Semantic Analysis

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Syntax

"The study of the rules whereby words or other elements of sentence structure are combined to form grammatical sentences."

The American Heritage Dictionary

Syntactic Analysis I

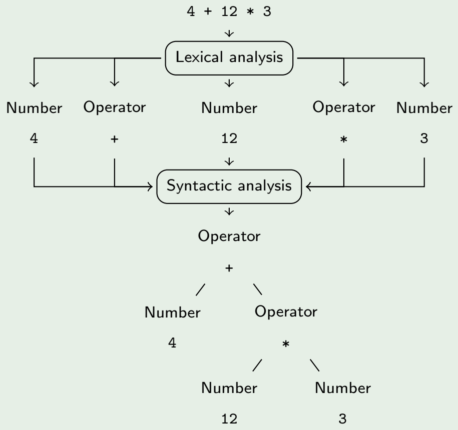
Given an input text we need to determine its *structure*:

- how statements are linked together
- operator precedence rules
- ...

The structure is defined by mean of a *grammar*.
Syntactic analysis is performed over *words*:

- the input is a tokenized stream
- usually a lexical analyzer prepares input for the semantic analysis

Structure of an algebraic expression



Semantic Analysis

It is the evaluation of the meaning of each (terminal and non-terminal) symbol, achieved by *decorating the Abstract Syntax Tree*:

Syntactic analysis

```
           Operator
              +
            /   \
      Number     Operator
        4           *
                  /   \
            Number     Number
              12         3
```

Semantic analysis

```
             Value 40
             Operator
                +
              /   \
      Value 4       Value 36
      Operator      Operator
         4             *
                     /   \
             Value 12     Value 3
              Number      Number
                12          3
```

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Parsing

A *parser* is a program that performs syntactic analysis.

Typically:

- **LL** descending parsing, can be constructed by hand (`c-parser.c` in `GCC` sources) or automatically (`ANTLR` Java parsers generator)
- **LR** ascending parsing, usually too complex to be constructed manually

Common duty: building the Abstract Syntax Tree.

bison

The standard tool to generate LR parsers is `bison`:

- free implementation of `yacc`
- strongly coupled with flex
- actually a LALR(1) parser generator

Getting `bison`

Available in your distribution repositories:

Debian `aptitude install bison`

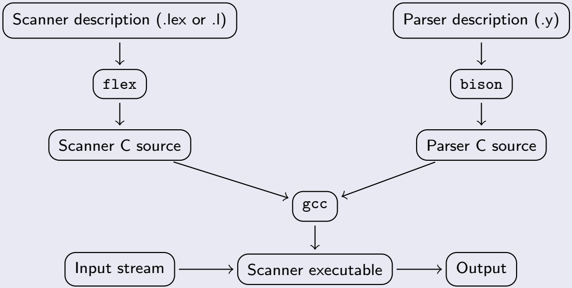
Fedora `yum install bison`

Parser Building

A parser consume tokens:

- a scanner must produces tokens
- natural choice is `flex`

Using `bison` and `flex` together



A Simple Example

Let's try to build a reverse polish notation calculator.

Grammar

$$
\begin{aligned}
S &\rightarrow E|\epsilon \\
E &\rightarrow NUMBER \\
E &\rightarrow EE+|EE*
\end{aligned}
$$

Don't worry about terminals:

- it is a scanner duty

The bison Input File

The `bison` input file resemble the one of `flex`:

C definitions header inclusions, var declarations, ...

definitions tokens, precedences, ...

grammar rules rules and semantic actions

user code main and service functions

bison input file [a]

```
%{
/* C definitions */
%}
/* Definitions */
%%
/* Grammar rules */
%%
/* User code */
```

[a] C89-style comments can appear in any of the sections.

Do You Remember flex? I

We must provide a scanner to bison:

- just implement the yylex function
- maybe better to exploit flex

scanner.l global section

```
%option noyywrap
%{
#include "rpn.tab.h"
#define UNKNOWN -1
%}
DIGIT [0-9]
BLANK [ \n\r\t]
%%
```

Do You Remember flex? II

scanner.l rules section

```
{BLANK}
{DIGIT}+ { return NUMBER; }
"+" { return OP_PLUS; }
"*" { return OP_MUL; }
. {
    yyerror("Unknown␣char");
    return UNKNOWN;
  }
```

There is no need to add extra C code:

- flex is only used to tokenize the input

Parser Definition I

Let's start with a parser that *recognize* reverse polish notation expressions:

rpn.y definitions section

```
%{
#include <stdio.h>
%}
%token NUMBER
%token OP_PLUS
%token OP_MUL
%%
```

The `%token` directive allows to define words read by the parser.

Parser Definition II

Syntax for grammar definition is straightforward:

rpn.y grammar section

```
calculus: /* Empty */
        | expression
        ;
expression: NUMBER
          | expression expression OP_PLUS
          | expression expression OP_MUL
          ;
%%
```

Parser Definition III

The last section contains:

- the error handling function `yyerror`
- the program entry point `main`

`rpn.y` C code

```
int yyerror(char* msg) {
  printf("%s\n", msg);
  return 0;
}

int main(int argc, char* argv[]) {
  return yyparse();
}
```

Compiling sources I

From the parser (`rpn.y` file) we build:

- the parser itself (`rpn.tab.c`)
- a description of tokens (`rpn.tab.h`)

Parser and scanner generation

```
$ bison -d rpn.y
$ flex scanner.l
```

Compiling sources II

To get the final executable compile and link:

Get your own polish parser

```
$ gcc rpn.tab.c lex.yy.c
```

I am lazy:

Using make [1]

```
YFLAGS=-d
rpn: rpn.o scanner.o
clean:
	rm -f rpn y.tab.h *.o
```

[1] Filenames are slightly different.

Adding semantic I

Beside each rule it is possible to add a code-block performing a semantic action:

- the semantic action is executed in the context of the associated rule

Rules full syntax

```
lhs: rhs_1 { ... }
   | rhs_2 { ... } rhs_3 { ... }
```

The `lhs` rule is an alternative:

- each alternative is independent from the other
- the first contains a semantic action
- the second contains two semantic actions

Adding semantic II

Semantic actions are executed just after the preceding rule. Given:

```
lhs: rhs { ... }
```

The parser:

1. recognizes `rhs`
2. executes the semantic action
3. recognizes `lhs`

The action is placed at rule tail:

- it is executed *every time* `lhs` is recognized

Adding semantic III

Given:

```
lhs: rhs1 { ... } rhs2 { ... }
```

The parser:

1. recognizes `rhs1`
2. executes the first semantic action
3. recognizes `rhs2`
4. executes the second semantic action
5. recognizes `lhs`

Semantic actions not at the tail of a rule are called *actions in the middle*.

Adding semantic IV

This is a logical view of semantic action execution:

- the execution of semantic actions can be postponed due to ambiguity

Semantic Values I

A variable is associated to every symbol:

- an `int` by default
- no distinction between terminal and non-terminal
- type customizable via `%union` directive [2]

Inside actions is possible to use these vars:

- accessed throuh `$n` notation
- index are 1-based
- the left-hand side semantic variable is `$$`
- counting includes semantic actions

Semantic Values II

Variables enumeration

Given:

```
lhs: rhs1 { ... } rhs2 { ... }
```

We have:

Component	Variable
`lhs`	`$$`
`rhs1`	`$1`
`{ ... }`	`$2`
`rhs2`	`$3`
`{ ... }`	`$4`

Semantic Values III

Obviously inside a semantic action we can access only variables associated to preceeding rules:

- rhs-vars mostly accessed in read-mode [3]

With an exception: the $$ variable:

- it is a *synthesized* attribute
- always written
- available only in the semantic action [4]

Default semantic action:

- `{ $$ = $1; }`

---

[2] More on this on next lesson.

[3] LALR parsing is bottom-up.

[4] The code block at rule tail.

Add and Multiply I

We must assign a semantic value to terminals:

scanner.l scanning naturals

```
{DIGIT}+ {
              yylval = atoi(yytext);
              return NUMBER;
         }
```

The `yylval` variable is declared by `bison`:

- must be filled with the semantic value of the terminal

Add and Multiply II

Sums and products must be performed by the parser:

rpn.y computing actions

```
expression:
  NUMBER { $$ = $1; }
  | expression expression OP_PLUS {
      $$ = $1 + $2;
    }
  | expression expression OP_MUL {
      $$ = $1 * $2;
    }
  ;
%%
```

Add and Multiply III

At last print the expression evaluation:

rpn.y reporting action

```
calculus:
  /* Empty */
  | expression {
      printf("Result:␣%d\n", $1);
    }
  ;
```

Ambiguity I

Consider the grammar of infix expressions:

Grammar

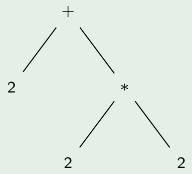
$$
\begin{aligned}
S &\rightarrow E | \epsilon \\
E &\rightarrow NUMBER \\
E &\rightarrow E + E | E * E
\end{aligned}
$$

It has a big problem: it is ambiguous!

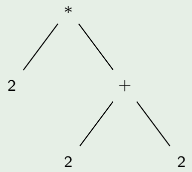
Ambiguity II

Let's try to generate $2 * 2 + 2$:

Produce $+$ first



Produce $*$ first



The grammar ambiguity between $+$ and $*$ rules generates a semantic ambiguity:

- what are the $+$ and $*$ precedences?

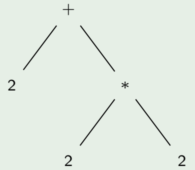
How To Resolve Ambiguity I

From theory, we can rewrite the grammar in a non ambiguous form:

Unambiguous grammar

$$
\begin{aligned}
S &\rightarrow E \mid \epsilon \\
E &\rightarrow E + T \mid T \\
T &\rightarrow NUMBER \\
T &\rightarrow T * NUMBER
\end{aligned}
$$

Unique tree



How To Resolve Ambiguity II

Since token are the same, we build only the parser:

`infix.y` rules [5]

```
expression:
  term { $$ = $1; }
  | expression OP_PLUS term {
      $$ = $1 + $3;
    }
term:
  NUMBER { $$ = $1; }
  | term OP_MUL NUMBER {
      $$ = $1 * $3;
    }
```

[5] Scaffolding is unchanged.

Precedence

Another way to handle operator precedence is to tell bison the precedence relation:

Precedence with bison [a]

```
%left TOKEN_1 TOKEN_2
%left TOKEN_3
```

[a] Precedences declared inside definitions section.

- TOKEN_1 and TOKEN_2 have the same precedence
- both have lower precedence than TOKEN_3

Associativity I

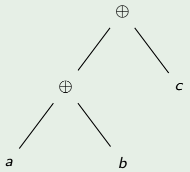
An operator $\oplus$ can be:

left-associative $a \oplus b \oplus c = (a \oplus b) \oplus c$

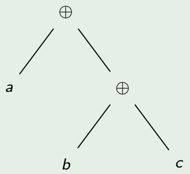
right-associative $a \oplus b \oplus c = a \oplus (b \oplus c)$

Associativity reflects on parsing:

AST of left-associative $\oplus$



AST of right-associative $\oplus$



Associativity II

Inside a `bison` file it is possible to declare the associativity of operators:

- operators are *tokens*

`bison` directives for operators associativity

Syntax	Meaning
`%left TOKEN`	`TOKEN` is left-associative
`%right TOKEN`	`TOKEN` is right-associative

Ambiguous Infix Calculator I

Declaring operator precedences allows to write ambiguous rules:

infix-ambiguous.y rules

```
expression:
  NUMBER { $$ = $1; }
  | expression OP_PLUS expression {
      $$ = $1 + $3;
  }
  | expression OP_MUL expression {
      $$ = $1 * $3;
  }
```

Ambiguous Infix Calculator II

Disambiguation is performed by `bison` consulting operator precedences:

Unambiguous tokens

```
%token NUMBER
%token OP_PLUS
%token OP_MUL
```

Ambiguous tokens

```
%token NUMBER
%left OP_PLUS
%left OP_MUL
```

Context-dependent Precedence I

Sometimes a character has a dual meaning:

- the - identifies both subtraction and unary minus

First of all, let's modify the infix scanner to recognize -:

infix-scanner.l minus token

```
"-" { return OP_MINUS; }
```

Context-dependent Precedence II

In the parser we introduce:

- the subtraction token `OP_MINUS`
- the unary minus `OP_UNARY_MINUS`

The latter is a *fake* token used to declare a precedence.

`infix-minus.y` minus token

```
%token NUMBER
%left OP_PLUS OP_MINUS
%left OP_MUL
%left OP_UNARY_MINUS
```

Context-dependent Precedence III

In the rules section we can force the right precedence:

infix-minus.y minus rules

```
expression:
  ...
  | expression OP_MINUS expression {
      $$ = $1 - $3;
    }
  ...
  | OP_MINUS expression
    %prec OP_UNARY_MINUS {
      $$ = -$2;
  }
```

Contents

Parse-First

Using `bison` requires both:

- writing the grammar
- adding semantic actions

Write the grammar first!

- try some examples
- if they are recognized, add semantic actions

Simple Grammars

As in coding, follow some conventions while writing grammars:

- terminals (tokens) are uppercase
- not-terminals are lowercase
- . . .

This keeps the grammar readable!

Contents

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