CSE130 Discussion Section

# Week 7 - Interpreters

11/12/2021

# Interpreter

```
interpret    :: String → Value¹
```

(1) Or throws an exception

# Interpreter

```
~~interpret    :: String → Value~~
parse          :: String → Expr
eval           :: Env → Expr → Value
```

```
eval :: Env → Expr → Value
```

**Pattern match** on expressions

**Check Types** are correct (lazily)

**Lookup** variables from the environment

(Sometimes) **Add** values to the environment

```
eval :: Env → Expr → Value
```

Lazy Type Checking

```
1 + "Burger"   →   throw (Error "type error")
```

```
eval :: Env → Expr → Value
```

Lazy Type Checking

Use a more meaningful message

```
1 + "Burger"   →   throw (Error "type error")
```

```
eval :: Env → Expr → Value
```

Environment:

```
type Env = [(Id, Value)]

type Id  = String
```

```haskell
eval :: Env → Expr → Value
```

Environment:

```haskell
type Env = [(Id, Value)]

type Id  = String

lookup :: Id → Env → Value
```

```
eval :: Env → Expr → Value
```

Environment:

```
type Env = [(Id, Value)]

type Id  = String
```

$\boxed{\texttt{lookup :: Id → Env → Value}}$

returns the most recent binding for the variable

# eval :: Env → Expr → Value

What is the result of evaluating this program?

```
let a = 1 in
  let b = 2 in
    let a = a + 1 in
      a + b
```

a) 3
b) 4
c) 5
d) Error

```
eval :: Env → Expr → Value
```

What is the result of evaluating this program?

```
let a = 1 in
  let b = 2 in
    let a = a + 1 in
      a + b
```

Environment

```
[
  ("a", VInt 1)
]
```

# `eval :: Env → Expr → Value`

What is the result of evaluating this program?

```
let a = 1 in
  let b = 2 in
    let a = a + 1 in
      a + b
```

Environment

```
[
  ("b", VInt 2)
, ("a", VInt 1)
]
```

# eval :: Env → Expr → Value

What is the result of evaluating this program?

```
let a = 1 in
  let b = 2 in
    let a = a + 1 in
      a + b
```

Environment

```
[
  ("a", VInt 2)
, ("b", VInt 2)
, ("a", VInt 1)
]
```

```
eval :: Env → Expr → Value
```

What is the result of evaluating this program?

```
let a = 1 in
  let b = 2 in
    let a = a + 1 in
      a + b
```

Environment

```
[
  ("a", VInt 2)
, ("b", VInt 2)
, (“a”, VInt 1)
]
```

```
eval :: Env → Expr → Value
```

What is the result of evaluating this program?

```
let a = 1 in
  let b = 2 in
    let a = a + 1 in
      a + b
```

```
2 + 2 ⇒ 4
```

Environment

```
[
  ("a", VInt 2)
, ("b", VInt 2)
, ("a", VInt 1)
]
```

# `eval :: Env → Expr → Value`

Closures

- Dynamic vs. Lexical Scoping
- Recursive Functions

# `eval :: Env → Expr → Value`

What is the result of evaluating this program?

```
let a = 1 in
  let f = \x → x + a in
    let a = 3
      in f a
```

# eval :: Env → Expr → Value

What is the result of evaluating this program?

```
let a = 1 in
  let f = \x → x + a in
    let a = 3
      in f a
```

Environment

```
[
  ("a", VInt 1)
]
```

# eval :: Env → Expr → Value

What is the result of evaluating this program?

```
let a = 1 in
  let f = \x → x + a in
    let a = 3
      in f a
```

Environment

```
[
  ("f", VClos [...])
, ("a", VInt 1)
]
```

```
eval :: Env → Expr → Value
```

What is the result of evaluating this program?

```
let a = 1 in
  let f = \x → x + a in
    let a = 3
      in f a
```

Environment

```
[
  ("a", VInt 3)
, ("f", VClos [...])
, ("a", VInt 1)
]
```

```
eval :: Env → Expr → Value
```

What is the result of evaluating this program?

```
let a = 1 in
  let f = \x → x + a in
    let a = 3
      in f a
```

Environment

```
[
  ("a", VInt 3)
, ("f", VClos [ … ])
, ("a", VInt 1)
]
```

```
eval :: Env → Expr → Value
```

What is the result of evaluating this program?

```
let a = 1 in
  let f = \x → x + a in
    let a = 3
      in f a
```

```
(\x → x + a) a
⇒ a + a
⇒ 3 + 1
⇒ 4
```

Environment

```
[
  ("a", VInt 3)
, ("f", VClos [...])
, ("a", VInt 1)
]
```

```
eval :: Env → Expr → Value
```

Closures

```
data Value
  = …
  | VClos Env Id Expr
  | …
```

The environment when the closure is define

# `eval :: Env → Expr → Value`

Recursive Closures

- Need to know function **Name** and **Definition**.
- Where in `eval` do we have this information?
    - `ELet`
    - Anywhere else?

# `eval :: Env → Expr → Value`

`VPrim`

- "Built-in" or "`Prim`itive" functions, provided in `prelude`
- `VPrim (Value → Value)`
- We require two:
  - `head` := Return the first element of a list
  - `tail` := Return all but the first element of the list

```
eval :: Env → Expr → Value
```

That's all for `eval`!

Questions?

# Lexing & Parsing

- Read this *carefully*:

  https://github.com/cse130-sp18/arith

- But, here's a summary:
  - Lexing with `Alex` (and Regular Expressions)
  - Parsing with `Happy`

# Lexing & Parsing

- Lexing

  Converting `Strings` (list of `Chars`) to `Tokens`

```
   ['f', ' ', '*', ' ', '1', '2', '3']
⇒ [ID p "f", MUL p, NUM p 123]
```

# Lexing & Parsing

- Lexing: Regular Expressions

| | |
|---|---|
| `a` | the *letter* `"a"` |
| `[ab]` | the letter `"a"`, *or* the letter `"b"` |
| `[a-z]` | *any* lowercase letter |
| `R1 R2` | a string where *some* first part matches `R1` and the *rest* matches `R2` |
| `R+` | *one or more* `R`s |
| `R*` | *zero* or more `R`s |

# Lexing & Parsing

- Lexing: Alex

```
-- Lexer.x

$digit = 0-9

tokens :-
  [\*]          { \p s → MUL p          }
  $digit+       { \p s → NUM p (read s) }
```

# Lexing & Parsing

- Lexing: Alex

```
-- Lexer.x

$digit = 0-9

tokens :-
  [\*]        { \p s → MUL p            }
  $digit+     { \p s → NUM p (read s)   }
```

```
AlexPosn → String → Token
```

# Lexing & Parsing

- Lexing: Alex

```
-- Lexer.x

$digit = 0-9

tokens :-
  [\*]          { \p s → MUL p            }
  $digit+       { \p s → NUM p (read s) }
```

```
['f', ' ', '*', ' ', '1', '2', '3']
```

# Lexing & Parsing

- Lexing: Alex

```
-- Lexer.x

$digit = 0-9

tokens :-
  [\*]          { \p s → MUL p            }
  $digit+       { \p s → NUM p (read s) }
```

```
['f', ' ', '*', ' ', '1', '2', '3']
```

# Lexing & Parsing

- Lexing: Alex

```
-- Lexer.x

$digit = 0-9

tokens :-
  [\*]          { \p s → PLUS p            }
  $digit+       { \p s → NUM  p (read s) }
```

```
['f', ' ', '*', ' ', '1', '2', '3']
```

# Lexing & Parsing

`IDs` must start with a letter, but otherwise can contain any letter, digit or underscore (`"_"`). Which of the following is a valid Regular Expression for matching `IDs`?

a) `$alpha+ $digit* $alpha* \_*`

b) `$alpha [$alpha $digit \_]+`

c) `$alpha [$digit $alpha \_]*`

d) None of the above

```
$digit = 0-9
$alpha = [a-zA-Z]
```

# Lexing & Parsing

`ID`s must start with a letter, but otherwise can contain any letter, digit or underscore (`"_"`). Which of the following is a valid Regular Expression for matching `ID`s?

a) `$alpha+ $digit* $alpha* \_*`

b) `$alpha [$alpha $digit \_]+`

c) **`$alpha [$digit $alpha \_]*`**

d) None of the above

```
$digit = 0-9
$alpha = [a-zA-Z]
```

# Lexing & Parsing

That's all for lexing!

Questions?

# Lexing & Parsing

- Parsing: Happy

  Convert list of `Tokens` to an `Expr`

```
  [ID p "f", MUL p, NUM p 123]
⇒ EBin Mul (EVar "f") (EInt 123)
```

# Lexing & Parsing

- Parsing: Grammar

  Recursive Definition of a set of trees

  1. Terminals:
     Leaf nodes of the tree (Tokens!)
  2. Non-terminals:
     Internal nodes of the tree
  3. Production Rules:
     Rules for building the tree
     What you will define in the assignment!

# Lexing & Parsing

- Parsing: Grammar

```
Aexpr : BinExp                   { $1                }
      | TNUM                     { EInt $1           }
      | ID                       { EVar $1           }

BinExp : Aexpr '*' Aexpr         { EBin Mul $1 $3 }
```

# Lexing & Parsing

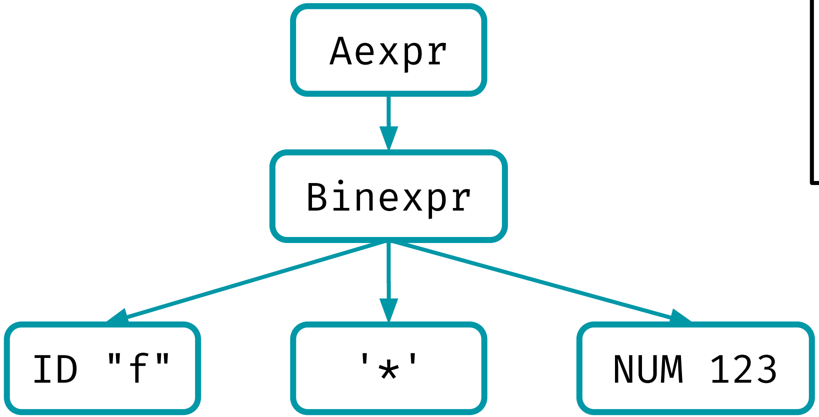
- Parsing: Grammar

```
                                                       Expr

Aexpr : BinExp                        { $1                  }
      | TNUM                          { EInt $1             }
      | ID                            { EVar $1             }

BinExp : Aexpr '*' Aexpr              { EBin Mul $1 $3      }
```

# Lexing & Parsing

- Parsing: Grammar

```
[ID p "f", MUL p, NUM p 123]
```




```
Aexpr  : BinExp                  { $1              }
       | TNUM                    { EInt $1         }
       | ID                      { EVar $1         }

BinExp : Aexpr '*' Aexpr         { EBin Mul $1 $3  }
```

# Lexing & Parsing

Which of the following *can't* be parsed with our grammar?

a) `1 * 2 * 3`
b) `x * 2 * z`
c) `1 * y * z * 1`
d) They can all be parsed

```
Aexpr : BinExp                  { $1            }
      | TNUM                    { EInt $1       }
      | ID                      { EVar $1       }

BinExp : Aexpr '*' Aexpr  { EBin Mul $1 $3 }
```

# Lexing & Parsing

Which of the following *can't* be parsed with our grammar?

a) `1 * 2 * 3`
b) `x * 2 * z`
c) `1 * y * z * 1`
d) **They can all be parsed**

```
Aexpr : BinExp                 { $1           }
      | TNUM                   { EInt $1      }
      | ID                     { EVar $1      }

BinExp : Aexpr '*' Aexpr       { EBin Mul $1 $3 }
```

# Lexing & Parsing

## Parsing: Operator Precedence

- Grammars can be *ambiguous* (multiple ways to parse a string)
- We can disambiguate by:
  a. Splitting the grammar into more non-terminals
  b. Using parser "directives" that specify operator precedence
- More in the Arith repo and lecture slides:
  a. https://github.com/cse130-sp18/arith#precedence-and-associativity
  b. https://nadia-polikarpova.github.io/cse130-web/lectures/06-parsing.html#precedence-and-associativity

# Lexing & Parsing

That's all for parsing!

Questions?

# Hints for HW4

- Start early!
- Type-check lazily
- Use meaningful error messages
- Test early, and test often:
  - `eval        :: Env    → Expr → Value`
  - `parseTokens :: String → Either String [Token]`
  - `parse       :: String → Expr`
- Run `make` before `ghci`
- Don't be afraid to split the grammar into more non-terminals for associativity