Principles of Abstract Interpretation

MIT press

Ch. **5**, Parsing

Patrick Cousot

pcousot.github.io

PrAbsInt@gmail.com   github.com/PrAbsInt/

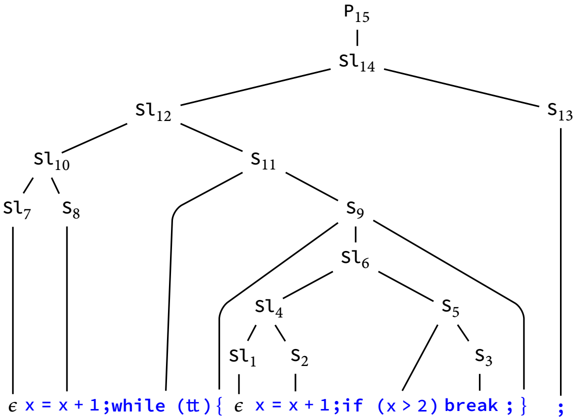
These slides are available at
http://github.com/PrAbsInt/slides/slides/slides-05--parsing-PrAbsInt.pdf

Chapter 5

Ch. **5**, Parsing

Parsing consists in building an abstract syntax tree (AST) of a program recognized by a context-free grammar (or rejecting that sentence because of a syntax error).

```
S   ::=  x = A ;
      |  ;
      |  if (B) S
      |  if (B) S else S
      |  while (B) S
      |  break ;
      |  { Sl }
Sl  ::=  Sl  S | ϵ
P   ::=  Sl
```



en.wikipedia.org/wiki/Context-free_grammar
en.wikipedia.org/wiki/Abstract_syntax_tree

Lexer

Lexing

- Consider the program

  `if (x<0)  x = -x ;`.

- In a first lexing phase, a program (called a lexer) will abstract the terminals in this input sentence by lexemes, as follows.

IF	LPARENT	IDENT	LT	NUM	RPARENT	IDENT	ASSIGN	MINUS	IDENT	SEMICOLON	END
if	(	x	<	0	)	x	=	-	x	;	

- The `END` lexeme represents the end of the program, for example the end of the input file.

en.wikipedia.org/wiki/Lexical_analysis

Lexer specification

Regular expressions

- The lexemes can be described by a regular expressions
- The syntax of regular expressions is

$$\mathsf{R} \quad ::= \quad \epsilon \;\Big|\; \texttt{'letter'} \;\Big|\; \texttt{"text"} \;\Big|\; \mathsf{R}_1\mathsf{R}_2 \;\Big|\; \mathsf{R}_1 \mid \mathsf{R}_2 \;\Big|\; \mathsf{R}^+ \;\Big|\; \mathsf{R}^* \;\Big|\; (\mathsf{R})$$

- The semantics of regular expressions is a set of strings, as follows
  - ϵ denotes the empty string
  - `'letter'` denotes the string of one letter `letter`
  - `"text"` denotes the string `text`
  - R_1R_2 denotes the concatenation of the strings denoted by R_1 and R_2
  - $R_1 \mid R_2$ denotes the string denoted either by R_1 or by R_2
  - R^+ denotes any concatenation of several strings denoted by R
  - R^* denotes the strings denoted by $\epsilon \mid R^+$

en.wikipedia.org/wiki/Regular_expression

Lexer generation

Lexer specification

The lexer can be generated automatically from a formal description of the lexemes by regular expressions as follows.

en.wikipedia.org/wiki/Lex_(software)
en.wikipedia.org/wiki/Flex_(lexical_analyser_generator)
caml.inria.fr/pub/docs/manual-ocaml/lexyacc.html

```
(* File lexer.mll *)
{
open Parser
exception Error of string
}
rule token = parse
    [' ' '\t' '\n'] { token lexbuf } (* skip blanks, tabs and newlines *)
  | "nand"      { NAND }
  | "if"        { IF }
  | "else"      { ELSE }
  | "while"     { WHILE }
  | "break"     { BREAK }
  | (['a'-'z'] | ['A'-'Z'])(['a'-'z'] | ['A'-'Z'] | ['0'-'9'])* as idt
                { IDENT idt }
  | ['0'-'9']+ as num
                { NUM (int_of_string num) }
  | '-'         { MINUS }
  | '<'         { LT }
  | '('         { LPAREN }
  | ')'         { RPAREN }
  | '='         { ASSIGN }
  | ';'         { SEMICOLON }
  | '{'         { LBRACKET }
  | '}'         { RBRACKET }
  | eof         { END }
  | _
    { raise (Error (Printf.sprintf "At offset %d: unexpected character.\n"
                                   (Lexing.lexeme_start lexbuf))) }
```

Comments on the lexer specification I

7,28: The `lexbuf` contains the input sentence which is a sequence of characters.

6: Each regular expression is considered in order.

6: For the first that applies a lexeme is returned and lexing goes on with the rest of the input sentence `lexbuf`.

7: the alternative `[' ' '\t' '\n']` is used to avoid repeating the same rule

7: `token lexbuf` moves to the next character in `lexbuf` so that space, tabulation, and end of line characters are skipped.

8–12: Then reserved keywords are checked.

13: Otherwise, an attempt is made to recognize an identifier that is the longest possible string, is any, starting by a lower or upper letter followed by zero or more letters or digits.

Comments on the lexer specification II

14: If an identifier is recognized, this string of characters is returned as part of the lexeme.

15: Otherwise an attempt is made to recognize a natural number as a nonempty sequence of digits.

16: The value returned with the lexeme is the value of that sequence of digits considered with the decimal encoding.

17–24: Otherwise an attempt is made to recognize symbols, where the end of file `eof` is considered to be the end of the program marqued by the lexeme `END`.

27,27: If none of the above cases applies, an error exception is raised.

Error exceptions

- For example for the input

  ```
  x=10; while (x>0) x=x-1;
  ```

  we get the error

  ```
  At offset 14: unexpected character.
  ```

  since `>` is not an integer comparison operator in our language.

Lexer generation

- A lexer is an OCaml program which, whenever called, will return the next lexeme recognized (in `lexbuf`).
- The lexemes will be OCaml values of the following

```
type token =  WHILE | SEMICOLON | RPAREN | RBRACKET | NUM of (int) | NAND | MINUS | LT
            | LPAREN | LBRACKET | IF | IDENT of (string) | END | ELSE | BREAK | ASSIGN
```

  (which is automatically generated from the parser specification in the file `parser.mly` below).

- The `lexbuf` buffer can be chosen to be a file, the input keyboard, or a string.
- The lexer generator `ocamllex` will take this specification and automatically produce a lexer, returning lexemes of that type `token`.

ocaml.org

Grammar

Expressions

The following grammar specifies a subset of C expressions

$\mathsf{x}, \mathsf{y}, \ldots$	$\in$	$\mathbb{V}$			variables ($\mathbb{V}$ not empty)
A	$\in$	$\mathbb{A}$	$::=$	$\mathsf{1} \mid \mathsf{x} \mid \mathsf{A}_1 - \mathsf{A}_2$	arithmetic expressions
B	$\in$	$\mathbb{B}$	$::=$	$\mathsf{A}_1 < \mathsf{A}_2 \mid \mathsf{B}_1 \textsf{ nand } \mathsf{B}_2$	boolean expressions
E	$\in$	$\mathbb{E}$	$::=$	$\mathsf{A} \mid \mathsf{B}$	expressions

en.wikipedia.org/wiki/Context-free_grammar
en.wikipedia.org/wiki/C_(programming_language)

Programs

The following grammar specifies a subset of C programs

`S`	$::=$		statement `S` $\in \mathbb{S}$
		`x = A ;`	assignment
	$\mid$	`;`	skip
	$\mid$	`if (B) S`	conditional
	$\mid$	`if (B) S else S`	
	$\mid$	`while (B) S`	iteration
	$\mid$	`break ;`	iteration break
	$\mid$	`{ Sl }`	compound statement
`Sl`	$::=$	`Sl S` $\mid$ ϵ	statement list `Sl` $\in \mathbb{S}\mathbb{l}$
`P`	$::=$	`Sl`	program `P` $\in \mathbb{P}$
$\mathbb{P}\mathbb{c}$	$\triangleq$	$\mathbb{S} \cup \mathbb{S}\mathbb{l} \cup \mathbb{P}$	program component `S` $\in \mathbb{P}\mathbb{c}$

Grammar specification

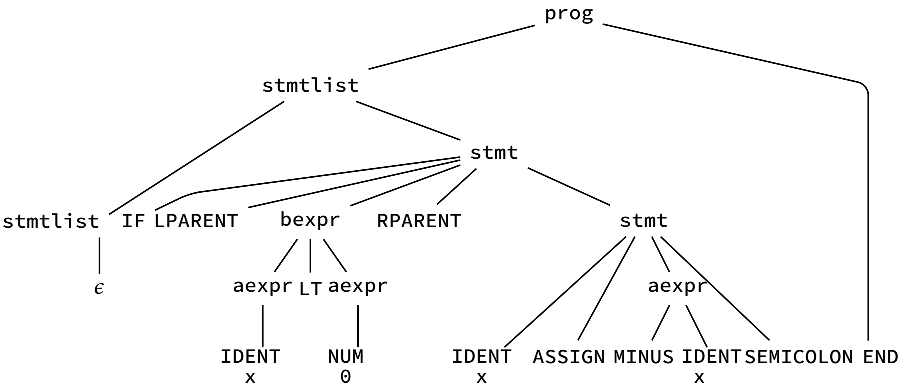
- The grammar of the language is specified by the grammar specification for the parser (on next slide)[1].
- Terminals in the input sentence have been replaced by lexemes so that the grammar input sentence is a sequence of lexemes.
- More precisely, whenever the next lexeme is required by the parser it is obtained by calling the lexer (for a specific input buffer `lexbuf`).

[1] There are many other different syntaxes for grammars such as `en.wikipedia.org/wiki/Backus-Naur_form`

```
prog:
   | stmtlist END

stmt:
   | IDENT ASSIGN aexpr SEMICOLON
   | SEMICOLON
   | IF LPAREN bexpr RPAREN stmt
   | IF LPAREN bexpr RPAREN stmt ELSE stmt
   | WHILE LPAREN bexpr RPAREN stmt
   | BREAK SEMICOLON
   | LBRACKET stmtlist RBRACKET

stmtlist:
   | stmtlist stmt
   |

aexpr:
   | NUM
   | IDENT
   | aexpr MINUS aexpr
   | MINUS aexpr
   | LPAREN aexpr RPAREN

bexpr:
   | aexpr LT aexpr
   | bexpr NAND bexpr
   | LPAREN bexpr RPAREN
```


Parser

- The objective of a parser is to built the parse/syntax tree of a program
- For the example program `if (x<0)  x = -x ;`, the parse tree is the following

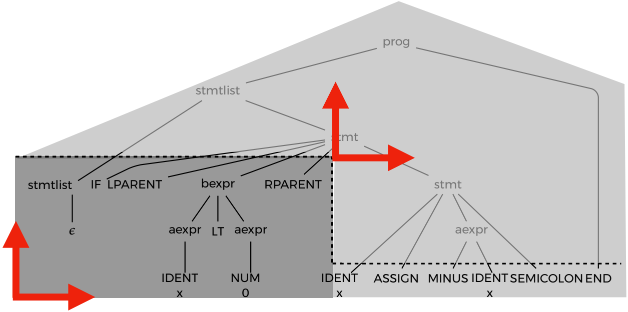


By the way, this program is not the absolute value with machine integers (because of the overflow with the smallest integer)

en.wikipedia.org/wiki/Parsing

Parser I

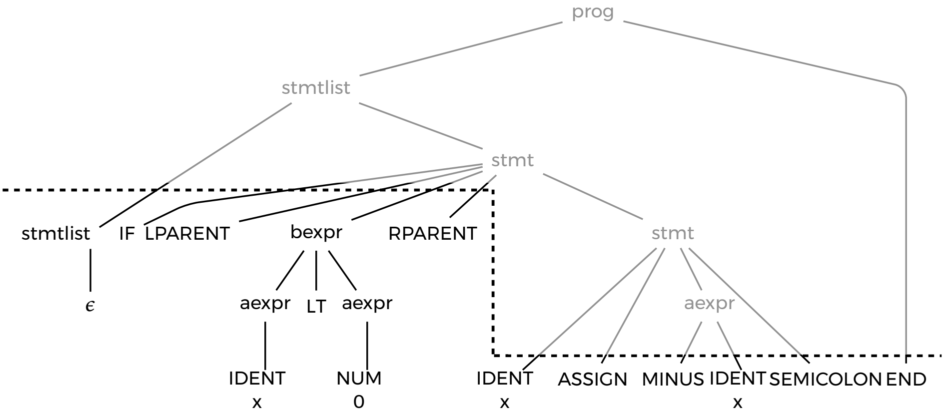
- We consider left-to-right, bottom-up parsing so that the syntax tree is built in prefix order from the input sentence of lexemes.
- Initially, the syntax tree is empty and the input sentence is the sequence of lexemes to be recognized.



en.wikipedia.org/wiki/LALR_parser

Parser II

An intermediate state of the parser would be the following.

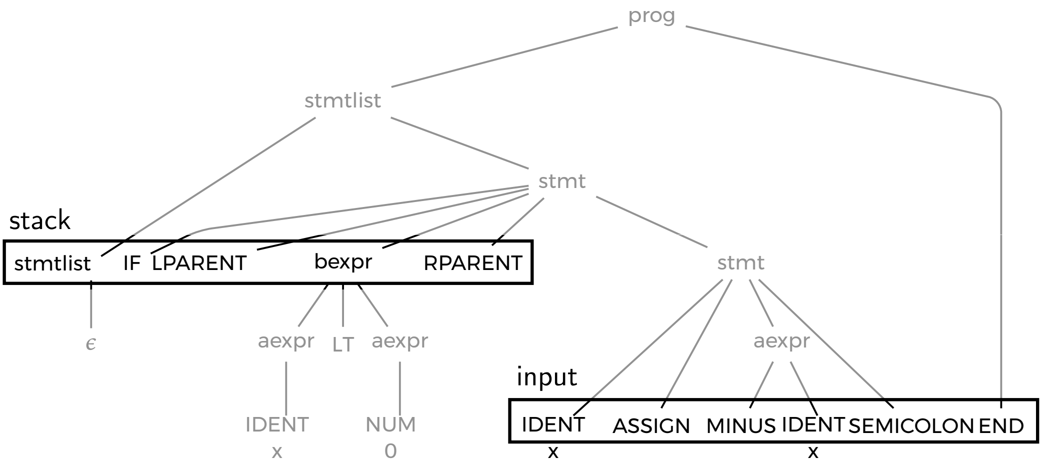


Parser III

- Only the top of the prefix of the parsing tree that has been recognized until now is used so that it can be stored in a stack.

- The input is the rest of the sequence of lexemes to be recognized.

Parser IV



prog
stmtlist
stmt
stack
stmtlist
IF
LPARENT
bexpr
RPARENT
stmt
ϵ
aexpr
LT
aexpr
aexpr
input
IDENT
NUM
IDENT
ASSIGN
MINUS
IDENT
SEMICOLON
END
x
0
x
x

Parser V

Depending on the state of the stack and the input, the next action of the parser will be either

- a shift (going right),
- a reduce (going up),
- an acceptance, or
- a rejection

of the sentence.

Parser VI

- A *reduce* consists in replacing the righthand side of a grammar rule recognized on top of the stack by the lefthand side of the rule.
- Example
  - stack: `stmtlist IF LPARENT aexpr LT aexpr`
  - input: `RPARENT IDENT ASSIGN MINUS IDENT SEMICOLON END`

  A reduction replaces the righthand side `aexpr LTaexpr` of the grammar rule by its lefthand side `bexpr`
  - stack: `stmtlist IF LPARENT bexpr`
  - input: unchanged `RPARENT IDENT ASSIGN MINUS IDENT SEMICOLON END`

Parser VII

- A *shift* is for the case when the stack contains part of the righthand side of a rule in construction and a lexeme is pushed from the input to the stack.
- Example
  - stack: `stmtlist IF LPARENT bexpr`
  - input: `RPARENT IDENT ASSIGN MINUS IDENT SEMICOLON END`

  The next lexeme `RPARENT` is shifted to the stack which becomes
  - stack: `stmtlist IF LPARENT bexpr RPARENT`
  - input:`IDENT ASSIGN MINUS IDENT SEMICOLON END`

Parser VIII

- An *acceptance* is when the stack is reduced to the grammar axiom and the input is empty.
- Otherwise it is a *rejection* *i.e.* the stack cannot be extended by the input to a meaningful sentence of the language defined by the grammar.

Parser IX

The parsing of the input sentence

`IF LPARENT IDENT LT NUM RPARENT IDENT ASSIGN MINUS IDENT SEMICOLON END`

proceeds as follows (a state has the form stack | input, $\xrightarrow{S}$ is a shift and $\xrightarrow{R}$ is a reduction).

$\phantom{\xrightarrow{R}}$ | `IF LPARENT IDENT LT NUM RPARENT IDENT ASSIGN MINUS IDENT SEMICOLON END`

$\xrightarrow{R}$ `stmtlist` | `IF LPARENT IDENT LT NUM RPARENT IDENT ASSIGN MINUS IDENT SEMICOLON END`

$\xrightarrow{S}$ `stmtlist IF` | `LPARENT IDENT LT NUM RPARENT IDENT ASSIGN MINUS IDENT SEMICOLON END`

$\xrightarrow{S}$ `stmtlist IF LPARENT` | `IDENT LT NUM RPARENT IDENT ASSIGN MINUS IDENT SEMICOLON END`

$\xrightarrow{S}$ `stmtlist IF LPARENT IDENT` | `LT NUM RPARENT IDENT ASSIGN MINUS IDENT SEMICOLON END`

$\xrightarrow{R}$ `stmtlist IF LPARENT aexpr` | `LT NUM RPARENT IDENT ASSIGN MINUS IDENT SEMICOLON END`

Parser X

$\xrightarrow{S}$ stmtlist IF LPARENT aexpr LT | NUM RPARENT IDENT ASSIGN MINUS IDENT SEMICOLON END

$\xrightarrow{S}$ stmtlist IF LPARENT aexpr LT NUM | RPARENT IDENT ASSIGN MINUS IDENT SEMICOLON END

$\xrightarrow{R}$ stmtlist IF LPARENT aexpr LT aexpr | RPARENT IDENT ASSIGN MINUS IDENT SEMICOLON END

$\xrightarrow{R}$ stmtlist IF LPARENT bexpr | RPARENT IDENT ASSIGN MINUS IDENT SEMICOLON END

$\xrightarrow{S}$ stmtlist IF LPARENT bexpr RPARENT | IDENT ASSIGN MINUS IDENT SEMICOLON END

$\xrightarrow{S}$ stmtlist IF LPARENT bexpr RPARENT IDENT | ASSIGN MINUS IDENT SEMICOLON END

$\xrightarrow{S}$ stmtlist IF LPARENT bexpr RPARENT IDENT ASSIGN | MINUS IDENT SEMICOLON END

$\xrightarrow{S}$ stmtlist IF LPARENT bexpr RPARENT IDENT ASSIGN MINUS | IDENT SEMICOLON END

$\xrightarrow{S}$ stmtlist IF LPARENT bexpr RPARENT IDENT ASSIGN MINUS IDENT | SEMICOLON END

$\xrightarrow{R}$ stmtlist IF LPARENT bexpr RPARENT IDENT ASSIGN aexpr | SEMICOLON END

$\xrightarrow{S}$ stmtlist IF LPARENT bexpr RPARENT IDENT ASSIGN aexpr SEMICOLON | END

Parser XI

$\xrightarrow{R}$ `stmtlist IF LPARENT bexpr RPARENT stmt` $|$ `END`

$\xrightarrow{R}$ `stmtlist stmt` $|$ `END`

$\xrightarrow{R}$ `stmtlist` $|$ `END`

$\xrightarrow{S}$ `stmtlist END` $|$

$\xrightarrow{R}$ `prog` $|$

A syntactically valid program has been recognized.

en.wikipedia.org/wiki/Shift-reduce_parser

Parsers

There are numerous deterministic parsers available for LALR(k) and LR(k) grammars.

en.wikipedia.org/wiki/LALR_parser
en.wikipedia.org/wiki/LR_parser

en.wikipedia.org/wiki/Yacc
en.wikipedia.org/wiki/GNU_Bison
caml.inria.fr/pub/docs/manual-ocaml/lexyacc.html (ocamlyacc)
gallium.inria.fr/~fpottier/menhir/

Ambiguities, shift-reduce conflicts

Ambiguity I

- The grammar is ambiguous in that a sentence can be parsed in different ways.
- For example `1-2-3` can be parsed as `((1-2)-3)` or `(1-(2-3))` which does not return the same result.
- In mathematics, `1-2-3` means `((1-2)-3)`
- The binary minus operation `-` is left-associative and evaluated left-to-right.
- The ambiguity is solved by the following declaration in the grammar specification.

```
%left MINUS
```

- This declares `MINUS` to be left-associative (*i.e.* do a reduce rather than a shift).

en.wikipedia.org/wiki/Ambiguous_grammar

Ambiguity II

- Another ambiguity is for expressions like `1 - -2` which should be evaluated as `(1 - (-2))` *i.e.* the unary operator `-` in `-2` should be evaluated before the binary operator `-` in `1 - ␣`.
- Another difficulty is that the unary and binary symbols are the same `-`.
- These two problems are solved by declaring that

(1) the unary minus is evaluated before the binary minus

```
%left MINUS           /* evaluated second */
%nonassoc UMINUS      /* evaluated first */
```

(2) the unary minus has the syntax of the binary minus but the precedence of the unary minus (which should be evaluated first)

```
aexpr:
  | NUM
  | IDENT
  | aexpr MINUS aexpr
  | MINUS aexpr %prec UMINUS
  | LPAREN aexpr RPAREN
```


Ambiguity III

- Another ambiguity is for expressions like `1-2<3` which should be parsed as `((1-2)<3)` and not `(1-(2<3))`
- The binary `-`
  should be evaluated before the logical comparison `<`, as indicated by the declaration

```
%left NAND            /* evaluated fourth */
%left LT              /* evaluated third */
%left MINUS           /* evaluated second */
%nonassoc UMINUS      /* evaluated first */
```

- The `NAND` is left-associative and should be evaluated last.

Shift-reduce conflict

- All this situations yield a shift-reduce conflict.
- For example during the analysis of `1-2-x`, we reach the state

  aexpr MINUS aexpr | *MINUS IDENT*

- We can either perform
  - a reduce

    $\xrightarrow{R}$ *aexpr* | *MINUS IDENT*

    in case of left-associativity or
  - a shift

    $\xrightarrow{S}$ *aexpr MINUS aexpr MINUS* | *IDENT*

    in case of right-associativity.
- The declaration indicates that the `MINUS` operator is left-associative so the reduce should be performed, not the shift.

Ambiguity IV (conditional)

- The grammar for the conditional is also ambiguous.
- For example

  $$\mathtt{if}\ (\mathit{bexpr}_1)\ \mathtt{if}\ (\mathit{bexpr}_2)\ \mathit{stmt}_1\ \mathtt{else}\ \mathit{stmt}_2$$

  can be understood either as

  $$\big(\mathtt{if}\ (\mathit{bexpr}_1)\ \big(\mathtt{if}\ (\mathit{bexpr}_2)\ \mathit{stmt}_1\big)\ \mathtt{else}\ \mathit{stmt}_2\big)$$

  or as

  $$\big(\mathtt{if}\ (\mathit{bexpr}_1)\ \big(\mathtt{if}\ (\mathit{bexpr}_2)\ \mathit{stmt}_1\ \mathtt{else}\ \mathit{stmt}_2\big)\big).$$

- In most programming languages, the `else` refers to the closest enclosing `if` *i.e.* the ambiguity is solved according to the second parsing.

en.wikipedia.org/wiki/Dangling_else

Ambiguity IV (conditional)

Again precedences can be used as follows.

```
%nonassoc NO_ELSE    /* evaluated sixth */
%nonassoc ELSE       /* evaluated fifth */
%left NAND           /* evaluated fourth */
%left LT             /* evaluated third */
%left MINUS          /* evaluated second */
%nonassoc UMINUS     /* evaluated first */
```

The grammar is now

```
stmt:
  | ...
  | IF LPAREN b = bexpr RPAREN s = stmt %prec NO_ELSE
  | IF LPAREN b = bexpr RPAREN s1 = stmt ELSE s2 = stmt
  | ...
```

The `%prec NO_ELSE` states that the lexeme `NO_ELSE` is fake (an empty string in the input).
Moreover it does not associate with itself and is evaluated last.

Ambiguity IV (conditional)

- Therefore an input

  $\mathit{if\ (bexpr_1)\ if\ (bexpr_2)\ stmt_1\ else\ if\ (bexpr_3)\ stmt_2\ else\ stmt_3}$,

  is parsed as

  $\big(\mathit{if\ (bexpr_1)\ if\ (bexpr_2)\ stmt_1\ else\ if\ (bexpr_3)\ stmt_2\ else\ stmt_3\ NO\_ELSE}\ \big)$

- Moreover the ELSE does not associate with itself
- *i.e.* interpreting ␣ ELSE ␣ ELSE ␣ as ((␣ ELSE ␣) ELSE ␣) or (␣ ELSE (␣ ELSE ␣)) is meaningless

- The parsing is

  $\big(\mathit{if\ (bexpr_1)}\ \big(\mathit{if\ (bexpr_2)\ stmt_1\ else}\ \big(\mathit{if\ (bexpr_3)\ stmt_2\ else\ stmt_3}\big)\big)\ \mathit{NO\_ELSE}\ \big)$

Ambiguities, reduce-reduce conflicts

Reduce-reduce conflict

A reduce-reduce conflict occurs during parsing when a reduction can be applied with two or more different grammar rule righthand sides, for the same input token.

Example of reduce-reduce conflict

```
/* File parser.mly */
%{ %}
%token NUM
%start s /* the grammar entry point */
%type  <unit> s
%type  <unit> t

%% /* rules */
s:
  | t       { () }
  | NUM     { () }

t:
  | NUM     { () }

%%
```

- A `NUM` can be reduced to a `s` or to a `t` and then to a `s`.

Error message for the reduce-reduce conflict

The `menhir` parser generator produces the following error message,

```
Warning: one state has reduce/reduce conflicts.
Warning: one reduce/reduce conflict was arbitrarily resolved.
File "parser.mly", line 14, characters 4-7:
Warning: production t -> NUM is never reduced.
```

- `menhir` explains the problem in the `parser.conflicts` file.
- `menhir` arbitrarily chooses the first alternative
- The second alternative is never used, which is most certainly an error in the design of the context free-grammar.

Solving ambiguities by grammar rewriting

It is always possible to resolve the ambiguities by rewriting the grammar.

For example, the grammar of arithmetic expressions would be

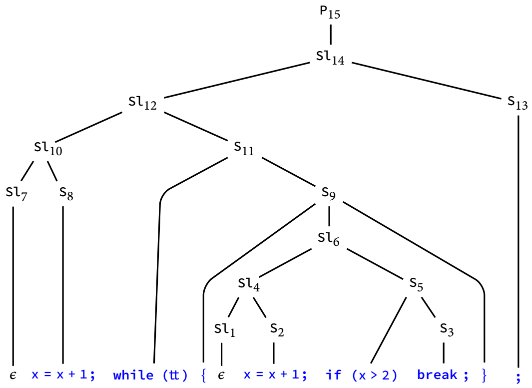
```
<Exp> ::= <Exp> + <Term> |
          <Exp> - <Term> |
          <Term>

<Term> ::= <Term> * <Factor> |
           <Term> / <Factor> |
           <Factor>

<Factor> ::= <Variable> |
             <Constant> |
             ( <Exp> ) |
             - <Factor>
```

Using priorities is usually much simpler.

Abstract syntax

Abstract syntax

- A program can be represented by a tree called its abstract syntax.



- For parsing only, the abstract syntax is unit ()

en.wikipedia.org/wiki/Abstract_syntax_tree

Abstract syntax

In the programming language OCaml [Leroy, Doligez, Frisch, Garrigue, Rémy, and Vouillon, 2020], the abstract syntax type is

```ocaml
(* file abstractSyntax.ml *)

type variable = string
type aexpr = Num of int | Var of string | Minus of aexpr * aexpr
type bexpr = Lt of aexpr * aexpr | Nand of bexpr * bexpr
type 'a tree =
   | Prog of 'a tree list * 'a
   | Assign of variable * aexpr * 'a
   | Emptystmt of 'a
   | If of bexpr * 'a tree * 'a
   | Ifelse of bexpr * 'a tree * 'a tree * 'a
   | While of bexpr * 'a tree * 'a
   | Break of 'a
   | Stmtlist of 'a tree list * 'a (* trees in inverse order *)
```

The abstract syntax tree type is parameterized by the type `'a` of the attributes attached to the nodes of the tree

ocaml.org
en.wikipedia.org/wiki/OCaml

Construction of the abstract syntax tree

- The abstract syntax tree can be constructed during parsing
- The stack elements ⟨`nt`, `ast`⟩ are pairs of a non-terminal `nt` (or terminal) and an abstract syntax subtree `ast`
- Each shift extends the tree left-to-right
- Each reduction extends the tree bottom-up

en.wikipedia.org/wiki/Attribute_grammar

Example, cont'd I

...

$\xrightarrow{S}$ ⟨`stmtlist, Emptystmt`⟩ `IF LPARENT` ⟨`bexpr, LT (Var "x",Num 0)`⟩ `RPARENT`
`IDENT "x"` `ASSIGN MINUS` ⟨`IDENT, Var "x"`⟩ | `SEMICOLON END`

$\xrightarrow{R}$ ⟨`stmtlist, Emptystmt`⟩ `IF LPARENT` ⟨`bexpr, LT (Var "x",Num 0)`⟩ `RPARENT`
`IDENT "x"` `ASSIGN` ⟨`aexpr, Minus (Num 0, Var "x")`⟩ | `SEMICOLON END`

$\xrightarrow{S}$ ⟨`stmtlist, Emptystmt`⟩ `IF LPARENT` ⟨`bexpr, LT (Var "x",Num 0)`⟩ `RPARENT`
`IDENT "x"` `ASSIGN` ⟨`aexpr, Minus (Num 0, Var "x")`⟩ `SEMICOLON` | `END`

$\xrightarrow{R}$ ⟨`stmtlist, Emptystmt`⟩ `IF LPARENT` ⟨`bexpr, LT (Var "x",Num 0)`⟩ `RPARENT` ⟨`stmt, Assign ("x",Minus (Num 0, Var "x"))`⟩ | `END`

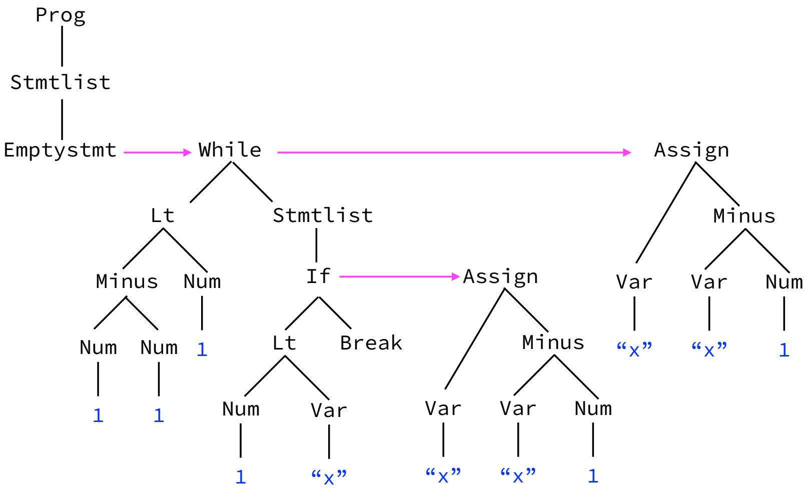
Example, cont'd II

$\xrightarrow{R}$ $\langle$`stmtlist, Emptystmt`$\rangle$ $\langle$`stmt,`

`If (LT (Var "x",Num 0), Assign ("x",Minus (Num 0, Var "x")))`$\rangle$ $\Big|$ `END`

...

Example of OCaml Abstract Syntax Tree




```
x = x + 1; while ((1 - 1) < 1) { x = x + 1; if (1 < x) break; } ;
```


Parser specification

Parser specification

- The parser specification on next slide lists
  - the lexemes (`%token`), possibly with an associated OCaml type,
  - the precedences (`%left`, `%right`, `%nonassoc`) in increasing priority order,
  - the grammar axiom (`%start`),
  - the OCaml type of the abstract syntax tree associated to the grammar nonterminals (`%type`)
  - the grammar rules.

en.wikipedia.org/wiki/Yacc
dev.realworldocaml.org/parsing-with-ocamllex-and-menhir.html


```
/* File parser.mly */

%{ (* header *)
open AbstractSyntax

%} /* declarations */

%token MINUS LT NAND LPAREN RPAREN ASSIGN /* lexer tokens */
%token SEMICOLON IF ELSE WHILE BREAK LBRACKET RBRACKET END
%token <string> IDENT
%token <int> NUM

%nonassoc NO_ELSE    /* evaluated fifth */
%nonassoc ELSE       /* evaluated fourth */
%left NAND           /* evaluated third */
%left MINUS          /* evaluated second */
%nonassoc UMINUS     /* evaluated first */

%start prog          /* the grammar entry point */
%type  <unit AbstractSyntax.tree> prog
%type  <aexpr> aexpr
%type  <bexpr> bexpr
%type  <unit AbstractSyntax.tree> stmt
```

```
%type  <unit AbstractSyntax.tree list> stmtlist

%% /* rules */

prog:
   | l = stmtlist END                            { Prog (l, ()) }
stmt:
   | x = IDENT ASSIGN a = aexpr SEMICOLON        { Assign (x, a, ()) }
   | SEMICOLON                                   { Emptystmt () }
   | IF LPAREN b = bexpr RPAREN s = stmt %prec NO_ELSE   { If (b, s, ()) }
   | IF LPAREN b = bexpr RPAREN s1 = stmt
     ELSE s2 = stmt                              { Ifelse (b, s1, s2, ()) }
   | WHILE LPAREN b = bexpr RPAREN s = stmt { While (b, s, ()) }
   | BREAK SEMICOLON                             { Break () }
   | LBRACKET l = stmtlist RBRACKET              { Stmtlist (l, ()) }
stmtlist:
   | l = stmtlist s = stmt                       { s :: l (* nodes in inverse order *) }
   |                                             { [] }
aexpr:
   | n = NUM                                     { Num n }
   | x = IDENT                                   { Var x }
   | a1 = aexpr MINUS a2 = aexpr                 { Minus (a1, a2) }
   | MINUS a = aexpr                             { Minus ((Num 0), a) } %prec UMINUS
```

```
  | LPAREN a = aexpr RPAREN                { a }
bexpr:
  | a1 = aexpr LT a2 = aexpr               { Lt (a1, a2) }
  | b1 = bexpr NAND b2 = bexpr             { Nand (b1, b2) }
  | LPAREN b = bexpr RPAREN                { b }

%% (* trailer *)
```

Comments on the parser specification

- The types are defined in the module `AbstractSyntax` (in file `abstractSyntax.ml`)
- The `AbstractSyntax` module is opened in the header to avoid explicit qualification (such as `AbstractSyntax.aexpr`).
- The grammar rules give a name to the abstract syntax trees already constructed (*e.g.* `l` in `l = stmtlist`)
- They use these named abstract syntax subtrees to construct the abstract syntax tree of the rule lefthand side non terminal upon reduction (*e.g.* `{ Prog l }`).

Parser generation

Automatic parser generation

- Given parser specification, parser generators such as `ocamlyacc` or `menhir` can automatically generate parsers in the OCaml programming language.
- Similar tools exist for others languages (`yacc`, `bison`, *etc.*)
- The parser can be called in a main program (called `main.ml` in our example).

en.wikipedia.org/wiki/Yacc
en.wikipedia.org/wiki/GNU_Bison


```
(* File main.ml *)

open AbstractSyntax

let rec print_aexpr a = ...;;
let rec print_bexpr a = ...;;

let rec print_program p = ...
and print_stmtlist sl = ...
and print_stmt s = ...;;

let lexbuf = Lexing.from_channel stdin in
  try
    print_program (Parser.prog Lexer.token lexbuf)
  with
  | Lexer.Error msg ->
      Printf.fprintf stderr "%s%!" msg
  | Parser.Error ->
      Printf.fprintf stderr "At offset %d: syntax error.\n%!"
                                                  (Lexing.lexeme_start lexbuf);;
```

Comments on the `main` program

- The lexing buffer is created by `lexbuf = Lexing.from_channel stdin` from the keyboard standard input (`stdin`)
- The lexing buffer `lexbuf` is passed as a parameter to the parser `Parser.prog` of programs.
- The `Lexer` module is created by `ocamllex` from the lexer specification and `Lexer.token` is the set of lexemes to be recognized.
- An exception is raised and captured in case of lexing or parsing error.
- Else, the parser returns an abstract syntax tree which is printed (in parenthesized form).

Compilation I

- The compilation through `make` [Feldman, 1979]

```
# file "makefile"

OCAMLBUILD := ocamlbuild -use-menhir -menhir "menhir --infer --explain"

all: delete built examples
built:
	$(OCAMLBUILD) main.native

examples:
	@echo "# using the parser:"
	@echo ";"| ./main.native
	@echo "x = 42;"| ./main.native
	@echo "break;"| ./main.native
	@echo "break; x = 7;"| ./main.native
	@echo "x = 7; ; break; "| ./main.native
	@echo "{}" | ./main.native
```

Compilation II

```
	@echo "x=-10-20--30;" | ./main.native
	@echo "x=1; y=2;" | ./main.native
	@echo "{x=10; ; y=20;}" | ./main.native
	@echo "if (1-2<3-4-5) x=-x;" | ./main.native
	@echo "if (0<x) if (x<0) x=1; else if (x<0) { x=2; x=3; } else { x=4; x=5; x=6; }" | ./main.native
	@echo "while (0<1){x = x - 1;} x = 42;" | ./main.native
	@echo "while (0<1){}" | ./main.native
	@echo "x=x-1;while (0<1){x=x-1;if(x<2)break;};" | ./main.native
	@echo "x=-10; while (x<0) if (x<0) if (0<x) x=-x;" | ./main.native
	@echo "x=-10; while (x<0) { x=x-1; break; }; x= 10;" | ./main.native
	@echo "x=0; while (x<0) { while (x<0) x=x-1; x= 10; }; x= 100;" | ./main.native
	@echo "x=0; while (x<0) { while (x<0) x=x-1; break; }; x= 100;" | ./main.native
	@echo "x=x-1; while (0<1) { x=x-1; if (2 < x) break; };" | ./main.native
	-@echo "x=10; while (x>0) x=x-1;" | ./main.native
```

Compilation III

```
	@echo "# end"

delete:
	rm -f *~ .*~ main.native
	ocamlbuild -clean
```

- The result is the following (syntax trees are printed in parenthesized form)

```
 # using the parser:
...
x = (x - 1); (while (0 < 1) { x = (x - 1); (if (x < (0 - 2)) break; ) } ) ;
At offset 14: unexpected character.
# end
```

en.wikipedia.org/wiki/Make_(software)

Builder I

- `ocamlbuild` [Durak and Pouillard, 2007] automatically determines the sequence of calls to the OCaml compiler to build a native OCaml-centric software project.
- This can be done manually by the following

- `makefile`

```
all:
      ocamllex -q lexer.mll
      menhir --infer --explain parser.mly
      ocamlc -c parser.mli
      ocamlc -c lexer.ml
      ocamlc -c parser.ml
      ocamlc -c main.ml
      ocamlc parser.cmo lexer.cmo main.cmo -o main
```

ocaml.org/learn/tutorials/ocamlbuild/

Conclusion

Conclusion

- Popular lexer and parser generators are `lex` [Lesk, 1975] and `yacc` [Johnson, 1975] *i.e.* `ocamllex` and `ocamlyacc` [Leroy, Doligez, Frisch, Garrigue, Rémy, and Vouillon, 2020, Chapter 12] for the OCaml functional programming language [Leroy, Doligez, Frisch, Garrigue, Rémy, and Vouillon, 2020].
- We prefer `menhir` [, given=Yann, giveni=Y., givenun=0Pottier and Régis-Gianas, given=Yann, giveni=Y., givenun=0, 2006, given=Yann, giveni=Y., givenun=0, 2020] to `ocamlyacc` since it reports errors with respect to the grammar (and not respect to the more obscure parser code).
- We have introduced parsing from an empirical practical user point of view.
- For the theoretic background, see [, given=Eljas, giveni=E., givenun=0Sippu and Soisalon-Soininen, given=Eljas, giveni=E., givenun=0, 1988, given=Eljas, giveni=E., givenun=0, 1990].
- Parsers are abstract interpretations of the semantics of grammars [P. Cousot and R. Cousot, 2003, 2011].

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Home work

- Read Ch. **5** "Parsing" of

  Principles of Abstract Interpretation
  Patrick Cousot
  MIT Press

- Install Ocaml and menhir on your computer (*e.g*. with brew[2] on Un*x), and experiment

[2] `https://brew.sh`

The End, Thank you