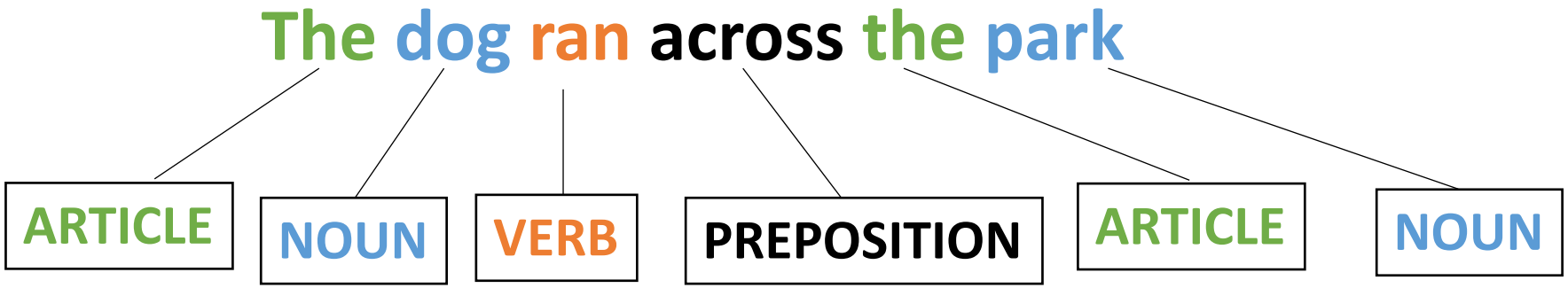
CSE110A: Compilers

April 12, 2024



- **Topics**:
  - *Finishing up Scanners*
    - *Token actions*
    - *PLY Scanner*

Announcements

- Homework 1 is out
  - You have until the 18th to complete it
  - No late submissions accepted
  - Try out gradescope and github classrooms ASAP
    - This will not be an excuse for late submissions
  - You have everything you need after today's lecture!

- Plenty of office hours left to get help!
- Let us know about any issues with the infastructure

Announcements

- No class on Monday
  - Got a last minute invite to give a talk at Microsoft Research
  - Work on homework and we'll resume class on Wednesday

- There will be a few other disruptions throughout the quarter but I'll let you know as soon as I know
  - Rithik or Sakshi can give guest lectures or potentially a zoom/async lecture.

Quiz

When implementing a Scanner using an exact RE matcher, the number of calls to the RE matcher depends on what?

- ◯ The number of tokens
- ◯ The length of the string that is being scanned
- ◯ Both of the above
- ◯ how many operators each RE has

EM Scanner

- Start with the whole string, remove one character at the end until a match is found. Then return the lexeme

```
ID     = “[a-z]+”
NUM    = “[0-9]+”
ASSIGN = ”=“
PLUS   = “+”
MULT   = “*”
IGNORE = “ |\n”
SEMI   = “;”
```

```
“variable = 50 + 30 * 20;”
```

Quiz

For which scanners can token definitions be reasoned about independently (e.g. when reasoning about if they can match strings with the same prefix)

- [ ] exact match scanner
- [ ] start of string scanner
- [ ] named group scanner
- [ ] naive scanner

EM Scanner

- Start with the whole string, remove one character at the end until a match is found. Then return the lexeme

```
ID     = “[a-z]+”
NUM    = “[0-9]+”
ASSIGN = ”=“
PLUS   = “+”
INCR   = “++”
MULT   = “*”
IGNORE = “ |\n”
SEMI   = “;”
```

“variable = 50 + 30 * 20;”

SOS Scanner

- Consideration

How to scan this string?

Try to match on each token

```
"CSE110A"
```

```
LETTERS = "[A-Z]+"
NUM     = "[0-9]+"
CLASS   = "CSE110A"
```

Two matches:

```
LETTERS: "CSE"
CLASS: "CSE110A"
```

Which one do we choose?

SOS Scanner

- One more consideration

Within 1 RE, how does this match?

"CSE110A"

```
CLASS = "CSE|110A|CSE110A"
```

Returns "CSE", but this isn't what we want!!!

When using the SOS Scanner: A token definition either should not:

- *contain choices where one choice is a prefix of another*
- *order choices such that the longest choice is the first one*

```
CLASS = "CSE110A|110A|CSE"
```

NG Scanner

- to implement `token()`

```
SINGLE_RE = "(?P<ID>[a-z]+)|
             (?P<NUM>[0-9]+)|
             (?P<ASSIGN>=)|
             (?P<PLUS>+)|
             (?P<MULT>*)|
             (?P<IGNORE> |\n)|
             (?P<SEMI>;)"
```

Try to match the whole string to the single RE

```
"variable = 50 + 30 * 20;"
```

```
{"ID"     : "variable"
 "NUM"    : None
 "ASSIGN" : None
 "PLUS"   : None
 "MULT"   : None
 "IGNORE" : None
 "SEMI"   : None}
```

How to deal with common prefixes in token definitions?

- Convert to a single RE

```
SINGLE_RE = "
        (?P<LETTERS>([A-Z]+)|
        (?P<NUM>([0-9]+)|
        (?P<CLASS>CSE110A)"
```

How to scan this string?

"CSE110A"

What do we think the dictionary will look like?

How to deal with common prefixes in token definitions?

- Convert to a single RE

```
SINGLE_RE = "
        (?P<LETTERS>([A-Z]+)|
        (?P<NUM>([0-9]+)|
        (?P<CLASS>CSE110A)"
```

How to scan this string?

"CSE110A"

```
{"LETTERS" : "CSE"
 "NUM"     : None
 "CLASS"   : None
}
```

How to deal with common prefixes in token definitions?

- Convert to a single RE

```
SINGLE_RE = "
        (?P<LETTERS>([A-Z]+)|
        (?P<NUM>([0-9]+)|
        (?P<CLASS>CSE110A)"
```

"CSE110A"

```
{"LETTERS" : "CSE"
 "NUM"     : None
 "CLASS"   : None
}
```

What does this mean?

- Tokens should not contain prefixes of each other

OR

- Tokens that share a common prefix should be ordered such that the longer token comes first

How to deal with common prefixes in token definitions?

- Careful with these tokens

```
INCR = “++”
ADD  = “+”

EQ = “==“
ASSIGN = “=“
```

Ensure that you provide them in the right order so that the longer one is first!

Quiz

For which scanners can token definitions be reasoned about independently (e.g. when reasoning about if they can match strings with the same prefix)

- [ ] exact match scanner
- [ ] start of string scanner
- [ ] named group scanner
- [ ] naive scanner

Quiz

Given C-style ids and numbers, can the following string be tokenized? If so? how many tokens will there be?

"123abc123"

- [ ] Token error
- [ ] 1 lexeme
- [ ] 2 lexeme
- [ ] 3 lexeme

tokenizing

“123abc123”

```
ID      = “[a-z][0-9a-z]+”
NUM     = “[0-9]+”
```

Quiz

Given a regular expression library, what sort of API calls would you look for in order to implement a scanner?

Regex API calls

`re.`**`fullmatch`**`(`*`pattern`*`, `*`string`*`, `*`flags=0`*`)` ¶

If the whole *string* matches the regular expression *pattern*, return a corresponding match object. Return `None` if the string does not match the pattern; note that this is different from a zero-length match.

`re.`**`match`**`(`*`pattern`*`, `*`string`*`, `*`flags=0`*`)`

If zero or more characters at the beginning of *string* match the regular expression *pattern*, return a corresponding match object. Return `None` if the string does not match the pattern; note that this is different from a zero-length match.

Regex API calls

- Other considerations?

Regex API calls

- Other considerations?
  - Named groups?
  - Operators to escape?
  - How it handles choice?
  - Speed?

Finishing up scanner implementations

Scanners we have discussed

- *Naïve Scanner*

- *RE based scanners*
  - Exact match (EM) scanners
  - Start-of-string (SOS) scanners
  - named group (NG) scanners

Which one to use?
Complex decision with performance, expressivity, and token requirements

In practice

- Most scanner generators that I am aware of have SOS semantics
  - You can reason about tokens independently
  - Use fast ”match” implementations under the hood

- Mainstream compilers:
  - have hand coded and hand optimized scanners
  - _very_ fast
  - _very_ hard to modify
  - *Only worth it to do this if you have the need and time*

Moving on

- Token actions
  - Replacement
  - Keywords
  - Error reporting
- Scanner error recovery

Moving on

- **Token actions**
  - Replacement
  - Keywords
  - Error reporting
- Scanner error recovery

First class functions

- A programming language is said to have first class functions if functions can be stored as variables
- Python has great support for this
- Functional languages have great support (and compiler helps out by checking types)
- In C++
  - Classically: function pointers
  - Newer: supports lambdas

Functions as part of a token definition

- In our scanners, we give them as the 3rd element in the token tuple definition

- A token action takes in a lexeme and returns a lexeme.
  - Possibly the same lexeme

They generally do three things:

- modify a token
- refine a token
- modify the scanner state

Functions as part of a token definition

- Once a token is matched, its token action is called on its lexeme,
- and the lexeme it returns is returned from the scanner,
- **Code example** in the EM

Examples

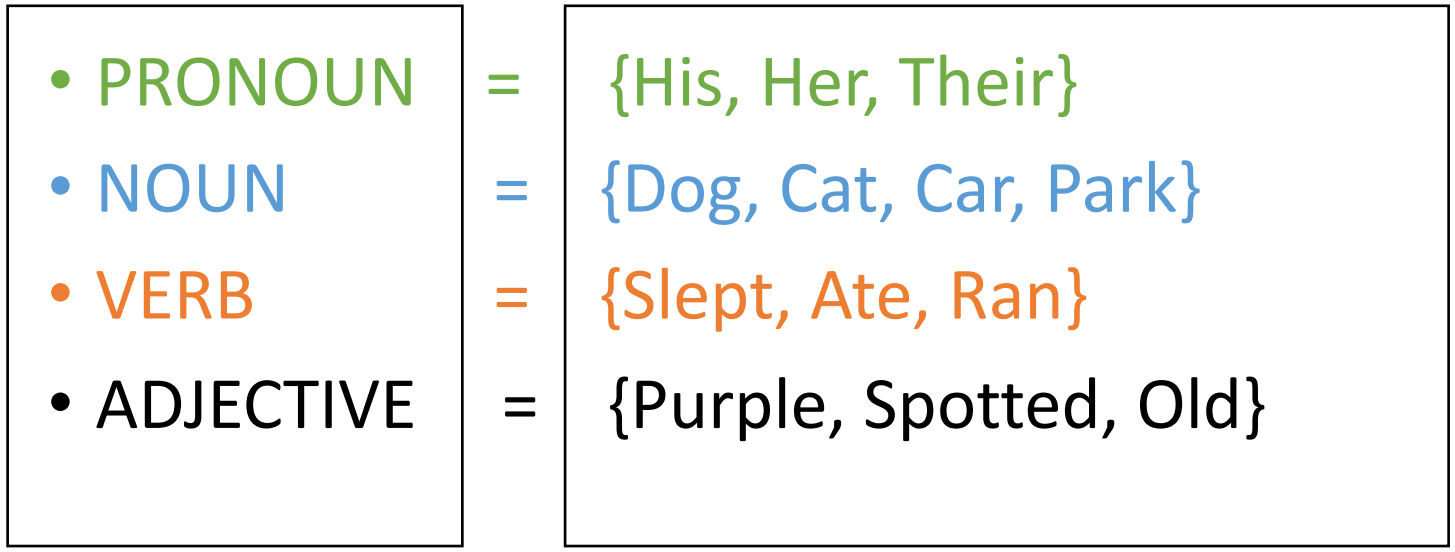
Token actions generally do three things:

- **modify a value**
- refine a token
- modify the scanner state

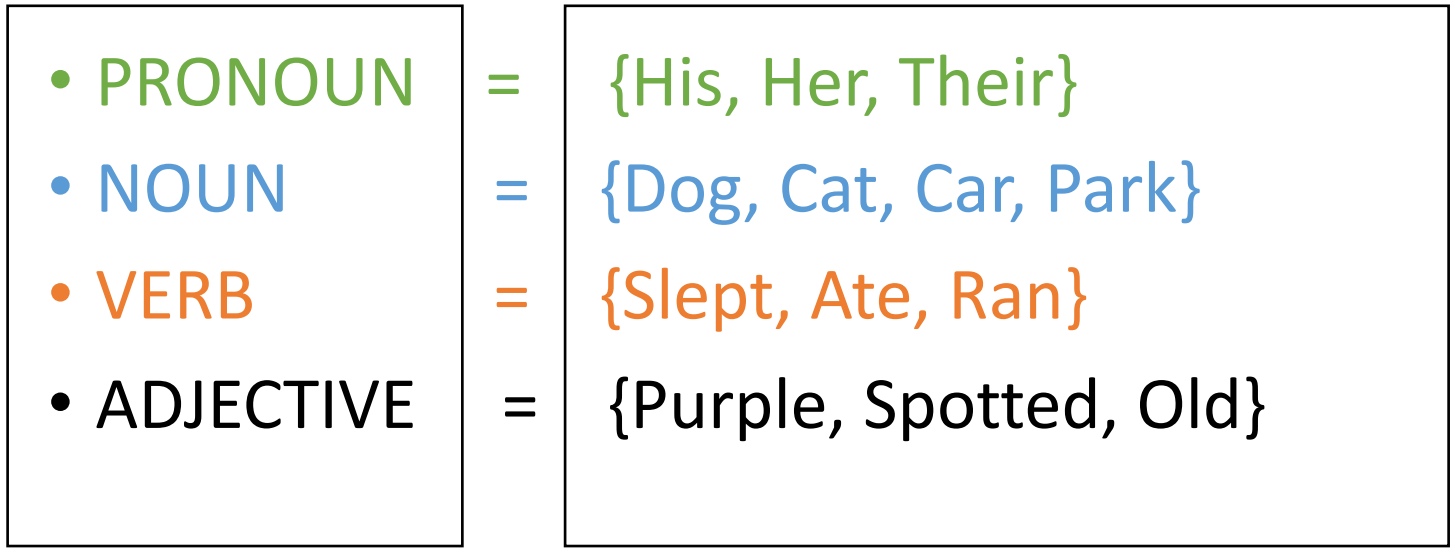
Modify a value

- Example using natural language

Modify a value



Modify a value



Example:
Can change any pronoun value to gender neutral (“Their”)

Modify a value

- Example using types

Some ML frameworks experiment with lower precision, e.g., **`float16`**

Change code to use lower precision

```
float x, y;
return x+y;
```

Scanner can easily change float16 to float with a token action

```
float16 x, y;
return x+y;
```

Examples

Token actions generally do three things:

- modify a value
- **refine a token**
- modify the scanner state

Keywords: *(finally!)*

Keywords

```
TOKENS
ID      = [a-z]+
NUM     = [0-9]+
ASSIGN  = "="
PLUS    = "+"
MULT    = "*"
IGNORE  = [" ", "\n"]

KEYWORDS
[(INT,"int"), (FLOAT, "float") ...]
```

Keywords

```
TOKENS
ID      = [a-z]+
NUM     = [0-9]+
ASSIGN  = "="
PLUS    = "+"
MULT    = "*"
IGNORE  = [" ", "\n"]

KEYWORDS
[(INT,"int"), (FLOAT, "float") ...]
```

Code example in EM Scanner

Examples

Token actions generally do three things:

- modify a value
- refine a token
- **modify the scanner state**

Modifying state

Our big use case here is error reporting

- Line number
- Column number

Doesn’t work in our homework

- Our homework has scanners import tokens
- Usually it is the other way around!!

- *Maybe some of you can think of a design where it does work in our homework*

Modifying state

In the common case, we can create a scanner and then update a class member in a token action

EM Scanner example:

Advanced topic

- Recovering from errors (syntax highlighting)
  - show Godbolt example
  - use the command line option: -fsyntax-only -Xclang -dump-tokens
  - try to tokenize weird symbols, such as `
- return an error token and try to recover
  - eating one character
  - eating until a space
  - eating until a newline

On Monday

- Enjoy your weekend!

- We will be starting Module 2 on parsing!

Next topic

- Using a scanner generator:
  - They have their own designs and it is important to understand trade-offs and design decisions
- Classically:
  - Lex and Flex
- Modern:
  - Antlr (ANother Tool for Language Recognition)
- A good in-between:
  - PLY - a Lex and Yacc implementation in Python

Lex/Flex

- Old tools - input is a token specification file. Produces a complicated C file that you would include in your project

- New language technology makes things a lot easier (higher order functions, fast RE matchers, etc.)

PLY

- written mostly for education purposes. Uses only core python features
- Personally, I have used it many times for little compiler projects
- Documented to be a python implementation of Lex, but uses a much nicer interface

How to use PLY’s Scanner

Scanner Demo

- *Library import*

```
import ply.lex as lex
```

- *Token list*

```
tokens = ["ADJECTIVE", "NOUN", "VERB", "ARTICLE"]
```

- *Token specification*

```
t_ADJECTIVE = "old|purple|spotted"
t_NOUN = "dog|computer|car"
t_ARTICLE = "the|my|a|your"
t_VERB = "ran|crashed|accelerated"
```

Scanner Demo

- *Build the lexer*

```
lexer = lex.lex()
```

what happens?

- *Need an error function*

```
# Error handling rule
def t_error(t):
    print("Illegal character '%s'" % t.value[0])
    exit(1)
```

Scanner Demo

- *Now give the lexer some input*

```
lexer.input("dog")
```

- *The lexer streams the input, we need to stream the tokens:*

```
# Tokenize
while True:
    tok = lexer.token()
    if not tok:
        break      # No more input
    print(tok)
```

Scanner Demo

- *output:*

line number (1 indexed)

```
LexToken(NOUN, 'dog', 1, 0)
```

number of characters streamed
(0 indexed)

- *try a longer string:*

```
lexer.input("dog computer")
```

What happens?

Scanner Demo

- *Need to add a token for whitespace!*

```
tokens = ["ADJECTIVE", "NOUN", "VERB", "ARTICLE", "WHITESPACE"]
```

…

```
t_WHITESPACE = '\ '
```

- *Now we can lex:*

```
LexToken(NOUN,'dog',1,0)
LexToken(WHITESPACE,' ',1,3)
LexToken(NOUN,'computer',1,4)
```

Scanner Demo

- *Now we can do a sentence*

```
lexer.input("my spotted dog ran")
```

```
LexToken(ARTICLE,'my',1,0)
LexToken(WHITESPACE,' ',1,2)
LexToken(ADJECTIVE,'spotted',1,3)
LexToken(WHITESPACE,' ',1,10)
LexToken(NOUN,'dog',1,11)
LexToken(WHITESPACE,' ',1,14)
LexToken(VERB,'ran',1,15)
```

Can we clean this up?

Scanner Demo

- *We can ignore whitespace*

```
#t_WHITESPACE = '\
t_ignore = ' '
```

```
LexToken(ARTICLE,'my',1,0)
LexToken(WHITESPACE,' ',1,2)
LexToken(ADJECTIVE,'spotted',1,3)
LexToken(WHITESPACE,' ',1,10)
LexToken(NOUN,'dog',1,11)
LexToken(WHITESPACE,' ',1,14)
LexToken(VERB,'ran',1,15)
```

gets simplified to:

```
LexToken(ARTICLE,'my',1,0)
LexToken(ADJECTIVE,'spotted',1,3)
LexToken(NOUN,'dog',1,11)
LexToken(VERB,'ran',1,15)
```

Scanner Demo

- *What about newlines?*

```
lexer.input("""
my spotted dog ran
the old computer crashed
""")
```

- *Need to add a newline token!*

Scanner Demo

- *What about newlines?*

```
lexer.input("""
my spotted dog ran
the old computer crashed
""")
```

- *Need to add a newline token!*

```
tokens = ["ADJECTIVE", "NOUN", "VERB", "ARTICLE", "NEWLINE"]

t_NEWLINE = "\\n"
```

Scanner Demo

```
LexToken(NEWLINE,'\n',1,0)
LexToken(ARTICLE,'my',1,1)
LexToken(ADJECTIVE,'spotted',1,4)
LexToken(NOUN,'dog',1,12)
LexToken(VERB,'ran',1,16)
LexToken(NEWLINE,'\n',1,19)
LexToken(ARTICLE,'the',1,20)
```

Line numbers are not updating

Scanner Demo

- *Token actions*

```
t_NEWLINE = "\\n"
```

Changes into:

```
def t_NEWLINE(t):
    "\\n"
    t.lexer.lineno += 1
    return t
```

docstring is the regex, lexer object which has a linenumber attribute.

If we don't return anything, then it is ignored.

Scanner Demo

- *Example: changing gendered pronouns into gender neutral pronouns*

```
tokens = ["ADJECTIVE", "NOUN", "VERB", "ARTICLE", "NEWLINE", "PRONOUN"]
t_PRONOUN = "her|his|their"
```

```
lexer.input("""
his spotted dog ran
her old computer crashed
""")
```

Scanner Demo

- *Add a token action:*

```
def t_PRONOUN(t):
    "her|his|their"
    if t.value in ["his", "her"]:
        t.value = "their"
    return t
```

Now output will have all gender neutral pronouns!