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Programming Assignment 2
LALR Parsing and Building ASTs

The goal of this assignment is to understand how to use LALR parsing for more complex grammars with expressions, and how to construct *Abstract Syntax Trees* (ASTs) during parsing. You will:

- Write a more complex context-free grammar and implement it using an LALR parser.
- Resolve ambiguities and experiment with LALR conflicts.
- Build an AST in the semantic actions of the parser.

In addition to JFlex, Beaver, and other tools you used in the previous assignment, you will use the *JastAdd* tool to define AST classes. For documentation of JastAdd, see `http://jastadd.org`.

You will define a language called *SimpliC* (Simplistic C), and generate a compiler that parses SimpliC into ASTs. To your help, there is a demonstration example *CalcAST* showing how to build ASTs for the Calc language.

Try to solve all parts of this assignment before going to the lab session. If you get stuck, use the Piazza forum to ask for help. If this does not help, you will have to ask at the lab session. Make notes about answers to questions in the tasks, and about things you would like to discuss at the lab session.

▶ Major tasks are marked with a black triangle, like this.

1 The CalcAST Demo

The CalcAST demonstration example implements an extended version of the *Calc* language from assignment 1, introducing some new features that will illustrate the use of lists and optionals. The language now allows a list of variable bindings in the `let` expression, and a new `ask user` expression with an optional default value has been added.

Here is an example of a Calc program:

```
let
    radius = ask user [1.0]
    pi = 3.14
in
    2.0 * pi * radius
end
```

The idea is that when this program is run, the `ask user` expression will ask the user to input a value, using the default value of `1.0`. An `ask user` expression without the optional default value would be written simply as `ask user`, without the square bracket clause.[1]

This example program is named `example2.calc` and can be found in the `testfiles/ast` directory.

▶ Download the CalcAST example. Run the tests and see that they pass.

[1] Note, however, that we will not actually run Calc or SimpliC programs until assignments 5 and 6.

1.1 The abstract grammar

The *Context Free Grammar* (CFG) for the new Calc language is

```
program  →  exp <EOF>
exp      →  factor | ( exp '*' factor )
factor   →  let | numeral | id | ask
let      →  'let' binding+ 'in' exp 'end'
binding  →  id '=' exp
numeral  →  <NUMERAL>
id       →  <ID>
ask      →  'ask' 'user' [ '[' exp ']' ]
```

To represent an AST in Java we will use a class hierarchy generated by JastAdd, and defined in an *abstract grammar*, in this case `calc.ast`. The abstract grammar is similar to the CFG:

```
Program ::= Expr;

abstract Expr;
Mul: Expr ::= Left:Expr Right:Expr;
Numeral: Expr ::= <NUMERAL:String>;
IdUse: Expr ::= <ID:String>;

Let: Expr ::= Binding* Expr;
Binding ::= IdDecl Expr;
IdDecl ::= <ID:String>;

Ask: Expr ::= [Default:Expr];
```

Here, an abstract grammar rule

```
A: B ::= children;
```

corresponds to a Java class `A` which extends the superclass `B` and has a number of *children* (composition relationships in UML). The children can be of the following kinds:

```
C       A child of type C
C*      A list of children of type C
[C]     An optional child of type C
<T:S>   A token named T of type S
```

Children may be explicitly named, for example:

```
N:C     A child named N of type C
```

and if no explicit name is given, the type name is used for the child.

The nonterminal `exp` in the CFG has been modelled as an abstract class `Expr` in the abstract grammar. The alternatives on the right-hand side in the CFG have been modelled using subclassing in the abstract grammar. This is a common pattern when using object-orientation for representing ASTs: replace alternatives with subclassing.

Note that we are not interested in having `factor` as a class in the abstract grammar: this nonterminal is only used for disambiguating the CFG so that we can parse text into a tree in an unambiguous way. Instead, all expressions (`Mul`, `Numeral`, `IdUse`) are direct subclasses of `Expr`.

Another difference is that the nonterminal `id` in the CFG has been replaced with two classes `IdUse` and `IdDecl` in the abstract grammar. This separation is practical when implementing name analysis, where name uses are bound to name declarations. We will implement name analysis later on, in another assignment.

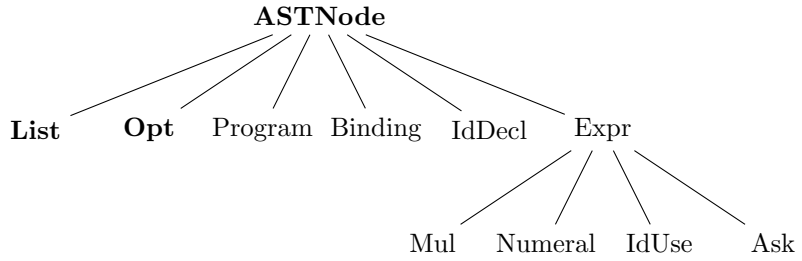
The JastAdd abstract grammar notation supports repetition of zero or more components (*), but not repetitions of one or more (+). It is highly recommended to use (X*) instead of trying to model (+) as `X X*` in the abstract grammar. This is because the abstract grammar should be kept simple to make it easy to program semantic analysis later on. The property of at least one element can easily be checked either by relying on the parser to check this, or by adding an attribute (see assignment 4).

1.2 Generated AST classes

The generated classes will contain accessor methods for the children and tokens, as the following simplified API illustrates for the classes `Mul` and `IdUse`.

```
public class Mul extends Expr {
    Expr getLeft();
    Expr getRight();
    void setLeft(Expr e);
    void setRight(Expr e);
}
public class IdUse extends Expr {
    String getID();
    void setID(String id);
}
```

The Java classes generated by JastAdd will have the following class hierarchy:



`ASTNode`, `Opt` and `List` are implicit, or predefined, AST classes. They are generated by JastAdd without any mention in the `.ast` file. `Opt` and `List` are used to represent optional and list components in the abstract syntax tree.

▶ Look at the abstract grammar specification (`src/jastadd/calc.ast`) and make sure you understand it. Look at the corresponding generated classes in `src/gen/lang/ast`. The classes contain lots of generated methods, but you should be able to find, for example, `Mul`'s `getLeft()` and `getRight()` methods mentioned above. Familiarize yourself briefly with the JastAdd reference manual[2] so that you know where to look for details later.

1.3 Well-formed ASTs

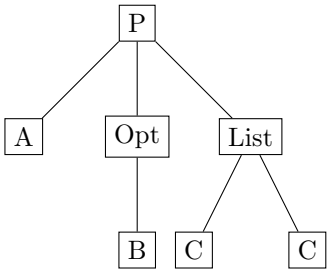
When building a JastAdd AST, care must be taken to build it so that it is *well-formed*. Suppose we have an abstract grammar class `P ::= A [B] C*`. A `P` node is well-formed if

- an ordinary child, like `A`, is represented by a node of type `A`.
- an optional child, like `[B]`, is represented by a node of type `Opt` which has zero or one nodes of type `B`.
- a list child, like `C*`, is represented by a node of type `List` which has zero or more nodes of type `B`.
- Each node must be a real object, i.e., not `null`.

[2] `http://jastadd.org/web/documentation/reference-manual.php`

- The node objects must form a tree, i.e., it is not allowed to reuse an node in several places in the same AST, or in different ASTs.

The example below shows a well-formed AST for `P ::= A [B] C*`



These conditions are not checked when generating the parser, and several of them are not even checked when the parser code is compiled. So take care in building the AST correctly, as you might otherwise run into runtime errors and problems that are difficult to debug.

▶ What would be examples of other well-formed ASTs for the `P ::= A [B] C*` class? What would be examples of ill-formed ASTs?

1.4 Building the AST

The abstract syntax tree is built by the parser, as specified in the `.beaver` file, using so called *semantic actions* of the production rules. We have to instruct Beaver what kind of JastAdd AST node is built by the productions for each Beaver nonterminal. This will become the return type of the semantic action in the generated parser. We specify this using Beaver's `%typeof` directive, as the following code fragment illustrates.

```
%typeof program = "Program";
%typeof exp = "Expr";
%typeof factor = "Expr";
%typeof let = "Let";
...
```

Note that to the left in each clause, we have a nonterminal in the Beaver CFG, like `program`. To the right, we have a class from the JastAdd abstract grammar, like `Program`.

1.4.1 Semantic Actions

To build AST nodes, the productions in the parser specification need to be extended with semantic actions. Semantic actions are code snippets that are run during parsing. Consider the production for the `program` nonterminal:

```
program = exp.a {: return new Program(a); :} ;
```

Note the code inside the `{:` and `:}`. This is the semantic action code – ordinary Java code for constructing the AST node representing the parsed production. In this case, the semantic action simply creates a new node of type `Program` with an expression as its child. Note that `program` is a nonterminal in the parser specification, whereas `Program` is an AST node type, specified in the abstract grammar. The expression inside the semantic action must have the same type as specified in the `%typeof` directive.

In Beaver, a right-hand side component can be *named* using dot notation: in the example above, the nonterminal `exp` has been named `a`, by writing `exp.a`. The name `a` refers to the AST subtree constructed by the `exp` nonterminal, and can be used inside the semantic action to refer to that subtree. In this case, `a` is used in the semantic action as an argument to the `Program` constructor.

1.4.2 Optional Components

For most productions, building the AST is straightforward as explained in the previous section. But if there are optional or list components in a production, an extra `Opt` or `List` node must be built.

Although Beaver does have some support for optionals and lists, it is easier to build the AST if we first rewrite the grammar to eliminate optionals and lists, using explicit alternatives. Recall the new `Ask` construct which has an optional default expression. The context-free rule is

$$\text{ask} \rightarrow \text{'ask' 'user' ['[' exp ']']}$$

and the abstract grammar rule is

```
Ask: Expr ::= [Default:Expr];
```

To implement this in Beaver, we first rewrite the context-free rule to eliminate the optional notation. We can do this by introducing a new nonterminal `opt_exp` with two alternatives: one non-empty and one empty:

$$\begin{aligned} \text{ask} &\rightarrow \text{'ask' 'user' opt\_exp} \\ \text{opt\_exp} &\rightarrow \text{'[' exp ']'} \mid \epsilon \end{aligned}$$

The Beaver specification can now be written as follows:

```
ask =
    ASK USER opt_exp.d {: return new Ask(d); :};

opt_exp =
      LBRACKET exp.a RBRACKET  {: return new Opt(a); :}
    | /* epsilon */            {: return new Opt(); :}
    ;
```

We also need to specify the type of the new `opt_exp` nonterminal, in the beginning of the Beaver file:

```
%typeof opt_exp = "Opt";
```

Note that the semantic action always builds an `Opt` node to match the optional expression, and that different `Opt` constructors are used depending on if the optional expression is present or missing.

1.4.3 List Components

In order to handle list components (repetition), we use a similar technique as for optionals, rewriting the parsing grammar to replace repetition with a new nonterminal with explicit alternatives.

Recall the abstract grammar rules for bindings in let-expressions:

```
Let: Expr ::= Binding* Expr;
Binding ::= IdDecl Expr;
```

To implement this in Beaver, we first rewrite the context-free grammar rule for `Let`:

$$\text{let} \rightarrow \text{binding}^{+}$$

replacing the repetition with a new nonterminal `binding_list`:

binding_list → binding | binding_list binding

The Beaver specification for `binding_list` can be written as follows:

```
%typeof binding_list = "List";
...
binding_list =
      binding.a                   {: return new List().add(a); :}
    | binding_list.list binding.a {: return list.add(a); :}
    ;
```

▶ Look at the parser specification (`src/parser/parser.beaver`) and make sure you understand how the AST is built. Where are the semantic actions? How are optionals and lists handled?

1.5 The DumpTree Aspect

The CalcAST example contains code for printing an AST, using indentation to show the tree structure. This is useful when writing test cases and for debugging, to check that the AST is well-formed and correct.

The code is located in an "aspect file" `DumpTree.jrag` in the `src/jastadd` directory in the CalcAST project. A JastAdd *aspect* may contain methods of AST classes, but specified in a separate file. The JastAdd system *weaves* those methods into the generated AST classes. The file `DumpTree.jrag` contains a single aspect declaration:

```
1  aspect DumpTree {
2      public String ASTNode.dumpTree() {
3          ByteArrayOutputStream bytes = new ByteArrayOutputStream();
4          dumpTree(new PrintStream(bytes));
5          return bytes.toString();
6      }
7
8      public void ASTNode.dumpTree(PrintStream out) {
9          [...]
10     }
11
12     [...]
13 }
```

The methods in the aspect have an extra qualifier before the method name, e.g., `ASTNode.dumpTree`. The JastAdd code generator will weave the method into the generated `ASTNode` class. This way of writing a declaration in an aspect instead of in the class in which it belongs is called an *inter-type declaration*. Later in the course, we will look at other kinds of inter-type declarations you can write in an aspect.

The `compiler.jar` main class is `DumpTree.java` and it will parse in a calc program and then print it using the `dumpTree` method.

▶ Try out `compiler.jar` on one of the test programs. For example:

```
ant jar
java -jar compiler.jar testfiles/ast/example2.calc
```

1.6 Testing framework

The CalcAST example uses a testing framework that is more advanced than the one used in assignment 1. The new test framework uses a JUnit feature called *parameterized tests*. With parameterized tests you don't need to write a test method for each test case: it is sufficient to add an input and expected output file to the `testfiles/ast` directory.

In CalcAST, this testing technique is used for the AST tests to check that correct ASTs are built when parsing different test programs. The framework starts one test per `.calc`-file in the `testfiles/ast` directory. Each test file is parsed and the tree is printed to a corresponding `.out` file. If there exists a matching `.expected` file then the contents of the output is checked against the expected output. The file extensions used may be changed by editing e.g. the `IN_EXTENSION` constant in the `AbstractParameterizedTest` class.

When adding new tests it is usually too tedious to hand-write each `.expected` file. Instead, you can add just the input file, run the tests to get the `.out` file, and then rename the `.out` file to use the `.expected` extension. Of course, it is important to inspect the `.out` file before renaming it, to make sure it really is correct!

Hint: You can use the Ant target `update-expected-output` to copy all `.out` files to the corresponding `.expected` file:

```
ant update-expected-output
```

- Look at the testcases in the `testfiles/ast` directory. The `.expected` files contain the expected output after parsing the corresponding `.calc`-file and printing the AST using the `dumpTree` method. Make sure you understand what AST an `.expected` file corresponds to.
- Add a new AST test case in the CalcAST project.

1.7 Build Script

The CalcAST Ant script (`build.xml`) contains some more elements and targets as compared to the script we used in assignment 1. To be able to run JastAdd, it contains a `taskdef` element as follows:

```
<taskdef classname="jastadd.JastAddTask"
         name="jastadd"
         classpath="${lib}/jastadd2.jar" />
```

This defines an Ant *task* named `jastadd`. The task is used by the new `ast-gen` target to invoke the JastAdd program and generate the AST classes.

The `taskdef` requires the `jastadd2.jar` file to be in the `lib` directory. This Jar file can be downloaded from `http://jastadd.org`, but you don't need to do that since CalcAST already contains the Jar file, together with all other required Jar libraries.

2 Debugging experiments

There are many things that can go wrong when you generate a parser. Your grammar might be non-LALR in which case the parser generator will report shift-reduce or reduce-reduce conflicts. In some cases you might write something incorrect in the .beaver specification which is not discovered until you compile the generated Java code, or until you run your generated compiler. It is very likely that you will run into problems like these, and it will be much easier to deal with them if you have encountered them before in a controlled setting. So in this section we will provoke some common errors so that you understand them better.

2.1 Provoke a shift-reduce conflict in expressions

▶ Add a shift-reduce conflict to the Beaver parser specification by changing the production

$$\mathsf{exp} \;\rightarrow\; \mathsf{exp}\ \text{'*'}\ \mathsf{factor}$$

to

$$\mathsf{exp} \;\rightarrow\; \mathsf{exp}\ \text{'*'}\ \mathsf{exp}$$

Rerun the parser generator (`build gen`). Don't forget to do "refresh" in your project if you are running Eclipse.[3]

- What does the parser generator say?
- Why is this a conflict?
- Try running the tests. Do they pass?
- Can you give an example program that could be parsed in two different ways with the new grammar?
- What happens when these programs are parsed if *shift* is chosen in the conflict? What happens when *reduce* is chosen?
- Why was there not a conflict in the original version of the grammar?

Undo the change and make sure all tests pass again.

2.2 Introduce a shift-reduce conflict through a subtle error

▶ Add an empty production to the `binding_list` production in the `.beaver` file by changing

```
binding_list =
   binding.a      {: return new List().add(a); :}
   | binding_list.a binding.b {: return a.add(b); :}
   ;
```

to

```
binding_list =
   | binding.a      {: return new List().add(a); :}
   | binding_list.a binding.b {: return a.add(b); :}
   ;
```

This is something that could easily result from a copy paste, but it has the effect of adding an empty production (ϵ) to the `binding_list` rule. So we now have three productions rather than two. If we really wanted this empty production, it would be a good idea to add a comment to make this more explicit, like this:

```
binding_list =
     /* epsilon */
   | binding.a      {: return new List().add(a); :}
   | binding_list.a binding.b {: return a.add(b); :}
   ;
```

[3] When you run unix commands, Eclipse does not automatically know that files have been added, changed, or removed. When you do a "refresh" in Eclipse, it will scan the files in the project directory to look for changes.

But of course, in this case, this extra empty production was just a mistake.

Rerun the parser generator on the grammar. What does the parser generator say? What does the error message mean? The parser automatically selects shift, which happens to be what we want it to do. But if you get warnings like this, you should always analyze them carefully and change the specification to resolve the conflict explicitly and thereby remove the warnings. Otherwise it will be difficult to see new warnings if you change the grammar later on.

Undo the change and make sure all tests pass again.

2.3 Errors in the generated Java code

The code you write in Beaver's semantic actions is Java code. But Beaver does not analyze it, so you will not see compile-time errors in it until you compile the generated code. It can be a bit tricky to understand how those errors correspond to the code you originally wrote in the semantic actions.

Try a couple of common mistakes:

- Remove one of the `%typeof` directives in the `.beaver` file. What happens when you generate the parser? What happens when you try to compile the code? If you are in Eclipse, what happens if you try to run the tests? Look at the compile-time error. Can you figure out how it relates to the error you inserted?
- In one of the semantic actions, remove the `return` keyword. What happens when you generate the parser? Look at the compile-time error. Can you figure out how it relates to the error you inserted?

2.4 Add print statements

As always, inserting print statements is a primitive but useful way to help with debugging. The semantic actions are just Java code inserted into the generated parser at different places. If you add more code than building ASTs, it will of course be run too.

As an experiment, add some print statement, for example `System.out.println("Hello")`, in one of the semantic actions. Generate the parser and run the tests.

3 The SimpliC Language

The main task in this assignment is to implement a parser for the SimpliC language. You should do this by specifying an abstract grammar using the JastAdd system, a parser specification using the Beaver system, and a scanner specification using the JFlex system. The parser should produce a well-formed abstract syntax tree, that follows the abstract grammar. Furthermore, there should be automated tests showing that the parser produces the correct AST for a number of examples. There should also be some negative tests, showing that the parser detects parsing errors in erroneous input files.

The SimpliC language is a C-like language that uses only integer variables. A SimpliC program consists of a list of function declarations. Function declarations may not be nested, and all user-defined functions must return an integer result. There are also two built-in functions: `read` which reads an integer from standard in, and `print` which prints its argument to standard out. These are not declared in the program, but can be called from the program.

There are no global variables, only local variables and function parameters. Statements supported include assignments, `return` statements, function call statements, `if`, and `while` statements. Expressions supported include identifier uses, function calls, and common binary arithmetic expressions like `+`, `-`, `*`, `/`, `%` and the comparison expressions `==`, `!=`, `<=`, `<`, `>=`, and `>`. Binary expressions should be represented as trees, where each node corresponds to an operator having its operands as left and right subtrees. The usual priority and associativity rules should apply. For example, "`<`" should have lower priority than `+` and be non-associative. The remainder operator, `%`, has the same priority and associativity as multiplication and division. Parentheses can be used in expressions. SimpliC also supports end-of-line comments.

3.1 SimpliC Code Sample

The example program below shows large parts of the SimpliC syntax. The `gcd1` and `gcd2` functions implement two different algorithms for finding the greatest common divisor (GCD) of two positive integers. The `main` function tests both algorithms with inputs provided by the user:

```
int gcd1(int a, int b) {
  while (a != b) {
    if (a > b) {
      a = a - b;
    } else {
      b = b - a;
    }
  }
  return a;
}

int gcd2(int a, int b) {
  if (b == 0) {
    return a;
  }
  return gcd2(b, a % b);
}

// Test two different GCD algorithms and print the results.
// The results should be equal when both inputs are positive.
int main() {
  int a;
  int b;
  a = read();
  b = read();
  print(gcd1(a, b));
  print(gcd2(a, b));
  int diff = gcd1(a, b) - gcd2(a, b);
  print(diff);
  return 0;
}
```

3.2 Implementing the parser

In implementing the parser, you should work in small steps: first implement a parser for a small subset of the language, then add a few constructs, and so on.

▶ For each of the implementation steps below, this is how you should work: Write down a test program that you want to be able to parse. Then design the abstract grammar (using the JastAdd .ast format), and a corresponding concrete grammar in EBNF (the latter can be on paper). Try to make the EBNF as similar as possible to the .ast grammar. However, it must be unambiguous, for example dealing with priorities and associativity, which might call for adding more rules. Then rewrite the EBNF grammar to eliminate lists and optionals, and code it up in a .beaver specification. Get the parser to work, and automate the test. Run all your tests to make sure you have not broken anything that worked previously. Review your implementation to make sure you use good names for classes and components in the abstract grammar. If you get stuck, take a look at the CalcAST example for inspiration.

To your help there is an example called MinimalAST that you can download and use as a starting point. MinimalAST is similar to CalcAST, but supports a very small language with just one token and one production.

There are many things that can go wrong when you implement a parser. It is a good idea to save versions of your project, for example using Git or some other version control system, so you can back up to an earlier stable state in case you get into a too big mess. (Remember to make your Git repository private.)

3.2.1 Step 1: Simplified function declarations

▶ As the first step, implement a parser for programs consisting of only a list of empty function declarations without parameters. For example:

```
int a() { }
int b() { }
```

3.2.2 Step 2: Variable declarations and uses

▶ As a next step, extend your parser to support variable declarations and uses, and also assignments and integer literals. Use the classes `IdDecl` and `IdUse` to distinguish between declarations and uses of identifiers in the abstract grammar. Here is an example test program:

```
int a() {
    int x;
    int y;
    x = 5;
    y = x;
}
```

3.2.3 Step 3: Expressions

▶ Expressions is usually the trickiest thing to get right in a parser. The abstract grammar should be simple, but the parser needs to deal with priorities and associativity. Extend your parser to support all the different kinds of expressions. First write down some simple test programs that will make it possible for you to check that you get everything right. Then try to make them work. It is a good idea to break this problem down into several subproblems. For example, start by making `+` and `*` work. Then add the other operators.

3.2.4 Step 4: Complete the language

▶ Complete the parser by adding new test cases and extending the specification. Remember to work in small steps: add one or a few language constructs at a time and make them work, before going on with the next step.

3.2.5 Step 5: Look over your test cases and specifications

▶ Look over your test cases and specifications. There should be test cases covering all parts of the syntax, and test cases covering tricky interactions between constructs (like priorities, etc.). There should also be negative test cases that check that the parser gives errors for syntactically incorrect input programs. The gcd program in section 3.1 should be one of the test cases. Make sure also that your abstract grammar is simple and well designed with good names for the different constructs. It is important to get everything correct and simple, as the following assignments will build on this one.