Introduction to Natural Language Processing

Part VI: NLP using Regular Expressions

Henning Wachsmuth

https://ai.uni-hannover.de

Learning Objectives

Concepts

- Different types of formal grammars in NLP
- Sequential patterns in language
- Main operators of regular expressions

Methods

- Identification of numeric entities with regular expressions

Covered text analyses

- Time expression recognition

Outline of the Course

I. Overview
II. Basics of Linguistics
III. NLP using Rules
IV. NLP using Lexicons
V. Basics of Empirical Methods
VI. NLP using Regular Expressions
    - Introduction
    - Regular Grammars
    - Regular Expressions in NLP
VII. NLP using Context-Free Grammars
VIII. NLP using Language Models
IX. Practical Issues

Introduction

Woodchuuucks

HOW MUCH WOOD WOULD A WOODCHUCK CHUCK,
IF A WOODCHUCK COULD CHUCK WOOD?

https://commons.wikimedia.org

So much wood as a woodchuck could,
if a woodchuck would chuck wood.

It would chuck, if it would, as much wood as
it could, if a woodchuck could chuck wood.

A woodchuck would chuck no amount of wood,
since woodchucks can't chuck wood.

But if Woodchucks Could and Would Chuck Some Wood,
What Amount of Wood Would each Woodchuck Chuck?

... and so forth

If you don't know, maybe you know the difference between
woodchucks and groundhogs?

There is none. A groundhog is a woodchuck.

Woodchuuucks

Mining Woodchucks from Text

Woodchucks in the text above

- “Woodchuuucks”
- “WOODCHUCK”
- “woodchuck”
- “woodchucks”
- “Woodchucks”
- “Woodchuck”
- “groundhogs”
- “groundhog”

along with “It” and “it”

https://commons.wikimedia.org

Questions

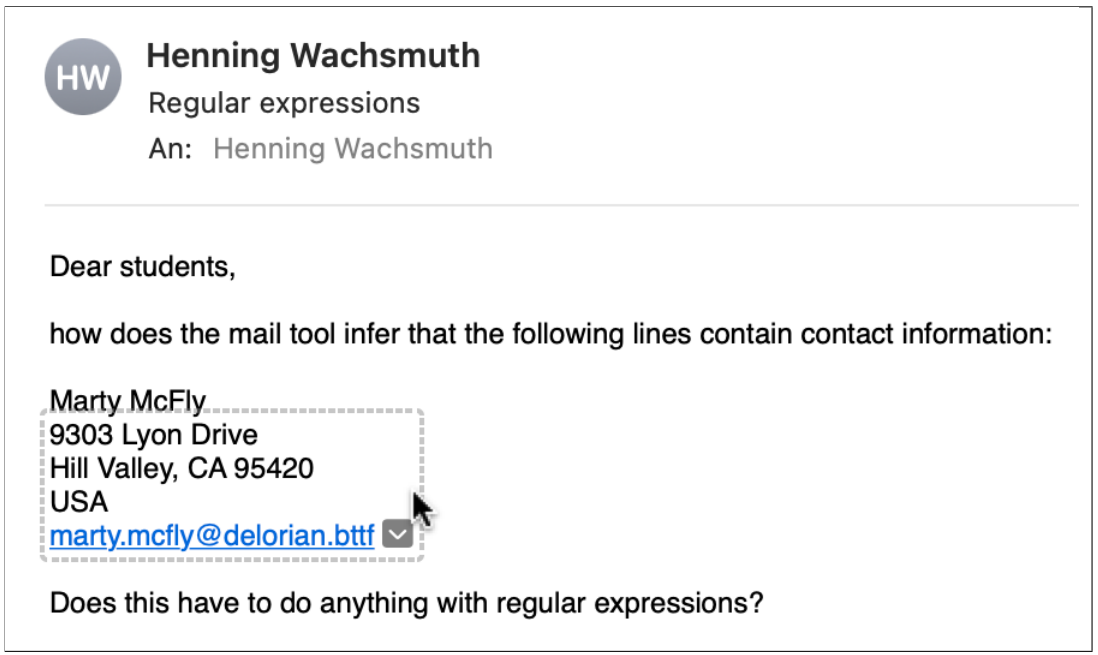
- How to find these and other references to woodchucks automatically?
- What makes woodchuck mining challenging?

Examples: Ambiguous cases, missing whitespaces, varying writings, ...

Contact Information

Finding contact information

- See the following e-mail:



https://pixabay.com

Questions

- How can we describe patterns in text sequences formally?
- What can be described well, what not?

NLP using Regular Expressions

Regular expression (regex)

- A sequence of characters that describes sequential text patterns
- A text can be matched against a regex to find all pattern instances

Use in NLP

- Effective for finding information that follows clear sequential structures
- Examples. Numeric entities, structural entities (e.g., e-mail addresses), lexico-syntactic relations (e.g., “<NN> is a <NN>”), ...

Numeric (and alphanumeric) entities

- Values, quantities, proportions, ranges, or similar
- This includes time periods, dates, monetary values, phone numbers, ...

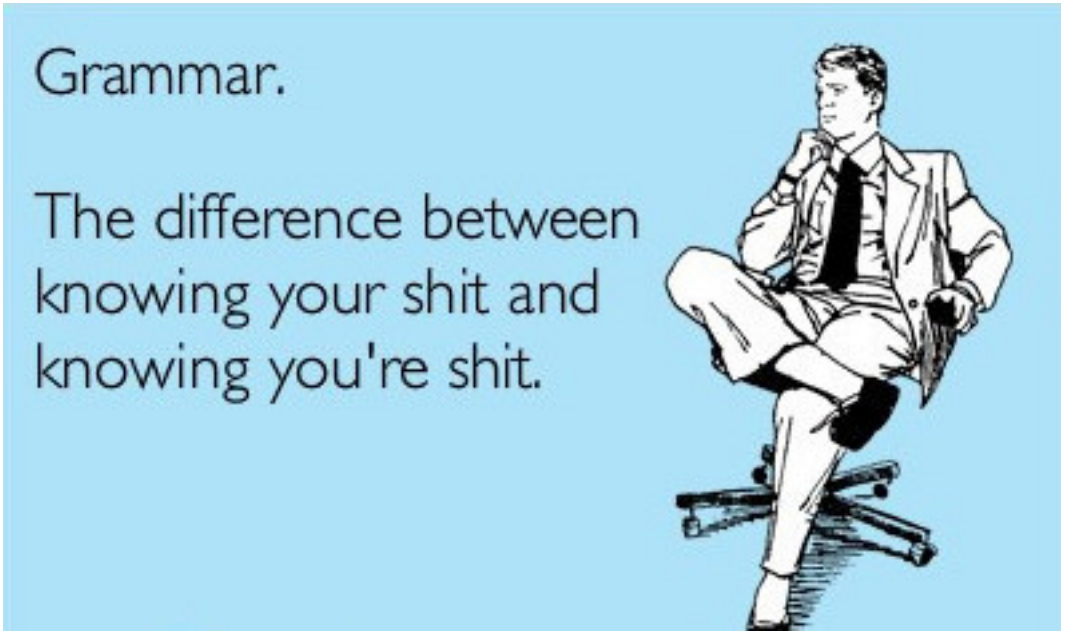
“in this year” “2023-06-15” “$ 100 000” “762-123 77”

Numeric entity recognition

- The text analysis that mines numeric entities from text
- Used in NLP within many information extraction tasks

Regular Grammars

Grammar


Grammar.
The difference between knowing your shit and knowing you're shit.
https://someecards.com

Grammar

Grammars

Grammars

- A grammar is a description of the valid structures of a language.
- One of the most central concepts of linguistics is *formal grammars*.

Formal grammars

- A formal grammar specifies a set of rules consisting of terminal and non-terminal symbols.
- Terminals. "Words" that cannot be rewritten any further
- Non-terminals. Clusters or generalizations of terminals

Grammar (Σ, N, S, R)

Σ An alphabet, i.e., a finite set of terminal symbols, $\Sigma = \{v_1, v_2, \ldots\}$

N A finite set of non-terminal symbols, $N = \{W_1, W_2, \ldots\}$

S A start non-terminal symbol, $S \in N$

R A finite set of production rules, $R \subseteq (\Sigma \cup N)^+ \setminus \Sigma^* \times (\Sigma \cup N)^*$

Here, $\Sigma^* := \Sigma \times \Sigma \times \ldots$

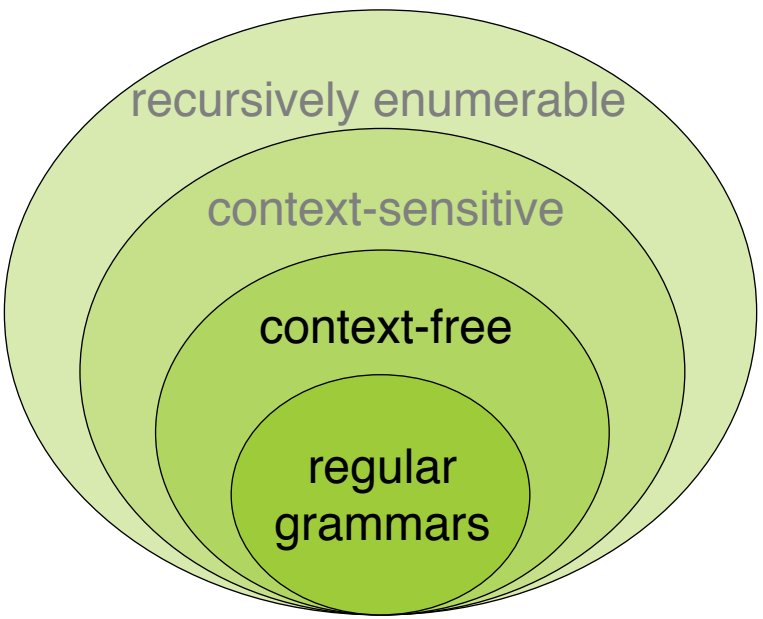
Grammar

Chomsky Grammars

Four types of formal grammars

- Chomsky-0 (recursively enumerable). Any (Σ, N, S, R) as defined
- Chomsky-1 (context-sensitive). Only rules $U \to V$ with $|U| \leq |V|$
- Chomsky-2 (context-free). Only rules $U \to V$ with $U \in N$
- Chomsky-3 (regular). Only rules $U \to V$ with $U \in N$ and $V \in \{\varepsilon, v, vW\}$, $v \in \Sigma$, $W \in N$

  ε is the empty word.



Grammars in NLP

- Only regular and context-free grammars are commonly used.
- Regular grammars are covered here, context-free grammars in the next part.

Regular Grammars

Regular grammar

- A grammar (Σ, N, S, R) where all rules in R are of the form $U \to V$ with $U \in N$ and $V \in \{\varepsilon, v, vW\}$, such that $v \in \Sigma$ and $W \in N$
- Extended. A regular grammar is *extended*, if $v \in \Sigma^*$

  Below, we refer to this also as *regular grammar* only.
- Right-regular. Intuitively, a structure defined by a regular grammar can be constructed from left to right.

Regular language

- A language is regular, if there is a regular grammar that defines it.

Representation

- Every regular grammar can be represented by a *finite-state automaton*.
- Every regular grammar can be represented by a *regular expression*.

  And vice versa

Regular Grammars

Finite-State Automata

Finite-state automaton (FSA) (recap)

- An FSA is a state machine that reads a string from a regular language.
- It represents the set of all strings belonging to the language.

FSA as a 5-tuple $(Q, \Sigma, q_0, F, \delta)$

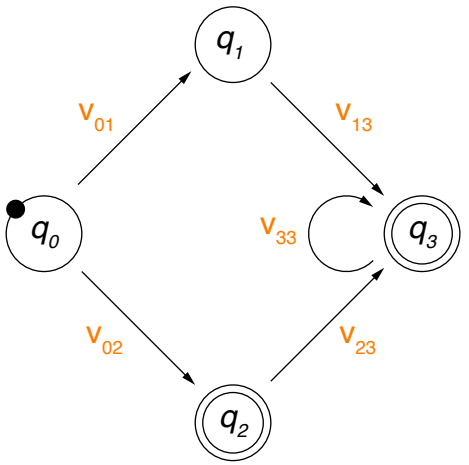
Q A finite set of $n > 0$ states, $Q = \{q_0, ..., q_n\}$

Σ An alphabet, i.e., a finite set of terminal symbols, $\Sigma = \{v_1, v_2, \ldots\}$, $\Sigma \cap Q = \emptyset$

q_0 A start state, $q_0 \in Q$

F A set of final states, $F \subseteq Q$

δ A transition function between states, triggered based on $v \in \Sigma$, $\delta : Q \times \Sigma \rightarrow Q$



Regular Expressions in NLP

Regular Expressions

Regular expression (regex)

- A regex defines a regular language over an alphabet Σ as a sequence of characters from Σ and *metacharacters*
- Metacharacters denote disjunction, negation, repetition, ... (see below)
- Example. The FSA above is defined by the following regex:

$$\mathrm{v}_{02} \mid (\mathrm{v}_{01}\mathrm{v}_{13} \mid \mathrm{v}_{02}\mathrm{v}_{23})\,\mathrm{v}_{33}{}^{*}$$

Use of regular expressions

- Definition of patterns that generalize over structures of a language
- A pattern matches all spans of text that contain any of the structures.

Regular expressions in NLP

- Regexes are a widely used technique in NLP, particularly for the extraction of numeric and similar entities.
- In statistical NLP, regexes often take on the role of features.

Regular Expressions

Characters and Metacharacters

Regular characters

- The default interpretation of a character sequence in a regex is a concatenation of each single character.

`woodchuck` matches “woodchuck”

Metacharacters

- A regex uses specific characters to encode specific regular language constructions, such as negation and repetition.
- The main metacharacters are the following (in Python notation):

`[]` `-` `|` `^` `.` `( )` `\` `*` `+` `?`

The characters used partly differ across literature and programming languages.

- Some languages also include certain *non-regular* constructions, e.g., `\b` matches if a word boundary is reached.

Regexes can solve this case only if given token information.

Regular Expressions

Disjunction

Disjunction of patterns

- Brackets `[]` specify a character class.

  `[wW]` matches "w" or "W"

  `[wod]` matches "w" or "o" or "d"

- Disjunctive ranges of characters can be specified with a hyphen `-`.

  `[a-zA-Z]` matches any letter

  `[0-8]` matches any digit except for "9"

- The pipe `|` specifies a disjunction of string sequences.

  `groundhog|woodchuck` matches "groundhog" and "woodchuck"

Notes on disjunctions

- Different disjunctions can be combined.

  `[gG]roundhog|[wW]oodchuck` matches "groundhog", "Woodchuck", ...

- In Python, many metacharacters are not active within brackets.

  `[wod.]` matches "w", "o", "d", and "."

Regular Expressions

Negation, Choice, Grouping

Negation

- The caret `^` inside brackets complements the specified character class.

`[^0-9]` matches anything but digits

`[^wo]` matches any character but “w”, “o”

- Outside brackets, the caret `^` is interpreted as a normal character.

`woodchuck^` matches “woodchuck^”

Free choice

- The period `.` matches any character.

  To match a period, it needs to be escaped as: `\.`

`w..dchuck` matches “woodchuck”, “woudchuck”, ...

Grouping

- Parentheses `()` can be used to group parts of a regex. A grouped part is treated as a single character.

`w[^(oo)]dchuck` matches any variation of the two o’s in “woodchuck”

Regular Expressions

Whitespaces and Predefined Character Classes

Whitespaces

- Different whitespaces are referred to with different special characters.
- For instance, `\n` is the regular new-line space.

Predefined character classes

- Several specific character classes are referred to by a backslash `\` followed by a specific letter.

`\d`	Any decimal digit	equivalent to `[0-9]`
`\D`	Any non-digit character	equivalent to `[^0-9]`
`\s`	Any whitespace character	equivalent to `[\t\n\r\f\v]`
`\S`	Any non-whitespace character	equivalent to `[^\t\n\r\f\v]`
`\w`	Any alphanumeric character	equivalent to `[a-zA-Z0-9]`
`\W`	Any non-alphanumeric character	equivalent to `[^a-zA-Z0-9]`

- These classes can be used within brackets.

`[\s0-9]` matches any space and digit.

Regular Expressions
Repetition

Repetition

- The asterisk `*` repeats the previous character zero or more times.

  `woo*dchuck` matches “wodchuck”, “woodchuck”, “woooodchuck”, ...

- The plus `+` repeats the previous character one or more times.

  `woodchu+ck` matches “woodchuck”, “woodchuuck”,“woodchuuuck”, ...

- The question mark `?` repeats the previous character zero or one time.

  `woodchucks?` matches “woodchuck” and “woodchucks”

Notes on repetitions

- Repetitions are implemented in a greedy manner in many programming languages, i.e., longer matches are preferred over shorter ones.

  `to*` matches “too”, not “too”, ...

- This may actually violate the regularity of the defined language.

  “woodchuck” needs to be processed twice for the regex `wo*odchuck`

Regular Expressions

Summary of Metacharacters

Char	Concept	Example
`[ ]`	Disjunction of characters	`[Ww]oodchuck`
`-`	Ranges in disjunctions	`There are [0-9]+ woodchucks\.`
`|`	Disjunction of regexes	`woodchuck|groundhog`
`^`	Negation	`[^0-9]`
`.`	Free choice	`What a (.)* woodchuck`
`( )`	Grouping of regex parts	`w(oo)+dchuck`
`\`	Special (sets of) characters	`\swoodchuck\s`
`*`	Zero or more repetitions	`wooo*dchuck`
`+`	One or more repetitions	`woodchu+ck`
`?`	Zero or one repetition	`woodchucks?`

Regular Expressions

Examples

The

- Regex for all variations of “the” in news article text:

```
the    (misses capitalized cases, matches “theology”, ...)
[^a-zA-Z][tT]he[^a-zA-Z]    (requires a character before and afterwards)
```

Woodchucks

- Regex for all woodchuck cases from above (and for similar):

```
( [wW][oO][oO][dD][cC][hH][uU]+[cC][kK] | [Gg]roundhog ) [sS]?
```

E-mail addresses

- All e-mail addresses with the German top-level domain, whose text segments contain no special characters:

```
[a-zA-Z0-9]+ @ ([a-zA-Z0-9]+\.)* [a-zA-Z0-9][a-zA-Z0-9]+ \.de
```

Time Expression Recognition with Regular Expressions

Time expression

- An alphanumeric entity that represents a date or a period

> "Cairo, August 25th 2010 — Forecast on Egyptian Automobile industry [...] In the next five years, revenues will rise by 97% to US-$ 19.6 bn. [...]"

Time expression recognition

- The text analysis that finds time expressions in natural language text
- Used in NLP within temporal relation extraction and event extraction

Approach in a nutshell

- Model sequential structure of time expressions with a complex regex.
- Include lexicons derived from training data to match closed-class terms.
  Example closed classes: Month names, prepositions, ...
- Match regex with sentences of a text.

Notice

- The approach can easily be adapted to other types of information.

Time Expression Recognition with Regular Expressions

Pseudocode

Signature

- Input. A text split into sentences, and a regex
- Output. All time expressions in the text

```
extractAllMatches(List<Sentence> sentences, Regex regex)
 1.     List<TimeExpression> matches ← ()
 2.     for each sentence ∈ sentences do
 3.         int index ← 0
 4.         while index < sentence.length - 1 do
 5.             int [] exp ← regex.match(sentence.sub(index))
 6.             if exp ≠ ⊥ then   // ⊥ represents "null"
 7.                 matches.add(new TimeExpression(exp[0], exp[1]))
 8.                 index ← exp[1]
 9.             index ← index + 1
10.     return matches
```

Notice

- Most programming languages provide explicit matching classes.

Time Expression Recognition with Regular Expressions

Complete Regex (Part 1 out of 2)

```
((((((iI]n|[wW]ithin|[tT]o\s\s?the|[tT]o|[fF]or\s\s?the|[fF]or|[fF]rom|[sS]ince|[aA]fter|[bB]efore|[bB]etween|[aA]t|[oO]n|[
oO]ver|[pP]er)((\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*([tT]he|[tT]his|[tT]hese|[tT]hose|[iI]ts))?)(\s+(\r(\n)?|\n)?|(\r(\n)?|\n))
\s*)?(((0?[123456789]|[12]\d|3[01])(\.|/))((\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*)?)(((month|time(span)?(\s+(\r(\n)?|\n)?|(\r(\n)
?|\n))\s*(from(\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*)?)?([Jj]anuary|[Jj]an\.|[Jj]an|[Ff]ebruary|[Ff]eb\.|[Ff]eb|[Mm]arch|[Mm]ar\
.|[Mm]ar|[Aa]pril|[Aa]pr\.|[Aa]pr|[Mm]ay|[Jj]une|[Jj]un\.|[Jj]un|[Jj]uly|[Jj]ul\.|[Jj]ul|[Aa]ugust|[Aa]ug\.|[Aa]ug|[Ss]epte
mber|[Ss]ep\.|[Ss]ep|[Oo]ctober|[Oo]ct\.|[Oo]ct|[Nn]ovember|[Nn]ov\.|[Nn]ov|[Dd]ecember|[Dd]ez\.|[Dd]ez|[Ss]pring|[Ss]ummer
|[Aa]utumn|[Ff]all|[Ww]inter))|((0?[123456789]|1[012])(\.|/))))(()?((19|20)?\d2))?)|((((((iI]n|[wW]ithin|[tT]o\s\s?the|[tT]o
|[fF]or\s\s?the|[fF]or|[fF]rom|[sS]ince|[aA]fter|[bB]efore|[bB]etween|[aA]t|[oO]n|[oO]ver|[pP]er)((\s+(\r(\n)?|\n)?|(\r(\n)
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n|[Ee]nd|[eE]nd|[Mm]idth|[mM]idth)((\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*([tT]he|[tT]his|[tT]hese|[tT]hose|[iI]ts))?)(\s+(\r(\n)
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\n))\s*([tT]he|[tT]his|[tT]hese|[tT]hose|[iI]ts))?)(\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*)([[a-z]]+(\s+(\r(\n)?|\n)?|(\r(\n)?|\n)
)\s*)?)?((((((lL]ast|[pP]receding|[pP]ast|[cC]urrent|[tT]his|[uU]pcoming|[fF]ollowing|[sS]ucceeding|[nN]ext))((\s+(\r(\n)?
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S]even|[eE]ight|[nN]ine|[tT]en|[eE]leven|[tT]welve|[tT]wenty|[tT]hirty|[fF]ourty|[fF]orty|[fF]ifty|[sS]ixty|[sS]eventy|[eE]
ighty|[nN]inety|[hH]undred|[aA]\s\s?hundred))|((1[012]?|2|3|4|5|6|7|8|9)(\.|())|([fF]irst|[sS]econd|[tT]hird|[fF]ourth|[fF]
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tT]hird|[fF]ourth|[fF]ifth|[sS]ixth|[sS]eventh|[eE]ighth|[nN]inth|[tT]enth|[eE]leventh)))?((\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\
s*((1|2|3|4|5|6|7|8|9)\d?|([oO]ne|[sS]everal|[sS]ome|[bB]oth|[tT]wo|[tT]hree|[fF]our|[fF]ive|[sS]ix|[sS]even|[eE]ight|[nN]i
ne|[tT]en|[eE]leven|[tT]welve|[tT]wenty|[tT]hirty|[fF]ourty|[fF]orty|[fF]ifty|[sS]ixty|[sS]eventy|[eE]ighty|[nN]inety|[hH]u
ndred|[aA]\s\s?hundred)))?))?(\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*)|((((1|2|3|4|5|6|7|8|9)\d?|([oO]ne|[sS]everal|[sS]ome|[bB]oth|[tT]wo|[tT]hree|[fF]our|[fF]ive|[sS]ix|[sS]even|[eE]ight|[nN]ine|[tT]en|[eE]leven|[tT]welve|[tT]wenty|[tT]hirty|[fF]ourty
|[fF]orty|[fF]ifty|[sS]ixty|[sS]eventy|[eE]ighty|[nN]inety|[hH]undred|[aA]\s\s?hundred))|((1[012]?|2|3|4|5|6|7|8|9)(\.|())|
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eventh)))?((\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*((1|2|3|4|5|6|7|8|9)\d?|([oO]ne|[sS]everal|[sS]ome|[bB]oth|[tT]wo|[tT]hree|[fF]
our|[fF]ive|[sS]ix|[sS]even|[eE]ight|[nN]ine|[tT]en|[eE]leven|[tT]welve|[tT]wenty|[tT]hirty|[fF]ourty|[fF]orty|[fF]ifty|[sS
]ixty|[sS]eventy|[eE]ighty|[nN]inety|[hH]undred|[aA]\s\s?hundred)))?)((\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*(([lL]ast|[pP]recedi
ng|[pP]ast|[cC]urrent|[tT]his|[uU]pcoming|[fF]ollowing|[sS]ucceeding|[nN]ext)))?(\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*))?(((Q(1
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?(\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*(from(\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*)?)?([Jj]anuary|[Jj]an\.|[Jj]an|[Ff]ebruary|[Ff]eb\
.|[Ff]eb|[Mm]arch|[Mm]ar\.|[Mm]ar|[Aa]pril|[Aa]pr\.|[Aa]pr|[Mm]ay|[Jj]une|[Jj]un\.|[Jj]un|[Jj]uly|[Jj]ul\.|[Jj]ul|[Aa]ugust
|[Aa]ug\.|[Aa]ug|[Ss]eptember|[Ss]ep\.|[Ss]ep|[Oo]ctober|[Oo]ct\.|[Oo]ct|[Nn]ovember|[Nn]ov\.|[Nn]ov|[Dd]ecember|[Dd]ez\.|[
Dd]ez|[Ss]pring|[Ss]ummer|[Aa]utumn|[Ff]all|[Ww]inter))|(([Rr]eported\s\s?time\s\s?span|[Rr]eported\s\s?time\s\s?span|[Rr]e
ported\s\s?time|[rR]eported\s\s?time|[Tt]ime\s\s?span|[tT]ime\s\s?span|[Ss]pan|[sS]pan|[Dd]ecade|[dD]ecade)))((\s+(\r(\n)?|\
n)?|(\r(\n)?|\n))\s*((19|20)\d2(/(19|20)?\d2)?|\d2/\d2))?|((19|20)\d2(/(19|20)?\d2)?|\d2/\d2)))|((((((lL]ast|[pP]receding|[p
P]ast|[cC]urrent|[tT]his|[uU]pcoming|[fF]ollowing|[sS]ucceeding|[nN]ext))((\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*(((1|2|3|4|5|6|
7|8|9)\d?|([oO]ne|[sS]everal|[sS]ome|[bB]oth|[tT]wo|[tT]hree|[fF]our|[fF]ive|[sS]ix|[sS]even|[eE]ight|[nN]ine|[tT]en|[eE]le
ven|[tT]welve|[tT]wenty|[tT]hirty|[fF]ourty|[fF]orty|[fF]ifty|[sS]ixty|[sS]eventy|[eE]ighty|[nN]inety|[hH]undred|[aA]\s\s?h
undred))|((1[012]?|2|3|4|5|6|7|8|9)(\.|())|([fF]irst|[sS]econd|[tT]hird|[fF]ourth|[fF]ifth|[sS]ixth|[sS]eventh|[eE]ighth|[n
N]inth|[tT]enth|[eE]leventh))(-((1[012]?|2|3|4|5|6|7|8|9)(\.|())|([fF]irst|[sS]econd|[tT]hird|[fF]ourth|[fF]ifth|[sS]ixth|[
sS]eventh|[eE]ighth|[nN]inth|[tT]enth|[eE]leventh)))?((\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*((1|2|3|4|5|6|7|8|9)\d?|([oO]ne|[sS]
everal|[sS]ome|[bB]oth|[tT]wo|[tT]hree|[fF]our|[fF]ive|[sS]ix|[sS]even|[eE]ight|[nN]ine|[tT]en|[eE]leven|[tT]welve|[tT]went
y|[tT]hirty|[fF]ourty|[fF]orty|[fF]ifty|[sS]ixty|[sS]eventy|[eE]ighty|[nN]inety|[hH]undred|
```

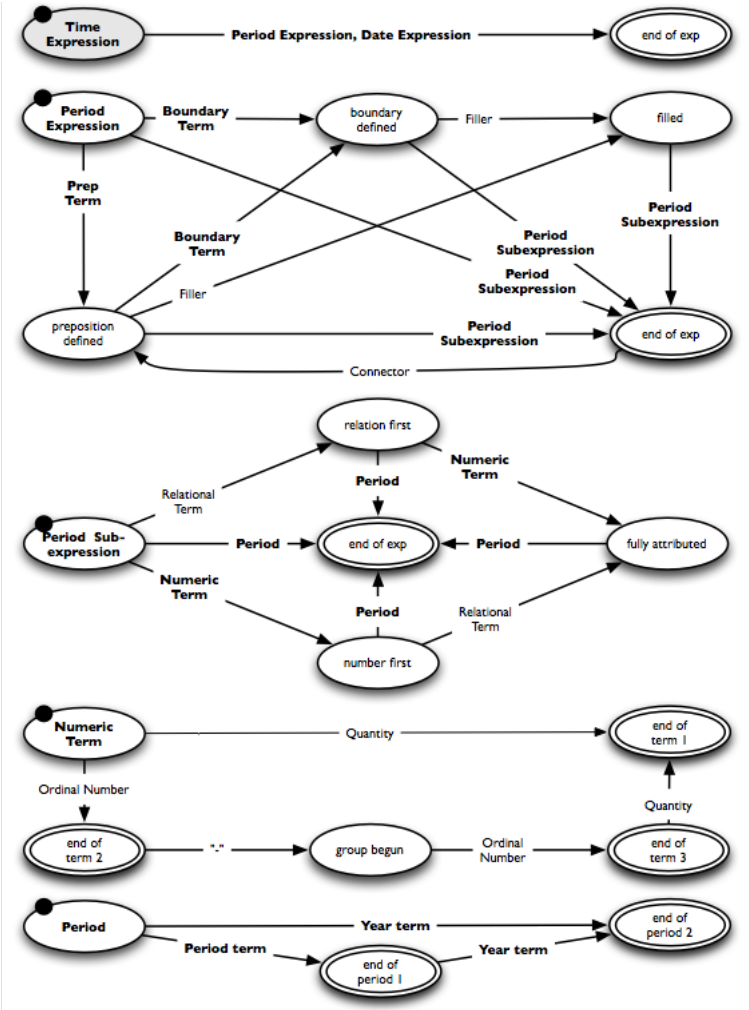
Time Expression Recognition with Regular Expressions

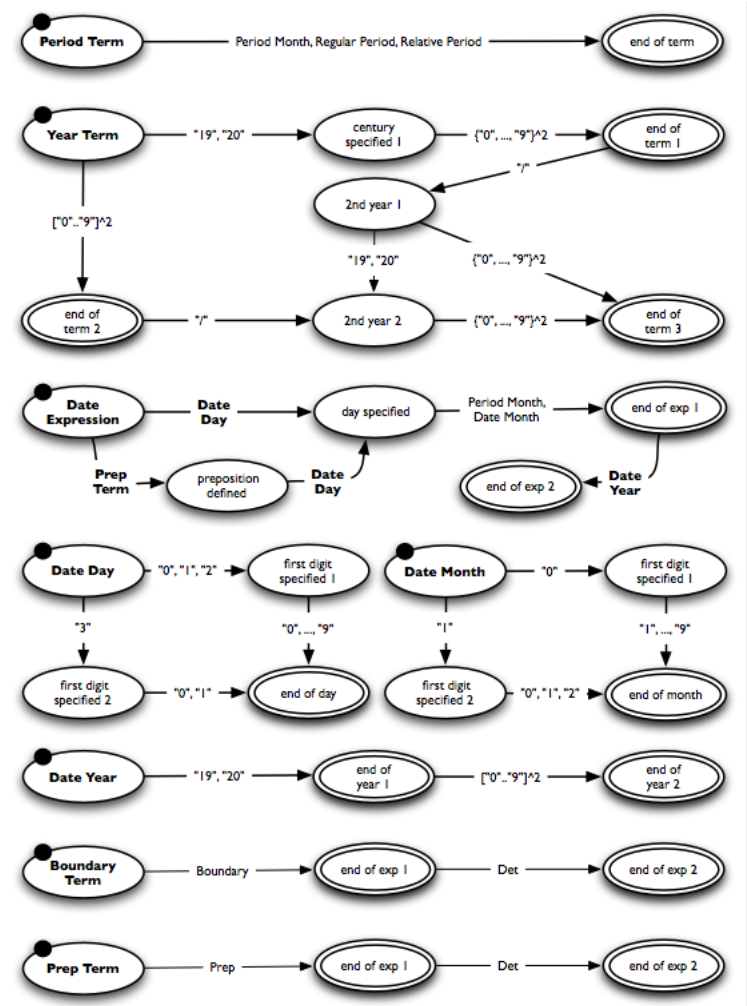
Complete Regex (Part 2 out of 2)

```
[aA]\s\s?hundred)))?))?(\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*)|((((1|2|3|4|5|6|7|8|9)\d?|([oO]ne|[sS]everal|[sS]ome|[bB]oth|[tT]
wo|[tT]hree|[fF]our|[fF]ive|[sS]ix|[sS]even|[eE]ight|[nN]ine|[tT]en|[eE]leven|[tT]welve|[tT]wenty|[tT]hirty|[fF]ourty|[fF]o
rty|[fF]ifty|[sS]ixty|[sS]eventy|[eE]ighty|[nN]inety|[hH]undred|[aA]\s\s?hundred))|((1[012]?|2|3|4|5|6|7|8|9)(\.|())|([fF]i
rst|[sS]econd|[tT]hird|[fF]ourth|[fF]ifth|[sS]ixth|[sS]eventh|[eE]ighth|[nN]inth|[tT]enth|[eE]leventh))(-((1[012]?|2|3|4|5|
6|7|8|9)(\.|())|([fF]irst|[sS]econd|[tT]hird|[fF]ourth|[fF]ifth|[sS]ixth|[sS]eventh|[eE]ighth|[nN]inth|[tT]enth|[eE]leventh
)))?((\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*((1|2|3|4|5|6|7|8|9)\d?|([oO]ne|[sS]everal|[sS]ome|[bB]oth|[tT]wo|[tT]hree|[fF]our|[f
F]ive|[sS]ix|[sS]even|[eE]ight|[nN]ine|[tT]en|[eE]leven|[tT]welve|[tT]wenty|[tT]hirty|[fF]ourty|[fF]orty|[fF]ifty|[sS]ixty|
[sS]eventy|[eE]ighty|[nN]inety|[hH]undred|[aA]\s\s?hundred))?)((\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*(([lL]ast|[pP]receding|[pP]
]ast|[cC]urrent|[tT]his|[uU]pcoming|[fF]ollowing|[sS]ucceeding|[nN]ext)))?(\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*))?(((Q(1|2|3|4
)|H(1|2)(\/(19|20)?\d2)?|(((\w([a-z])*(\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*)?(year|quarter))([a-z])*))|((month|time(span)?(\s+(
\r(\n)?|\n)?|(\r(\n)?|\n))\s*(from(\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*)?)?([Jj]anuary|[Jj]an\.|[Jj]an|[Ff]ebruary|[Ff]eb\.|[Ff]
eb|[Mm]arch|[Mm]ar\.|[Mm]ar|[Aa]pril|[Aa]pr\.|[Aa]pr|[Mm]ay|[Jj]une|[Jj]un\.|[Jj]un|[Jj]uly|[Jj]ul\.|[Jj]ul|[Aa]ugust|[Aa]u
g\.|[Aa]ug|[Ss]eptember|[Ss]ep\.|[Ss]ep|[Oo]ctober|[Oo]ct\.|[Oo]ct|[Nn]ovember|[Nn]ov\.|[Nn]ov|[Dd]ecember|[Dd]ez\.|[Dd]ez|
[Ss]pring|[Ss]ummer|[Aa]utumn|[Ff]all|[Ww]inter))|(([Rr]eported\s\s?time\s\s?span|[Rr]eported\s\s?time\s\s?span|[Rr]eported\
s\s?time|[rR]eported\s\s?time|[Tt]ime\s\s?span|[tT]ime\s\s?span|[Ss]pan|[sS]pan|[Dd]ecade|[dD]ecade)))((\s+(\r(\n)?|\n)?|(\r
(\n)?|\n))\s*((19|20)\d2(/(19|20)?\d2)?|\d2/\d2))?|((19|20)\d2(/(19|20)?\d2)?|\d2/\d2))))((\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*(
[tT]o|[aA]nd|[oO]r|[oO]n|[aA]t|[oO]f\s\s?the|[oO]f|[tT]he|[tT]his|[iI]ts|[iI]nstead\s\s?of)((\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\
s*(([sS]tart|[bB]egin|[Ss]tart|[Bb]egin|[Ee]nd|[eE]nd|[Mm]idth|[mM]idth)((\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*([tT]he|[tT]his|
[tT]hese|[tT]hose|[iI]ts))?))?((\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*[[a-z]]+)?(\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*((((((lL]ast|[p
P]receding|[pP]ast|[cC]urrent|[tT]his|[uU]pcoming|[fF]ollowing|[sS]ucceeding|[nN]ext))((\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*((
(1|2|3|4|5|6|7|8|9)\d?|([oO]ne|[sS]everal|[sS]ome|[bB]oth|[tT]wo|[tT]hree|[fF]our|[fF]ive|[sS]ix|[sS]even|[eE]ight|[nN]ine|
[tT]en|[eE]leven|[tT]welve|[tT]wenty|[tT]hirty|[fF]ourty|[fF]orty|[fF]ifty|[sS]ixty|[sS]eventy|[eE]ighty|[nN]inety|[hH]undr
ed|[aA]\s\s?hundred))|((1[012]?|2|3|4|5|6|7|8|9)(\.|())|([fF]irst|[sS]econd|[tT]hird|[fF]ourth|[fF]ifth|[sS]ixth|[sS]eventh
|[eE]ighth|[nN]inth|[tT]enth|[eE]leventh))(-((1[012]?|2|3|4|5|6|7|8|9)(\.|())|([fF]irst|[sS]econd|[tT]hird|[fF]ourth|[fF]if
th|[sS]ixth|[sS]eventh|[eE]ighth|[nN]inth|[tT]enth|[eE]leventh)))?((\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*((1|2|3|4|5|6|7|8|9)\d?
|([oO]ne|[sS]everal|[sS]ome|[bB]oth|[tT]wo|[tT]hree|[fF]our|[fF]ive|[sS]ix|[sS]even|[eE]ight|[nN]ine|[tT]en|[eE]leven|[tT]w
elve|[tT]wenty|[tT]hirty|[fF]ourty|[fF]orty|[fF]ifty|[sS]ixty|[sS]eventy|[eE]ighty|[nN]inety|[hH]undred|[aA]\s\s?hundred)))
?))?(\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*)|((((1|2|3|4|5|6|7|8|9)\d?|([oO]ne|[sS]everal|[sS]ome|[bB]oth|[tT]wo|[tT]hree|[fF]our
|[fF]ive|[sS]ix|[sS]even|[eE]ight|[nN]ine|[tT]en|[eE]leven|[tT]welve|[tT]wenty|[tT]hirty|[fF]ourty|[fF]orty|[fF]ifty|[sS]ix
ty|[sS]eventy|[eE]ighty|[nN]inety|[hH]undred|[aA]\s\s?hundred))|((1[012]?|2|3|4|5|6|7|8|9)(\.|())|([fF]irst|[sS]econd|[tT]h
ird|[fF]ourth|[fF]ifth|[sS]ixth|[sS]eventh|[eE]ighth|[nN]inth|[tT]enth|[eE]leventh))(-((1[012]?|2|3|4|5|6|7|8|9)(\.|())|([f
F]irst|[sS]econd|[tT]hird|[fF]ourth|[fF]ifth|[sS]ixth|[sS]eventh|[eE]ighth|[nN]inth|[tT]enth|[eE]leventh)))?((\s+(\r(\n)?|\
n)?|(\r(\n)?|\n))\s*((1|2|3|4|5|6|7|8|9)\d?|([oO]ne|[sS]everal|[sS]ome|[bB]oth|[tT]wo|[tT]hree|[fF]our|[fF]ive|[sS]ix|[sS]e
ven|[eE]ight|[nN]ine|[tT]en|[eE]leven|[tT]welve|[tT]wenty|[tT]hirty|[fF]ourty|[fF]orty|[fF]ifty|[sS]ixty|[sS]eventy|[eE]igh
ty|[nN]inety|[hH]undred|[aA]\s\s?hundred)))?)((\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*(([lL]ast|[pP]receding|[pP]ast|[cC]urrent|[t
T]his|[uU]pcoming|[fF]ollowing|[sS]ucceeding|[nN]ext)))?(\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*))?(((Q(1|2|3|4)|H(1|2)(\/(19|20)?
\d2)?|(((\w([a-z])*(\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*)?(year|quarter))([a-z])*))|((month|time(span)?(\s+(\r(\n)?|\n)?|(\r(\n
)?|\n))\s*(from(\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*)?)?([Jj]anuary|[Jj]an\.|[Jj]an|[Ff]ebruary|[Ff]eb\.|[Ff]eb|[Mm]arch|[Mm]ar
\.|[Mm]ar|[Aa]pril|[Aa]pr\.|[Aa]pr|[Mm]ay|[Jj]une|[Jj]un\.|[Jj]un|[Jj]uly|[Jj]ul\.|[Jj]ul|[Aa]ugust|[Aa]ug\.|[Aa]ug|[Ss]ept
ember|[Ss]ep\.|[Ss]ep|[Oo]ctober|[Oo]ct\.|[Oo]ct|[Nn]ovember|[Nn]ov\.|[Nn]ov|[Dd]ecember|[Dd]ez\.|[Dd]ez|[Ss]pring|[Ss]umme
r|[Aa]utumn|[Ff]all|[Ww]inter))|(([Rr]eported\s\s?time\s\s?span|[Rr]eported\s\s?time\s\s?span|[Rr]eported\s\s?time|[rR]eport
ed\s\s?time|[Tt]ime\s\s?span|[tT]ime\s\s?span|[Ss]pan|[sS]pan|[Dd]ecade|[dD]ecade)))((\s+(\r(\n)?|\n)?|(\r(\n)?|\n))\s*((19|
20)\d2(/(19|20)?\d2)?|\d2/\d2))?|((19|20)\d2(/(19|20)?\d2)?|\d2/\d2))))*))
```

Time Expression Recognition with Regular Expressions

Complete Regex as a Finite-State Automaton





Time Expression Recognition with Regular Expressions

Top-level FSA of Complete Regex

Notice

- Bold edge labels indicate sub-FSAs, regular labels indicate lexicons.
- Below, the FSA of period expressions is decomposed top-down.
  The regex for date expressions is left out for brevity.
- During development, building a regex rather works bottom-up.

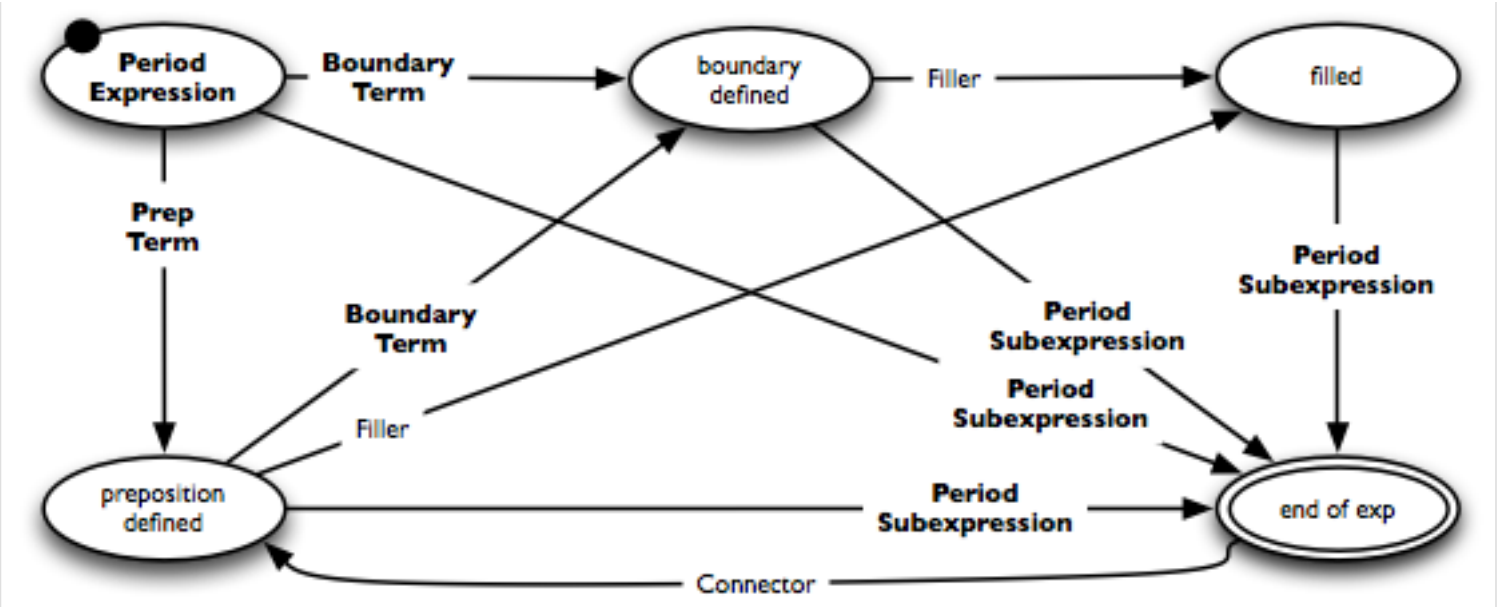
Example period expression

- “From the very end of last year to the 2nd half of 2019”

  prep filler boundary relational period connector ordinal period year

Time Expression Recognition with Regular Expressions

Sub-FSA for Period Expressions

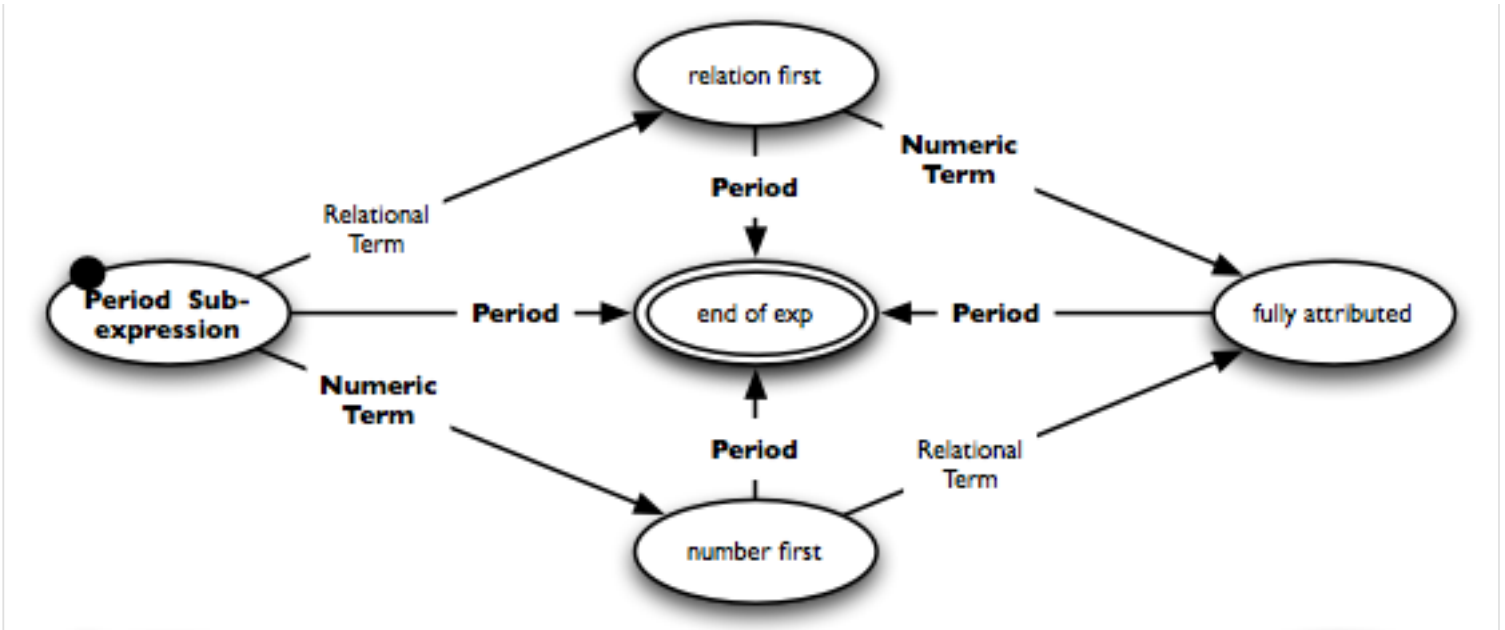


Lexicons

- Connector lexicon. “to the”, “to”, “and”, “of the”, “of”, ...
- Fillers. *Any* single word, such as “very” in the example above

Time Expression Recognition with Regular Expressions

Sub-FSA for Period Subexpressions

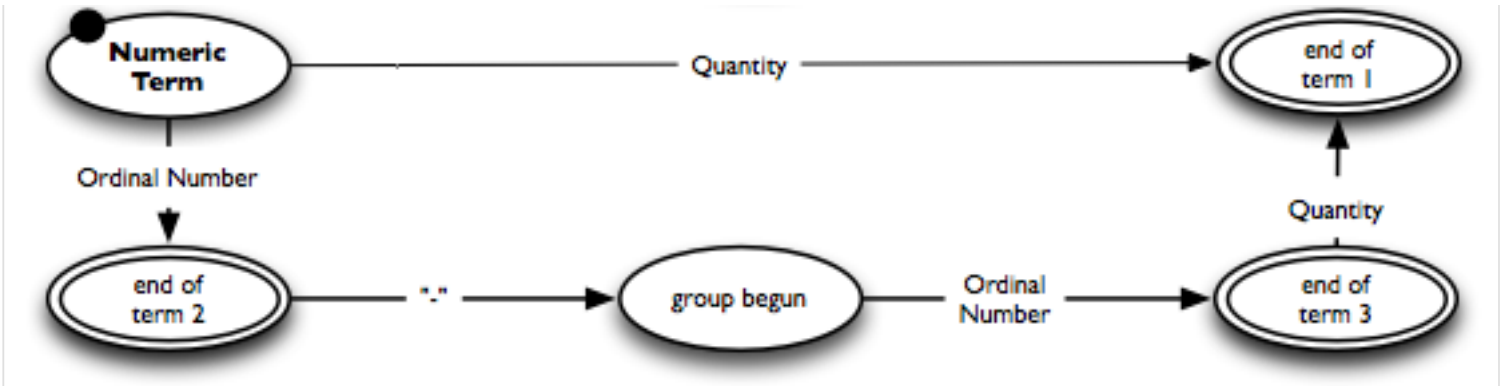


Lexicons

- Relational term lexicon. “last”, “preceding”, “past”, “current”, “this”, “upcoming”, “next”, ...

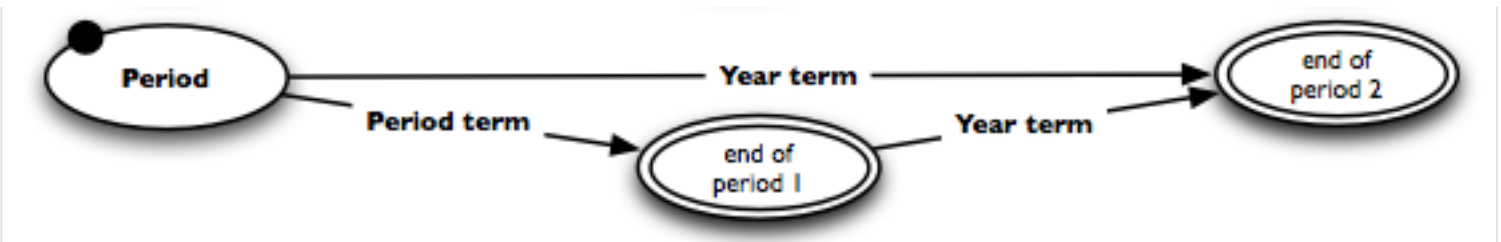
Time Expression Recognition with Regular Expressions

Sub-FSAs for Numeric Terms and Periods



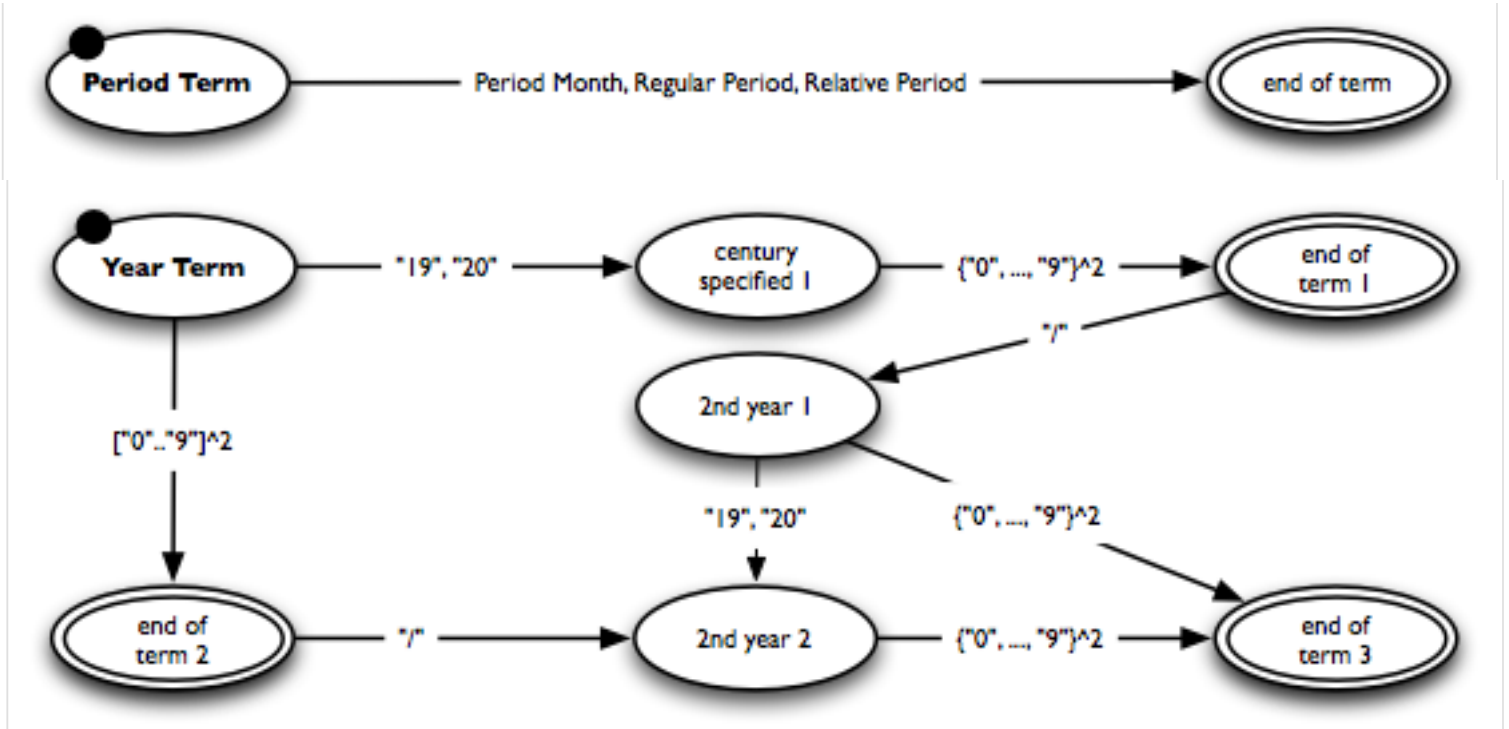
Lexicons

- Ordinal number lexicon. “first”, “1st”, “second”, “2nd”, “third”, “3rd”, ...
- Quantity lexicon. “one”, “two”, “three”, “both”, “several”, “a hundred”, ...



Time Expression Recognition with Regular Expressions

Sub-FSAs for Period Terms and Year Terms

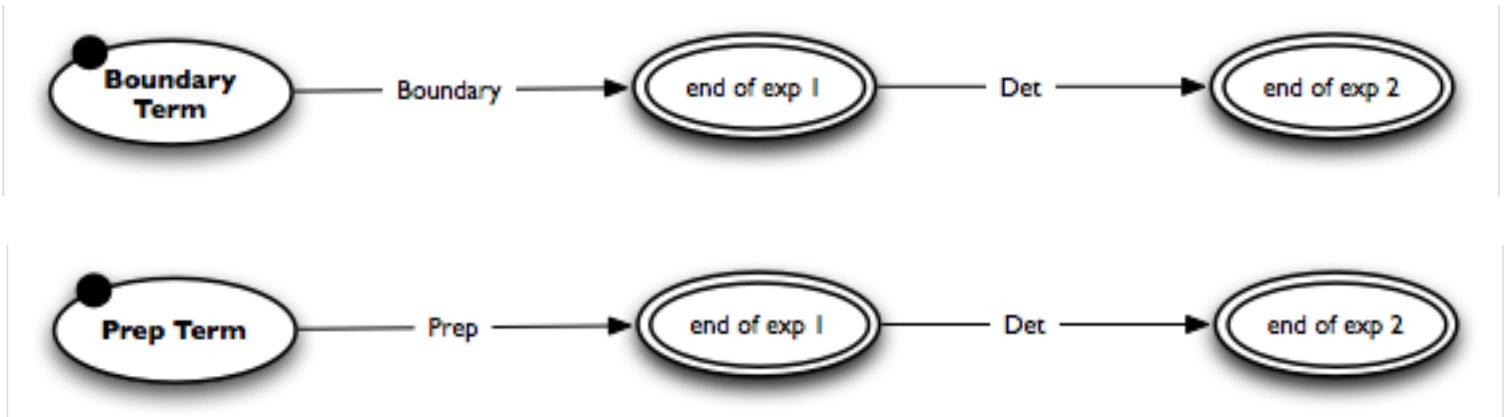


Lexicon

- Period month lexicon. “March”, “Mar.”, “Mar”, “Fall”, “fall”, “Autumn”, ...
- Regular period lexicon. “year”, “month”, “quarter”, “half”, ...
- Relative period lexicon. “decade”, “reported time”, “time span”, ...

Time Expression Recognition with Regular Expressions

Sub-FSAs for Boundary Terms and Prepositional Terms



Lexicons

- Boundary lexicon. “Beginning”, “beginning”, “End”, “end”, “Midth”, ...
- Prep lexicon. “in”, “within”, “to”, “for”, “from”, “since”, ...
- Det lexicon. “the”, “a”, “an”

Time Expression Recognition with Regular Expressions

Evaluation

Effectiveness of regular expressions (Wachsmuth, 2015)

- Originally developed for German texts; only this version was evaluated
- Data. Test set of *InfexBA Corpus* with 6038 business news sentences
- Evaluation metrics. Precision, recall, F_1-score, run-time per sentence

  Run-time measured on a standard computer from 2009

Results compared to other analyses

Task	Technique	Precision	Recall	F_1-score	ms/sent.
Time expression recognition	Regex	0.91	0.97	0.94	0.36
Money expression recognition	Regex	0.99	0.95	0.97	0.68
Forecast event extraction	Linear SVM	0.87	0.93	0.90	0.81
Time/Money relation extraction	Linear SVM	0.75	0.88	0.81	10.41

Observations

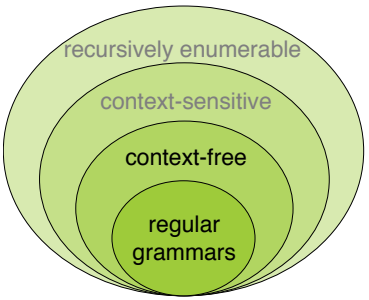
- Regexes for semi-closed-class entity types such as time expressions can achieve very high effectiveness and efficiency.
- Their development is complex and time-intensive, though.

Conclusion

Conclusion

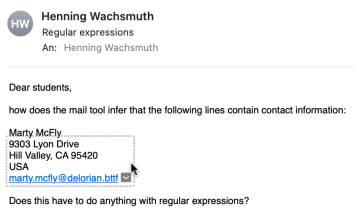
Formal grammars

- Descriptions of valid structures in a language
- Production rules map non-terminals to terminals
- Regular grammars model sequential structures



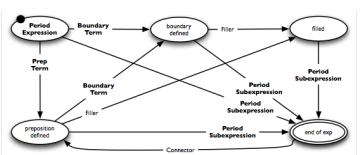
Regular expressions

- Describe regular grammars with (meta)characters
- Matched against texts to find instances of concepts
- Used in NLP particularly for (alpha)numeric entities



Benefits and limitations

- Effective for semi-closed classes, often very efficient
- Development complex for sophisticated concepts
- Restriction to sequential patterns limits applicability



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Much content and many examples taken from

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