4. Parsing in Practice

Prof. O. Nierstrasz

Thanks to Jens Palsberg and Tony Hosking for their kind permission to reuse and adapt the CS132 and CS502 lecture notes.
http://www.cs.ucla.edu/~palsberg/
http://www.cs.purdue.edu/homes/hosking/
Roadmap

- Bottom-up parsing
- LR(k) grammars
- JavaCC, Java Tree Builder and the Visitor pattern
- Example: a straightline interpreter

See, Modern compiler implementation in Java (Second edition), chapters 3-4.
Roadmap

> Bottom-up parsing
> LR(k) grammars
> JavaCC, Java Tree Builder and the Visitor pattern
> Example: a straightline interpreter
Some definitions

Recall:

> For a grammar $G$, with start symbol $S$, any string $\alpha$ such that $S \Rightarrow^* \alpha$ is called a **sentential form**

  — If $\alpha \in V_t^*$, then $\alpha$ is called a **sentence** in $L(G)$
  — Otherwise it is just a sentential form (not a sentence in $L(G)$)

> A **left-sentential form** is a sentential form that occurs in the leftmost derivation of some sentence.

> A **right-sentential form** is a sentential form that occurs in the rightmost derivation of some sentence.
Bottom-up parsing

**Goal:**

— Given an input string \( w \) and a grammar \( G \), construct a parse tree by starting at the leaves and working to the root.

> The parser repeatedly matches a *right-sentential form* from the language against the tree’s upper frontier.

> At each match, it applies a *reduction* to build on the frontier:

  — each reduction matches an upper frontier of the partially built tree to the RHS of some production
  — each reduction adds a node on top of the frontier

> The final result is a *rightmost derivation*, in reverse.
Example

Consider the grammar:

1. \( S \to aABe \)
2. \( A \to Abc \)
3. \( \mid \to b \)
4. \( B \to d \)

and the input string: \( abbcde \)

<table>
<thead>
<tr>
<th>Production</th>
<th>Sentential Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>( abcde )</td>
</tr>
<tr>
<td>2</td>
<td>( aAbcde )</td>
</tr>
<tr>
<td>4</td>
<td>( aAde )</td>
</tr>
<tr>
<td>1</td>
<td>( aABe )</td>
</tr>
</tbody>
</table>

The trick appears to be scanning the input and finding valid sentential forms.
A handle of a right-sentential form $\gamma$ is a production $A \rightarrow \beta$ and a position in $\gamma$ where $\beta$ may be found and replaced by $A$ to produce the previous right-sentential form in a rightmost derivation of $\gamma$.

Suppose: $S \Rightarrow^* \alpha Aw \Rightarrow \alpha \beta w$.

Then $A \rightarrow \beta$ in the position following $\alpha$ is a handle of $\alpha \beta w$.

**NB:** Because $\gamma$ is a right-sentential form, the substring to the right of a handle contains *only* terminal symbols.
The handle $A \rightarrow \beta$ in the parse tree for $\alpha\beta w$
# Handles

> **Theorem:**
> If $G$ is unambiguous then every right-sentential form has a unique handle.

> **Proof:** (by definition)
1. $G$ is unambiguous $\Rightarrow$ rightmost derivation is unique
2. $\Rightarrow$ a unique production $A \rightarrow \beta$ applied to take $\gamma_{i-1}$ to $\gamma_i$
3. $\Rightarrow$ a unique position $k$ at which $A \rightarrow \beta$ is applied
4. $\Rightarrow$ a unique handle $A \rightarrow \beta$
The left-recursive expression grammar *(original form)*

<table>
<thead>
<tr>
<th>Prod’n.</th>
<th>Sentential Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>⟨goal⟩</td>
</tr>
<tr>
<td>2</td>
<td>⟨expr⟩</td>
</tr>
<tr>
<td>3</td>
<td>⟨expr⟩ − ⟨term⟩</td>
</tr>
<tr>
<td>4</td>
<td>⟨term⟩</td>
</tr>
<tr>
<td>5</td>
<td>⟨expr⟩ − ⟨term⟩ * ⟨factor⟩</td>
</tr>
<tr>
<td>6</td>
<td>⟨term⟩ / ⟨factor⟩</td>
</tr>
<tr>
<td>7</td>
<td>⟨factor⟩</td>
</tr>
<tr>
<td>8</td>
<td>⟨expr⟩ − num * id</td>
</tr>
<tr>
<td>9</td>
<td>id − num * id</td>
</tr>
</tbody>
</table>
Handle-pruning

The process to construct a bottom-up parse is called **handle-pruning**.

To construct a rightmost derivation

\[ S = \gamma_0 \Rightarrow \gamma_1 \Rightarrow \gamma_2 \Rightarrow \ldots \Rightarrow \gamma_{n-1} \Rightarrow \gamma_n = w \]

we set \( i \) to \( n \) and apply the following simple algorithm:

1. Find the handle \( A_i \rightarrow \beta_i \) in \( \gamma_i \)
2. Replace \( \beta_i \) with \( A_i \) to generate \( \gamma_{i-1} \)

**This takes 2n steps, where \( n \) is the length of the derivation**
One scheme to implement a handle-pruning, bottom-up parser is called a *shift-reduce parser*.

Shift-reduce parsers use a *stack* and an *input buffer*

1. Initialize stack with $\$
2. Repeat until the top of the stack is the goal symbol and the input token is $\$
   
   a) **Find the handle.**
      
      If we don’t have a handle on top of the stack, *shift* (push) an input symbol onto the stack
   
   b) **Prune the handle.**
      
      If we have a handle $A \rightarrow \beta$ on the stack, *reduce*
      
      I. Pop $|\beta|$ symbols off the stack
      II. Push $A$ onto the stack

*NB: In practice we also lookahead to determine whether to shift or reduce!*
Example: back to $x - 2y$

1. Shift until top of stack is the right end of a handle
2. Find the left end of the handle and reduce

<table>
<thead>
<tr>
<th>Stack</th>
<th>Input</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle expr\rangle$</td>
<td>$id$</td>
<td>shift $num \ast id$</td>
</tr>
<tr>
<td>$\langle factor\rangle$</td>
<td>$- num \ast id$</td>
<td>reduce 9</td>
</tr>
<tr>
<td>$\langle term\rangle$</td>
<td>$- num \ast id$</td>
<td>reduce 7</td>
</tr>
<tr>
<td>$\langle expr\rangle$</td>
<td>$- num \ast id$</td>
<td>reduce 4</td>
</tr>
<tr>
<td>$\langle expr\rangle$</td>
<td>$- num \ast id$</td>
<td>shift $num \ast id$</td>
</tr>
<tr>
<td>$\langle term\rangle$</td>
<td>$\ast id$</td>
<td>reduce 8</td>
</tr>
<tr>
<td>$\langle factor\rangle$</td>
<td>$\ast id$</td>
<td>reduce 7</td>
</tr>
<tr>
<td>$\langle expr\rangle$</td>
<td>$\ast id$</td>
<td>shift</td>
</tr>
<tr>
<td>$\langle factor\rangle$</td>
<td>$\ast id$</td>
<td>shift</td>
</tr>
<tr>
<td>$\langle term\rangle$</td>
<td>$\ast id$</td>
<td>reduce 9</td>
</tr>
<tr>
<td>$\langle term\rangle$</td>
<td>$\ast id$</td>
<td>reduce 5</td>
</tr>
<tr>
<td>$\langle factor\rangle$</td>
<td>$\ast id$</td>
<td>reduce 3</td>
</tr>
<tr>
<td>$\langle expr\rangle$</td>
<td>$\ast id$</td>
<td>reduce 1</td>
</tr>
<tr>
<td>$\langle goal\rangle$</td>
<td></td>
<td>accept</td>
</tr>
</tbody>
</table>

5 shifts + 9 reduces + 1 accept
### Shift-reduce parsing

A *shift-reduce parser has just four canonical actions*:

<table>
<thead>
<tr>
<th>Action</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>shift</strong></td>
<td>next input symbol is shifted (pushed) onto the top of the stack</td>
</tr>
<tr>
<td><strong>reduce</strong></td>
<td>right end of handle is on top of stack; locate left end of handle within the stack; pop handle off stack and push appropriate non-terminal LHS</td>
</tr>
<tr>
<td><strong>accept</strong></td>
<td>terminate parsing and signal success</td>
</tr>
<tr>
<td><strong>error</strong></td>
<td>call an error recovery routine</td>
</tr>
</tbody>
</table>
Roadmap

> Bottom-up parsing
> LR(k) grammars
> JavaCC, Java Tree Builder and the Visitor pattern
> Example: a straightline interpreter
LR(k) grammars

A grammar G is LR(k) iff:

1. $S \Rightarrow_{rm}^* \alpha Aw \Rightarrow_{rm} \alpha \beta w$
2. $S \Rightarrow_{rm}^* \gamma Bx \Rightarrow_{rm} \alpha \beta y$
3. $\text{FIRST}_k(w) = \text{FIRST}_k(y) \Rightarrow \alpha Ay = \gamma Bx$

I.e., if $\alpha \beta w$ and $\alpha \beta y$ have the same $k$-symbol lookahead, then there is a unique handle to reduce in the rightmost derivation.
Why study LR grammars?

**LR(1) grammars are used to construct LR(1) parsers.**

- everyone’s favorite parser
- virtually all context-free programming language constructs can be expressed in an LR(1) form
- LR grammars are the most general grammars parsable by a deterministic, bottom-up parser
- efficient parsers can be implemented for LR(1) grammars
- LR parsers detect an error as soon as possible in a left-to-right scan of the input
- LR grammars describe a proper superset of the languages recognized by predictive (i.e., LL) parsers

**LL(k):** recognize use of a production \( A \rightarrow \beta \) seeing first \( k \) symbols of \( \beta \)

**LR(k):** recognize occurrence of \( \beta \) (the handle) having seen all of what is derived from \( \beta \) plus \( k \) symbols of look-ahead
Left versus right recursion

> **Right Recursion:**
  — needed for termination in predictive parsers
  — requires more stack space
  — right associative operators

> **Left Recursion:**
  — works fine in bottom-up parsers
  — limits required stack space
  — left associative operators

> **Rule of thumb:**
  — right recursion for *top-down parsers*
  — left recursion for *bottom-up parsers*
Recursive descent

A hand coded recursive descent parser directly encodes a grammar (typically an LL(1) grammar) into a series of mutually recursive procedures. It has most of the linguistic limitations of LL(1).

LL(k):

must be able to recognize the use of a production after seeing only the first k symbols of its right hand side.

LR(k):

must be able to recognize the occurrence of the right hand side of a production after having seen all that is derived from that right hand side with k symbols of look-ahead.

The dilemmas:

LL dilemma: pick \( A \rightarrow b \) or \( A \rightarrow c \) ?

LR dilemma: pick \( A \rightarrow b \) or \( B \rightarrow b \) ?
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- **JavaCC, Java Tree Builder and the Visitor pattern**
- Example: a straightline interpreter
The Java Compiler Compiler

> “Lex and Yacc for Java.”
> Based on LL(k) rather than LR(1) or LALR(1).
> Grammars are written in EBNF.
> Transforms an EBNF grammar into an LL(k) parser.
> Supports embedded action code written in Java (just like Yacc supports embedded C action code)
> The look-ahead can be changed by writing `LOOKAHEAD (...)`
> The whole input is given in just one file (not two).
The JavaCC input format

> Single file:
  — header
  — token specifications for lexical analysis
  — grammar
Examples

Token specification:

```
TOKEN :
{
   < INTEGER_LITERAL: ( ["1"-"9"] (["0"-"9"])* | "0" ) >
}
```

Production:

```
void StatementListReturn() :
{}
{
   ( Statement() )* "return" Expression() ";" 
}
```
Generating a parser with JavaCC

javacc fortran.jj // generates a parser
javac Main.java // Main.java calls the parser
java Main < prog.f // parses the program prog.f

NB: JavaCC is just one of many tools available ...
See: http://catalog.compilertools.net/java.html
The Visitor Pattern

> **Intent:**
> — Represent an operation to be performed on the elements of an object structure. Visitor lets you define a new operation without changing the classes of the elements on which it operates.

> *Design Patterns*, 1995, Gamma, Helm, Johnson, Vlissides
> When using the Visitor pattern,
>   — the set of classes must be fixed in advance, and
>   — each class must have an `accept` method.
First Approach: `instanceof` and downcasts

The running Java example: summing an integer list.

```java
public interface List {}
public class Nil implements List {
    int head;
    List tail;
    Nil(int head, List tail) {
        this.head = head;
        this.tail = tail;
    }
}

public class Cons implements List {
    int head;
    List tail;
    Cons(int head, List tail) {
        this.head = head;
        this.tail = tail;
    }
}

public class SumList {
    public static void main(String[] args) {
        List l = new Cons(5, new Cons(4, new Cons(3, new Nil())));
        int sum = 0;
        boolean proceed = true;
        while (proceed) {
            if (l instanceof Nil) {
                proceed = false;
            } else if (l instanceof Cons) {
                sum = sum + ((Cons) l).head;
                l = ((Cons) l).tail;
            }
        }
        System.out.println("Sum = " + sum);
    }
}
```

**Advantage:** The code does not touch the classes Nil and Cons.

**Drawback:** The code must use downcasts and `instanceof` to check what kind of List object it has.
Second Approach: Dedicated Methods

The classical OO approach is to offer dedicated methods through a common interface.

```java
public interface List {
    public int sum();
}

public class Nil implements List {
    public int sum() {
        return 0;
    }
}

public class Cons implements List {
    int head;
    List tail;
    Cons(int head, List tail) {
        this.head = head;
        this.tail = tail;
    }
    public int sum() {
        return head + tail.sum();
    }
}

public class SumList {
    public static void main(String[] args) {
        List l = new Cons(5, new Cons(4, new Cons(3, new Nil())));
        System.out.println("Sum = " + l.sum());
    }
}
```

**Advantage:** Downcasts and `instanceof` calls are gone, and the code can be written in a systematic way.

**Disadvantage:** For each new operation on `List`-objects, new dedicated methods have to be written, and all classes must be recompiled.
Third Approach: The Visitor Pattern

> The Idea:
  — Divide the code into an object structure and a Visitor
  — Insert an `accept` method in each class. Each accept method takes a Visitor as argument.
  — A Visitor contains a `visit` method for each class (overloading!).
    A method for a class C takes an argument of type C.
Third Approach: The Visitor Pattern

public interface List {
    public void accept(Visitor v);
}

public class Nil implements List {
    public void accept(Visitor v) {
        v.visit(this);
    }
}

public class Cons implements List {
    int head;
    List tail;
    Cons(int head, List tail) { ... }
    public void accept(Visitor v) {
        v.visit(this);
    }
}

public interface Visitor {
    void visit(Nil l);
    void visit(Cons l);
}

public class SumVisitor implements Visitor {
    int sum = 0;
    public void visit(Nil l) {
    }
    public void visit(Cons l) {
        sum = sum + l.head;
        l.tail.accept(this);
    }
}

public static void main(String[] args) {
    List l = new Cons(5, new Cons(4, new Cons(3, new Nil())));
    SumVisitor sv = new SumVisitor();
    l.accept(sv);
    System.out.println("Sum = " + sv.sum);
}
**Comparison**

The Visitor pattern combines the advantages of the two other approaches.

<table>
<thead>
<tr>
<th></th>
<th>Frequent downcasts?</th>
<th>Frequent recompilation?</th>
</tr>
</thead>
<tbody>
<tr>
<td>instanceof + downcasting</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>dedicated methods</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Visitor pattern</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

JJTree (Sun) and Java Tree Builder (Purdue/UCLA) are front-ends for JavaCC that are based on Visitors.
Visitors: Summary

> A visitor gathers related operations.
  — It also separates unrelated ones.
  — Visitors can accumulate state.

> Visitor makes adding new operations easy.
  — Simply write a new visitor.

> Adding new classes to the object structure is hard.
  — Key consideration: are you most likely to change the algorithm applied over an object structure, or are you most likely to change the classes of objects that make up the structure?

> Visitor can break encapsulation.
  — Visitor’s approach assumes that the interface of the data structure classes is powerful enough to let visitors do their job. As a result, the pattern often forces you to provide public operations that access internal state, which may compromise its encapsulation.
The Java Tree Builder (JTB)

> front-end for The Java Compiler Compiler.
> supports the building of syntax trees which can be traversed using visitors.
> transforms a bare JavaCC grammar into three components:
> — a JavaCC grammar with embedded Java code for building a syntax tree;
> — one class for every form of syntax tree node; and
> — a default visitor which can do a depth-first traversal of a syntax tree.

http://compilers.cs.ucla.edu/jtb/
The produced JavaCC grammar can then be processed by the Java Compiler Compiler to give a parser which produces syntax trees. The produced syntax trees can now be traversed by a Java program by writing subclasses of the default visitor.
Using JTB

<table>
<thead>
<tr>
<th>Command</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>jtb fortran.jj</td>
<td>generates jtb.out.jj</td>
</tr>
<tr>
<td>javacc jtb.out.jj</td>
<td>generates a parser</td>
</tr>
<tr>
<td>javac Main.java</td>
<td>Main.java calls the parser and visitors</td>
</tr>
<tr>
<td>java Main &lt; prog.f</td>
<td>builds a syntax tree and executes visitors</td>
</tr>
</tbody>
</table>
Roadmap

> Bottom-up parsing
> LR(k) grammars
> JavaCC, Java Tree Builder and the Visitor pattern
> **Example: a straightline interpreter**
Recall our straight-line grammar

- **Stm** → **Stm** ; **Stm**
- **Stm** → **id** := **Exp**
- **Stm** → **print** ( **ExpList** )
- **Exp** → **id**
- **Exp** → **num**
- **Exp** → **Exp** **Binop** **Exp**
- **Exp** → (**Stm**, **Exp**)  
- **ExpList** → **Exp** , **ExpList**
- **ExpList** → **Exp**
- **Binop** → +
- **Binop** → –
- **Binop** → ×
- **Binop** → /

**CompoundStm**
**AssignStm**
**PrintStm**
**IdExp**
**NumExp**
**OpExp**
**EseqExp**
**PairExpList**
**LastExpList**
**Plus**
**Minus**
**Times**
**Div**
slpl.jj starts with the scanner declarations

```java
options {
    JAVA_UNICODE_ESCAPE = true;
}

PARSER_BEGIN(StraightLineParser)
    package parser;
    public class StraightLineParser {}
PARSER_END(StraightLineParser)

SKIP : /* WHITE SPACE */
    { " " | "\t" | "\n" | "\r" | "\f" }

TOKEN :
    { < SEMICOLON: ';' >
    | < ASSIGN: "=" >
    ... more tokens here!
    }

TOKEN : /* LITERALS */
    { < INTEGER_LITERAL: ( ["1"-"9"] (["0"-"9"])* |
    | "0" ) >
    }

TOKEN : /* IDENTIFIERS */
    { < IDENTIFIER: <LETTER> (<LETTER>|<DIGIT>)* >
    | < #LETTER: [ "a"-"z", "A"-"Z" ] >
    | < #DIGIT: ["0"-"9"] >
    }
```
Rewriting our grammar

We introduce a start rule, eliminate all left-recursion, and establish precedence.
The grammar rules directly reflect our BNF!

NB: We add some non-terminals to help our visitors.

```c
void Goal() : {} { StmList() <EOF> }
void StmList() : {}{ Stm() ( ";" Stm() ) * }

void Stm() : {} { Assignment() | PrintStm() }

/* distinguish reading and writing Id */
void Assignment() : {} { WriteId() "=" Exp() }
void WriteId() : {} { <IDENTIFIER> }

void PrintStm() : {} { "print" "(" ExpList() ")" }
void ExpList() : {} { Exp() ( AppendExp() ) * }
void AppendExp() : {} { "," Exp() }

void Exp() : {} { MulExp() ( PlusOp() | MinOp() ) * }
void PlusOp() : {} { "+" MulExp() }
void MinOp() : {} { "-" MulExp() }

void MulExp() : {} { PrimExp() ( MulOp() | DivOp() ) * }
void MulOp() : {} { "*" PrimExp() }
void DivOp() : {} { "/" PrimExp() }

void PrimExp() : {}{ ReadId() | Num() | StmExp() }
void ReadId() : {}{ <IDENTIFIER> }
void Num() : {} { <INTEGER_LITERAL> }
void StmExp() : {}{ "(" StmList() "," Exp() ")" }
```

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JTB automatically generates actions to build the syntax tree, and visitors to visit it.

```java
// Generated by JTB 1.3.2
options {
    JAVA_UNICODE_ESCAPE = true;
}
PARSER_BEGIN(StraightLineParser)
package parser;
import syntaxtree.*;
import java.util.Vector;
public class StraightLineParser {
    ...  
    Goal Goal() {
    
        StmList n0;
        NodeToken n1;
        Token n2;
    
        n0=StmList()
        n2=<EOF> {
            n2.beginColumn++; n2.endColumn++;
            n1 = JTBToolkit.makeNodeToken(n2);
        }
    
        { return new Goal(n0,n1); }
    }
    ...  
```
The interpreter

```java
package interpreter;
import ...;
public class StraightLineInterpreter {
    Goal parse;
    StraightLineParser parser;

    public static void main(String [] args) {
        System.out.println(new StraightLineInterpreter(System.in).interpret());
    }

    public StraightLineInterpreter(InputStream in) {
        parser = new StraightLineParser(in);
        this.initParse();
    }

    private void initParse() {
        try {
            parse = parser.Goal();
        } catch (ParseException e) { ... }
    }

    public String interpret() {
        assert(parse != null);
        Visitor visitor = new Visitor();
        visitor.visit(parse);
        return visitor.result();
    }
}
```

The interpreter simply runs the parser and visits the parse tree.
An abstract machine for straight line code

package interpreter;
import java.util.*;
public class Machine {
    private Hashtable<String,Integer> store; // current values of variables
    private StringBuffer output; // print stream so far
    private int value; // result of current expression
    private Vector<Integer> vlist; // list of expressions computed

    public Machine() {
        store = new Hashtable<String,Integer>();
        output = new StringBuffer();
        setValue(0);
        vlist = new Vector<Integer>();
    }
    void assignValue(String id) { store.put(id, getValue()); }
    void appendExp() { vlist.add(getValue()); }
    void printValues() {...}
    void setValue(int value) {...}
    int getValue() { return value; }
    void readValueFromId(String id) {
        assert isDefined(id); // precondition
        this.setValue(store.get(id));
    }
    private boolean isDefined(String id) { return store.containsKey(id); }
    String result() { return this.output.toString(); }
}
The visitor

```java
package interpreter;
import visitor.DepthFirstVisitor;
import syntaxtree.*;

public class Visitor extends DepthFirstVisitor {
    Machine machine;
    public Visitor() { machine = new Machine(); }
    public String result() { return machine.result(); }

    public void visit(Assignment n) {
        n.f0.accept(this);
        n.f1.accept(this);
        n.f2.accept(this);
        String id = n.f0.f0.tokenImage;
        machine.assignValue(id);
    }
    public void visit(PrintStm n) { ... }
    public void visit(AppendExp n) { ... }
    public void visit(PlusOp n) { ... }
    public void visit(MinOp n) { ... }
    public void visit(MulOp n) { ... }
    public void visit(DivOp n) { ... }
    public void visit(ReadId n) { ... }
    public void visit(Num n) { ... }
}

The Visitor interprets interesting nodes by directly interacting with the abstract machine.
```
What you should know!

✎ Why do bottom-up parsers yield rightmost derivations?
✎ What is a “handle”? How is it used?
✎ What is “handle-pruning”? How does a shift-reduce parser work?
✎ When is a grammar LR(k)?
✎ Which is better for hand-coded parsers, LL(1) or LR(1)?
✎ What kind of parsers does JavaCC generate?
✎ How does the Visitor pattern help you to implement parsers?
Can you answer these questions?

✎ What are “shift-reduce” errors?
✎ How do you eliminate them?
✎ Which is more expressive? LL(k) or LR(k)?
✎ How would you implement the Visitor pattern in a dynamic language (without overloading)?
✎ How can you manipulate your grammar to simplify your JTB-based visitors?
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