Compilation (#3): Semantics, Interpreters from theory to practice.

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Lyon 1

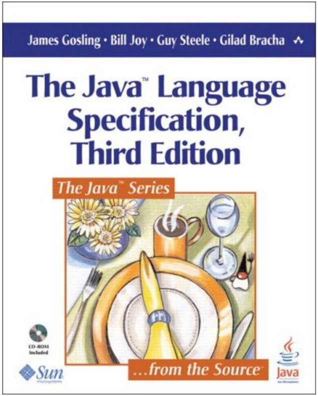
ENS DE LYON

Meaning

How to define the meaning of programs in a given language ?

- Informal description most of the time (natural language, ISO, reference book…)
- Unprecise, ambiguous.

Informal Semantics



The Java programming language guarantees that the operands of operators appear to be evaluated in a specific evaluation order, namely, from left to right.

It is recommended that code not rely crucially on this specification.

Formal semantics

The formal semantics mathematically characterises the computations done by a given program:

- useful to design tools (compilers, interpreters).
- mandatory to reason about programs and properties of the language.

Objective of this course

Implementation of program semantics with interpreters.

So far

From our grammars, we only generated **acceptors**.

► We want to execute some action/code each time a grammar rule is matched.

Semantic actions: example (ANTLR)

Semantic actions: code executed each time a grammar rule is matched:

Printing as a semantic action in ANTLR

```
s : A s B { System.out.println("rule s"); }//java
```

Right rule : Python/Java/C++, depending on the back-end

Demo time!

Semantic actions in theory - attributes

An attribute is a set “of information” attached to non-terminals/terminals of the grammar

They are usually of two types:

- synthetized: sons $\rightarrow$ father.
- inherited: the converse.

Synthetized grammar attributes

We extend production rules $S \to S_1.S_2$ with arributes r_i, and we write:

$$S\{r\} \to S_1\{r_1\}.S_2\{r_2\}; \{r := f(r_1, r_2)\}$$

with the meaning:

- S recognizes a chain if the begining is recognized with S_1 and the rest by S_2.
- Recognizing a S(resp. S_1, S_2) produces a result r (resp. r_1, r_2)
- The result r is computed from the two results r_1, r_2 by the instruction $r := f(r_1, r_2)$
- All rules that produce a S should have attributes of the same type.

Example of a synthetized attribute

Value of an arithmetic expression, simple grammar:

$E \rightarrow E_1 + E_2 | c$

We define : $value(E) = v$ and $value(c) = v_c$ two attributes <u>of type int</u> for the propagation. Then:

$E\{v\} \rightarrow E_1\{v_1\} + E_2\{v_2\}\ ;\ \{v := v_1 + v_2\}$

$E\{v\} \rightarrow c\{v_c\};\ \{v := v_c\}$

which we can simply write:

```
E-> E1 + E2 {value(E):=value(E1)+value(E2)}
E-> c       {value(E):=value(c)}
```

In practice the value of c is given by the lexer.

Inherited grammar attributes

(left : inherited/right : synthetised) Now

$$\{r\}S\{r'\} \to \{r'_1 = h(r)\}; \{r_1\}S_1\{r'_1\} \quad ; \quad \{r_2 = g(r, r'_1)\}S_2\{r'_2\}$$
$$; \quad \{r' := f(r, r'_1, r'_2)\}$$

with the meaning:

- S recognizes a chain if the begining is recognized with S_1 and the rest by S_2.
- Recognizing a S_1 produces r'_1 from r_1 st $r'_1 = h(r)$.
- After recognizing $S_1.S_2$, the result r' is computed with $f(r, r'_1, r'2)$.

Example

Consider the grammar: $G = \begin{cases} S \to S' \\ S \to \varepsilon | SC \\ C \to' 0'|'1'| \dots |'9' \end{cases}$

To compute $eval("27") = (int)27$ (attribution for C is left as exercice):

$S \to \{i\}\, S'\, \{o\}$; $\{res := o\}$

$\{i\}\, S'\, \{o\} \to \varepsilon$; $\{o := i\}$

$\to C\{c\}$; $\{10\,i + c\}\, S\, \{o'\}$

; $\{o = o'\}$

An important remark

- Synthetised attributes are easy to implement, thus they exist in most parser generators.
- Inherited attributes are often implemented as global/class variables (see later)

Semantic action in practice - ANTLR

ArithExprParser.g4 - Warning this is java

```
parser grammar ArithExprParser;
options {tokenVocab=ArithExprLexer;}

prog : expr EOF { System.out.println("Result: "+$expr.val); } ;

expr returns [ int val ] : // expr has an integer attribute
  LPAR e=expr RPAR { $val=$e.val; }
| INT { $val=$INT.int; } // implicit attribute for INT
| e1=expr PLUS e2=expr // name sub-parts
  { $val=$e1.val+$e2.val; } // access attributes
| e1=expr MINUS e2=expr { $val=$e1.val-$e2.val; }
;
```

A bit about syntax

The texts:

```
2*(x+1)
```

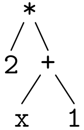
and

```
(2 * ((x) + 1))
```

and

```
2 * (* blablabla *) ( x + 1 )
```

have the same semantics ▶ they should have the **same internal representation**.



Example: syntax of expressions

The (abstract) grammar of arithmetic expressions is (avoiding parenthesis, syntactic sugar . . .):

$$
\begin{array}{rcll}
e & ::= & c & \textit{constant} \\
 & \mid & x & \textit{variable} \\
 & \mid & e + e & \textit{addition} \\
 & \mid & e \times e & \textit{multiplication} \\
 & \mid & \ldots &
\end{array}
$$

$\mathcal{A}$ ranges over arithmetic expressions: $e \in \mathcal{A}$

- The notion of AST.

Semantics

On the abstract syntax we define a semantics (its meaning):

- The example of numerical expressions
- And programs!

Definition

From Wikipedia:

> *In computer science, an interpreter is a computer program that* ***directly executes instructions*** *written in a programming or scripting language, without requiring them previously to have been compiled into a machine language program.*

- An **interpreter** executes the input program according to the programming language **semantics**.

Implementation strategies

From Wikipedia:

An interpreter generally uses one of the following strategies for program execution:

1. *Parse the source code and perform its behavior directly;* ▶ *Semantic actions !*
2. *Translate source code into some* ***efficient intermediate representation*** *and immediately execute this;* ▶ *Explicit or implicit* ***Abstract Syntax Tree****.*
3. *(Explicitly execute stored precompiled code made by a compiler which is part of the interpreter system.)*

How

Use semantic attributes to “evaluate” your input program, by induction on the syntax.

$$(string)"37 + 5" \rightarrow \ldots \rightarrow (int)42$$

Recall the example

The evaluation of arithmetical expressions is defined by induction:

ArithExprParser.g4 - Warning this is java

```
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prog : expr EOF { System.out.println("Result: "+$expr.val); } ;

expr returns [ int val ] : // expr has an integer attribute
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| e1=expr PLUS e2=expr // name sub-parts
  { $val=$e1.val+$e2.val; } // access attributes
| e1=expr MINUS e2=expr { $val=$e1.val-$e2.val; }
;
```
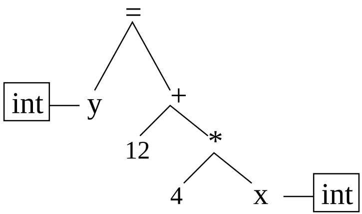

Separation of concerns

- The meaning/semantics of the program could be defined in the semantic actions (of the grammar). Usually though:
  - Syntax analyzer only produces the Abstract Syntax Tree.
  - The rest of the compiler directly **works with this AST**.
- Why ?
  - Manipulating a tree (AST) is easy (recursive style);
  - Separate language syntax from language semantics;
  - During later compiler phases, we can assume that the AST is **syntactically correct** $\Rightarrow$ simplifies the rest of the compilation.

1. Program Semantics
2. Grammars attributions and semantic actions
3. Useful notions: abstract syntax, AST
4. Interpreter
   - Interpreter with semantic actions
   - **Interpreter with explicit AST construction**
   - Interpreter with implicit AST

Abstract Syntax Tree



- AST: memory representation of a program;
- Node: a language construct;
- Sub-nodes: parameters of the construct;
- Leaves: usually constants or variables.

Running example : semantics for numerical expressions

$$
\begin{array}{rcll}
e & ::= & c & \textit{constant} \\
  & | & x & \textit{variable} \\
  & | & e + e & \textit{add} \\
  & | & e \times e & \textit{mult} \\
  & | & \ldots &
\end{array}
$$

Explicit construction of the AST

- Declare a type for the abstract syntax.
- Construct instances of these types during parsing (trees).
- Evaluate with tree traversal.

Example in OCaml 1/3

Types for the abstract syntax:

```
type binop = Add | Mul | ...

type expr_e =
  | Cte of int
  | Var of string
  | Bin of binop * expression * expression
  | ...
```

Example in OCaml 2/3

Pattern matching in parsing rules:

```
%type<Mysyntax.expr_e> expr

  expr:
  INT {Cte (Int64.of_string $1)}
  | LPAREN expr RPAREN { $2 }
  | expr PLUS expr { Bin(Add, $1, $3) }
  | var { Var ($1) }
```

Example in OCaml 3/3

Tree traversal with pattern matching (for expression eval):

```
let rec eval sigma = function
  | Cte(i) -> i
  | Bin(bop,e1,e2) -> let num1= eval sigma e1
                  and num2 = eval sigma e2 in ....
  | Var(s) -> Hashtbl.find sigma s
```

- we need σ, the environnement (map from variables to values).

See the interpreter order, we made a choice !

Example in Java 1/3

AST definition in Java: one class per language construct.

AExpr.java

```
public class APlus extends AExpr {
    AExpr e1,e2;

    public APlus (AExpr e1,AExpr e2) { this.e1=e1; this.e2=e2; }

}
public class AMinus extends AExpr { ...
```

Example in Java 2/3

The parser builds an AST instance using AST classes defined previously.

ArithExprASTParser.g4

```
parser grammar ArithExprASTParser ;
options {tokenVocab=ArithExprASTLexer;}

prog returns [ AExpr e ] : expr EOF { $e=$expr.e; } ;

// We create an AExpr instead of computing a value
expr returns [ AExpr e ] :
 LPAR x=expr RPAR { $e=$x.e; }
| INT { $e=new AInt($INT.int); }
| e1=expr PLUS e2=expr { $e=new APlus($e1.e,$e2.e); }
| e1=expr MINUS e2=expr { $e=new AMinus($e1.e,$e2.e); }
;
```

Example in Java 3/3

Evaluation is an eval function per class:

AExpr.java

```
public abstract class AExpr {
    abstract int eval(); // need to provide semantics
}
```

APlus.java

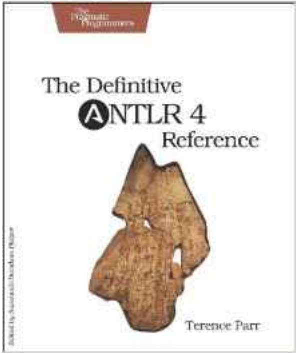
```
public class APlus extends AExpr {
    AExpr e1,e2;
    public APlus (AExpr e1,AExpr e2) { this.e1=e1; this.e2=e2; }
    // semantics below
    int eval() { return (e1.eval()+e2.eval()); }
}
```

Principle - OO programming

> *The visitor design pattern is a way of separating an algorithm from an object structure on which it operates.[...] In essence, the visitor allows one to add new virtual functions to a family of classes without modifying the classes themselves; instead, one creates a visitor class that implements all of the appropriate specializations of the virtual function.*

https://en.wikipedia.org/wiki/Visitor_pattern

Application



Designing interpreters / tree traversal in ANTLR-Python

- The ANTLR compiler generates a Visitor class.
- We override this class to traverse the parsed instance.

Arit Example with ANTLR/Python 1/3

AritParser.g4

```
expr:
     expr mdop=(MULT | DIV) expr #multiplicationExpr
    | expr pmop=(PLUS | MINUS) expr #additiveExpr
    | atom #atomExpr
    ;

atom
    : INT #int
    | ID #id
    | '(' expr ')' #parens
```

- compilation with `-Dlanguage=Python3 -visitor`

Arit Example with ANTLR/Python 2/3 -generated file

AritVisitor.py (generated)

```
class AritVisitor(ParseTreeVisitor):
...
    # Visit a parse tree produced by AritParser#multiplicationExpr.
    def visitMultiplicationExpr(self, ctx):
        return self.visitChildren(ctx)


    # Visit a parse tree produced by AritParser#atomExpr.
    def visitAtomExpr(self, ctx):
        return self.visitChildren(ctx)
..
```

Arit Example with ANTLR/Python 3/3

Visitor class overriding to write the interpreter:

MyAritVisitor.py

```
class MyAritVisitor(AritVisitor):

    def visitInt(self, ctx):
        return int(ctx.getText())

    def visitMultiplicationExpr(self, ctx):
        leftval = self.visit(ctx.expr(0))
        rightval = self.visit(ctx.expr(1))
        if ctx.mdop.type == AritParser.MULT:
            return leftval * rightval
        else:
            return leftval / rightval

    def visitAdditiveExpr(self, ctx):
```

Arit Example with ANTLR/Python - Main

And now we have a full interpret for arithmetical expressions!

arit.py (Main)

```
lexer = AritLexer(InputStream(sys.stdin.read()))
stream = CommonTokenStream(lexer)
parser = AritParser(stream)
tree = parser.prog()
print("I'm here : nothing has been done")

visitor = MyAritVisitor()
visitor.visit(tree)
```

Bilan

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