Nano: Lexing + Parsing

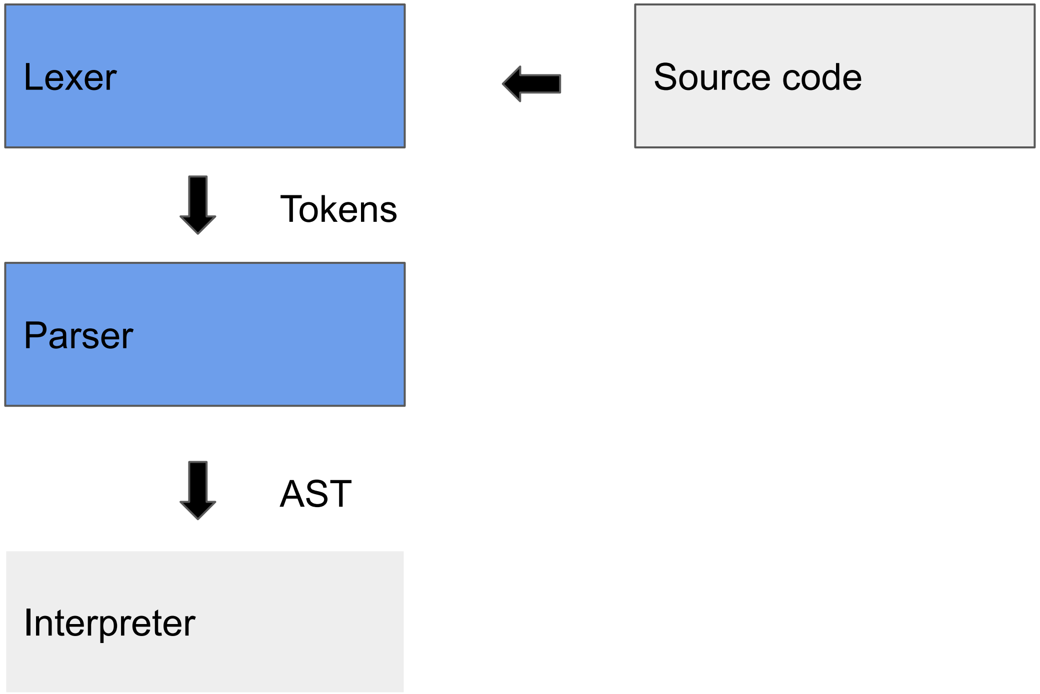
CSE 130

11.19.20

Today:

1. The big picture: what are lexers and parsers?
2. How to write a lexer
3. How to write a parser

The big picture



Goal: Convert strings to AST

“12 + 2” `=> Plus 12 2`

“1 + (2 / “a”)” `=> Plus 1 (Div 2 (Var “a”))`

```
lexer :: String -> [Token]

parser :: [Token] -> Expr
```

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```

A lexer converts a list of Chars to a high-level representation of the *same* information:

[‘5’,’0’,’0’,’ ‘,’+’,’ ‘,’1’,’2’] => [500, Plus, 12]

[‘1’,’ ‘,’+’,’ ‘,’(‘,’3’,’ ‘,’*’,’ ‘,’2’,’)’] -> [1, Plus, LParen, 3, Times, 2, RParen]

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Alex: generates a lexer (in Haskell) from a .x file

```
parser :: [Token] -> Expr
```

`parser :: [Token] -> Expr`

A parser converts a list of tokens to an AST representing the *structure* of the language

[500,Plus,12] -> `Plus 500 12`

[1,Plus,LParen,3,Times,2,RParen] -> `Plus 1 (Times 3 2)` `parser :: [Token] -> Expr`

A parser converts a list of tokens to an AST representing the *structure* of the language

[500,Plus,12] -> `Plus 500 12`

[1,Plus,LParen,3,Times,2,RParen] -> `Plus 1 (Times 3 2)`

Happy: generates a parser (in Haskell) from a .y file

A simple example language

```
AExp ::= Int
       | String
       | Plus AExp AExp
       | Minus AExp AExp
       | Mul AExp AExp
       | Div AExp AExp
```

Writing a Lexer (with Alex)

Writing a Lexer

Need to define mappings from sequences of characters to tokens

```
data Token
  = NUM    AlexPosn Int
  | ID     AlexPosn String
  | PLUS   AlexPosn
```

....

This will be provided in the assignment

Writing a Lexer

How do we actually generate tokens?

Writing a Lexer

```
data Token
  = NUM    AlexPosn Int
  | ID     AlexPosn String
  | PLUS   AlexPosn
```

....

Define rules of the form | <regexp> {haskell-expr}

When <regexp> is matched, we evaluate {haskell-expr} to generate a token

Writing a Lexer

```
data Token
  = NUM    AlexPosn Int
  | ID     AlexPosn String
  | PLUS   AlexPosn
```

….

Define rules of the form “<regexp> {haskell-expr}”

When <regexp> is matched, we evaluate {haskell-expr} to generate a token

```
haskell-expr :: AlexPosn -> String -> Token
```

More lexing

```
data Token
  = NUM    AlexPosn Int
  | ID     AlexPosn String
  | PLUS   AlexPosn
```

Declare a mapping from patterns to a corresponding Haskell expression that returns a Token:

```
\+      { \p _ ->  PLUS p }

“<=”    {\p _ -> LEQ p }

$digit+ { \p s -> NUM p (read s) }
```

Writing regexes

https://www.haskell.org/alex/doc/html/regexps.html

More lexing

Macros: “`$digit`” is a macro that matches any number [0-9]. Some useful macros will be provided

Regexes will use these macros:

`$white+` matches a sequence of at least 1 whitespace char

`$white*` also matches the empty string (be careful! This would mean the lexer will never fail to match something)

Parsing :: [Token] -> AST

Parsing :: [Token] -> AST

Happy uses a **Context-Free Grammar** to define the tree structure

Terminal objects (leaf nodes of tree): TNUM and ID. Other token declarations simply map to values of the Token type. Tokens are re-defined

```
%tokentype { Token }

%token
    TNUM  { NUM _ $$ }
    ID    { ID _ $$  }
    '+'   { PLUS _   }
    '-'   { MINUS _  }
    '*'   { MUL _    } ...
```

A simple language (again)

```
AExp ::= Int
       | String
       | Plus AExp AExp
       | Minus AExp AExp
       | Mul AExp AExp
       | Div AExp AExp
```

We need to define a grammar describing these expressions

Parsing :: [Token] -> AST

Terminal nodes to not have subexpressions

```
Aexpr : BinExp                          { $1              }
      | TNUM                            { AConst $1       }
      | ID                              { AVar   $1       }
      | '(' Aexpr ')'                   { $2              }

BinExp : Aexpr '*' Aexpr                { AMul   $1 $3 }
       | Aexpr '+' Aexpr                { APlus  $1 $3 }
       | Aexpr '-' Aexpr                { AMinus $1 $3 }
       | Aexpr '/' Aexpr                { ADiv   $1 $3 }
```

Parsing :: [Token] -> AST

Non-terminals describe internal nodes of AST:

```
Aexpr : BinExp                         { $1              }
      | TNUM                           { AConst $1       }
      | ID                             { AVar   $1       }
      | '(' Aexpr ')'                  { $2              }

BinExp : Aexpr '*' Aexpr               { AMul   $1 $3 }
       | Aexpr '+' Aexpr               { APlus  $1 $3 }
       | Aexpr '-' Aexpr               { AMinus $1 $3 }
       | Aexpr '/' Aexpr               { ADiv   $1 $3 }
```

Parsing :: [Token] -> AST

Use $X to generate AST nodes

```
Aexpr : BinExp                      { $1            }
      | TNUM                        { AConst $1     }
      | ID                          { AVar   $1     }
      | '(' Aexpr ')'               { $2            }

BinExp : Aexpr '*' Aexpr            { AMul   $1 $3 }
       | Aexpr '+' Aexpr            { APlus  $1 $3 }
       | Aexpr '-' Aexpr            { AMinus $1 $3 }
       | Aexpr '/' Aexpr            { ADiv   $1 $3 }
```

Parsing :: [Token] -> AST

Structure of rules corresponds to recursive structure of type definitions:

```
Aexpr : BinExp
      | TNUM
      | ID
      | '(' Aexpr ')'

BinExp : Aexpr '*' Aexpr
       | Aexpr '+' Aexpr
       | Aexpr '-' Aexpr
       | Aexpr '/' Aexpr
```

```
data Aexpr
  = AConst  Int
  | AVar    String
  | APlus   Aexpr Aexpr
  | AMinus  Aexpr Aexpr
  | AMul    Aexpr Aexpr
  | ADiv    Aexpr Aexp
```

Parsing :: [Token] -> AST

The hardest part of writing parsers is figuring out the grammar.

A problem

```
evalString [] “2 * 5 + 5” = 20

evalString [] “2 - 1 - 1” = 2
```

A problem

```
evalString [] “2 * 5 + 5” = 20

Should be

(2 * 5) + 5
```

A problem

```
evalString [] “2 * 5 + 5” = 20

Should be

(2 * 5) + 5 = 15

Can be parsed as

(2 * 5) + 5

OR

2 * (5 + 5)
```

A problem

```
evalString [] “2 - 1 - 1” = 2

Should be

(2 - 1) - 1
```

A problem

```
evalString [] “2 - 1 - 1” = 2

Should be

(2 - 1) - 1

Can be parsed as

(2 - 1) - 1

OR

2 - (1 - 1)
```

A problem

We want to indicate that * has higher **precedence** than +

We want to indicate that - is **left-associative**

A solution

```
Aexpr : Aexpr '+' Aexpr2
      | Aexpr '-' Aexpr2
      | Aexpr2

Aexpr2 : Aexpr2 '*' Aexpr3
       | Aexpr2 '/' Aexpr3
       | Aexpr3

Aexpr3 : TNUM
       | ID
       | '(' Aexpr ')'
```

Why does this work?

“2 * 5 + 5”

Parser first looks for + or -

_ + 5 -> Plus _ 5

Why does this work?

“2 * 5 + 5”

There is now only ONE unique way to generate this string from our grammar

Start by applying the “+” rule:

_ + 5

Then apply the “*” rule:

(2 * 5) + 5

Why does this work?

“2 - 1 - 1”

There is now only ONE unique way to generate this string from our grammar

Any expression with more than one subtraction operation must have the extra subtractions in the LEFT subtree of the AST:

(2 - 1) - 1 is valid, but 2 - (1 - 1) is not, since anything on the right side of a subtraction must be generated by the Aexpr2 rule.

Another solution

```
%left '+' '-'
%left '*' '/'
```

Tells parser generator that operators are left-associative

Operators declared on bottom have higher precedence

Another solution

```
%left '+' '-'
%left '*' '/'
```

Tells parser generator that operators are left-associative

Operators declared on bottom have higher precedence

These will be provided!

More precedence

Happy will allow you to define *operator* precedence:

```
%left '+' '-'
%left '*' '/'
```

But that's not all we have to worry about:

`“foo x + 1”:` is this `(plus (foo x) 1)` or `(foo (plus x 1))`?

Your grammar will need to accomodate precedence!

Parsing :: [Token] -> AST

We could have defined our parser grammar exactly like the datatype:

```
Aexpr : TNUM
      | ID
      | '(' Aexpr ')'
      | Aexpr '*' Aexpr
      | Aexpr '+' Aexpr
      | Aexpr '-' Aexpr
      | Aexpr '/' Aexpr
```

```
data Aexpr
  = AConst  Int
  | AVar    String
  | APlus   Aexpr Aexpr
  | AMinus  Aexpr Aexpr
  | AMul    Aexpr Aexpr
  | ADiv    Aexpr Aexp
```

Parsing :: [Token] -> AST

It's generally easier to reason about the grammar if split into subtrees (AND you can deal with operator precedence):

```
Aexpr : BinExp
      | TNUM
      | ID
      | '(' Aexpr ')'

BinExp : Aexpr '*' Aexpr
       | Aexpr '+' Aexpr
       | Aexpr '-' Aexpr
       | Aexpr '/' Aexpr
```

```
data Aexpr
  = AConst  Int
  | AVar    String
  | APlus   Aexpr Aexpr
  | AMinus  Aexpr Aexpr
  | AMul    Aexpr Aexpr
  | ADiv    Aexpr Aexp
```

Extending our parser and lexer

What if we want to add boolean expressions to our language?

data AExpr = … | ITE BExpr AExpr AExpr

```
data BExpr = BTrue
           | BFalse
           | Eq AExpr AExpr
```

New tokens and matching regexes:

```
data Token = …
           | TRUE AlexPosn
           | FALSE AlexPosn
           | BEQ AlexPosn
           | IF AlexPosn
           | THEN AlexPosn
          …

“==” { \p _ -> BEQ p }
if   { \p _ -> IF p }
then { \p _ -> THEN p }
...
```

Extend the grammar

Declare more tokens in the .x file

```
...
then { THEN _ }
else { ELSE _ }
'==' {BEq _}
...
```

Extend the grammar

```
Aexpr : BinExp                                { $1           }
      | TNUM                                  { AConst $1    }
      | ID                                    { AVar   $1    }
      | '(' Aexpr ')'                         { $2           }
      | if BoolExp then Aexpr else Aexpr { ITE $2 $4 $6 }

BoolExp : true                       { BTrue }
        | false                      { BTrue }
        | Aexpr eq Aexpr             { BEq $1 $3 }
```

Breaking the grammar up makes it easier to extend!