Lecture 3 – Syntax and Semantics (2)

COSE212: Programming Languages

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PLRG

2023 Fall

Recall

We learn how to define **syntax** and **semantics** of a programming language with (AE) as an example.

- **Syntax**
  - Backus-Naur Form (BNF)
  - Concrete Syntax
  - Abstract Syntax
  - Concrete vs. Abstract Syntax
- **Semantics**
  - Inference Rules
  - Big-Step Operational (Natural) Semantics
  - Small-Step Operational (Reduction) Semantics

Recall

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  - Abstract Syntax
  - Concrete vs. Abstract Syntax
- **Semantics**
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In this lecture, we learn how to implement the **interpreter** for AE.

- **Parser**: from **strings** to **abstract syntax trees (ASTs)**
- **Interpreter**: from **ASTs** to **values**

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ADTs for Abstract Syntax

Let's define Scala **ADTs** to represent the **abstract syntax** of AE.

$$
\begin{array}{rrll}
e & ::= & n & (\texttt{Num}) \\
 & \mid & e + e & (\texttt{Add}) \\
 & \mid & e \times e & (\texttt{Mul})
\end{array}
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ADTs for Abstract Syntax

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```scala
// expressions
enum Expr:
  // numbers
  case Num(number: BigInt) // `BigInt` rather than `Int` for integers
  // additions
  case Add(left: Expr, right: Expr)
  // multiplications
  case Mul(left: Expr, right: Expr)
```

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  case Mul(left: Expr, right: Expr)
```

For example, the AE expressions $1 + 2 \times 3$ is represented as follows:

```scala
Add(Num(1), Mul(Num(2), Num(3)))
```

Parsers for Concrete Syntax

We learned the **concrete syntax** of AE in the last lecture.

```
<expr> ::= <number>
         | <expr> "+" <expr>
         | <expr> "*" <expr>
         | "(" <expr> ")"
```

Then, how can we implement a **parser** for AE?

[1] https://github.com/scala/scala-parser-combinators

[2] https://en.wikipedia.org/wiki/Parsing_expression_grammar

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```

Then, how can we implement a **parser** for AE?

Let's use **parser combinators** in Scala!

I will explain basic ideas of parser combinators in this lecture. If you are interested in details, please refer to here[1], and **parsing expression grammars (PEGs)**.[2]

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- **regular expressions** (`"...".r`) as parsers.

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lazy val parser: Parser[String] = "-?[0-9]+".r // parsing integers
```

Parser Combinators

What can we do with **parser combinators** in Scala?

- **regular expressions** (`"...".r`) as parsers.

```
lazy val parser: Parser[String] = "-?[0-9]+".r // parsing integers
```

- **combine** them using sequence (~, <~, ~>) and alternative (|).

```
lazy val parser1: Parser[X] = ...
lazy val parser2: Parser[Y] = ...
parser1 ~ parser2   // Parser[X ~ X]
parser1 <~ parser2  // Parser[X]  (discard the result of `parser2`)
parser1 ~> parser2  // Parser[X]  (discard the result of `parser1`)
parser1 | parser2   // Parser[X]
```

Parser Combinators

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- **combine** them using sequence (`~`, `<~`, `~>`) and alternative (`|`).

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parser1 ~> parser2  // Parser[X]  (discard the result of `parser1`)
parser1 | parser2   // Parser[X]
```

- **transform** the result of a parser using the operator (`^^`).

```
lazy val parser1: Parser[X] = ...
val f: X => Y = ...
parser1 ^^ f  // Parser[Y]  (apply `f` to the result of `parser1`)
```

Parser Combinators

For example, let's implement a parser for **list of integers**:

"[]"   "[7]"   "[-042, 4, 20]"

```
type P[+T] = PackratParser[T]
lazy val num    : P[BigInt]       = "-?[0-9]+".r ^^ { BigInt(_) }
```

Parser Combinators

For example, let's implement a parser for **list of integers**:

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```scala
type P[+T] = PackratParser[T]
lazy val num   : P[BigInt]       = "-?[0-9]+".r ^^ { BigInt(_) }
lazy val numSeq: P[List[BigInt]] =
  (num <~ ",") ~ numSeq ^^ { case x ~ xs => x :: xs } |
  num                   ^^ { case x      => List(x) } |
  ""                    ^^ { case _      => Nil     }
```

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Parser Combinators

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  (num <~ ",") ~ numSeq ^^ { case x ~ xs => x :: xs } |
  num                   ^^ { case x      => List(x) } |
  ""                    ^^ { case _      => Nil     }
lazy val list   : P[List[BigInt]] = "[" ~> numSeq <~ "]"

parseAll(list, "[]").get            // Nil                  : List[BigInt]
parseAll(list, "[7]").get           // List(7)              : List[BigInt]
parseAll(list, "[-042, 4, 20]").get // List(-42, 4, 20)    : List[BigInt]
```

Parser Combinators

For example, let's implement a parser for **list of integers**:

`"[]"` `"[7]"` `"[-042, 4, 20]"`

```
type P[+T] = PackratParser[T]
lazy val num    : P[BigInt]        = "-?[0-9]+".r ^^ { BigInt(_) }
lazy val numSeq: P[List[BigInt]] = rep1sep(num, ",")
lazy val list   : P[List[BigInt]] = "[" ~> numSeq <~ "]"

parseAll(list, "[]").get            // Nil               : List[BigInt]
parseAll(list, "[7]").get           // List(7)           : List[BigInt]
parseAll(list, "[-042, 4, 20]").get // List(-42, 4, 20) : List[BigInt]
```

We can simplify it using `rep1sep` (repeat one or more times separated by `","`). There are other helper functions that help us write parsers.

Parsers using Parser Combinators

Let's implement a **parser** for AE using Scala **parser combinators**.

```
<expr> ::= <number>
         | <expr> "+" <expr>
         | <expr> "*" <expr>
         | "(" <expr> ")"
```

Parsers using Parser Combinators

Let's implement a **parser** for AE using Scala **parser combinators**.

```
<expr> ::= <number>
         | <expr> "+" <expr>
         | <expr> "*" <expr>
         | "(" <expr> ")"
```

```scala
lazy val num: P[BigInt] = "-?[0-9]+".r ^^ { BigInt(_) }
lazy val expr: P[Expr] =
  import Expr.*
  lazy val e0: P[Expr] = (e0<~"+")~e1 ^^ { case l~r => Add(l, r) } | e1
  lazy val e1: P[Expr] = (e1<~"*")~e2 ^^ { case l~r => Mul(l, r) } | e2
  lazy val e2: P[Expr] = num          ^^ { case n   => Num(n)    } | e3
  lazy val e3: P[Expr] = "(" ~> e0 <~ ")"
  e0

parseAll(expr, "42").get        // Num(42)                          : Expr
parseAll(expr, "-1 + 7").get    // Add(Num(-1),Num(7))              : Expr
parseAll(expr, "1 + 2 * 3").get // Add(Num(1),Mul(Num(2),Num(3))) : Expr
```

Parsers using Parser Combinators

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You **don't need to know** the details of parser combinators.

We **provide all parsers** of programming languages in this course.

If you want to use the parser, please just call `Expr` as follows:

```
val x: Expr = Expr("42")        // Num(42)                             : Expr
val y: Expr = Expr("-1 + 7")    // Add(Num(-1),Num(7))                 : Expr
val z: Expr = Expr("1 + 2 * 3") // Add(Num(1),Mul(Num(2),Num(3)))      : Expr
```

If you want to get the **string form** of the expression, please use `stringForm` method as follows:

```
x.stringForm // "42"            : String
y.stringForm // "(-1 + 7)"      : String
z.stringForm // "(1 + (2 * 3))" : String
```

Contents

Interpreters

We will implement the **interpreter** for AE according to the following **big-step operational (natural) semantics**:

$$\boxed{\vdash e \Rightarrow n}$$

$$\textsc{Num}\ \frac{}{\vdash n \Rightarrow n} \qquad \textsc{Add}\ \frac{\vdash e_1 \Rightarrow n_1 \qquad \vdash e_2 \Rightarrow n_2}{\vdash e_1 + e_2 \Rightarrow n_1 + n_2} \qquad \textsc{Mul}\ \frac{\vdash e_1 \Rightarrow n_1 \qquad \vdash e_2 \Rightarrow n_2}{\vdash e_1 \times e_2 \Rightarrow n_1 \times n_2}$$

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We will implement the **interpreter** for AE according to the following **big-step operational (natural) semantics**:

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$$\textsc{Num}\ \frac{}{\vdash n \Rightarrow n} \qquad \textsc{Add}\ \frac{\vdash e_1 \Rightarrow n_1 \qquad \vdash e_2 \Rightarrow n_2}{\vdash e_1 + e_2 \Rightarrow n_1 + n_2} \qquad \textsc{Mul}\ \frac{\vdash e_1 \Rightarrow n_1 \qquad \vdash e_2 \Rightarrow n_2}{\vdash e_1 \times e_2 \Rightarrow n_1 \times n_2}$$

```scala
type Value = BigInt

def interp(expr: Expr): Value = expr match
  case Num(n)    => n
  case Add(l, r) => interp(l) + interp(r)
  case Mul(l, r) => interp(l) * interp(r)

interp(Expr("42"))        // 42 : Value (= BigInt)
interp(Expr("-1 + 7"))    // 6  : Value (= BigInt)
interp(Expr("1 + 2 * 3")) // 7  : Value (= BigInt)
```

Exercise #1

- Please see this document[3] on GitHub.
- It is just an exercise, and you **don't need to submit** anything.
- However, some exam questions might be related to this exercise.

[3] https://github.com/ku-plrg-classroom/docs/tree/main/cose212/ae.

Summary

1. Parsers
    - ADTs for Abstract Syntax
    - Parsers for Concrete Syntax
2. Interpreters

Next Lecture

- Identifiers (1)

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