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OF NEW JERSEY

CS415 Compilers

Attribute Grammars, Syntax-Directed Translation

These slides are based on slides copyrighted by Keith Cooper, Ken Kennedy & Linda Torczon at Rice University

Review: LR(0) versus SLR(1) versus LR(1)

LR(0) -- set of LR(0) items as states

LR(1) -- set of LR(1) items as states (potentially more states)

SLR(1) -- set of augmented LR(0) items as states

SLR(1): add FOLLOW(A) to each LR(0) item $[A \rightarrow \gamma \bullet]$ as its second component: $[A \rightarrow \gamma \bullet, \underline{a}]$, $\forall a \in FOLLOW(A)$

Review: LR(0) versus SLR(1) versus LR(1)

Example:

$$S' \rightarrow S$$
$$S \rightarrow S\ ;\ a \mid a$$

LR(0) ?

LR(1) ?

SLR(1) ?

Review: LR(0) versus SLR(1) versus LR(1)

S' → S
S → S ; a | a

LR(0) States

s0 = Closure({[S' → •S]}) = {[S' -> •S], [S -> •S; a], [S -> •a] }

s1 = GoTo (s0, S) =
{[S' → S.],
[S → S•; a] }

s2 = GoTo (s0, a) =
{[S → a•]}

s3 = GoTo (s1, ;) =
{[S → S; • a]}

s4 = GoTo (s3, a) =
{[S → S;a •] }

LR(1) States

s0 = Closure({[S' → •S,eof]}) = {[S' -> •S,eof], [S -> •S; a,eof], [S -> •a,;] }

s1 = GoTo (s0, S) =
{[S' → S •, eof],
[S → S•; a, eof] }

s2 = GoTo (s0, a) =
{[S → a•, ;]}

s3 = GoTo (s1, ;) =
{[S → S; • a, eof]}

s4 = GoTo (s3, a) =
{[S → S;a •, eof] }

Grammar is not LR(0), but LR(1) and SLR(1)

LALR(1) versus LR(1)

LALR(1) : using LR(1) items, State -> Grouped LR(1) states

LALR(1): Merge two sets of LR(1) items (states), if they have the same core.

core of set of LR(1) items: a production rule with • marker, the first part of a LR(1) item.

LALR(1) versus LR(1)

s0 = Closure({[S' → •S, eof]})

s1 = GoTo (s0, a) =
{[S → a • Ad, eof],
[S → a • Be, eof],
[A → •c, d], [B → •c, e]}

s2 = GoTo (s0, b) =
{[S → b • Ae, eof],
[S → b • Bd, eof],
[A → •c, e], [B → •c, d]}

s3 = GoTo (s1, c) =
{[A → c• , d],
[B → c• , e]}

s4 = GoTo (s2, c) =
{[A → c• , e],
[B → c• , d]}

There are other states that are not listed here!

LALR(1) versus LR(1)

s0 = Closure({[S' → •S, eof]})

s1 = GoTo (s0, a) =
{[S → a • Ad, eof],
[S → a • Be, eof],
[A → •c, d], [B → •c, e]}

s2 = GoTo (s0, b) =
{[S → b • Ae, eof],
[S → b • Bd, eof],
[A → •c, e], [B → •c, d]}

s3 = GoTo (s1, c) =
{[A → c• , d],
[B → c• , e]}

s4 = GoTo (s2, c) =
{[A → c• , e],
[B → c• , d]}

s34 =
{[A → c• , d],
[A → c• , e],
[B → c• , d],
[B → c• , e], }

There are other states that are not listed here!

LALR(1) versus LR(1)

s0 = Closure({[S' → •S, eof]})

s1 = GoTo (s0, a) =
{[S → a • Ad, eof],
[S → a • Be, eof],
[A → •c, d], [B → •c, e]}

s2 = GoTo (s0, b) =
{[S → b • Ae, eof],
[S → b • Bd, eof],
[A → •c, e], [B → •c, d]}

s3 = GoTo (s1, c) =
{[A → c• , d],
[B → c• , e]}

s4 = GoTo (s2, c) =
{[A → c• , e],
[B → c• , d]}

s34 =
{[A → c• , d],
[A → c• , e],
[B → c• , d],
[B → c• , e], }

There are other states that are not listed here!

Grammar is LR(1), but not LALR(1), since collapsing s3 and s4 (same core) will introduce reduce-reduce conflict.

LALR(1) versus LR(1)

LALR(1) : using LR(1) items, State -> Grouped LR(1) states

LALR(1): Merge two sets of LR(1) items (states), if they have the same core.

core of set of LR(1) items: set of LR(0) items derived by ignoring the lookahead symbols

Question: would collapsing LR(1) states into LALR(1) states introduce shift/reduce conflicts

Context-sensitive Analysis

Context-Sensitive Analysis: Beyond Syntax

There is a level of correctness that is deeper than grammar

```
fie(a,b,c,d)
    int a, b, c, d;
{ … }

fee() {
    int f[3],g[1],
        h, i, j, k;
  char *p;
    fie(h,i,“ab”,j, k);
    k = f * i + j;
    h = g[17];
    printf(“<%s,%s>.\n”,
        p,q);
    p = 10;
}
```

What is wrong with this program?

(let me count the ways …)

Beyond Syntax

There is a level of correctness that is deeper than grammar

```
fie(a,b,c,d)
    int a, b, c, d;
{ … }

fee() {
    int f[3],g[1],
        h, i, j, k;
  char *p;
    fie(h,i,“ab”,j, k);
    k = f * i + j;
    h = g[17];
    printf(“<%s,%s>.\n”,
        p,q);
    p = 10;
}
```

What is wrong with this program?

(let me count the ways …)

- **declared g[1], used g[17]**
- **wrong number of args to fie()**
- **“ab” is not an int**
- **wrong dimension on use of f**
- **undeclared variable q**
- **10 is not a character string**

All of these are

“deeper than syntax”

To generate code, we need to understand the context !

Beyond Syntax

These questions are part of context-sensitive analysis

- Answers depend on "values", not parts of speech
- Questions & answers involve non-local information
- Answers may involve computation

How can we answer these questions?

- Use formal methods
  - → Context-sensitive grammars
  - → Attribute grammars *(attributed grammars)*
- Use *ad-hoc* techniques
- Symbol tables
  - → *Ad-hoc* code *(action routines)*

Beyond Syntax

Telling the story

- The attribute grammar formalism is important
  - → Succinctly makes many points clear
  - → Sets the stage for actual, *ad-hoc* practice (e.g.: yacc)
- The problems with attribute grammars motivate practice
  - → Non-local computation
  - → Need for centralized information

We will cover attribute grammars, then move on to *ad-hoc* ideas

Attribute Grammars

What is an attribute grammar?

- A context-free grammar augmented with a set of rules
- Each symbol in the derivation has a set of values, or *attributes*
- The rules specify how to compute a value for each attribute

Example grammar

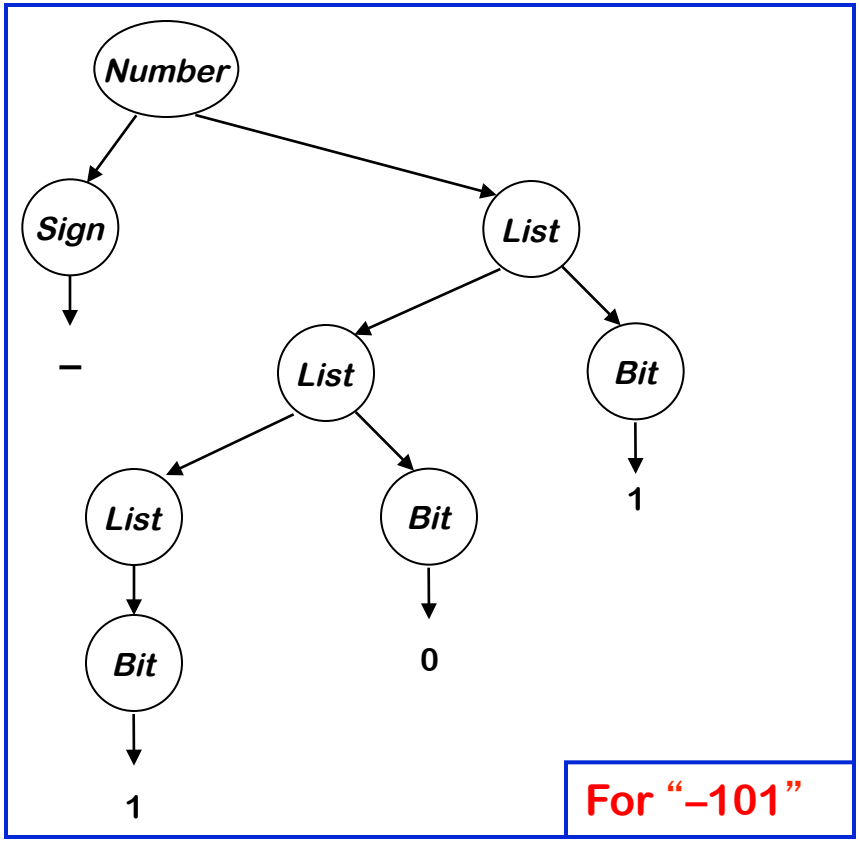
Number	→	Sign List
Sign	→	+
	|	-
List	→	List Bit
	|	Bit
Bit	→	0
	|	1

This grammar describes signed binary numbers

We would like to augment it with rules that compute the decimal value of each valid input string

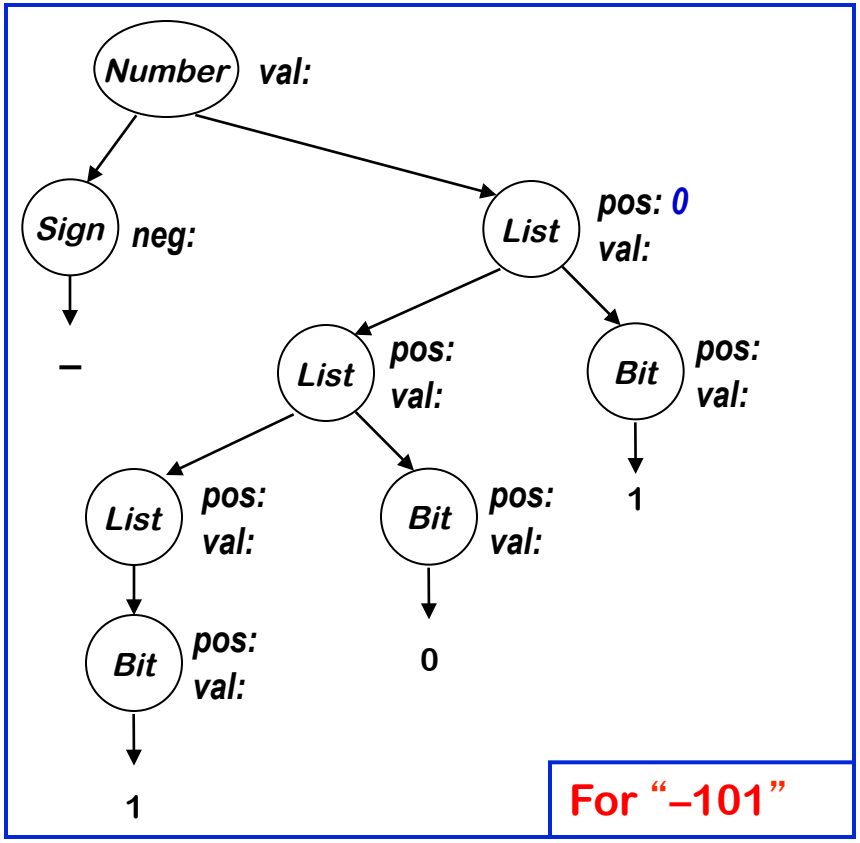
Example

Compute the decimal value of a signed binary number



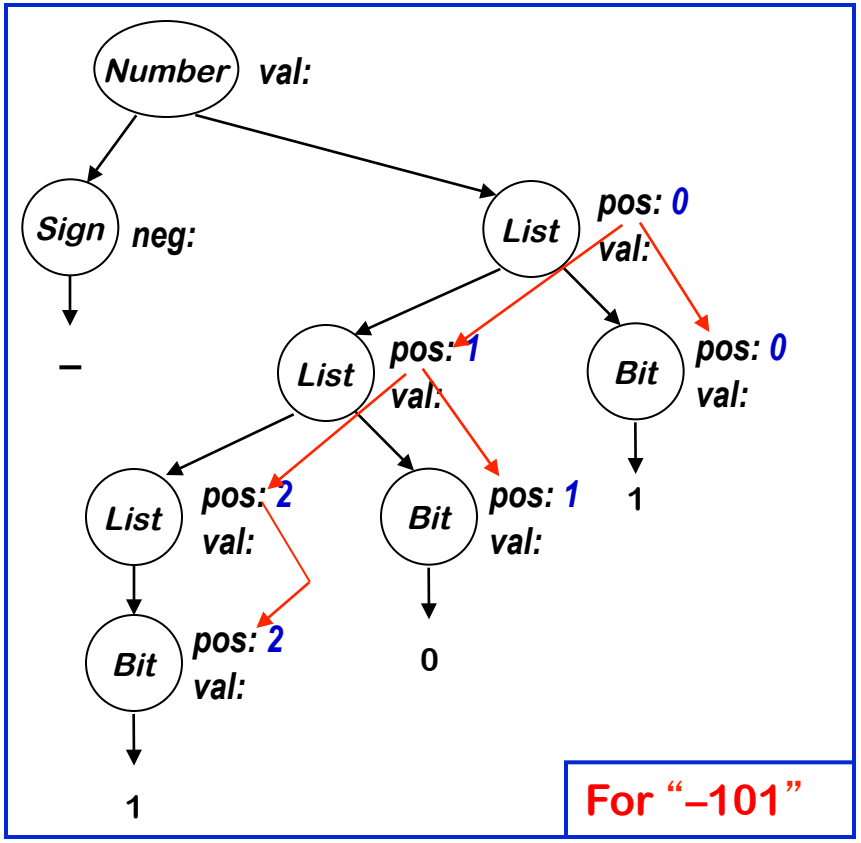
Example

Compute the decimal value of a signed binary number



Example

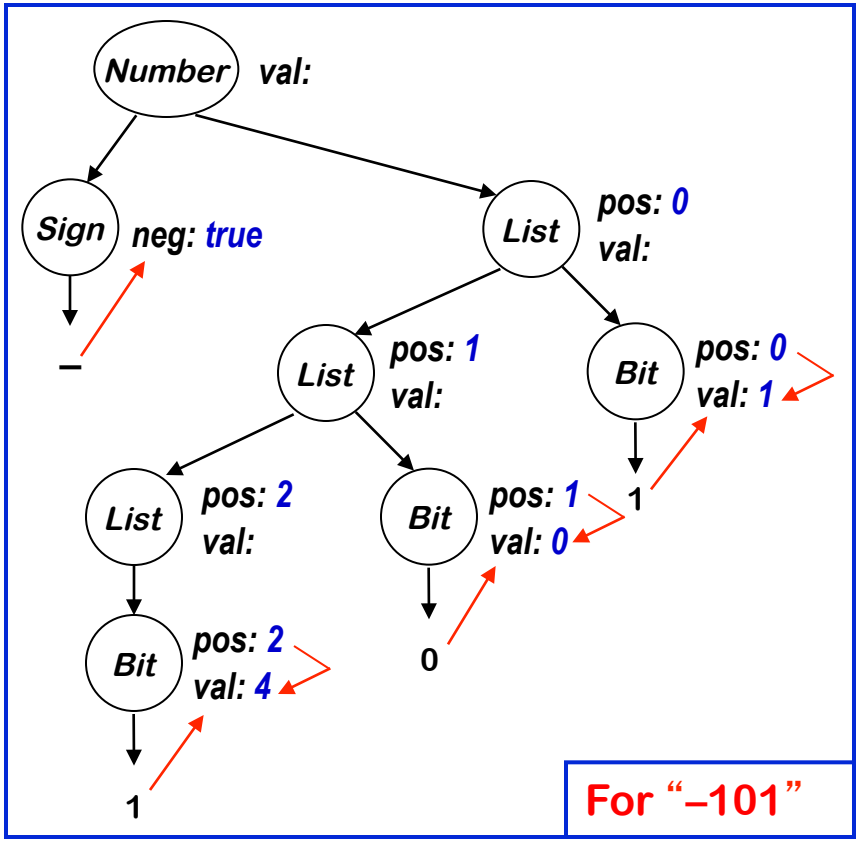
Compute the decimal value of a signed binary number



Inherited Attributes

Example

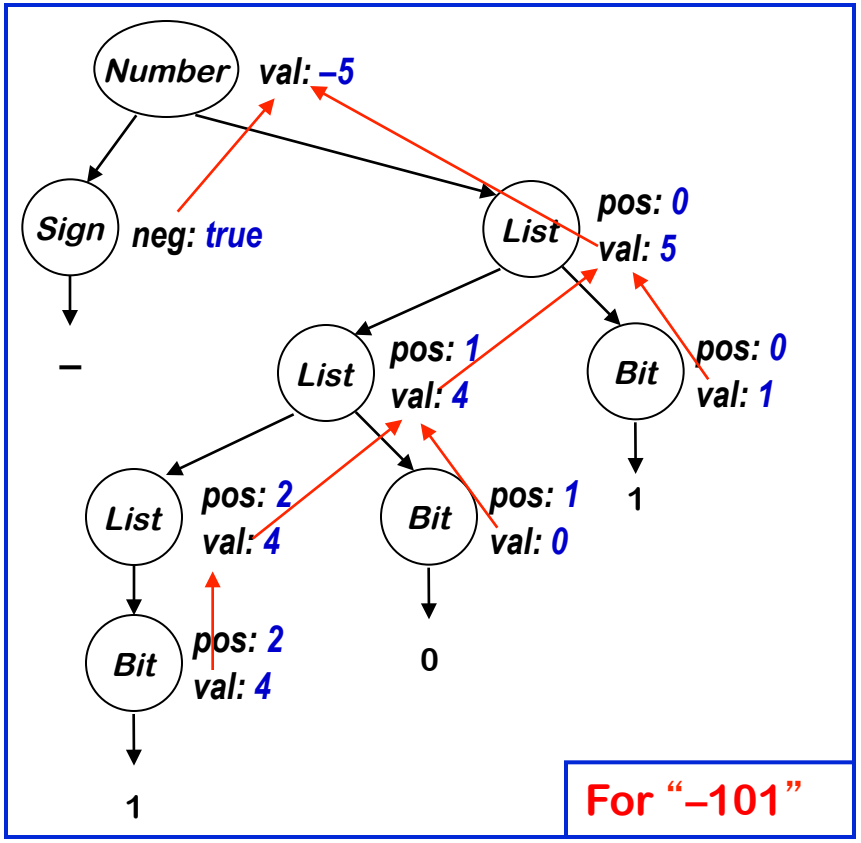
Compute the decimal value of a signed binary number



Synthesized attributes

Example

Compute the decimal value of a signed binary number



Synthesized attributes

Attribute Grammars

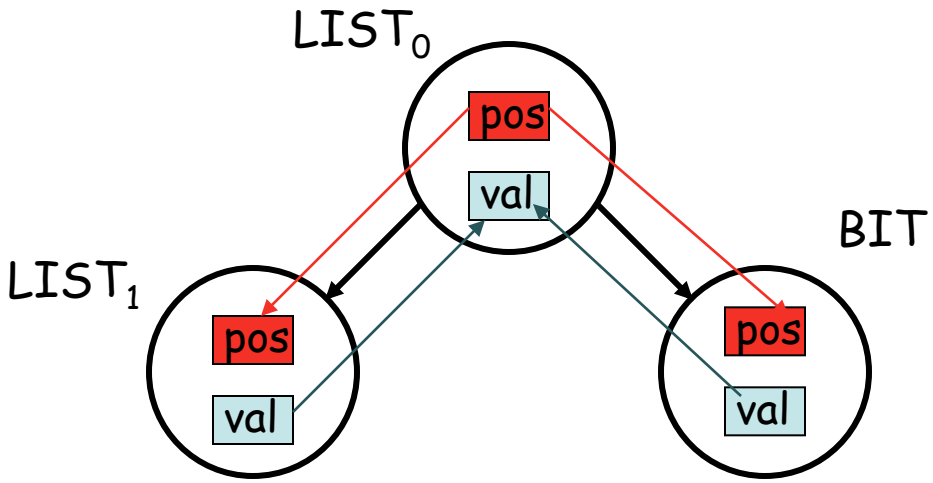
Add rules to compute the decimal value of a signed binary number

Productions			Attribution Rules
Number	→	*Sign List*	*List.pos ← 0* *If Sign.neg* *then Number.val ← – List.val* *else Number.val ← List.val*
Sign	→	+	*Sign.neg ← false*
	|	–	*Sign.neg ← true*
$List_0$	→	$List_1$ *Bit*	$List_1.pos \leftarrow List_0.pos + 1$ $Bit.pos \leftarrow List_0.pos$ $List_0.val \leftarrow List_1.val + Bit.val$
	|	*Bit*	*Bit.pos ← List.pos* *List.val ← Bit.val*
Bit	→	0	*Bit.val ← 0*
	|	1	$Bit.val \leftarrow 2^{Bit.pos}$

Symbol	Attributes
Number	val
Sign	neg
List	pos, val
Bit	pos, val

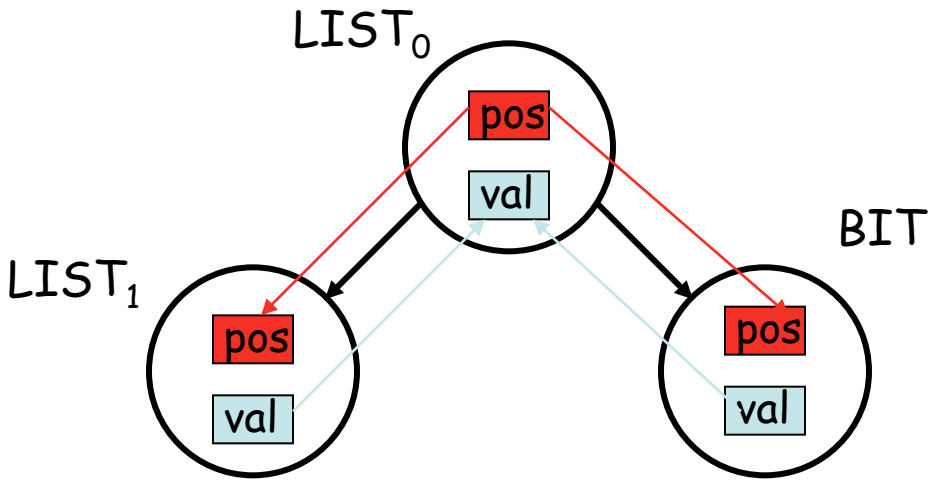
Attribute Grammars

Productions	Attribution Rules
$List_0 \rightarrow List_1\ Bit$	$List_1.pos \leftarrow List_0.pos + 1$ $Bit.pos \leftarrow List_0.pos$ $List_0.val \leftarrow List_1.val + Bit.val$



- semantic rules define partial dependency graph
- value flow top down or across: inherited attributes
- value flow bottom-up: synthesized attributes

Attribute Grammars



Note:

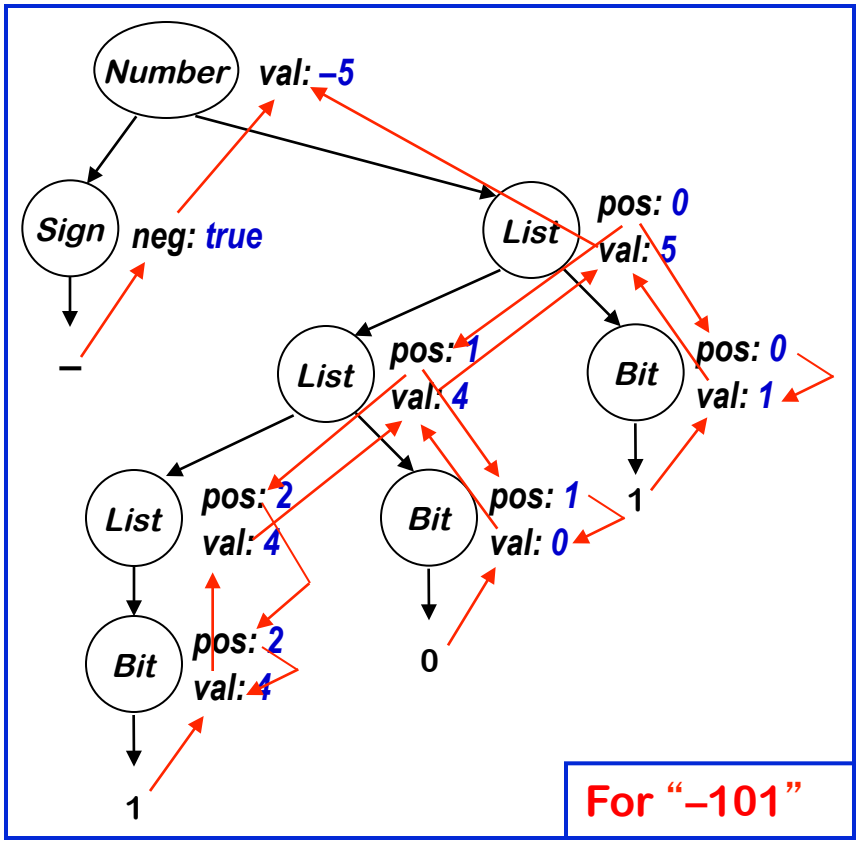
- semantic rules associated with production $A \rightarrow \alpha$ have to specify the values for all
  - synthesized attributes for A (root)
  - inherited attributes for grammar symbols in α (children)

  $\Rightarrow$ rules must specify local value flow!

- terminals can be associated with values returned by the scanner. These input values are associated with a synthesized attribute.
- Starting symbol cannot have inherited attributes.

Example revisited

compute the decimal value of a signed binary number

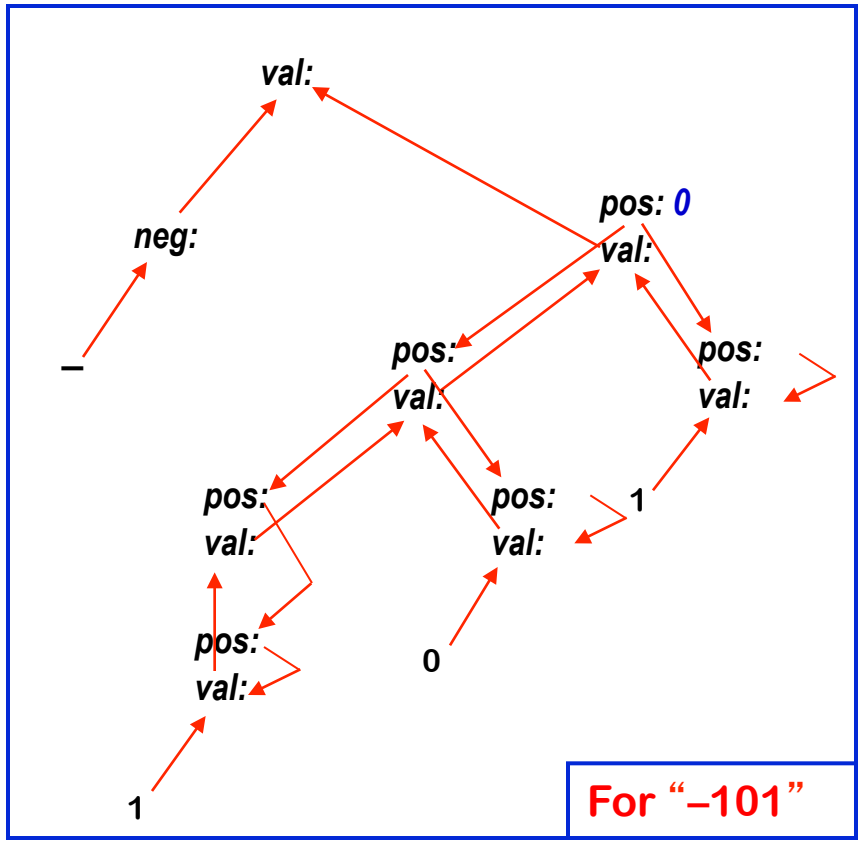


If we show the computation …

& then peel away the parse tree …

Example revisited

compute the decimal value of a signed binary number



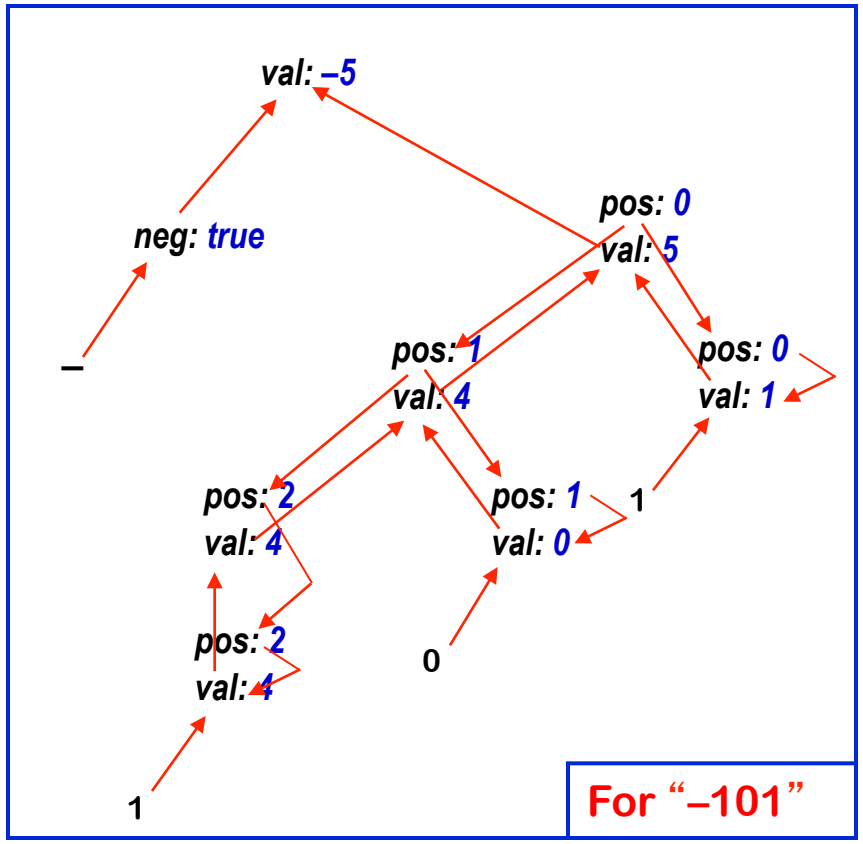
All that is left is the attribute dependence graph.

This succinctly represents the flow of values in the problem instance.

The dependence graph must be acyclic

Example revisited

compute the decimal value of a signed binary number



All that is left is the attribute dependence graph.

This succinctly represents the flow of values in the problem instance.

The dynamic methods sort this graph to find independent values, then work along graph edges.

The rule-based methods try to discover "good" orders by analyzing the rules.

The oblivious methods ignore the structure of this graph.

The dependence graph must be acyclic

Using Attribute Grammars

Attribute grammars can specify context-sensitive actions

- Take values from syntax
- Perform computations with values
- Insert tests, logic, …

Synthesized Attributes

- Use values from children & from constants
- S-attributed grammars: synthesized attributes only
- Evaluate in a single bottom-up pass

Good match to LR parsing

Inherited Attributes

- Use values from parent, constants, & siblings
- L-attributed grammars:

$A \rightarrow X_1 X_2 \ldots X_n$ and each inherited attribute of X_i depends on
- attributes of $X_1 X_2 \ldots X_{i-1}$, and
- inherited attributes of A

- Evaluate in a single top-down pass (left to right)

Good match for LL parsing

An Extended Example

Grammar for a basic block (§ 4.3.3)

$Block_0$	→	$Block_1$ Assign
	|	Assign
Assign	→	Ident = Expr ;
$Expr_0$	→	$Expr_1$ + Term
	|	$Expr_1$ – Term
	|	Term
$Term_0$	→	$Term_1$ * Factor
	|	$Term_1$ / Factor
	|	Factor
Factor	→	(Expr)
	|	Number
	|	Identifier

Let's estimate cycle counts

- Each operation has a COST
- Add them, bottom up
- Assume a load per value
- Assume no reuse

Simple problem for an *AG*

An Extended Example (*continued*)

$Block_0$	→	$Block_1$ *Assign*	$Block_0$.cost ← $Block_1$.cost + Assign.cost
	|	*Assign*	$Block_0$.cost ← Assign.cost
Assign	→	*Ident = Expr ;*	Assign.cost ← **COST**(store) + Expr.cost
$Expr_0$	→	$Expr_1$ + *Term*	$Expr_0$.cost ← $Expr_1$.cost + **COST**(add) + Term.cost
	|	$Expr_1$ - *Term*	$Expr_0$.cost ← $Expr_1$.cost + **COST**(sub) + Term.cost
	|	*Term*	$Expr_0$.cost ← Term.cost
$Term_0$	→	$Term_1$ * *Factor*	$Term_0$.cost ← $Term_1$.cost + **COST**(mult) + Factor.cost
	|	$Term_1$ / *Factor*	$Term_0$.cost ← $Term_1$.cost + **COST**(div) + Factor.cost
	|	*Factor*	$Term_0$.cost ← Factor.cost
Factor	→	*(Expr)*	Factor.cost ← Expr.cost
	|	*Number*	Factor.cost ← **COST**(loadI)
	|	*Identifier*	Factor.cost ← **COST**(load)

These are all synthesized attributes !

Values flow from *rhs* to *lhs* in prod' ns

An Extended Example (*continued*)

Properties of the example grammar

- All attributes are synthesized ⇒ S-attributed grammar
- Rules can be evaluated bottom-up in a single pass
  - → Good fit to bottom-up, shift/reduce parser
- Easily understood solution
- Seems to fit the problem well

What about an improvement?

- Values are loaded only once per block (not at each use)
- Need to track which values have been already loaded

Things will get more complicated.

A Better Execution Model

Adding load tracking

- Need sets *Before* and *After* for each production

- Must be initialized, updated, and passed around the tree

Factor → (Expr)	Factor.cost ← Expr.cost ; Expr.Before ← Factor.Before ; Factor.After ← Expr.After
| Number	Factor.cost ← COST(loadi) ; Factor.After ← Factor.Before

| Identifier	If (Identifier.name ∉ Factor.Before)
	then
	Factor.cost ← COST(load);
	Factor.After ← Factor.Before
	∪ Identifier.name
	else
	Factor.cost ← 0
	Factor.After ← Factor.Before

This looks more complex!

A Better Execution Model

Adding load tracking

- Need sets *Before* and *After* for each production

  Question: synthesized or inherited?

- Must be initialized, updated, and passed around the tree

Factor → (Expr)	Factor.cost ← Expr.cost ; Expr.Before ← Factor.Before ; Factor.After ← Expr.After
| Number	Factor.cost ← COST(loadi) ; Factor.After ← Factor.Before

| Identifier	If (Identifier.name ∉ Factor.Before)
	then
	Factor.cost ← COST(load);
	Factor.After ← Factor.Before
	∪ Identifier.name
	else
	Factor.cost ← 0
	Factor.After ← Factor.Before

This looks more complex!

A Better Execution Model

- Load tracking adds complexity
- But, most of it is in the "copy rules"
- Every production needs rules to copy *Before* & *After*

A sample production

$Expr_0 \rightarrow Expr_1 + Term$	$Expr_0.cost \leftarrow Expr_1.cost +$ COST(add) + Term.cost ; $Expr_1.Before \leftarrow Expr_0.Before$; $Term.Before \leftarrow Expr_1.After$; $Expr_0.After \leftarrow Term.After$

These copy rules multiply rapidly

Each creates an instance of the set

Lots of work, lots of space, lots of rules to write

The Moral of the Story

- Non-local computation needed lots of supporting rules
- "Complex" local computation is relatively easy

The Problems

- Copy rules increase cognitive overhead
- Copy rules increase space requirements
  - → Need copies of attributes
- Result is an attributed tree
  - → Must build the parse tree first
  - → Either search tree for answers or copy them to the root

Addressing the Problem

What would a good programmer do (with the shift-reduce parser)?

- Introduce a central repository for facts
- Table of names
  - → Field in table for loaded/not_loaded state
- Avoids all the copy rules, allocation & storage headaches
- All inter-assignment attribute flow is through table
  - → Clean, efficient implementation
  - → Good techniques for implementing the table *(hashing, § B.4)*
  - → When its done, information is in the table !
  - → Cures most of the problems
- Unfortunately, this design violates the functional, AG paradigm

The Realist's Alternative

Ad-hoc syntax-directed translation

- Associate pieces of code with each production
- At each reduction, the corresponding code is executed
- Allowing arbitrary code provides complete flexibility
  - → Includes ability to do tasteless & bad things

To make this work

- Need names for attributes of each symbol on *lhs* & *rhs*
  - → Typically, one attribute passed through parser + arbitrary code (structures, globals, …)
  - → Yacc (tool used in project #2) introduced **$$, $1, $2, … $n**, left to right
- Need an evaluation scheme
  - → Fits nicely into **LR(1)** parsing algorithm

Reworking the Example (*with load tracking*)

$Block_0$	→	$Block_1$ Assign	
	|	Assign	
Assign	→	Ident = Expr ;	cost ← cost + COST(store);
$Expr_0$	→	$Expr_1$ + Term	cost ← cost + COST(add);
	|	$Expr_1$ - Term	cost ← cost + COST(sub);
	|	Term	
$Term_0$	→	$Term_1$ * Factor	cost ← cost + COST(mult);
	|	$Term_1$ / Factor	cost ← cost + COST(div);
	|	Factor	
Factor	→	(Expr)	
	|	Number	cost ← cost + COST(loadi);
	|	Identifier	{ i ← hash(Identifier);
			if (Table[i].loaded = false)
			then {
			cost ← cost + COST(load);
			Table[i].loaded ← true;
			}
			}

This looks cleaner & simpler than the AG sol'n ! "cost" and Table[ ] are global variables

Reworking the Example (*with load tracking*)

$Block_0$	→	$Block_1$ Assign	
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	|	Term	
$Term_0$	→	$Term_1$ * Factor	cost ← cost + COST(mult);
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Factor	→	(Expr)	
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			then {
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			}
			}

This looks cleaner & simpler than the AG sol'n ! "cost" and Table[ ] are global variables

One missing detail: initializing "cost"; (we ignore "Table[ ] for now)

Reworking the Example (*with load tracking*)

Start	→	Init Block	
Init	→	ε	cost ← 0;
$Block_0$	→	$Block_1$ Assign	
	|	Assign	
Assign	→	Ident = Expr ;	cost ← cost + COST(store);

… and so on as in the previous version of the example …

- Before parser can reach Block, it must reduce Init
- Reduction by Init sets cost to zero

This is an example of splitting a production to create a reduction in the middle — for the sole purpose of hanging an action routine there (marker production)!

Reworking the Example (*with load tracking*)

$Block_0$	→	$Block_1$ Assign	$$ ← $1 + $2 ;
	|	Assign	$$ ← $1 ;
Assign	→	Ident = Expr ;	$$← COST(store) + $3;
$Expr_0$	→	$Expr_1$ + Term	$$← $1 + COST(add) + $3;
	|	$Expr_1$ - Term	$$← $1 + COST(sub) + $3;
	|	Term	$$ ← $1;
$Term_0$	→	$Term_1$ * Factor	$$ ← $1 + COST(mult) + $3;
	|	$Term_1$ / Factor	$$ ← $1 + COST(div) + $3;
	|	Factor	$$ ← $1;
Factor	→	(Expr)	$$ ← $2;
	|	Number	$$ ← COST(loadi);
	|	Identifier	{ i← hash(Identifier);
			if (Table[i].loaded = false)
			then {
			$$ ← COST(load);
			Table[i].loaded ← true;
			}
			else $$ ← 0
			}

This version passes the values through attributes. It avoids the need for initializing "cost"

However, Table[ ] still needs to be initialized

Using A Parser Generator -- Yacc

parse.y :

```
%{
#include <stdio.h>
#include "attr.h"
int yylex();
void yyerror(char * s);
#include "symtab.h"
%}
```

Will be included verbatim in parse.tab.c

List and assign attributes

```
%union {tokentype token; }

%token PROG PERIOD PROC VAR ARRAY RANGE OF
%token INT REAL DOUBLE WRITELN THEN ELSE IF
%token BEG END ASG NOT
%token EQ NEQ LT LEQ GEQ GT OR EXOR AND DIV NOT
%token <token> ID CCONST ICONST RCONST

%start program

%%
program : PROG ID ';' block PERIOD { }
     ;
block       : BEG ID ASG ICONST END { }
     ;

%%
```

Rules with semantic actions

```
void yyerror(char* s) {
        fprintf(stderr,"%s\n",s);
        }
int
main() {
    printf("1\t");
    yyparse();
    return 1;
    }
```

Main program and "helper" functions; may contain initialization code of global structures. Will be included verbatim in parse.tab.c

Error Recovery in Shift-Reduce Parsers

The problem: parser encounters an invalid token

Goal: Want to parse the rest of the file

Basic idea:

- Assume something went wrong while trying to find handle for nonterminal A
- Pretend handle for A has been found; pop "handle", skip over input to find terminal that can follow A

Restarting the parser:

- find a restartable state on the stack (has transition for nonterminal A)
- move to a consistent place in the input (token that can follow A)
- perform (error) reduction (for nonterminal A)
- print an informative message

Error Recovery in YACC

Yacc's (bison's) error mechanism (note: version dependent!)

- designated token **`error`**
- used in error productions of the form

  $A \rightarrow$ **`error`** α // basic case
- α specifies synchronization points

When error is discovered

- pops stack until it finds state where it can shift the **`error`** token
- resumes parsing to match α

  special cases:
  - α = w, where w is string of terminals: skip input until w has been read
  - $\alpha = \varepsilon$: skip input until state transition on input token is defined
- error productions can have actions

Error Recovery in YACC

```
cmpdstmt: BEG stmt_list END
stmt_list : stmt
          | stmt_list  ';'  stmt
          | error { yyerror("\n***Error: illegal statement\n");}
```

This should

- throw out the erroneous statement
- synchronize at ";" or "end" (implicit: $\alpha = \varepsilon$)
- writes message "***Error: illegal statement" to stderr

Example: begin a & 5 | hello ; a := 3 end

↑ ↑ resume parsing

***Error: illegal statement

Next class

SDT & Intermediate representations

Read EaC: Chapter 4.4 & Chapters 5.1 – 5.3