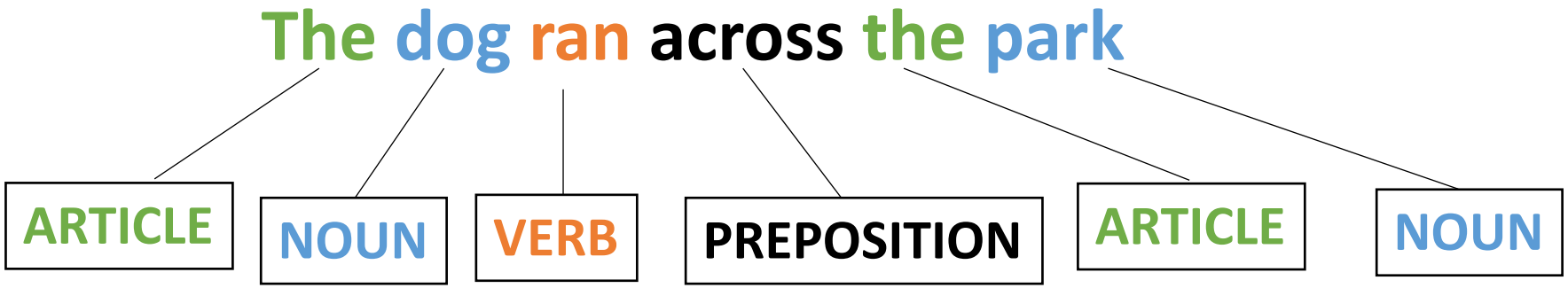
CSE110A: Compilers

April 4, 2022



- **Topics**:
  - *Lexical Analysis:*
    - Short comings of naïve scanner
  - *Regular expressions:*
    - Recursive definition
    - Syntactic sugar
    - groups

Announcements

- HW 1 will be released by midnight tonight
  - You have what you need to start working on part 1
  - You will have what you need for part 2 after Wednesday
  - You will have what you need for part 3 after Friday
- Due one week from today (by midnight)
- We will have office hours this week, come see us!

Announcements

- My office hours:
  - Thursday, 3 - 5 PM
  - Sign-up sheet goes live around noon
  - 10 minute slots
- Other office hours:

TA Office Hours:

Mondays from 1 PM to 2 PM (Virtual)

Fridays from 2 PM to 3 PM (Room BE-151)

Yanwen's office hours will be hybrid and he will use a similar sign-up sheet.

Mentoring Hours:

Arrian is Tuesday from 1 PM to 3 PM, virtual.

Neal is Wednesday 1:30 PM - 2:30 PM, virtual; and Friday 2 PM to 3 PM sharing a room with Yanwen.

Announcements

- Docker setup instructions are available
- https://sorensenucsc.github.io/CSE110A-sp2022/homework-setup.html
- We will add the required software needed for the HWs to the docker image.
- Please try this out over the next few days and let us know if you have issues
- Your code must run in the docker to be graded!
  - There can be tons of tiny differences when developing Python natively
  - If you want packages installed globally, let us know!

Quiz

Scanner API

The scanner member function "token" returns a list of the tokens that can recognize

- ◯ True
- ◯ False

Programs for Lexical Analysis

Scanner (sometimes called lexer)

Defined by a list of tokens and definitions:

Tokens		Tokens Definitions
• ARTICLE	=	{The, A, My, Your}
• NOUN	=	{Dog, Car, Computer}
• VERB	=	{Ran, Crashed, Accelerated}
• ADJECTIVE	=	{Purple, Spotted, Old}

Original program:
Lex

https://en.wikipedia.org/wiki/Lex_(software)

Popular implementations
Flex

Scanner API

```
# Constructor, generates a Scanner
s = ScannerGenerator(tokens)

# The string we want to do
# lexical analysis on
s.input("My Old Computer Crashed")

# Returns the next lexeme
s.token()
```

```
> s = ScanerGenerator(tokens)
> s.input("My Old Computer Crashed")
> s.token()
(ARTICLE, "My")
> s.token()
(ADJECTIVE, "Old")
> s.token()
(NOUN, "Computer")
> s.token()
(VERB, "Crashed")
> s.token()
None
```

Scanning vs. Parsing

A scanner should make sure that the sequence of lexemes is valid, e.g. the scanner should make sure two numbers are separated by a valid operator.

- ○ True
- ○ False

Programs for Lexical Analysis

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Popular implementations
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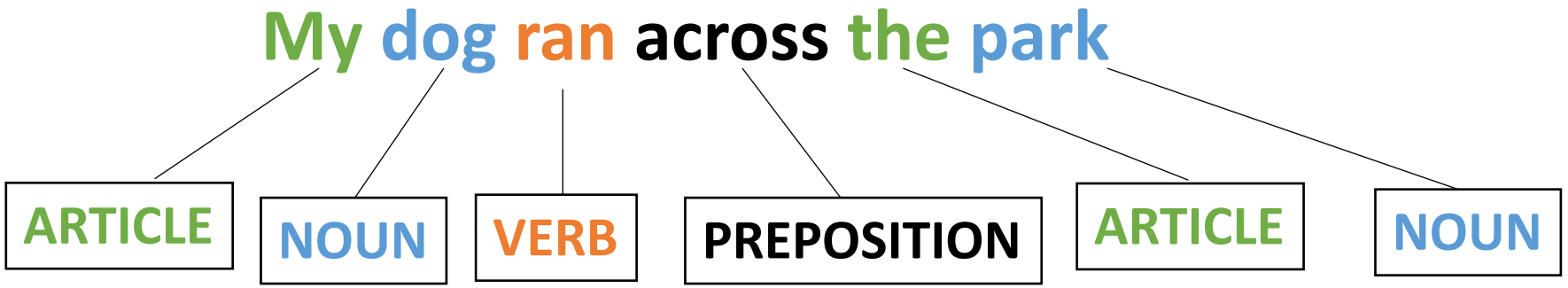
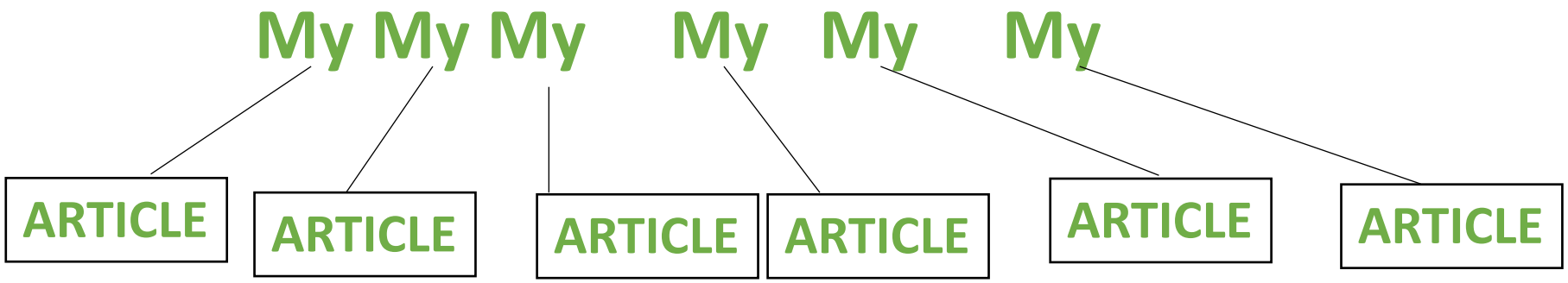
Parsing is the first step in a compiler

- How do we parse a sentence in English?



Parsing is the first step in a compiler

- How do we parse a sentence in English?



Lexical analysis doesn't care about the order of tokens. Just so long as there are valid tokens.

Programs for Lexical Analysis

Scanner (sometimes called lexer)

Defined by a list of tokens and definitions:

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Lex

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Popular implementations
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Parsing is the first step in a compiler

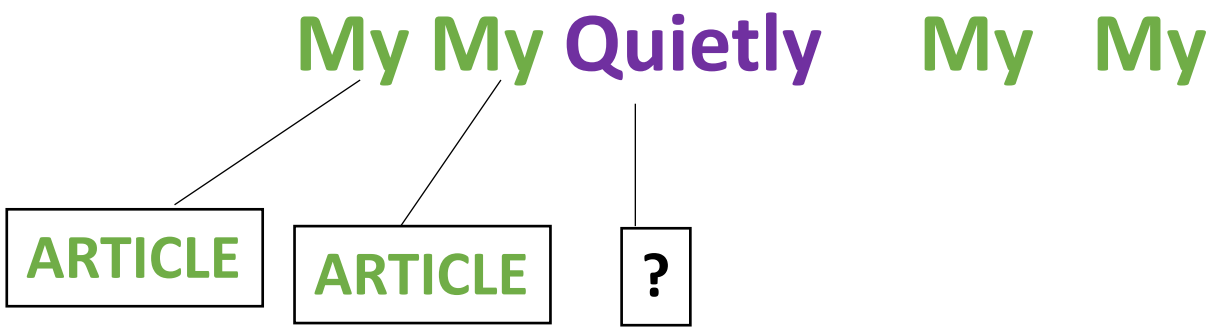
- How do we parse a sentence in English?

My My Quietly My My My

What happens here?

Parsing is the first step in a compiler

- How do we parse a sentence in English?



What happens here?

Scanner error here. Many scanners stop and report the error location

Parsing is the first step in a compiler

- How do we parse a sentence in English?

What happens here?

Scanner error here. Some scanners try to recover and keep going (difficult, and requires ad hoc rules)

Scanning vs. Parsing

A scanner should make sure that the sequence of lexemes is valid, e.g. the scanner should make sure two numbers are separated by a valid operator.

- ○ True
- ○ False

False! The order of tokens will be checked by the parser later on!

Scanning a simple PL statement

How many lexemes do you think the following statement should have?

```
for (int i = 0; i <=5; i++)
```

What lexemes do you think they should be?

Scanning a simple PL statement

```
for (int i = 0; i <= 5; i++)
```

Scanning a simple PL statement

```
for (int i = 0; i <= 5; i++)
```

```
[(ID, “for”),   (PAR, “(“), (ID, “int”), (ID, “i”),
 (ASSIGN, “=“), (NUM, “0”), (SEMI, “;”), (ID, “i”),
 (LE, “<=“),    (NUM, “5”), (SEMI, “;”), (ID, “i”),
 (INCR, “++”),  (PAR, “)”)]
```

Scanning a simple PL statement

```
for (int i = 0; i <= 5; i++)
```

```
[(ID, “for”),   (PAR, “(“), (ID, “int”), (ID, “i”),
 (ASSIGN, “=“), (NUM, “0”), (SEMI, “;”), (ID, “i”),
 (LE, “<=“),    (NUM, “5”), (SEMI, “;”), (ID, “i”),
 (INCR, “++”),  (PAR, “)”)]
```

Why not: ”<“ and “=“ separately?

Scanning a simple PL statement

```
for (int i = 0; i <= 5; i++)
```

```
[(ID, “for”),    (PAR, “(“), (ID, “int”), (ID, “i”),
 (ASSIGN, “=“), (NUM, “0”), (SEMI, “;”), (ID, “i”),
 (LE, “<=“),    (NUM, “5”), (SEMI, “;”), (ID, “i”),
 (INCR, “++”),  (PAR, “)”)]
```

Should these be the same token?

Scanning a simple PL statement

```
for (int i = 0; i <= 5; i++)
```

```
[(ID, “for”),    (LPAR, “(“), (ID, “int”), (ID, “i”),
 (ASSIGN, “=“), (NUM, “0”),   (SEMI, “;”), (ID, “i”),
 (LE, “<=“),     (NUM, “5”),   (SEMI, “;”), (ID, “i”),
 (INCR, “++”),   (RPAR, “)”)]
```

Should these be the same token? Probably not

Review

Naïve implementation

- A scanner that implements

```
ID     = [characters]
NUM    = [numbers]
ASSIGN = "="
PLUS   = "+"
MULT   = "*"
IGNORE = [" "]
```

Naïve implementation

Building block:

```
class StringStream:
    def __init__(self, input_string):
        self.string = input_string


    def is_empty(self):
        return len(self.string) == 0


    def peek_char(self):
        if not self.is_empty():
            return self.string[0]
        return None


    def eat_char(self):
        self.string = self.string[1:]
```

Naïve implementation

First step in implementing the scanner

```
class NaiveScanner:

    def __init__(self, input_string):
        self.ss = StringStream(input_string)

    def token(self):

        while self.ss.peek_char() in IGNORE:
            self.ss.eat_char()

        if self.ss.is_empty():
            return None
```

```
ID     = [characters]
NUM    = [numbers]
ASSIGN = "="
PLUS   = "+"
MULT   = "*"
IGNORE = [" "]
```

Naïve implementation

First step in implementing the scanner

```
class NaiveScanner:

    def token(self):
        ...
        if self.ss.peek_char() == "+":
            value = self.ss.peek_char()
            self.ss.eat_char()
            return ("ADD", value)


        if self.ss.peek_char() == "*":
            value = self.ss.peek_char()
            self.ss.eat_char()
            return ("MULT", value)
```

```
ID     = [characters]
NUM    = [numbers]
ASSIGN = "="
PLUS   = "+"
MULT   = "*"
IGNORE = [" "]
```

Naïve implementation

First step in implementing the scanner

```
class NaiveScanner:

    def token(self):
        ...
        if self.ss.peek_char() in NUMS:
            value = ""
            while self.ss.peek_char() in NUMS:
                value += self.ss.peek_char()
                self.ss.eat_char()
            return ("NUM", value)
```

```
ID     = [characters]
NUM    = [numbers]
ASSIGN = "="
PLUS   = "+"
MULT   = "*"
IGNORE = [" "]
```

Schedule

- Naïve Parser:
  - Code demo and discussion
- Regular expressions

Code Demo

Shortcomings of Naïve scanner

- Any thoughts?

Shortcomings of Naïve scanner

- IDs with numbers in them?
  - `x1, y1, etc.`
  - how would you solve?
- Numbers with a decimal point in them?
  - `4.5, 9999.99998`
  - how would you solve this?
- Two character operators:
  - `++, +=`
  - how would you solve this?

Shortcomings of Naïve scanner

- IDs with numbers in them?
  - `x1, y1, etc.`
  - how would you solve?
- Numbers with a decimal point in them?
  - `4.5, 9999.99998`
  - how would you solve this?
- Two character operators:
  - `++, +=`
  - how would you solve this?

Things get really hacky really quickly!

Creates a bad design that is not easily extended or maintained

How do we solve this?

A new token definition language:

- **Regular expressions**
- Tokens will be defined using regular expressions
- Scanners can then utilize regular expression matchers

Benefits:

- Extensible design
  - easy to add new tokens, modify existing definitions
- Modular
  - Scanner can utilize common regex libraries

Cons:

How do we solve this?

A new token definition language:

- **Regular expressions**
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Benefits:

- Extensible design
  - easy to add new tokens, modify existing definitions
- Modular
  - Scanner can utilize common regex libraries

Cons:

- Token definitions are restricted to regular languages
- Potentially slower
- Regular expression matchers are complicated

Schedule

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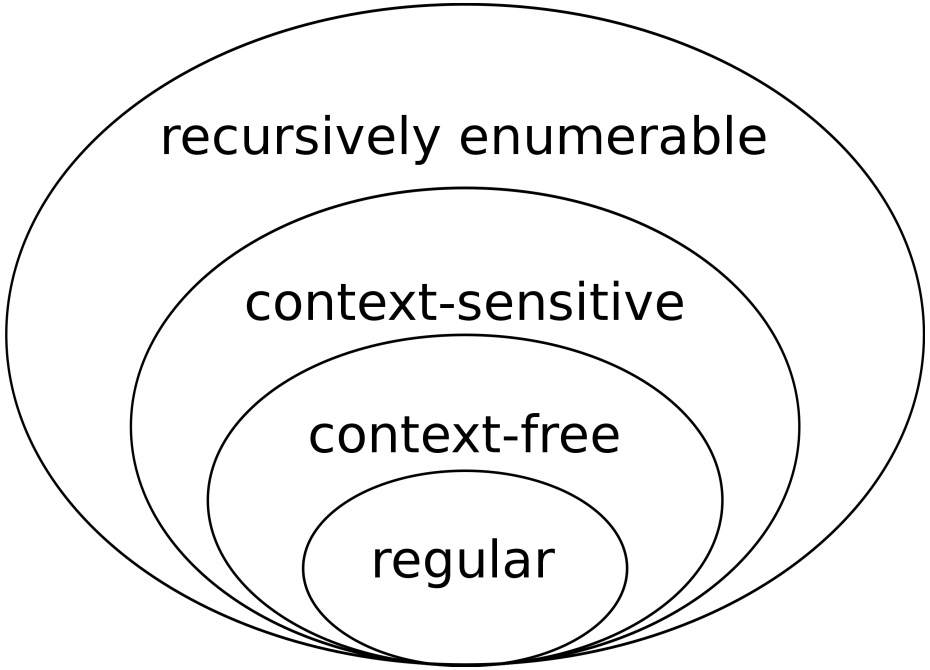
Regular expressions

Some theory:

- Given a language *L*, a string *s* is either part of that language or not
  - Integers are a language: “5”, “6”, “-7” is in the language. “abc” is not.
- Languages are grouped into families depending on how “hard” it is to determine if a string is part of that language.

Regular expressions



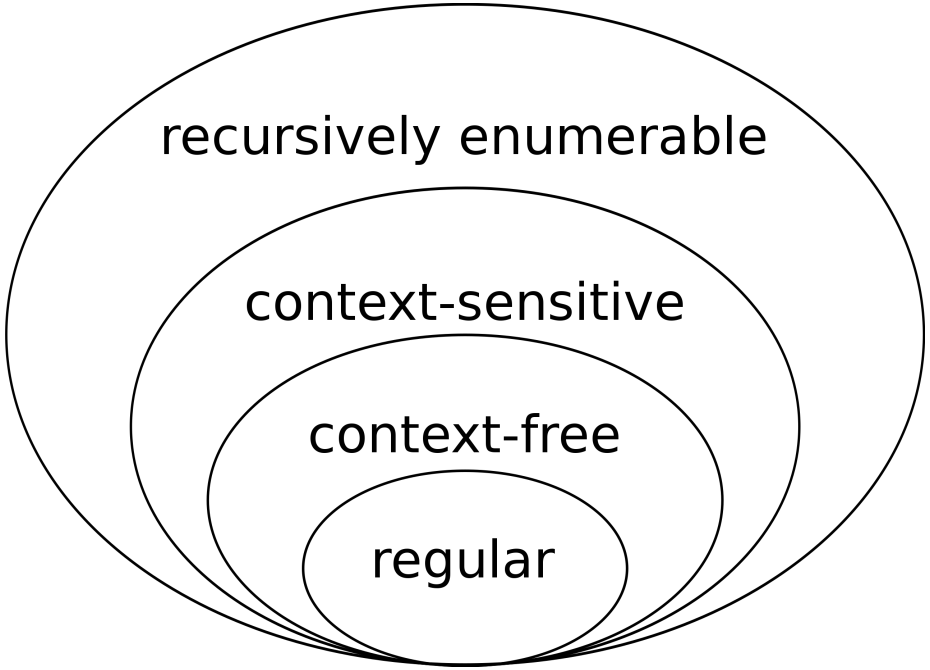
The simplest languages are regular. We will use regular languages as our token language.

We will use the next level: context-free, as the language for our parser.

Higher levels are interesting, but not as useful in compilers. Why?

image source: wikipedia

Regular expressions



The simplest languages are regular. We will use regular languages as our token language.

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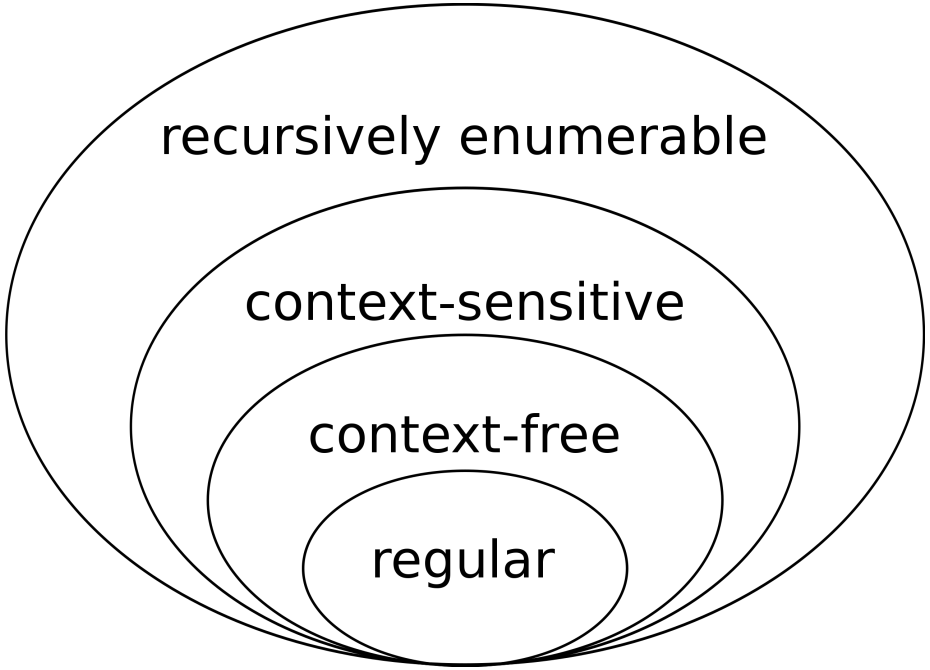
Higher levels are interesting, but not as useful in compilers. Why?

Because deciding if a string is in a recursively enumerable language is undecidable.

image source: wikipedia

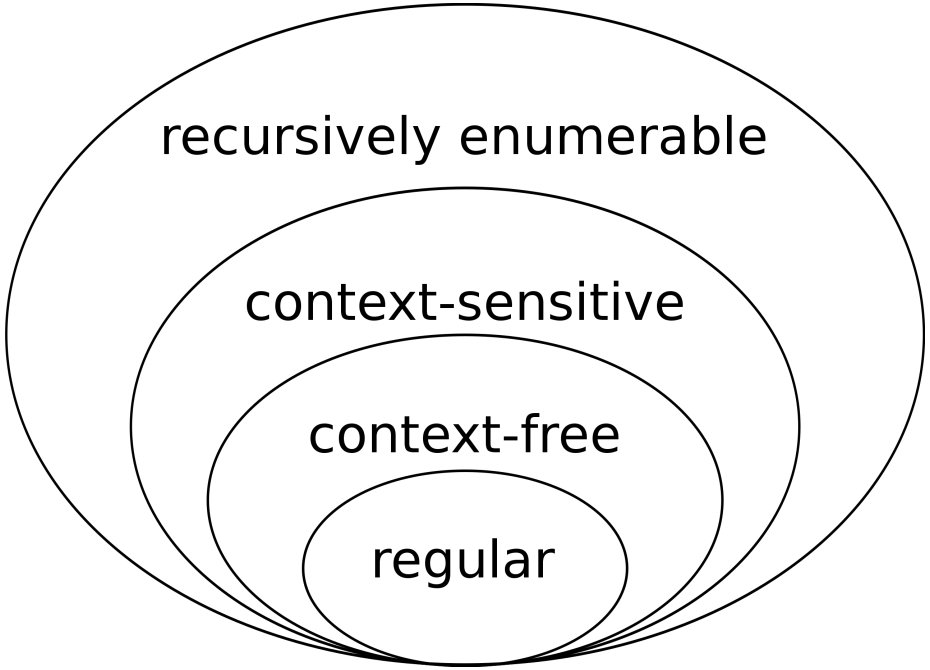
Regular expressions



What is a regular language?

image source: wikipedia

Regular expressions

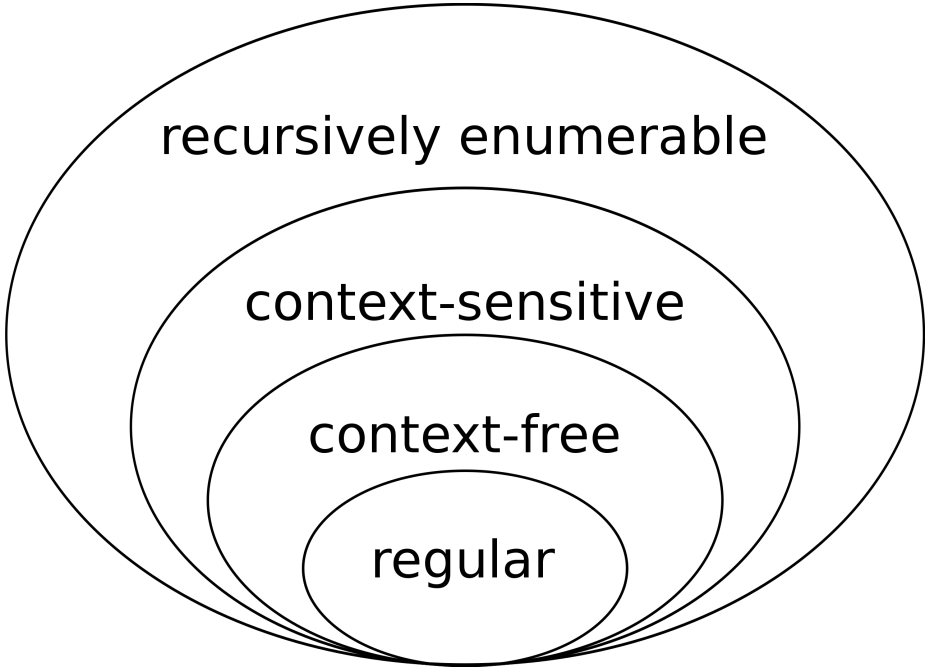


What is a regular language?

For this class: *A regular language is a language that can be expressed as a regular expression.*

image source: wikipedia

Regular expressions



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What is a regular expression?

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Schedule

- Naïve Parser:
  - Code demo and discussion
- Regular expressions

Regular expressions

- We will define regular expressions (RE) recursively
- We will show examples at each step.
- And show to match them in Python
  - *A string matches an RE if it belongs to the regular language defined by the RE*
  - Python has a great RE matching library

Regular expressions

```
# import the library
import re

# pattern is a string representing the RE
# the function reports whether string matches RE
re.fullmatch(pattern, string)
```

Regular expressions

- **We will define regular expressions (RE) recursively**

- Like any recursive function, we can start with the base case:

a regular expression can be a single character or the empty string

Regular expressions

- **We will define regular expressions (RE) recursively**

- Like any recursive function, we can start with the base case:

a regular expression can be a single character or the empty string

Example:

```
ASSIGN = “=“
PLUS   = ”+”
```

Python:

```
import re
re.fullmatch(“=“, “=“)

re.fullmatch(“+”, “+”) # what happens here?
```

Regular expressions

- When we define regular expressions, some characters are special.
  - They are operators in the regular expression language
  - If we want to use them as a character, then we need to ”escape them” with a \
  - “+” happens to be one of those characters

https://riptutorial.com/regex/example/15848/what-characters-need-to-be-escaped-

Python:

```
import re
re.fullmatch(“=“, “=“)

re.fullmatch(“\+”, “+”) # what happens here?
```

Regular expressions

- **We will define regular expressions (RE) recursively**

- Like any recursive function, we can start with the base case:

a regular expression can be a single character or the empty string

Python:

```
import re
re.fullmatch(“”, “”)
```

Not super useful for us, but useful for the theory

Regular expressions

- First recursive case: **concatenation**

- Two REs can be concatenated by simply writing them in sequence:
  - RE1 = ”a”, RE2 = “b”
  - concatenated it is: RE12 = “ab”

- This allows us to build words

Example:

```
FOR   = “for“
WHILE = ”while”
```

Python:

```
import re
re.fullmatch(“for“, “for“)
re.fullmatch(“a+b”, “a+b”) # what happens here?
```

Can we define these tokens yet?

Tokens		Tokens Definitions
• ARTICLE	=	{The, A, My, Your}
• NOUN	=	{Dog, Car, Computer}
• VERB	=	{Ran, Crashed, Accelerated}
• ADJECTIVE	=	{Purple, Spotted, Old}

Can we define these tokens yet? No, we need one more operator

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Regular expressions

- Second recursive operator: **choice** (sometimes called ”union”, or “or”)

- Two REs can be choiced together using the “|” operator
  - RE1 = “a”, RE2 = “b”
  - The choice is: RE1|2 = “a|b”
  - Matches either

Example:

```
OP    = “*|+“
CMP   = “==|<=|>=”
```

Python:

```
import re
re.fullmatch(“*|+“, “+“)
re.fullmatch(“==|<=|>=”, “==”)
```

Can we define these tokens yet?

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• ADJECTIVE	=	{Purple, Spotted, Old}

Can we define these tokens yet? Yes!

Tokens		Tokens Definitions
• ARTICLE	=	“The|A|Mine|Your”
• NOUN	=	“Dog|Car|Computer”
• VERB	=	“Ran|Crashed|Accelerated”
• ADJECTIVE	=	“Purple|Spotted|Old”

Can we define these tokens yet?

```
ID     = [characters]
NUM    = [numbers]
ASSIGN = "="
PLUS   = "+"
MULT   = "*"
IGNORE = [" "]
```

Can we define these tokens yet? No!

```
ID     = [characters]
NUM    = [numbers]
ASSIGN = "="
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IGNORE = [" "]
```

Regular expressions

- Last recursive operator: **Repeat**

- Unary operator: *
  - RE1 = “a”
  - Repeat RE1 zero or more times: ”a*”

Example:

```
RE1   = “a*“
RE2   = “a*|b*”
RE3   = ”a|b*
```

Python:

```
import re
re.fullmatch(“a*|b*“, “aaa“)
re.fullmatch(“a*|b*”, “”)
```

Regular expressions

- Last recursive operator: **Repeat**

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Example:

```
RE1   = “a*“
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RE3   = ”a|b*
```

Precidence?

Python:

```
import re
re.fullmatch(“a*|b*“, “aaa“)
re.fullmatch(“a*|b*”, “”)
```

Regular expressions

- Lets make an RE for binary numbers

- Lets make an RE for decimal numbers

Regular expressions

- These are the theoretical foundational operators.
- Most languages give syntactic sugar to make common cases easier
- Most languages also break the theory
  - Perl regexes are extremely complicated
    - https://www.perlmonks.org/?node_id=809842
  - Python regexes (with recursion) are can capture context free languages
    - https://www.npopov.com/2012/06/15/The-true-power-of-regular-expressions.html#matching-context-free-languages

Regular expressions

- strict repeat operator: +
- one or more repeats (the * operator is 0 or more repeats)
- derivation: “r+” = “rr*”
- *Let’s revisit binary numbers and decimal numbers*

“(0|1)+”

Regular expressions

- Ranges:
  - digits [0-9]
  - alpha [a-z], [A-Z]
- Derivation: [0-9] = ”1|2|3|4|5|6|7|8|9”
- Lets try C style IDs:
- Hexadecimal numbers:

Regular expressions

- Ranges:
  - digits [0-9]
  - alpha [a-z], [A-Z]
- Derivation: [0-9] = ”1|2|3|4|5|6|7|8|9”
- Lets try C style IDs: “[a-zA-Z][0-9a-zA-Z]*”
- Hexadecimal numbers: “0x[0-9a-fA-F]”

Regular expressions

- optional operator ?
  - optional characters
- “r?” = “|r”
- Example: “ab?”
- Let’s do simple floating point numbers

Regular expressions

- optional operator ?
  - optional characters

- “r?” = “|r”

- Example: “ab?”

- Let’s do simple floating point numbers: “[0-9]+(\.[0-9]+)?”

Regular expressions

- any character ‘.’

- example using email (this is probably too general!)

Regular expressions

- any character ‘.’
- example using email (this is probably too general!)
- ”.*@.*\.com”

Using REs

- What if we want either the domain or user name from the email?
- We can use groups!
  - use ()s to deliminate groups
- ”(.*)@(.*\.com)”
- Index the resulting object with [1] and [2] to get to the user name and domain respectively

Using REs

- you can give groups id names rather than using indices

- “(?P<name>.+)@(?P<domain>.+\.com)”

RE examples

XKCD comic

https://xkcd.com/208/

REs are good for?

- Scanning large amounts of documents quickly, looking for:
  - Websites
  - Email
  - Profiling numbers
  - Variable usages
  - **What else?**

RE examples

- **What can REs not do?**

- Nested structures, such as parathesis matching:
  - Try doing arithmetic expressions
  - You will not be able to match ()s

- Classical example: REs cannot capture same number of repeats:
  - A{N}B{N}

- REs cannot parse HTML!!!
  - One of the most upvoted answers on stackoverflow!
  - https://stackoverflow.com/questions/1732348/regex-match-open-tags-except-xhtml-self-contained-tags/1732454#1732454

Let’s write our tokens as regular expressions

- For our simple programming language

```
ID     = [characters]
NUM    = [numbers]
ASSIGN = ”=“
PLUS   = “+”
MULT   = “*”
IGNORE = [“ “]
```

How to implement an RE matcher?

- Overview: first you have to parse the RE...
  - Chicken and egg problem
  - The language of REs is not a regular language. It is context sensitive (because it has ()s)

  - But once you can parse the RE, there are several options

How to implement an RE matcher?

- parsing with derivatives
  - We discuss this in CSE211
  - Elegant solution, but difficult to make fast

- Convert to an automata
  - Learn more about this CSE103
  - A cool website
  - https://ivanzuzak.info/noam/webapps/fsm_simulator/

How to use REs in a scanner implementation?

- We will discuss next class
- See you on Wednesday!