Approximate String Search and Matching

COMP90049
COMP30018
Knowledge Technologies

Lea Frermann and Justin Zobel and Karin Verspoor

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THE UNIVERSITY OF MELBOURNE

Roadmap

Last week... Probability and similarity

Nuts and bolts of knowledge technologies!

- quantifying similarity of complex structures
- estimate the (conditional, joint) probability of observations
- identify high entropy (=informative) information

This week... Approximate String Search and Matching

Another bolt!

- back to similarity
- methods, applications, evaluation

Exact String Search

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- Given a string (document), find all occurrences of some substring

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Not (really) a Knowledge Technology!

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Not present!

...But what is the "closest" or "best" match?

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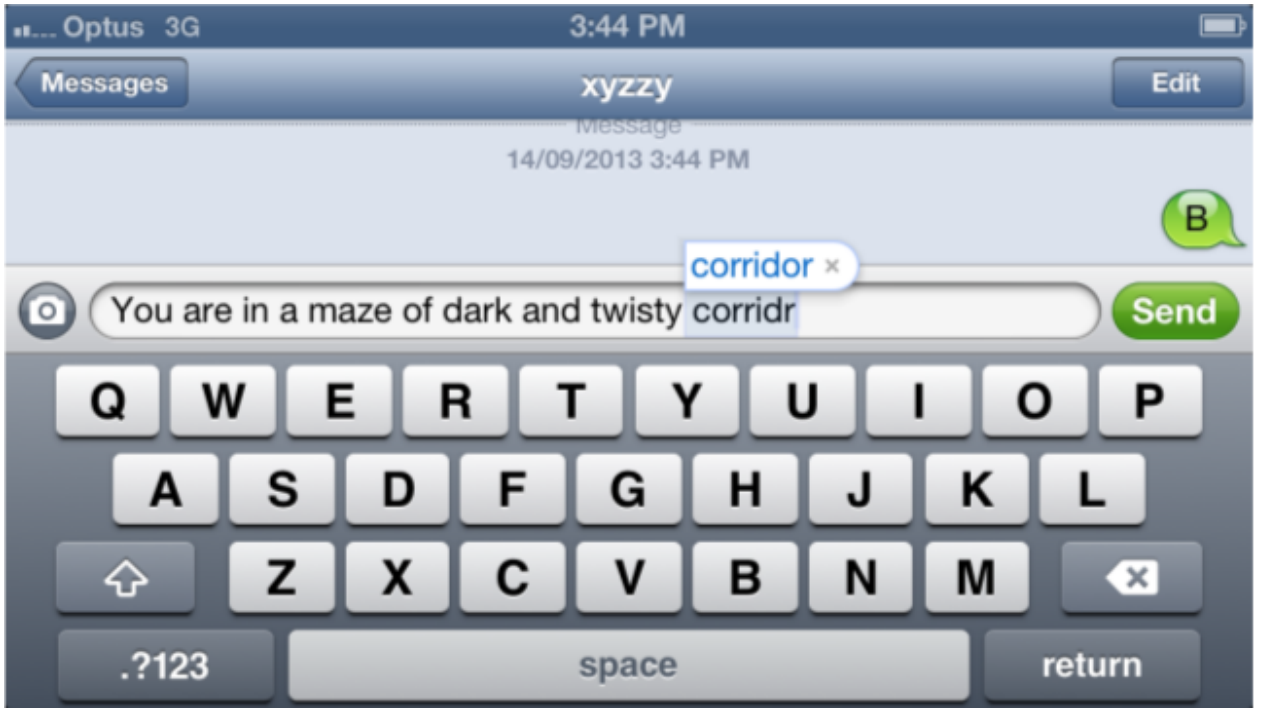
This is a Knowledge Technology!

Spelling Correction



Spelling Correction

Need the notion of a **dictionary**:

- Here, a list of words

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- We can break our input into ~~words~~ substrings that we wish to match, and compare each of them against the entries in the dictionary
- A ~~word~~ item in the input which *doesn't* appear in the dictionary is *misspelled*
- A ~~word~~ item in the input which *does* appear in the dictionary might be correctly spelled *or* misspelled (probably slightly beyond the scope of this subject)

Spelling Correction

Therefore, the problem here:

Given some item of interest — which does not appear in our dictionary — which entry from the dictionary was truly intended?

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Therefore, the problem here:

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Depends on the person who wrote the original string!

Detecting novel words

Word Blending:

- forming novel words by "blending" two other words
- not simple concatenation (e.g., football is not a blend word)

breakfast	+	lunch	$\rightarrow$	brunch
fork	+	spoon	$\rightarrow$	spork
Britain	+	exit	$\rightarrow$	Brexit

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- Language changes constantly!
- New terms often coined in colloquial language (e.g., Twitter)
- Can we build **knowledge technologies** that detect novel blends? ...or help us understand what their **components** are?
- **Assignment 1**

Other Problems of Interest

Name matching

the name *Gorbachev* is spelled (at least) 20 different ways in a corpus of newswire text!

`Gorbachev, Gorbacahev, Gorbahev, Gorbatchev, Gorbechev, Gorbachov, Gorachev, Gorbacheva, Gorbechyev, Gorbacev, Gorbachyov, Gorabchev, Grobachev, ...`

street and place name conventions

`boulevard|blvd|bd|bde|blv|bl|blvde|blvrd|boulavard|boul|bvd`
`apartment|apt|ap|aprt|aptmnt`
`village|vil|vge|vill|villag|villg|vlg|vlge|vllg`

Other Problems of Interest

- Computational Genomics
- Name matching
- Query repair
- Phonetic matching
- Data cleaning (e.g., deduplication)
- ...

Aside: Text Normalization

Before we start... fix some irregularities which may distract the matching algorithm.

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1. Consistent Casing

map all characters to upper (or lower) case

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2. Unify or remove numbers

map numbers to a consistent representation or remove (replace) them entirely

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3. Remove unnecessary spacing

e.g., duplicate white spaces

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Normalized: `i had an amazing trip to italy , coffee is only two bucks , sometimes three ! it 's increadible ! ! ! Right ?`

4. Word Tokenization

split text into individual tokens (aka words)

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`exon` →	Exxon	**Insert** `x`
`exon` →	exo	**Delete** `n`
`exon` →	axon	**Replace** `e` with `a` (Sometimes **Substitute**)
`exon` →	oxen	**Transpose** `e` and `o` (not covered here)

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Consider: alphabet size is Σ, length of string is $|w|$:

For 1 edit, roughly $\mathcal{O}(\Sigma \cdot |w|)$ neighbours

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Assuming D entries, binary search yields $\mathcal{O}(|w|^k \log D)$ string comparisons

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`agrep` example

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Scan through each dictionary entry looking for the "best" match

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Item of interest	`crat`
Dictionary	`cart`, `arts`
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`cart` is the better match

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Why?

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But we can make it one

- Global edit distance with parameters:

  Match (0), Insert (+1), Delete (+1), Replace (+1)

- counts the number of edits required to transform one string into the other
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- **Levenshtein Distance**

Often,

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- score of Replace depends on the character being replaced

Is `faxing` more likely to be `facing` or `faking`?

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Scores	Match 0, Insert +1, Delete +1, Replace +1

1. Transform `crat` → `cart`

Match `c`	Delete `r`	Match `a`	Insert `r`	Match `t`	
0	+1	0	+1	0	= +2

2. Transform `crat` → `arts`

Replace `c`, `a`	Match `r`	Delete `a`	Match `t`	Insert s	
+1	0	+1	0	+1	= +3

3 changes vs 2 changes: `cart` is the better match

Global Edit Distance – Choice of Parameter

Hypothetically, any parameter is possible!

But some choices make no sense, e.g.:

Match (+4), Insert (-2), Delete (+8), Replace (0)

Consider `aba`: which corresponds to best match?

- `foo`
- `aba`
- `cbc`

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- `foo`: Insert, Delete, Insert, Delete, Insert, Delete
- `aba`: Match, Match, Match
- `cbc`: Replace, Match, Replace

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Consider `aba`: which corresponds to best match?

- `foo`: Insert, Delete, Insert, Delete, Insert, Delete = +18
- `aba`: Match, Match, Match = +12
- `cbc`: Replace, Match, Replace = +4

Global Edit Distance Algorithm

Computer can't find best sequence of operations by inspection

Global Edit Distance Algorithm

From string f to string t, given array A of $|f| + 1$ columns and $|t| + 1$ rows, we can solve using the Needleman–Wunsch algorithm:

```
lf = strlen(f); lt = strlen(t);
A[0][0]=0;
for (j=1; j<=lt; j++) A[j][0] = j * i;
for (k=1; k<=lf; k++) A[0][k] = k * d;

for (j=1; j<=lt; j++)
   for (k=1; k<=lf; k++)
      A[j][k] = max3( //Or min3 if m<i,d,r
         A[j][k-1] + d, //Deletion
         A[j-1][k] + i, //Insertion
         A[j-1][k-1] + equal(f[k-1],t[j-1])); //Replace or match
```

`equal()` returns m if characters match, r otherwise

Final score is at $A[lt][lf]$

Global Edit Distance in Action

In action: from `crat` to `arts`, Match (+1), Insert/Delete/Replace (-1)

$\rightarrow$ delete source word
$\downarrow$ insert target word

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	ε	c	r	a	t
ε					
a					
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t					
s					

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Initialise table:

	ε	c	r	a	t
ε	0	-1	-2	-3	-4
a	-1				
r	-2				
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s	-4				

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For `c`–`a` correspondence, consider three neighbours:

	ε	c	r	a	t
ε	0	-1	-2	-3	-4
a	-1	?			
r	-2				
t	-3				
s	-4				

Global Edit Distance in Action

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For `c`–`a` correspondence, Delete `c`:

	ε	c	r	a	t
ε	0	-1	-2	-3	-4
a	-1	-2			
r	-2				
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For `c`–`a` correspondence, Insert `a`:

	ε	c	r	a	t
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For `c`–`a` correspondence, Replace `c` with `a`:

	ε	c	r	a	t
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And so on:

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Global Edit Distance: -1 (Replace, Match, Delete, Match, Insert)

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  A[j-1][k-1] + equal(f[k-1],t[j-1])); //Replace or match
```

→ Match score greater than Insert/Delete/Replace

e.g. Match (+1), Insert/Delete/Replace (-1)

More parameter concerns

Algorithm actually depends on parameter!

```
A[j][k] = min3(
  A[j][k-1] + d, //Deletion
  A[j-1][k] + i, //Insertion
  A[j-1][k-1] + equal(f[k-1],t[j-1])); //Replace or match
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```

$\rightarrow$ Match score less than Insert/Delete/Replace

e.g. Match (0), Insert/Delete/Replace (+1)

(Levenshtein Distance)

Local Edit Distance

like Global Edit Distance, but we are searching for the best substring match

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Particularly suitable when comparing two strings of very different lengths, e.g.

- a suffix of a word
- a word in a sentence
- a sentence in an entire document

Local Edit Distance Algorithm

From string f to string t, given array A of $|f| + 1$ columns and $|t| + 1$ rows, we can solve using the Smith–Waterman algorithm:

```
lf = strlen(f); lt = strlen(t);
A[0][0]=0;
for (j=1; j<=lt; j++) A[j][0] = 0;
for (k=1; k<=lf; k++) A[0][k] = 0;

for (j=1; j<=lt; j++)
   for (k=1; k<=lf; k++)
      A[j][k] = max4( //Or min4 if m<i,d,r
         0,
         A[j][k-1] + d, //Deletion
         A[j-1][k] + i, //Insertion
         A[j-1][k-1] + equal(f[k-1],t[j-1])); //Replace or match
```

`equal()` returns m if characters match, r otherwise

Final score is greatest value in the entire table (or least value, if $m < i, d, r$)

Local Edit Distance in Action

In action: from `cart` to `arts`, Match (+1), Insert/Delete/Replace (-1)

$\rightarrow$ delete source word
$\downarrow$ insert target word

(For Local Edit Distance, Match must have different $+/-$ sign to Insert/Delete/Replace)

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	ε	c	a	r	t
ε					
a					
r					
t					
s					

Local Edit Distance in Action

In action: from `cart` to `arts`, Match (+1), Insert/Delete/Replace (-1)

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Initialise table:

	ε	c	a	r	t
ε	0	0	0	0	0
a	0				
r	0				
t	0				
s	0				

Local Edit Distance in Action

In action: from `cart` to `arts`, Match (+1), Insert/Delete/Replace (-1)

$\rightarrow$ delete source word
$\downarrow$ insert target word

For `c`–`a` correspondence, consider three neighbours:

	ε	c	a	r	t
ε	0	0	0	0	0
a	0	?			
r	0				
t	0				
s	0				

Local Edit Distance in Action

In action: from `cart` to `arts`, Match (+1), Insert/Delete/Replace (-1)

→ delete source word
↓ insert target word

For `c`–`a` correspondence, Delete `c`:

	ε	c	a	r	t
ε	0	0	0	0	0
a	0	-1			
r	0				
t	0				
s	0				

Local Edit Distance in Action

In action: from `cart` to `arts`, Match (+1), Insert/Delete/Replace (-1)

$\rightarrow$ delete source word
$\downarrow$ insert target word

For `c`–`a` correspondence, Insert `a`:

	ε	c	a	r	t
ε	0	0	0	0	0
a	0	-1			
r	0				
t	0				
s	0				

Local Edit Distance in Action

In action: from `cart` to `arts`, Match (+1), Insert/Delete/Replace (-1)

$\rightarrow$ delete source word
$\downarrow$ insert target word

For `c`–`a` correspondence, Replace `c` with `a`:

	ε	c	a	r	t
ε	0	0	0	0	0
a	0	-1			
r	0				
t	0				
s	0				

Local Edit Distance in Action

In action: from `cart` to `arts`, Match (+1), Insert/Delete/Replace (-1)

$\rightarrow$ delete source word
$\downarrow$ insert target word

For `c`–`a` correspondence, 0 is better:

	ε	c	a	r	t
ε	0	0	0	0	0
a	0	0			
r	0				
t	0				
s	0				

Local Edit Distance in Action

In action: from `cart` to `arts`, Match (+1), Insert/Delete/Replace (-1)

$\rightarrow$ delete source word
$\downarrow$ insert target word

For `a`–`a` correspondence (Match), 1 is better:

	ε	c	a	r	t
ε	0	0	0	0	0
a	0	0	1		
r	0				
t	0				
s	0				

Local Edit Distance in Action

In action: from `cart` to `arts`, Match (+1), Insert/Delete/Replace (-1)

$\rightarrow$ delete source word
$\downarrow$ insert target word

For `a`–`r` correspondence, back to 0:

	ε	c	a	r	t
ε	0	0	0	0	0
a	0	0	1	0	
r	0				
t	0				
s	0				

Local Edit Distance in Action

In action: from `cart` to `arts`, Match (+1), Insert/Delete/Replace (-1)

$\rightarrow$ delete source word
$\downarrow$ insert target word

And so on:

	ε	c	a	r	t
ε	0	0	0	0	0
a	0	0	1	0	0
r	0	0	0	2	1
t	0	0	0	1	3
s	0	0	0	0	2

Local Edit Distance in Action

In action: from `cart` to `arts`, Match (+1), Insert/Delete/Replace (-1)

$\rightarrow$ delete source word
$\downarrow$ insert target word

And so on:

	ε	c	a	r	t
ε	0	0	0	0	0
a	0	0	1	0	0
r	0	0	0	2	1
t	0	0	0	1	3
s	0	0	0	0	2

Best match: `art` with `art` (+3); ties are possible.

Edit Distance Efficiency

- single source string f
- multiple target strings t in dictionary D

- a single approximate match (both global and local)

$$\mathcal{O}(|f||t|)$$

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- **feasibility depends (linearly) on size of the dictionary**

Background Readings

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Soundex

One (ineffectual) mechanism: Soundex

Soundex

One mechanism: Soundex

Translation table:

`aehiouwy`	→	0 (vowels)
`bpfv`	→	1 (labials)
`cgjkqsxz`	→	2 (misc: fricatives, velars, etc.)
`dt`	→	3 (dentals)
`l`	→	4 (lateral)
`mn`	→	5 (nasals)
`r`	→	6 (rhotic)

Soundex

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Four step process:

1. Except for initial character, translate string characters according to table
2. Remove duplicates (e.g. `4444` → `4`)
3. Remove 0s
4. Truncate to four symbols

Soundex

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Four step process:

`king`	`kyngge`
`k052`	`k05220`
`k052`	`k0520`
`k52`	`k52`

Soundex

One mechanism: Soundex

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`r`	→	6 (rhotic)

Four step process:

`knight`	`night`
`k50203`	`n0203`
`k50203`	`n0203`
`k523`	`n23`

Soundex

One mechanism: Soundex

Translation table:

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`r`	→	6 (rhotic)

Four step process:

`loan`	`loew`	`lough`	`lewicks`
`1005`	`1000`	`10020`	`1000222`
`105`	`10`	`1020`	`102`
`15`	`1`	`12`	`12`

Other Phonetic Methods

Better phonetic methods make use of the fact that some letters sounds alike in certain contexts, and different in other contexts

Editex uses the Edit Distance to compare strings based on a similar translation table to Soundex

lpadist uses a text–to–sound algorithm to represent tokens according to the International Phonetic Alphabet (but context matters a lot)

There are also worse variants, like Phonix.