;
}
```

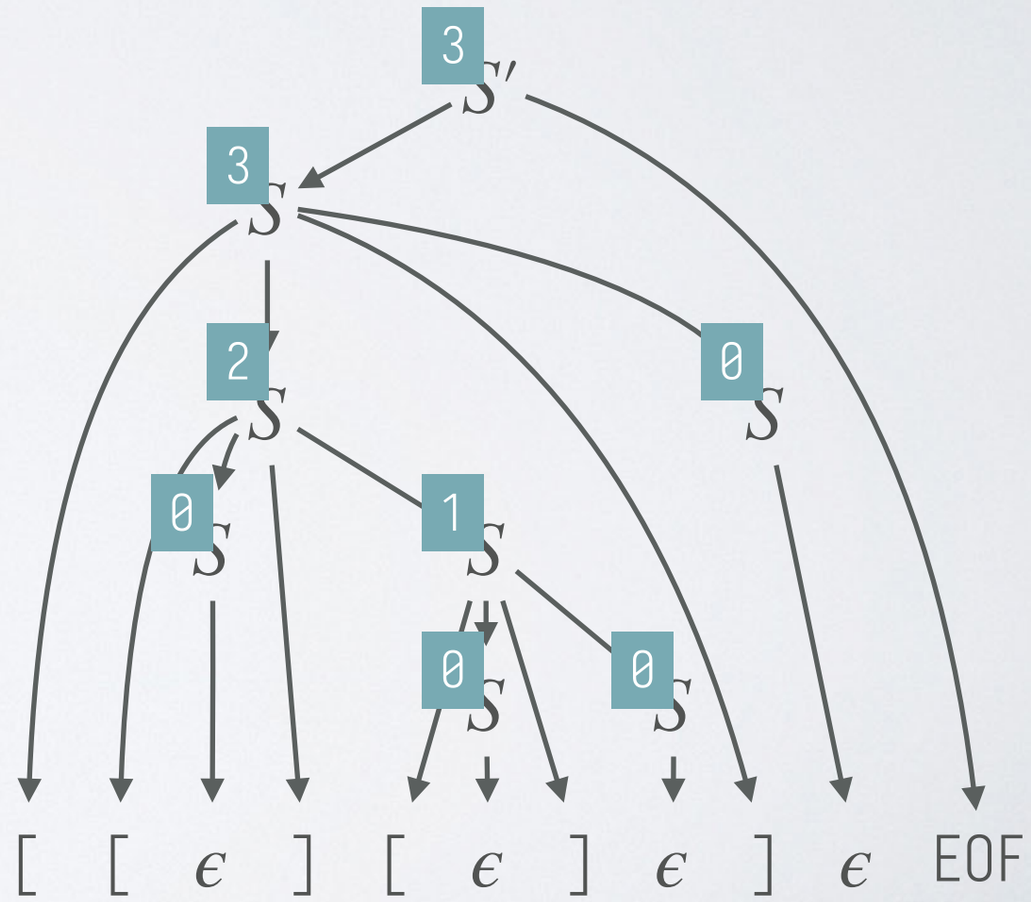
```
S() {
  if (token == LSQUARE) {
    token = next_token();
    if (S()) {
      if (token == RSQUARE) {
        token = next_token();
        if (S()) return true;
      }
    }
  } else if (token == EOF ||
             token == RSQUARE) {
    return true;
  }
  return false;
}
```

自顶向下的语义分析



综合属性 $S'.\text{cnt}$ 和 $S.\text{cnt}$ 记录匹配的括号对数

产生规则	属性计算规则
[0] $S' \to S\ \text{EOF}$	$S'.\text{cnt} = S.\text{cnt}$
[1] $S \to \epsilon$	$S.\text{cnt} = 0$
[2] $S \to [\ S_1\ ]\ S_2$	$S.\text{cnt} = 1 + S_1.\text{cnt} + S_2.\text{cnt}$



S 属性的文法的递归下降实现

- 回顾：S 属性的文法中只有综合属性
- 回顾：递归下降语法分析对每个非终结符号有一个递归过程
  - 过程没有参数，返回一个布尔值表示是否分析成功
- **S 属性的文法的递归下降分析**
  - 每个非终结符号的过程**返回该符号所有的综合属性**

$A ::= \alpha_1 \mid \ldots$

```
A() {
  if (token ∈ FIRST(α1)) {
    按照 α1 中符号依次进行 token 匹配或递归调用;
    按照 A → α1 的属性计算规则进行计算;
    return A 的综合属性;
  } else {
    ......
  }
  error();
}
```

S 属性的文法的递归下降实现

产生规则	属性计算规则
[0] $S' \to S\ \texttt{EOF}$	$S'.\texttt{cnt} = S.\texttt{cnt}$
[1] $S \to \epsilon$	$S.\texttt{cnt} = 0$
[2] $S \to [\ S_1\ ]\ S_2$	$S.\texttt{cnt} = 1 + S_1.\texttt{cnt} + S_2.\texttt{cnt}$

```
S'() {
  if (token == LSQUARE || token == EOF) {
    cnt = S();
    if (token == EOF) {
      return cnt;
    }
  }
  error();
}
```

```
S() {
  if (token == LSQUARE) {
    token = next_token();
    cnt1 = S();
    if (token == RSQUARE) {
      token = next_token();
      cnt2 = S();
      return 1 + cnt1 + cnt2;
    }
  } else if (token == EOF || token == RSQUARE) {
    return 0;
  }
  error();
}
```

L 属性的文法的递归下降实现

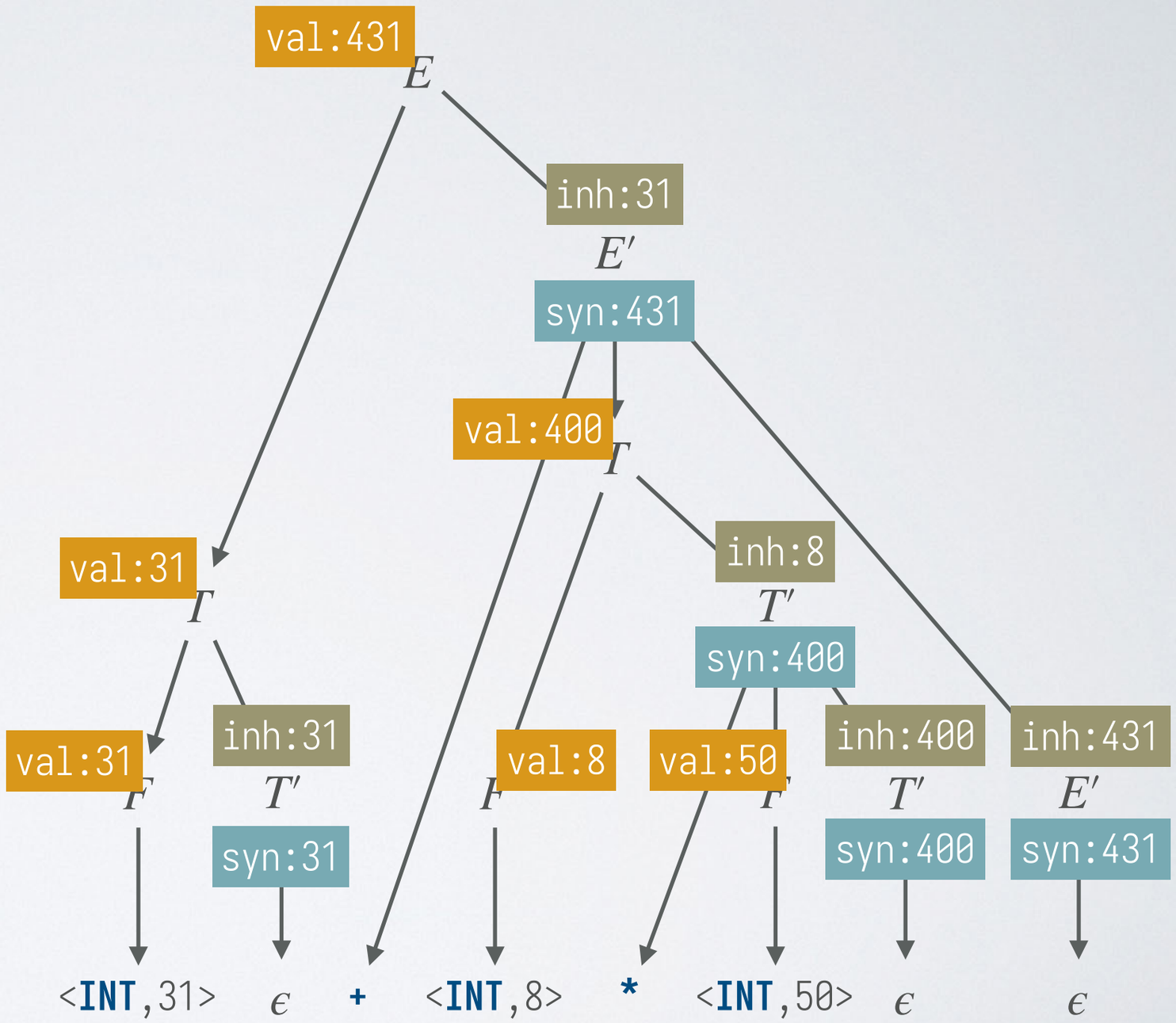
- 回顾：L 属性的文法中既有综合属性也有继承属性
  - 每个继承属性可以依赖左侧结点的属性和 parent 结点的继承属性
- **L 属性的文法的递归下降分析**
  - 每个非终结符号的过程**以其所有的继承属性为参数**
  - 每个非终结符号的过程**返回该符号所有的综合属性**

$A ::= \alpha_1 \mid \ldots$

```
A(A 的继承属性) {
  if (token ∈ FIRST(α1)) {
    按照 α1 中符号依次进行 token 匹配或递归调用;
    因为是 L 属性的文法，有足够的信息计算中途的递归调用所需的继承属性;
    return A 的综合属性;
  } else {
    ......
  }
  error();
}
```

L 属性的文法的递归下降实现

产生规则	属性计算规则
$E \to T\,E'$	$E'.\mathrm{inh} = T.\mathrm{val}$ $E.\mathrm{val} = E'.\mathrm{syn}$
$E' \to +\,T\,E'_1$	$E'_1.\mathrm{inh} = E'.\mathrm{inh} + T.\mathrm{val}$ $E'.\mathrm{syn} = E'_1.\mathrm{syn}$
$E' \to \epsilon$	$E'.\mathrm{syn} = E'.\mathrm{inh}$
$T \to F\,T'$	$T'.\mathrm{inh} = F.\mathrm{val}$ $T.\mathrm{val} = T'.\mathrm{syn}$
$T' \to *\,F\,T'_1$	$T'_1.\mathrm{inh} = T'.\mathrm{inh} \times F.\mathrm{val}$ $T'.\mathrm{syn} = T'_1.\mathrm{syn}$
$T' \to \epsilon$	$T'.\mathrm{syn} = T'.\mathrm{inh}$
$F \to (\,E\,)$	$F.\mathrm{val} = E.\mathrm{val}$
$F \to \mathrm{INT}$	$F.\mathrm{val} = \mathrm{INT}.\mathrm{intval}$



L 属性的文法的递归下降实现

产生规则	属性计算规则
$E \to T\,E'$	$E'.\text{inh} = T.\text{val}$ $E.\text{val} = E'.\text{syn}$
$E' \to +\,T\,E'_1$	$E'_1.\text{inh} = E'.\text{inh} + T.\text{val}$ $E'.\text{syn} = E'_1.\text{syn}$
$E' \to \epsilon$	$E'.\text{syn} = E'.\text{inh}$
$T \to F\,T'$	$T'.\text{inh} = F.\text{val}$ $T.\text{val} = T'.\text{syn}$
$T' \to *\,F\,T'_1$	$T'_1.\text{inh} = T'.\text{inh} \times F.\text{val}$ $T'.\text{syn} = T'_1.\text{syn}$
$T' \to \epsilon$	$T'.\text{syn} = T'.\text{inh}$
$F \to (\,E\,)$	$F.\text{val} = E.\text{val}$
$F \to \text{INT}$	$F.\text{val} = \text{INT}.\text{intval}$

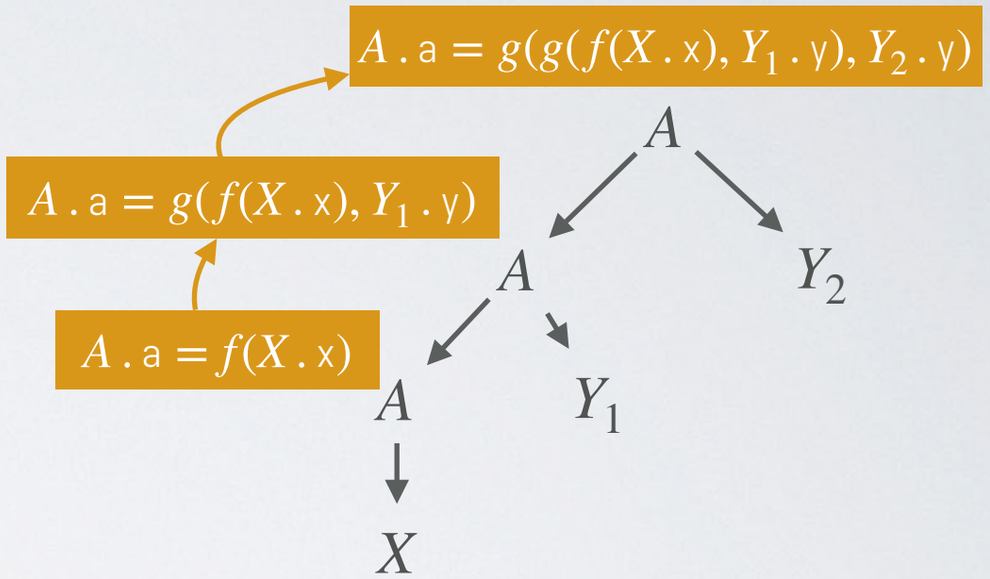
```
E() {
  if (token == LPAREN || token == INT) {
    T_val = T();
    E'_syn = E'(T_val);
    return E'_syn;
  }
  error();
}
```

```
E'(E'_inh) {
  if (token == PLUS) {
    token = next_token();
    T_val = T();
    E'1_syn = E'(E'_inh + T_val);
    return E'1_syn;
  } else if (token == EOF || token == RPAREN) {
    return E'_inh;
  }
  error();
}
```

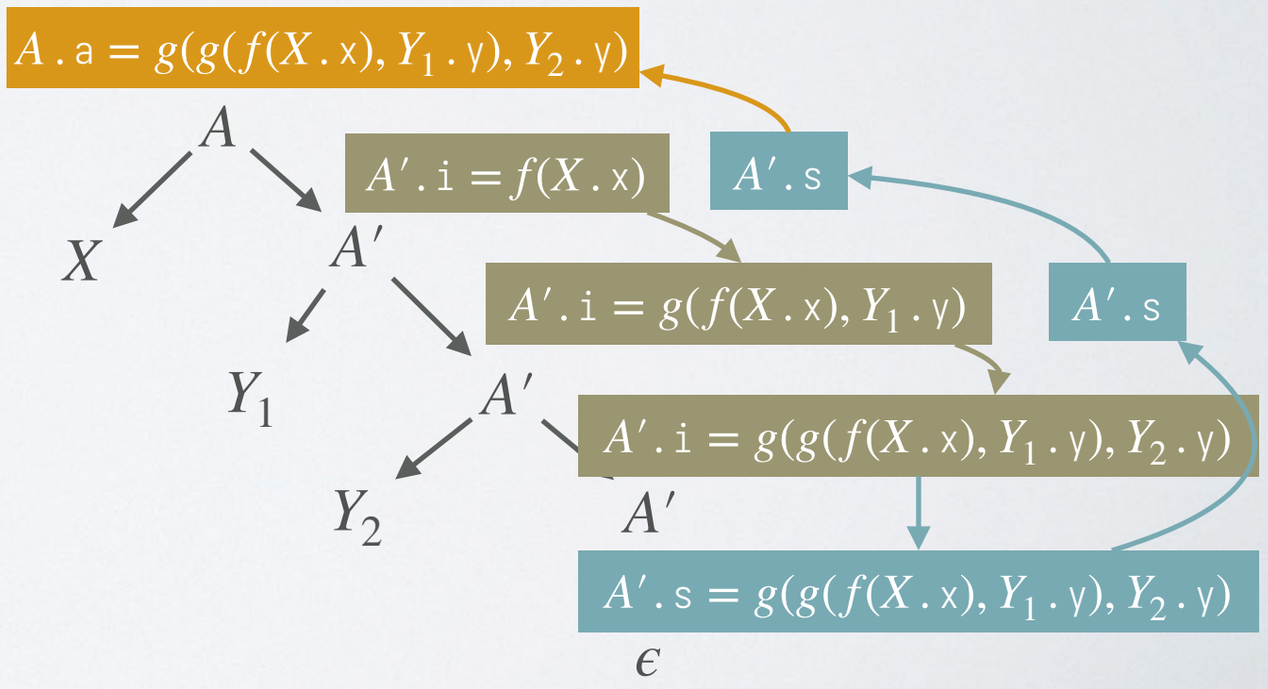
带左递归的 S 属性的文法

- **消除左递归时，可能需要引入继承属性**
- 例：

产生规则	属性计算规则
$A \to A_1\, Y$	$A.\mathrm{a} = g(A_1.\mathrm{a}, Y.\mathrm{y})$
$A \to X$	$A.\mathrm{a} = f(X.\mathrm{x})$



产生规则	属性计算规则
$A \to X\, A'$	$A'.\mathrm{i} = f(X.\mathrm{x})$ $A.\mathrm{a} = A'.\mathrm{s}$
$A' \to Y\, A'_1$	$A'_1.\mathrm{i} = g(A'.\mathrm{i}, Y.\mathrm{y})$ $A'.\mathrm{s} = A'_1.\mathrm{s}$
$A' \to \epsilon$	$A'.\mathrm{s} = A'.\mathrm{i}$



主要内容

- 语义分析的作用
- 语义分析的规约
- 语义分析的手动实现

- **实践演示**

玩具语言

- C 语言，但只有主函数，只有 int 类型，只有直线代码

```c
int main() {
  int x = 10;
  int y = x + 1 * x;
  int z = x * (y + 1);
  return z % 66;
}
```

```c
int main() {
  int y;
  y = 1;
  int main;
  main = y + 1;
  return main;
}
```

```c
int main() {
  int a = 1;
  {
    a = a + 2;
    int a = 3;
    a = a + 4;
  }
  a = a + 5;
  return a;
}
```

```c
int main() {
  int a = 1;
  int b = a + 2;
  {
    b = a + b;
    {
      int a = 3;
      b = b + a;
      { int b = 1; }
      { return b; }
    }
    int b = 1;
  }
}
```

玩具语言的抽象语法树表示

具体语法

$$
\begin{aligned}
Expr &\leftarrow Term\ ((\texttt{+} \mid \texttt{-})\ Term)^* \\
Term &\leftarrow Factor\ ((\texttt{*} \mid \texttt{/} \mid \texttt{\%})\ Factor)^* \\
Factor &\leftarrow \texttt{(}\ Expr\ \texttt{)} \mid \texttt{ID} \mid \texttt{NUMBER} \\
Stmt &\leftarrow Block \mid \texttt{int ID (=}\ Expr\texttt{)?;} \mid \texttt{ID =}\ Expr\ \texttt{;} \mid \texttt{return}\ Expr\ \texttt{;} \\
Block &\leftarrow \texttt{\{}\ Stmt^*\ \texttt{\}} \\
Func &\leftarrow \texttt{int ID ( )}\ Block \\
Prog &\leftarrow Func\ \texttt{EOF}
\end{aligned}
$$

抽象语法

$$
\begin{aligned}
E &::= \texttt{binop}(op, E, E) \mid \texttt{id}(x) \mid \texttt{number}(i) \\
op &::= \texttt{add} \mid \texttt{sub} \mid \texttt{mul} \mid \texttt{div} \mid \texttt{mod} \\
S &::= \texttt{block}(\vec{S}) \mid \texttt{decl}(x) \mid \texttt{decl}(x, E) \mid \texttt{assign}(x, E) \mid \texttt{ret}(E) \\
F &::= \texttt{func}(x, S) \\
P &::= \texttt{prog}(F)
\end{aligned}
$$

对抽象语法树进一步语义推敲

$S ::= \texttt{block}(\vec{S}) \mid \texttt{decl}(x) \mid \texttt{decl}(x, E) \mid \texttt{assign}(x, E) \mid \texttt{ret}(E)$

简化结构，使得语义更显然

$\hat{S} ::= \texttt{scope}(\hat{S}) \mid \texttt{decl}(x, \hat{S}) \mid \texttt{assign}(x, E) \mid \texttt{ret}(E) \mid \texttt{seq}(\hat{S}, \hat{S}) \mid \texttt{nop}$

```
int x = 10;
int y = x + 1 * x;
int z = x * (y + 1);
return z % 66;
```

```
decl(x, seq(assign(x, 10),
            decl(y, seq(assign(y, x + (1 * x)),
                        decl(z, seq(assign(z, x * (y + 1)),
                                    ret(z % 66)))))))
```

```
int a = 1;
{
  a = a + 2;
  int a = 3;
  a = a + 4;
}
a = a + 5;
return a;
```

```
decl(a,
     seq(assign(a, 1),
         seq(scope(seq(assign(a, a + 2),
                       decl(a,
                            seq(assign(a, 3),
                                assign(a, a + 4))))),
             seq(assign(a, a + 5),
                 ret(a)))))
```

进行语义推敲的 R 属性的文法

$$\hat{S} ::= \texttt{scope}(\hat{S}) \mid \texttt{decl}(x, \hat{S}) \mid \texttt{assign}(x, E) \mid \texttt{ret}(E) \mid \texttt{seq}(\hat{S}, \hat{S}) \mid \texttt{nop}$$

$$\begin{aligned}
S ::= {} & \texttt{block}(SS) \\
\mid {} & \texttt{decl}(x) \\
\mid {} & \texttt{decl}(x, E) \\
\mid {} & \texttt{assign}(x, E) \\
\mid {} & \texttt{ret}(E) \\
SS ::= {} & \epsilon \\
\mid {} & S, SS
\end{aligned}$$

继承属性 cont 记录后面已经推敲完的语句

综合属性 elab 记录在 cont 基础上完成推敲的语句

产生	属性计
$S \to \texttt{block}(SS)$	$SS.\texttt{cont} = \texttt{nop}$ $S.\texttt{elab} = \texttt{seq}(\texttt{scope}(SS.\texttt{elab}), S.\texttt{cont})$
$SS \to \epsilon$	$SS.\texttt{elab} = SS.\texttt{cont}$
$SS \to S, SS_1$	$SS_1.\texttt{cont} = SS.\texttt{cont}$ $S.\texttt{cont} = SS_1.\texttt{elab}$ $SS.\texttt{elab} = S.\texttt{elab}$
$S \to \texttt{decl}(x)$	$S.\texttt{elab} = \texttt{decl}(x, S.\texttt{cont})$
$S \to \texttt{decl}(x, E)$	$S.\texttt{elab} = \texttt{decl}(x, \texttt{seq}(\texttt{assign}(x, E), S.\texttt{cont}))$
$S \to \texttt{assign}(x, E)$	$S.\texttt{elab} = \texttt{seq}(\texttt{assign}(x, E), S.\texttt{cont})$
$S \to \texttt{ret}(E)$	$S.\texttt{elab} = \texttt{seq}(\texttt{ret}(E), S.\texttt{cont})$

在抽象语法树上进行类型检查

- 需要检查的性质：
  - **没有未经声明或赋值就使用的变量**
  - **同一作用域内没有重复声明的变量**

```
int n;
int a;
int b;
n = 10; a = 1; b = 1;
{
  int t;
  t = a + b; a = b; b = t;
  n = n - 1;
}
return a;
```

```
int n;
n 的作用域
int a;
int b;
n = 10; a = 1; b = 1;
a 的作用域
{
  { int n;
b 的作用域
    n = a + b; a = b; b = n;
  }
  t 的作用域
  n = n - 1;
}
return a;
```

- **问题：如何正确处理作用域？比如重复的变量名？**

编译中使用的符号表

- 编译器通过**符号表(symbol table)**来汇总不同名字的信息
  - 在本部分我们重点考虑程序变量

```
{ int n;
  int a;
  int b;
  ...
}
```

名字	类型	声明位置	其它信息
n	int	…	
a	int	…	
b	int	…	

?

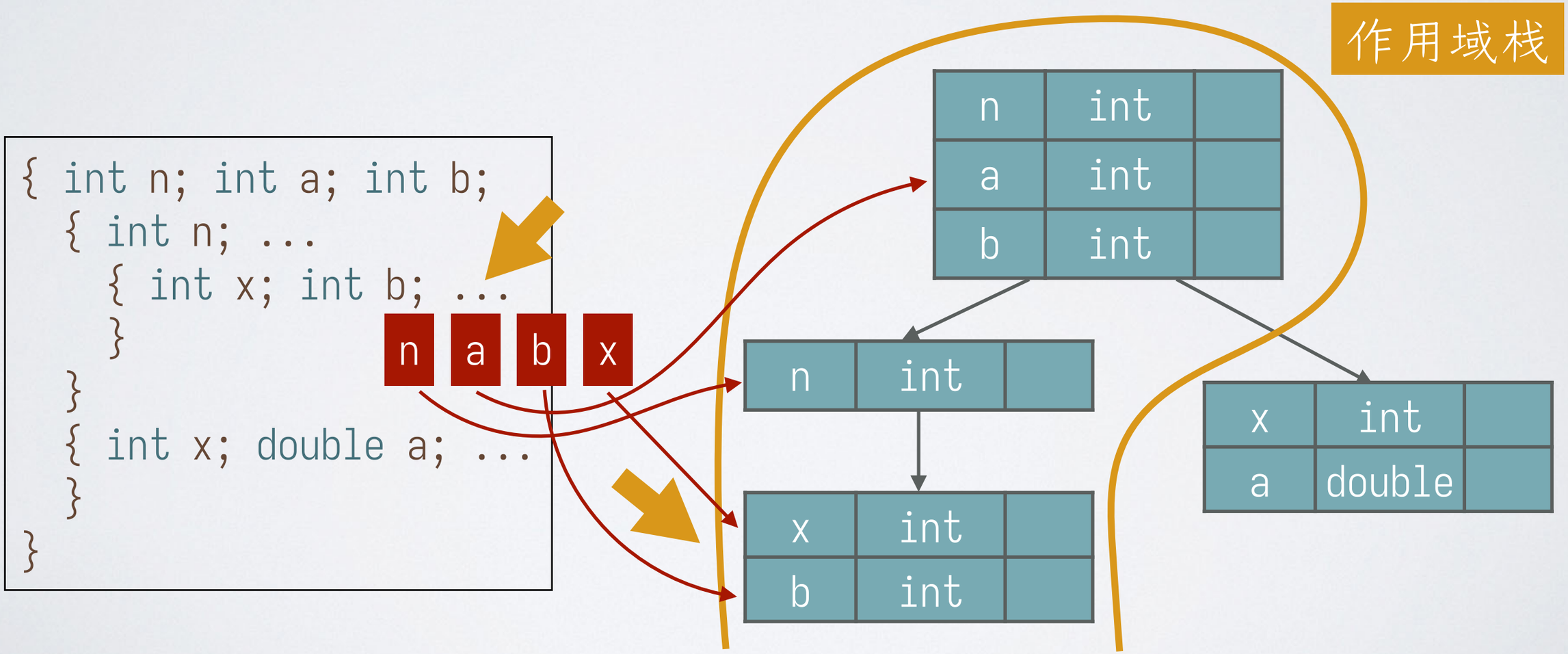
```
{ int n;
  int a;
  int b;
  { int n; ...
  }
}
```

?

名字	类型	声明位置	其它信息
n	int	…	
a	int	…	
b	int	…	
n	int	…	

通过符号表管理作用域

- **每个作用域对应一个符号表**：多个符号表形成树状结构
- 在实现时，可以通过栈来存放当前符号表及其祖先
  - 对程序变量 x 的使用需查看**最靠近栈顶**的声明了 x 的作用域



符号表提供的接口

- `push_scope()`：在栈顶压入一个新的作用域
- `pop_scope()`：弹出栈顶的作用域
- `insert(name, info)`：在栈顶作用域中记录名字和它的信息
- `lookup(name)`：查找最靠近栈顶的名字对应的信息

```
{ int n; int a; int b;
  { int n; ...
    { int x; int b;
      x = n + a + b;
      ...
    }
  }
  { int x; double a; ...
  }
}
```

```
1. push_scope()
2. insert(n)
3. insert(a)
4. insert(b)
5. push_scope()
6. insert(n)
7. push_scope()
8. insert(x)
9. insert(b)
10.lookup(n)
```

```
11.lookup(a)
12.lookup(b)
13.lookup(x)
14.pop_scope()
15.pop_scope()
16.push_scope()
17.insert(x)
18.insert(a)
19.pop_scope()
20.pop_scope()
```

进行类型检查的 L 属性的文法

$$\hat{S} ::= \texttt{scope}(\hat{S}) \mid \texttt{decl}(x, \hat{S}) \mid \texttt{assign}(x, E) \mid \texttt{ret}(E) \mid \texttt{seq}(\hat{S}, \hat{S}) \mid \texttt{nop}$$

$$E ::= \texttt{binop}(op, E, E) \mid \texttt{id}(x) \mid \texttt{number}(i)$$

继承属性 table_in 记录处理完前面语句后的符号表

综合属性 table_out 表示处理完该语句后的符号表

产	属性计算规则
$\hat{S} \to \texttt{scope}(\hat{S}_1)$	$\hat{S}_1.\texttt{table\_in} = \hat{S}.\texttt{table\_in}.\texttt{push\_scope}()$ $\hat{S}.\texttt{table\_out} = \hat{S}_1.\texttt{table\_out}.\texttt{pop\_scope}()$
$\hat{S} \to \texttt{decl}(x, \hat{S}_1)$	$\hat{S}_1.\texttt{table\_in} = \hat{S}.\texttt{table\_in}.\texttt{insert}(x, \texttt{UNASSIGNED})$ $\hat{S}.\texttt{table\_out} = \hat{S}_1.\texttt{table\_out}.\texttt{remove}(x)$
$\hat{S} \to \texttt{assign}(x, E)$	$E.\texttt{table} = \hat{S}.\texttt{table\_in}$ $\hat{S}.\texttt{table\_out} = \hat{S}.\texttt{table\_in}.\texttt{update}(x, \texttt{ASSIGNED})$
$\hat{S} \to \texttt{ret}(E)$	$E.\texttt{table} = \hat{S}.\texttt{table\_in}$　　$\hat{S}.\texttt{table\_out} = \hat{S}.\texttt{table\_in}$
$\hat{S} \to \texttt{seq}(\hat{S}_1, \hat{S}_2)$	$\hat{S}_1.\texttt{table\_in} = \hat{S}.\texttt{table\_in}$　　$\hat{S}_2.\texttt{table\_in} = \hat{S}_1.\texttt{table\_out}$ $\hat{S}.\texttt{table\_out} = \hat{S}_2.\texttt{table\_out}$
$E \to \texttt{binop}(op, E_1, E_2)$	$E_1.\texttt{table} = E.\texttt{table}$　　$E_2.\texttt{table} = E.\texttt{table}$
$E \to \texttt{id}(x)$	error if $E.\texttt{table}.\texttt{lookup}(x)$ == UNASSIGNED

Visitor Pattern

```
struct Stmt {
  virtual void accept(StmtVisitor &visitor) = 0;
};
```

```
struct StmtVisitor {
  virtual void visit_block(BlockStmt &stmt) = 0;
  virtual void visit_decl(DeclStmt &stmt) = 0;
  virtual void visit_assign(AssignStmt &stmt) = 0;
  virtual void visit_ret(RetStmt &stmt) = 0;
};
```

```
void BlockStmt::accept(StmtVisitor &visitor) override { visitor.visit_block(*this); }
void DeclStmt::accept(StmtVisitor &visitor) override { visitor.visit_decl(*this); }
void AssignStmt::accept(StmtVisitor &visitor) override { visitor.visit_assign(*this); }
void RetStmt::accept(StmtVisitor &visitor) override { visitor.visit_ret(*this); }
```

通过从 StmtVisitor 派生子类给 Stmt 添加功能，而不用改动 Stmt 本身的实现

```
struct StmtPrinter : public StmtVisitor {
  ostream &os;
  string prefix;
  StmtPrinter(ostream &os, const string &prefix = "")
      : os(os), prefix(prefix) {}

  void visit_block(BlockStmt &stmt) override;
  void visit_decl(DeclStmt &stmt) override;
  void visit_assign(AssignStmt &stmt) override;
  void visit_ret(RetStmt &stmt) override;
};
```

本讲小结

- 语义分析基于语法分析树，提取程序的核心语义
  - 通常体现为翻译到中间表示、类型检查、解释执行等任务
- 语义分析的规约可以使用属性文法(也称为语法制导定义)
  - 综合属性、继承属性、属性依赖图、S 属性和 L 属性的文法
- 语义分析可以独立于语法分析，通过遍历语法分析树实现
- 语义分析也可以结合自顶向下语法分析进行同步实现
- **后续可能讲的专题：**
  - **自底向上语义分析**
  - **类型系统的设计和实现**

思考问题

- 为什么编译过程需要语义分析？
- 语义分析需要知道编程语言的哪些信息？
- 属性文法作为语义分析的规约，有哪些优势和缺陷？
- 我们尤其关注 L 属性的文法，为什么？根据对称性，类似可以定义 R 属性的文法，其是否有意义？
- 属性依赖有环的文法是否有实际意义？是否可以对属性值域和计算加一些限制，使得有环文法的属性值仍是良定义的？
- 语义分析和语法分析结合，有什么优点？有什么缺点？