Lecture 2: Static Analysis Principles – Lexical and Syntactical Language Analysis

Passive Testing Techniques for Communication Protocols

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Outline

Goal & Motivation

Lexical Analysis using Finite State Automata / Regular Expressions

Syntactical Analysis with Context Free Grammars

STATIC ANALYSIS

```
/*Test equal distribution of random number generation algorithm*/
#include <stdio.h>
#include <stdlib.h>
#define NUM 30
#define MEM_SIZE 512*1024 //512MB
int main()
{
        long i = 0 , j;
        short acc = 0;
        if(!numbers)
        {
                printf(``Can't allocate memory\n'');
                exit(-1);
        }
        while (1)
        {
                numbers[i] = rand() % NUM ;  //random numbers from 0 - NUM
                acc = 0;
                for (j = 0; j < i; j++)
                        acc += numbers[j];
                printf(``New average: %ld\n'',  acc/++i); //should converge to NUM/2
        }
}
```

Do you see any problems with this code?

Static Analysis (cont.)

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See how hard it is? :)

STATIC ANALYSIS PRINCIPLES

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- A text representation of “computer instructions” in a specific **programming language**

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- The analysis (performed by a program) of code without executing the program

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Static Analysis is?..

- The analysis (performed by a program) of code without executing the program
- Not looking for lexical, syntactical, or *type* errors that a compiler finds, i.e., the code is assumed to be compilable

Static Analysis Principles (cont.)

How do we analyze source code then?

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How to structure code: A natural language comparison

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- A language can produce sentences. Sentences are structured; composed by words

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How to structure code: A natural language comparison

- A language can produce sentences. Sentences are structured; composed by words
- How to recognize allowed words in a language?

Lexical Analysis

using Deterministic Finite Automata (DFA) and Regular Expressions (RE)

Lexical Analysis

DFA and RE equivalence

Lexical Analysis

DFA and RE equivalence

- A DFA can recognize a language

LEXICAL ANALYSIS

DFA and RE equivalence

- A DFA can recognize a language
- A RE can describe how to generate a language

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DFA and RE equivalence

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- There is a way to go from one to the other, describing the same language

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Let's start with regular expressions…

Regular expressions

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- r^* – Kleene star = $\varepsilon | r | rr | rrr | \ldots$

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Example

Over the alphabet $\{0, 1, 2, 3, 4, 5, 6, 7, 8, 9\}$,
$(1|2|3|4|5|6|7|8|9)(0|1|2|3|4|5|6|7|8|9)^*$

Regular expressions (cont.)

Generating from $(1|2|3|4|5|6|7|8|9)(0|1|2|3|4|5|6|7|8|9)^*$

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- $(1|2|3|4|5|6|7|8|9) \mapsto 8$
  $8(0|1|2|3|4|5|6|7|8|9)^*$

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- Can be non-deterministic, applying different rules will produce different results
- Our goal is to describe language with a regular expression

EXERCISES WITH REs

What language the RE describes?

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Create the RE such that…

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Create the RE such that…

- It generates valid Binary Code Decimal (BCD) strings (In case you don't know, binary strings of length 4, representing digits, example: 1001 1000 0011 = 983, note that 1100 0000 0101 is not valid)

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  - $A = \{0, 1, \text{“ ”}\}$, RE = $100(1|0)|0(1|0)(1|0)(1|0)\text{“ ”}(100(1|0)|0(1|0)(1|0)(1|0)\text{“ ”})^*$

Short RE notations

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  - e.g., for $A = \{a,b\}$, RE = $aaa(a|b)(a|b) \mapsto a\{3\}.\{2\}$

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- $\{m,n\}$ represents at least m, and at most n occurrences of the preceding RE
  - e.g., for $A = \{a,b\}$, RE = $(a|aa|aaa)b \mapsto a\{1,3\}b$

Short RE notations (cont.)

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- $[a_1 a_2 \ldots a_n]$ represents choice between all a_i
  - e.g., $A = \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9\}$, the RE $(0|1|2|3|4|5|6|7|8|9) \mapsto [0123456789]$ (note it is different from 0123456789 which is concatenation)

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- $[a_1 - a_n]$ represents choice between a range. Note that it only makes sense for ranges
  - e.g., $A = \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9\}$, the RE $(0|1|2|3|4|5|6|7|8|9) \mapsto [0 - 9]$ (note it is different from $0| - |9$, $-$ has a special meaning inside brackets, useful for REs like $[a - z]$ or $[a - zA - Z]$, the later combined with the previous short notation)

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- $[\hat{}r]$ negation of r
  - e.g., $A = \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9\}$, the RE $(1|2|3|4|5|6|7|8|9) \mapsto [\hat{}0]$ (note it is different from $0|\hat{}$ by using the "short OR")

Short RE notations – Final Remarks

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- The alphabet is usually omitted and assumed from the symbols appearing in the RE
  - e.g., the RE $[0-9]$ is assumed to have the alphabet $A = \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9\}$

Short RE notations – Final Remarks

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- The alphabet is usually omitted and assumed from the symbols appearing in the RE
  - e.g., the RE $[0-9]$ is assumed to have the alphabet $A = \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9\}$
- REs are used for **pattern matching**, which means if a part of a string can be generated by the RE (or accepted by the equivalent automaton, more on this later), the string matches the pattern described by the RE. This leads to some notations, as: ^ to denote the beginning of the string, and \$ for the end of the string.
  - e.g., the RE $\hat{}a.*b\$$ means anything that starts with a, and finishes with b

Exercises with short RE notations

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  - Dates in the format yyyy-mm-dd (not well specified since it accepts 2016-02-31, for example)

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  - Dates in the format yyyy-mm-dd (not well specified since it accepts 2016-02-31, for example)
- $bb|[\hat{}(2b)]$
  - Two 'b' or not '2b', that's the question... Actually, a bad example, it accepts anything that is not '2b', but it's a classical :)

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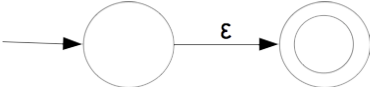

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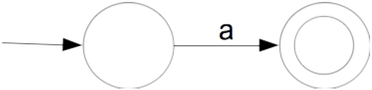

Converting REs to NFA (cont.)

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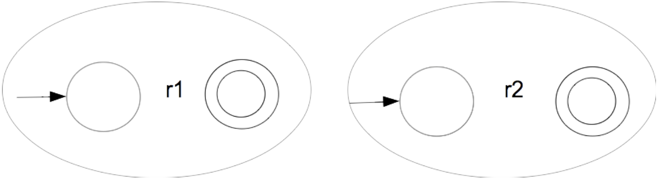

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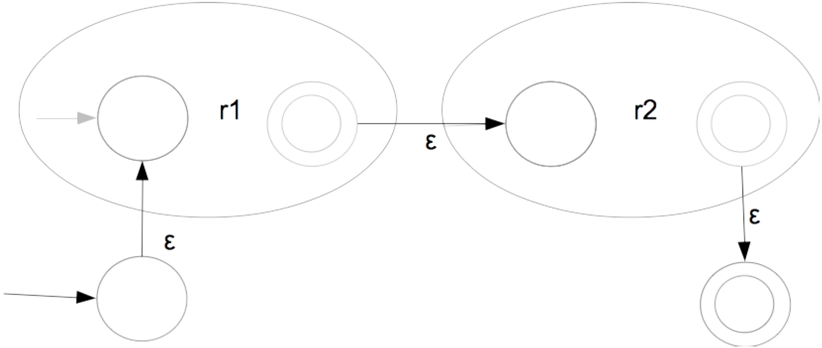

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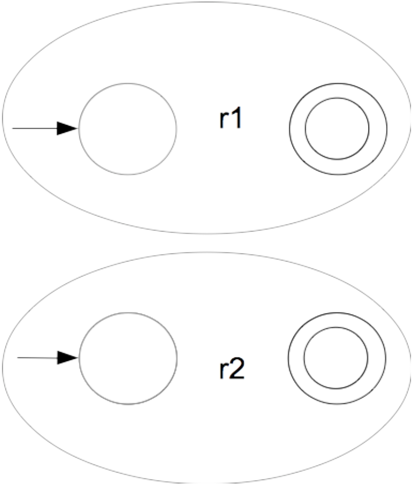

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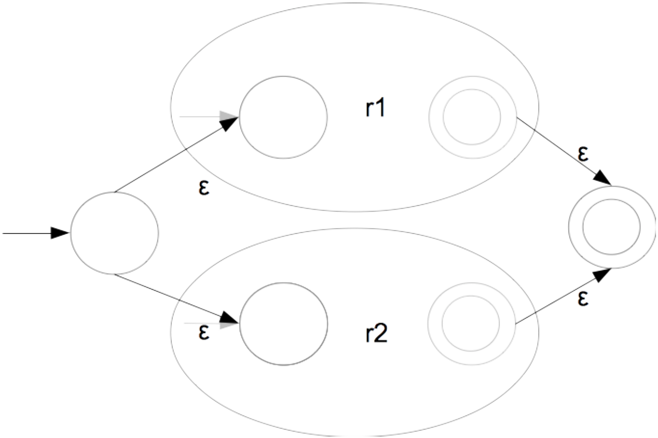

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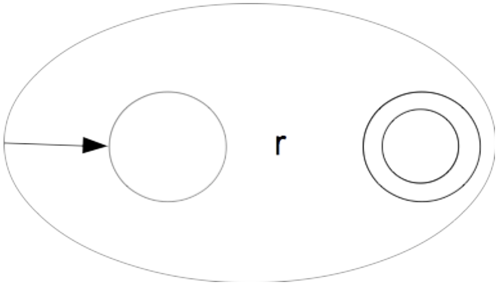

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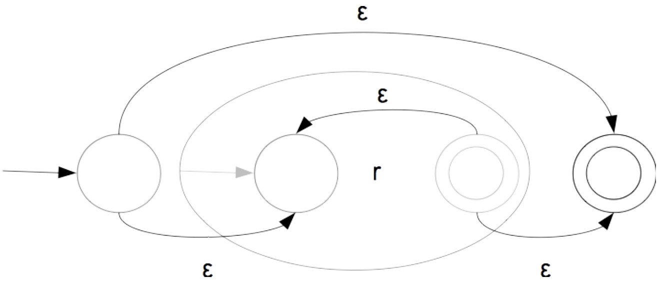

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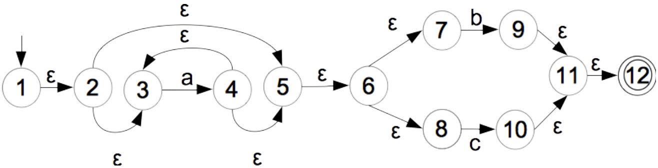

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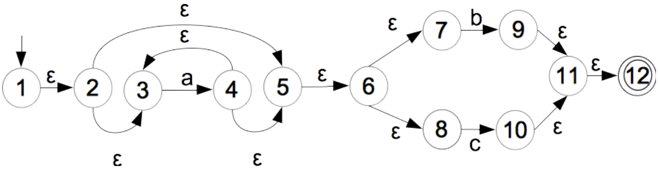

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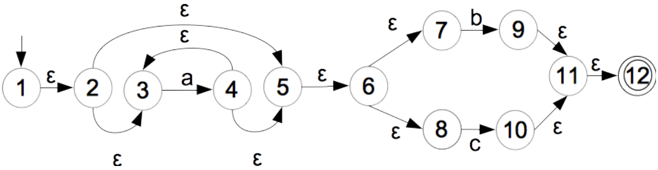

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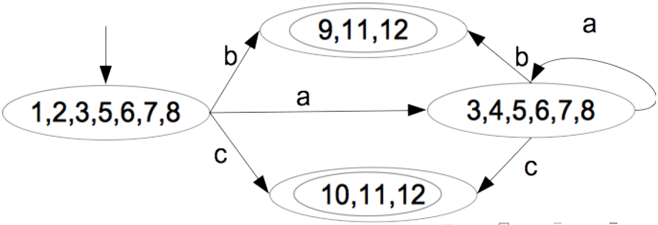

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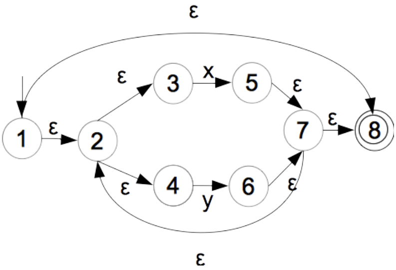

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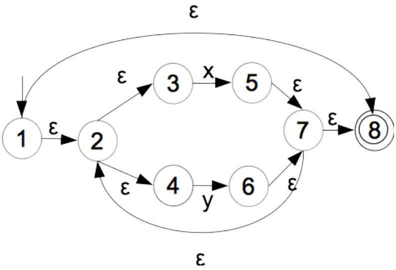

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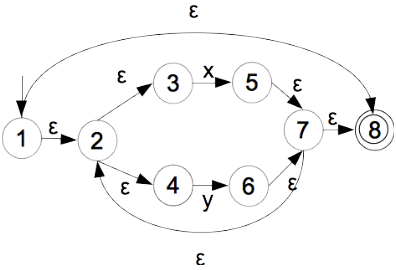

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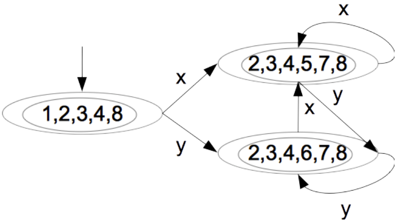

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- The important REs for the source code include keywords (if, while, for, etc.), numbers (floats, ints, etc.) identifiers (variable names, etc.), each category is specified with a RE.
- When the source code is passed to the lexer (the program performing the lexical analysis), it returns a **tokenized** string. For example:

```
if(j + 2) return 10;
```

Yields:

```
keyword(if) l_paren identifier(j) add_op num(2) r_paren keyword(return) num(10) sc
```

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Solution:

Syntactical analysis with a **Context-Free Grammar (CFG)**

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using Context-Free Grammars (CFG)

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- As a DFA (or NFA) recognizes a regular language, a Push Down Automaton (PDA) recognizes a non-regular language
- To describe a push down automaton, it can be convenient to do it through a CFG, as it is more convenient to describe a DFA with a very elegant and simple RE (instead of state transition, etc)

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- $p \in P$ has the notation $N \mapsto \alpha$, where $\alpha \in (T \cup N)^*$. This means, in the left hand side of the production rule there is only one non-terminal (which makes it context-free), and on the right hand a sequence of terminal and non-terminal symbols

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- Important note: different choices produce different "sentences"

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- $int\ op\ opar\ int\ op\ int\ cpar$ (3)

Example CFG, generating a string of the CFG

- $op = +|-|/|*$
- $int = [0-9]^+$
- $opar = ($
- $cpar =)$

1. $Start \mapsto Expr$
2. $Expr \mapsto Expr\ op\ Expr$
3. $Expr \mapsto int$
4. $Expr \mapsto opar\ Expr\ cpar$

Let's derive...

- $Start$
- $Expr$ (1)
- $Expr\ op\ Expr$ (2)
- $int\ op\ Expr$ (3)
- $int\ op\ opar\ Expr\ cpar$ (4)
- $int\ op\ opar\ Expr\ op\ Expr\ cpar$ (2)
- $int\ op\ opar\ int\ op\ Expr\ cpar$ (3)
- $int\ op\ opar\ int\ op\ int\ cpar$ (3)
- 10 / (7 – 5)

Example CFG, generating a string of the CFG

- $op = +|-|/|*$
- $int = [0-9]^+$
- $opar = ($
- $cpar =)$

1. $Start \mapsto Expr$
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Let's derive…

- $Start$
- $Expr$ (1)
- $Expr\ op\ Expr$ (2)
- $int\ op\ Expr$ (3)
- $int\ op\ opar\ Expr\ cpar$ (4)
- $int\ op\ opar\ Expr\ op\ Expr\ cpar$ (2)
- $int\ op\ opar\ int\ op\ Expr\ cpar$ (3)
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- 10 / (7 – 5)

Please, derive one yourselves

Constructing a CFG

Let's assume we want to describe the non-regular language for a for HTML tables (looks like this):

Constructing a CFG

Let's assume we want to describe the non-regular language for a for HTML tables (looks like this):

```
<table style="width:100%">
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    <th>Name</th>
    <th>Lastname</th>
    <th>Score</th>
  </tr>
  <tr>
    <td>Eve</td>
    <td>Jackson-Renard</td>
    <td>94</td>
  </tr>
  <tr>
    <td>Vladimir</td>
    <td>López</td>
    <td>80</td>
  </tr>
</table>
```

Constructing a CFG

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  <tr>
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    <td>94</td>
  </tr>
  <tr>
    <td>Vladimir</td>
    <td>López</td>
    <td>80</td>
  </tr>
</table>
```

Produces (close-enough):

Name	Lastname	Score
Eve	Jackson-Renard	94
Vladimir	López	80

Constructing a CFG (cont.)

Let's assume we want to describe the non-regular language for a for HTML tables (looks like this):

```
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  </tr>
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    <td>Vladimir</td>
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  </tr>
</table>
```

Constructing a CFG (cont.)

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    <td>94</td>
  </tr>
  <tr>
    <td>Vladimir</td>
    <td>Lopez</td>
    <td>80</td>
  </tr>
</table>
```

REs:

- table attributes (class, border, etc.)

Constructing a CFG (cont.)

Let's assume we want to describe the non-regular language for a for HTML tables (looks like this):

```
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    <th>Name</th>
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  <tr>
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    <td>Lopez</td>
    <td>80</td>
  </tr>
</table>
```

REs:

- $attributes = style|class|border|\ldots$

Constructing a CFG (cont.)

Let's assume we want to describe the non-regular language for a for HTML tables (looks like this):

```
<table style="width:100%">
  <tr>
    <th>Name</th>
    <th>Lastname</th>
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    <td>Lopez</td>
    <td>80</td>
  </tr>
</table>
```

REs:

- $attributes = style|class|border|\ldots$
- values of the attributes

Constructing a CFG (cont.)

Let's assume we want to describe the non-regular language for a for HTML tables (looks like this):

```
<table style="width:100%">
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    <td>Lopez</td>
    <td>80</td>
  </tr>
</table>
```

REs:

- $attributes = style|class|border|\ldots$
- $values = \backslash''[\hat{}\ \backslash\ '']^*\ \backslash\ ''$

Constructing a CFG (cont.)

Let's assume we want to describe the non-regular language for a for HTML tables (looks like this):

```
<table style="width:100%">
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  <tr>
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    <td>Lopez</td>
    <td>80</td>
  </tr>
</table>
```

REs:

- $attributes = style|class|border|\ldots$
- $values = \backslash''[\hat{}\ \backslash'']^* \backslash''$
- data

Constructing a CFG (cont.)

Let's assume we want to describe the non-regular language for a for HTML tables (looks like this):

```
<table style="width:100%">
  <tr>
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  </tr>
  <tr>
    <td>Vladimir</td>
    <td>Lopez</td>
    <td>80</td>
  </tr>
</table>
```

REs:

- $attributes = style|class|border|\ldots$
- $values = \backslash''[\hat{}\ \backslash\ '']^*\ \backslash\ ''$
- $data = [a - zA - Z0 - 9]^*\ldots$

Constructing a CFG (cont.++)

Let's assume we want to describe the non-regular language for a for HTML tables (looks like this):

```
<table style="width:100%">
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Constructing a CFG (cont.++)

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```

Production rules:

Constructing a CFG (cont.++)

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  </tr>
  <tr>
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    <td>Lopez</td>
    <td>80</td>
  </tr>
</table>
```

Production rules:

1. $S \mapsto < table\ A1 > S2 < /table >$

CONSTRUCTING A CFG (CONT.++)

Let's assume we want to describe the non-regular language for a for HTML tables (looks like this):

```
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  <tr>
    <td>Vladimir</td>
    <td>Lopez</td>
    <td>80</td>
  </tr>
</table>
```

Production rules:

1. $S \mapsto < table\ A1 > S2 < /table >$
2. $S2 \mapsto < tr > S3 < /tr >$

CONSTRUCTING A CFG (CONT.++)

Let's assume we want to describe the non-regular language for a for HTML tables (looks like this):

```
<table style="width:100%">
  <tr>
    <th>Name</th>
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  <tr>
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  </tr>
</table>
```

Production rules:

1. $S \mapsto < table\ A1 > S2 < /table >$
2. $S2 \mapsto < tr > S3 < /tr >$
3. $S2 \mapsto S2\ S2$

Constructing a CFG (cont.++)

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    <td>Lopez</td>
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  </tr>
</table>
```

Production rules:

1. $S \mapsto < table\ A1 > S2 < /table >$
2. $S2 \mapsto < tr > S3 < /tr >$
3. $S2 \mapsto S2\ S2$
4. $S3 \mapsto < th > S4 < /th >$

Constructing a CFG (cont.++)

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```
<table style="width:100%">
  <tr>
    <th>Name</th>
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```

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3. $S2 \mapsto S2\ S2$
4. $S3 \mapsto < th > S4 < /th >$
5. $S3 \mapsto < td > S4 < /td >$

Constructing a CFG (cont.++)

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```

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1. $S \mapsto < table\ A1 > S2 < /table >$
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3. $S2 \mapsto S2\ S2$
4. $S3 \mapsto < th > S4 < /th >$
5. $S3 \mapsto < td > S4 < /td >$
6. $S3 \mapsto S3\ S3$

Constructing a CFG (cont.++)

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```

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4. $S3 \mapsto < th > S4 < /th >$
5. $S3 \mapsto < td > S4 < /td >$
6. $S3 \mapsto S3\ S3$
7. $S4 \mapsto data$

CONSTRUCTING A CFG (CONT.++)

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8. $S4 \mapsto S2$ //(assume no table def needed)

Constructing a CFG (cont.++)

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5. $S3 \mapsto < td > S4 < /td >$
6. $S3 \mapsto S3\ S3$
7. $S4 \mapsto data$
8. $S4 \mapsto S2$ //(assume no table def needed)
9. $A1 \mapsto attributes = values$

CONSTRUCTING A CFG (CONT.++)

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8. $S4 \mapsto S2$ //(assume no table def needed)
9. $A1 \mapsto attributes = values$
10. $A1 \mapsto A1\ A1$

Exercises – Describing languages through CFG

Please, describe the grammar for the language:

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  - $P \mapsto (P)$
  - $P \mapsto ()$ //E-Z, right?

EXERCISES – DESCRIBING LANGUAGES THROUGH CFG

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Exercises – Describing languages through CFG

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  - $S \mapsto aSa|aS_1a$ // Note the "OR"(|) notation
  - $S_1 \mapsto b|bS_1|\varepsilon$ //E-Zer, right?

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- Last one, balanced brackets [] and (), including ε quite simple for you now…

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  - $S_1 \mapsto b | bS_1 | \varepsilon$ //E-Zer, right?
- Last one, balanced brackets [] and (), including ε quite simple for you now…
  - $S \mapsto SS | (S) | [S] | () | [] | \varepsilon$

Grammars...

Every regular grammar is a CFG

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- The grammar generated by: $(a|b)^*$ can be generated by $S \mapsto aS|bS|\varepsilon$

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Not every CFG is a regular grammar (canonical balanced parenthesis example)

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A hierarchical power of grammars, and corresponding automata

GRAMMARS...

Every regular grammar is a CFG

- The grammar generated by: $(a|b)^*$ can be generated by $S \mapsto aS|bS|\varepsilon$

Not every CFG is a regular grammar (canonical balanced parenthesis example)

A hierarchical power of grammars, and corresponding automata

- Regular Grammars & Finite State Automata
- Context-Free Grammars & Push Down Automata
- Context-Sensitive Grammars & Turing Machines
- I mean, just in case you forgot :)

You are here ↓

What we know

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What we know

- How to describe context-free languages using CFGs + REs

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- How to describe context-free languages using CFGs + REs
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What we do not know (yet)

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- How to obtain the structure to analyze the code (which was the final goal) :(

You are here ↓

What we know

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- To obtain such structure, we focus on the grammar derivation, grammar ambiguities are harmful, and we will see how to correct them

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What we know

- How to describe context-free languages using CFGs + REs
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What we do not know (yet)

- How to obtain the structure to analyze the code (which was the final goal) :(
- To obtain such structure, we focus on the grammar derivation, grammar ambiguities are harmful, and we will see how to correct them
- But, do not worry, next Tuesday(?) you'll know...