Text Retrieval and Web Search
IIR 3: Dictionaries and tolerant retrieval

Mihai Surdeanu

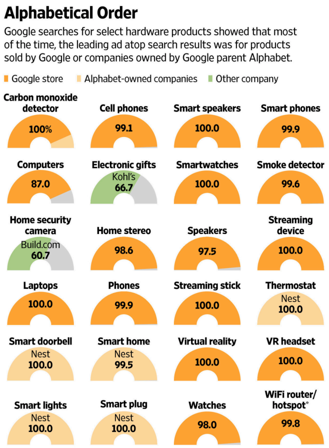
(Based on slides by Hinrich Schütze at `informationretrieval.org`)

Spring 2017

Ethics in Information Retrieval

Google Uses Its Search Engine to Hawk Its Products

http://www.wsj.com/articles/google-uses-its-search-engine-to-hawk-its-products-1484827203



Overview

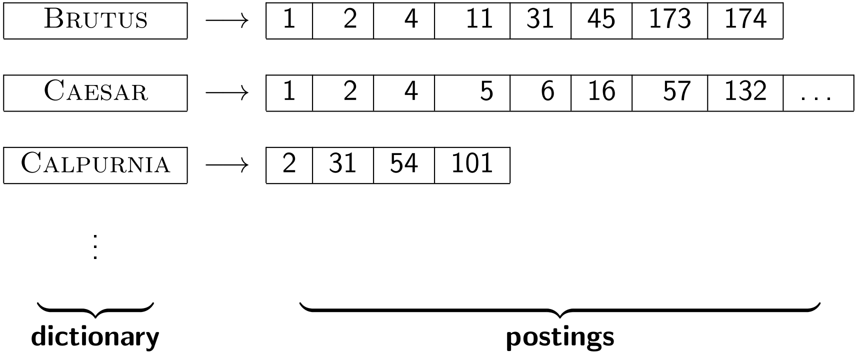
Take-away

- Tolerant retrieval: What to do if there is no exact match between query term and document term
- Wildcard queries
- Spelling correction

Outline

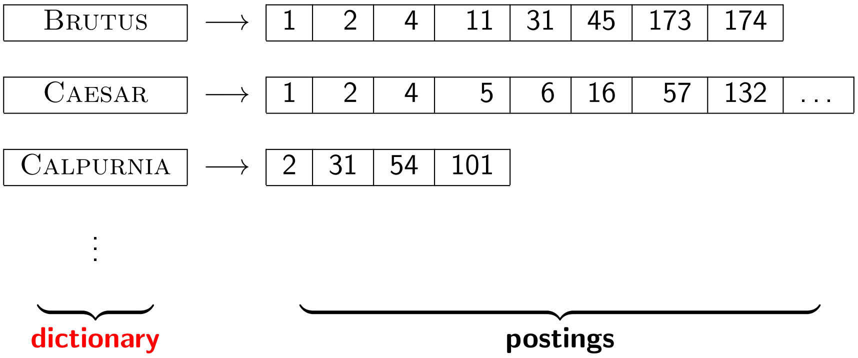
Inverted index

For each term *t*, we store a list of all documents that contain *t*.



Inverted index

For each term *t*, we store a list of all documents that contain *t*.



BRUTUS	$\longrightarrow$	1	2	4	11	31	45	173	174
CAESAR	$\longrightarrow$	1	2	4	5	6	16	57	132	...
CALPURNIA	$\longrightarrow$	2	31	54	101				

Dictionaries

- The dictionary is the data structure for storing the term vocabulary.
- Term vocabulary: the data
- Dictionary: the data structure for storing the term vocabulary

Dictionary as array of fixed-width entries

- For each term, we need to store a couple of items:
  - document frequency
  - pointer to postings list
  - ...
- Assume for the time being that we can store this information in a fixed-length entry.
- Assume that we store these entries in an array.

Dictionary as array of fixed-width entries

	term	document frequency	pointer to postings list
	a	656,265	$\longrightarrow$
	aachen	65	$\longrightarrow$
	...	...	...
	zulu	221	$\longrightarrow$
space needed:	20 bytes	4 bytes	4 bytes

How do we look up a query term q_i in this array at query time? That is: which data structure do we use to locate the entry (row) in the array where q_i is stored?

Data structures for looking up term

- Two main classes of data structures: hashes and trees
- Some IR systems use hashes, some use trees.

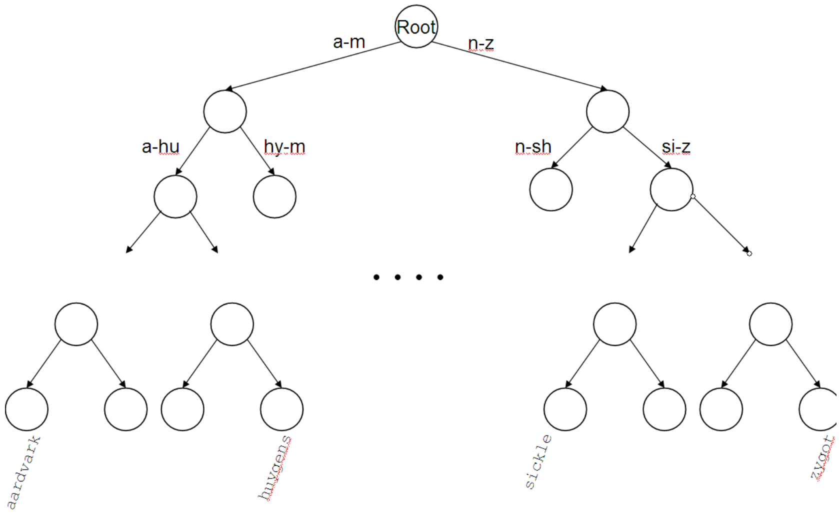
Hashes

- Each vocabulary term is hashed into an integer, its row number in the array
- At query time: hash query term,locate entry in fixed-width array
- Pros: Lookup in a hash is faster than lookup in a tree.
    - Lookup time is constant.
- Cons
    - no way to find minor variants (*resume* vs. *résumé*)
    - no prefix search (all terms starting with *automat*)
    - need to rehash everything periodically if vocabulary keeps growing

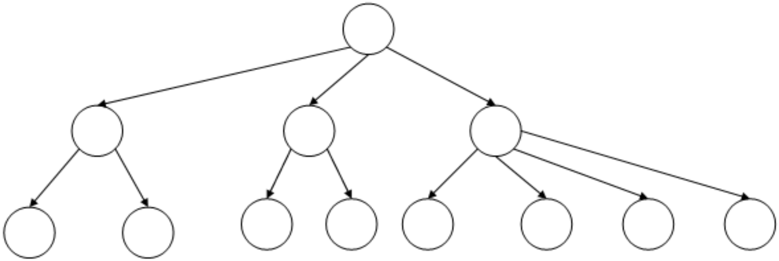
Trees

- Trees solve the prefix problem (find all terms starting with *automat*).
- Simplest tree: binary tree
- Search is slightly slower than in hashes: $O(\log M)$, where M is the size of the vocabulary.
- $O(\log M)$ only holds for balanced trees.
- Rebalancing binary trees is expensive.
- B-trees mitigate the rebalancing problem.
- B-tree definition: every internal node has a number of children in the interval $[a, b]$ where a, b are appropriate positive integers, e.g., $[2, 4]$.

Binary tree



B-tree



Outline

Wildcard queries

- Trailing wildcard: mon*: find all docs containing any term beginning with *mon*
    - Binary tree: traverse down the symbols: m $>$ o $>$ n
    - Easy with B-tree dictionary: retrieve all terms t in the range: mon $\leq t <$ moo
- Leading wildcard: *mon: find all docs containing any term ending with *mon*
    - How would you do this?

Wildcard queries

- Trailing wildcard: mon*: find all docs containing any term beginning with *mon*
    - Binary tree: traverse down the symbols: m $>$ o $>$ n
    - Easy with B-tree dictionary: retrieve all terms t in the range: mon $\leq t <$ moo
- Leading wildcard: *mon: find all docs containing any term ending with *mon*
    - How would you do this?
    - Maintain an additional tree for terms *backwards*
    - Then retrieve all terms t in the range: nom $\leq t <$ non
- Result: A set of terms that are matches for wildcard query
- Then retrieve documents that contain any of these terms

How to handle * in the middle of a term

- Example: m*nchen
- We could look up m* and *nchen in the B-tree and intersect the two term sets.
- Expensive

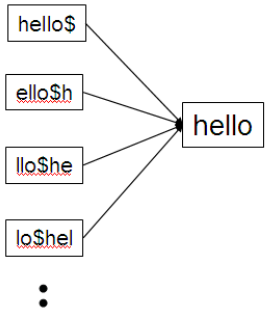
How to handle * in the middle of a term

- Example: m*nchen
- We could look up m* and *nchen in the B-tree and intersect the two term sets.
- Expensive
- Alternative: permuterm index
- Basic idea: Rotate every wildcard query, so that the * occurs at the end.
- Store each of these rotations in the dictionary, say, in a B-tree

Permuterm index

- For term HELLO: add *hello$*, *ello$h*, *llo$he*, *lo$hel*, *o$hell*, and *$hello* to the B-tree where $ is a special symbol
- This is done at indexing time for every word!

Permuterm → term mapping



Permuterm index

- For HELLO, we've stored: *hello$*, *ello$h*, *llo$he*, *lo$hel*, *o$hell*, *$hello*
- Queries
  - For X, look up X$
  - For X*, look up $X*
  - For *X, look up X$*
  - For X*Y, look up Y$X*
  - Example: For hel*o, look up o$hel*
  - How about the query fi*mo*er ("fishmonger" should match; but not "filibuster")?
- "Permuterm index" is a really bad name! It would better be called a permuterm tree.
- But permuterm index is the more common name.

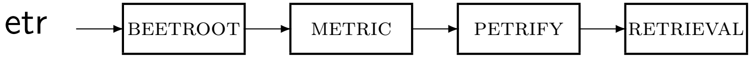
Processing a lookup in the permuterm index

- Rotate query wildcard to the right
- Use B-tree lookup as before
- Problem: Permuterm more than quadruples the size of the dictionary compared to a regular B-tree. (empirical number)

k-gram indexes

- More space-efficient than permuterm index
- Enumerate all character *k*-grams (sequence of *k* characters) occurring in a term
- 2-grams are called bigrams.
- Example: from *April is the cruelest month* we get the bigrams: *\$a ap pr ri il l\$ \$i is s\$ \$t th he e\$ \$c cr ru ue el le es st t\$ \$m mo on nt h\$*
- \$ is a special word boundary symbol, as before. But we use it now to mark both beginning and ending of words!
- Maintain an inverted index from bigrams to the terms that contain the bigram

Postings list in a 3-gram inverted index



k-gram (bigram, trigram, . . .) indexes

- Note that we now have two different types of inverted indexes
- The term-document inverted index for finding documents based on a query consisting of terms
- The *k*-gram index for finding terms based on a query consisting of *k*-grams

Processing wildcarded terms in a bigram index

- Query mon* can now be run as:
  $m AND mo AND on
- Gets us all terms with the prefix *mon* . . .
- . . . but also many "false positives" like MOON.
- We must postfilter these terms against query.
- Surviving terms are then looked up in the term-document inverted index.
- *k*-gram index vs. permuterm index
  - *k*-gram index is more space efficient.
  - Permuterm index doesn't require postfiltering.

Exercise

- Google has limited support for wildcard queries.
- For example, this query doesn't work very well on Google: [gen* universit*]
  - Intention: you are looking for the University of Geneva, but don't know which accents to use for the French words for university and Geneva.
  - These actually work well now!
- According to Google search basics, 2010-04-29: "Note that the * operator works only on whole words, not parts of words."
- Exercise: Why doesn't (didn't) Google fully support wildcard queries?

Processing wildcard queries in the term-document index

- Problem 1: we must potentially execute a large number of Boolean queries.
- Most straightforward semantics: Conjunction of disjunctions
- For [gen* universit*]: geneva university OR geneva université OR genève university OR genève université OR general universities OR . . .
- Very expensive
- Problem 2: Users hate to type.
- If abbreviated queries like [pyth* theo*] for [pythagoras' theorem] are allowed, users will use them a lot.
- This would significantly increase the cost of answering queries.
- Somewhat alleviated by Google Suggest

More Exercises

- Exercise 3.3
- Exercise 3.4
- Exercise 3.5

Outline

Spelling correction

- Two principal uses
  - Correcting documents being indexed
  - Correcting user queries
- Two different methods for spelling correction
- Isolated word spelling correction
  - Check each word on its own for misspelling
  - Will not catch typos resulting in correctly spelled words, e.g., *an asteroid that fell form the sky*
- Context-sensitive spelling correction
  - Look at surrounding words
  - Can correct *form*/*from* error above

Correcting documents

- We're not interested in interactive spelling correction of documents (e.g., MS Word) in this class.
- In IR, we use document correction primarily for OCR'ed documents. (OCR = optical character recognition)
- The general philosophy in IR is: don't change the documents.

Correcting queries

- First: isolated word spelling correction
- Premise 1: There is a list of "correct words" from which the correct spellings come.
- Premise 2: We have a way of computing the distance between a misspelled word and a correct word.
- Simple spelling correction algorithm: return the "correct" word that has the smallest distance to the misspelled word.
- Example: *informaton* → *information*
- For the list of correct words, we can use the vocabulary of all words that occur in our collection.
- Why is this problematic?

Alternatives to using the term vocabulary

- A standard dictionary (Webster's, OED etc.)
- An industry-specific dictionary (for specialized IR systems)

Distance between misspelled word and “correct” word

- We will study several alternatives.
- Edit distance and Levenshtein distance
- Weighted edit distance
- *k*-gram overlap

Edit distance

- The edit distance between string s_1 and string s_2 is the minimum number of basic operations that convert s_1 to s_2.
- Levenshtein distance: The admissible basic operations are insert, delete, and replace
- Levenshtein distance *dog*-*do*: 1
- Levenshtein distance *cat*-*cart*: 1
- Levenshtein distance *cat*-*cut*: 1
- Levenshtein distance *cat*-*act*: 2
- Damerau-Levenshtein distance *cat*-*act*: 1
- Damerau-Levenshtein includes transposition as a fourth possible operation.

Levenshtein distance: Computation

		f	a	s	t
	0	1	2	3	4
c	1	1	2	3	4
a	2	2	1	2	3
t	3	3	2	2	2
s	4	4	3	2	3

Levenshtein distance: Algorithm

```
LevenshteinDistance($s_1, s_2$)
for $i \leftarrow 0$ to $|s_1|$
do $m[i, 0] = i$
for $j \leftarrow 0$ to $|s_2|$
do $m[0, j] = j$
for $i \leftarrow 1$ to $|s_1|$
do for $j \leftarrow 1$ to $|s_2|$
    do if $s_1[i] = s_2[j]$
          then $m[i, j] = \min\{m[i\text{-}1, j]+1, m[i, j\text{-}1]+1, m[i\text{-}1, j\text{-}1]\}$
          else $m[i, j] = \min\{m[i\text{-}1, j]+1, m[i, j\text{-}1]+1, m[i\text{-}1, j\text{-}1]+1\}$
return $m[|s_1|, |s_2|]$
```

Operations: insert (cost 1), delete (cost 1), replace (cost 1), copy (cost 0)

Levenshtein distance: Algorithm

```
LevenshteinDistance($s_1, s_2$)
 1  for $i \leftarrow 0$ to $|s_1|$
 2  do $m[i, 0] = i$
 3  for $j \leftarrow 0$ to $|s_2|$
 4  do $m[0, j] = j$
 5  for $i \leftarrow 1$ to $|s_1|$
 6  do for $j \leftarrow 1$ to $|s_2|$
 7       do if $s_1[i] = s_2[j]$
 8             then $m[i, j] = \min\{m[i\text{-}1, j]+1, m[i, j\text{-}1]+1, m[i\text{-}1, j\text{-}1]\}$
 9             else  $m[i, j] = \min\{m[i\text{-}1, j]+1, m[i, j\text{-}1]+1, m[i\text{-}1, j\text{-}1]+1\}$
10  return $m[|s_1|, |s_2|]$
```

Operations: insert (cost 1), delete (cost 1), replace (cost 1), copy (cost 0)

Levenshtein distance: Algorithm

```
LevenshteinDistance($s_1, s_2$)
 1  for $i \leftarrow 0$ to $|s_1|$
 2  do $m[i,0] = i$
 3  for $j \leftarrow 0$ to $|s_2|$
 4  do $m[0,j] = j$
 5  for $i \leftarrow 1$ to $|s_1|$
 6  do for $j \leftarrow 1$ to $|s_2|$
 7       do if $s_1[i] = s_2[j]$
 8             then $m[i,j] = \min\{m[i\text{-}1,j]+1, m[i,j\text{-}1]+1, m[i\text{-}1,j\text{-}1]\}$
 9             else $m[i,j] = \min\{m[i\text{-}1,j]+1, m[i,j\text{-}1]+1, m[i\text{-}1,j\text{-}1]+1\}$
10  return $m[|s_1|,|s_2|]$
```

Operations: insert (cost 1), delete (cost 1), replace (cost 1), copy (cost 0)

Levenshtein distance: Algorithm

```
LevenshteinDistance($s_1, s_2$)
for $i \leftarrow 0$ to $|s_1|$
do $m[i,0] = i$
for $j \leftarrow 0$ to $|s_2|$
do $m[0,j] = j$
for $i \leftarrow 1$ to $|s_1|$
do for $j \leftarrow 1$ to $|s_2|$
    do if $s_1[i] = s_2[j]$
          then $m[i,j] = \min\{m[i\text{-}1,j]+1, m[i,j\text{-}1]+1, m[i\text{-}1,j\text{-}1]\}$
          else $m[i,j] = \min\{m[i\text{-}1,j]+1, m[i,j\text{-}1]+1, m[i\text{-}1,j\text{-}1]+1\}$
return $m[|s_1|,|s_2|]$
```

Operations: insert (cost 1), delete (cost 1), replace (cost 1), copy (cost 0)

Levenshtein distance: Algorithm

```
LevenshteinDistance($s_1, s_2$)
 1  for $i \leftarrow 0$ to $|s_1|$
 2  do $m[i, 0] = i$
 3  for $j \leftarrow 0$ to $|s_2|$
 4  do $m[0, j] = j$
 5  for $i \leftarrow 1$ to $|s_1|$
 6  do for $j \leftarrow 1$ to $|s_2|$
 7       do if $s_1[i] = s_2[j]$
 8             then $m[i, j] = \min\{m[i\text{-}1, j]+1, m[i, j\text{-}1]+1, m[i\text{-}1, j\text{-}1]\}$
 9             else $m[i, j] = \min\{m[i\text{-}1, j]+1, m[i, j\text{-}1]+1, m[i\text{-}1, j\text{-}1]+1\}$
10  return $m[|s_1|, |s_2|]$
```

Operations: insert (cost 1), delete (cost 1), replace (cost 1), copy (cost 0)

Levenshtein distance: Example

			f		a		s		t	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
c		**1**	*1*	*2*	**2**	3	**3**	4	**4**	5
		1	*2*	*1*	**2**	**2**	**3**	**3**	**4**	**4**
a		**2**	**2**	**2**	*1*	*3*	*3*	*4*	4	5
		2	3	**2**	*3*	*1*	*2*	*2*	**3**	**3**
t		**3**	**3**	**3**	3	**2**	*2*	*3*	*2*	*4*
		3	4	**3**	4	**2**	*3*	*2*	*3*	*2*
s		**4**	**4**	**4**	4	**3**	**2**	3	*3*	*3*
		4	5	**4**	5	**3**	4	**2**	*3*	*3*

Each cell of Levenshtein matrix

cost of getting here from my upper left neighbor (copy or replace)	cost of getting here from my upper neighbor (delete)
cost of getting here from my left neighbor (insert)	the minimum of the three possible "movements"; the cheapest way of getting here

Levenshtein distance: Example

			f		a		s		t	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
c		**1**	*1*	*2*	**2**	3	**3**	4	**4**	5
		1	*2*	*1*	**2**	**2**	**3**	**3**	**4**	**4**
a		**2**	**2**	**2**	*1*	*3*	*3*	*4*	4	5
		2	3	**2**	*3*	*1*	*2*	*2*	**3**	**3**
t		**3**	**3**	**3**	3	**2**	*2*	*3*	*2*	*4*
		3	4	**3**	4	**2**	*3*	*2*	*3*	*2*
s		**4**	**4**	**4**	4	**3**	**2**	3	*3*	*3*
		4	5	**4**	5	**3**	4	**2**	*3*	*3*

Dynamic programming (Cormen et al.)

- Optimal substructure: The optimal solution to the problem contains within it subsolutions, i.e., optimal solutions to subproblems.
- Overlapping subsolutions: The subsolutions overlap. These subsolutions are computed over and over again when computing the global optimal solution in a brute-force algorithm.
- Subproblem in the case of edit distance: what is the edit distance of two prefixes
- Overlapping subsolutions: We need most distances of prefixes 3 times – this corresponds to moving right, diagonally, down.

Weighted edit distance

- As above, but weight of an operation depends on the characters involved.
- Meant to capture keyboard errors, e.g., *m* more likely to be mistyped as *n* than as *q*.
- Therefore, replacing *m* by *n* is a smaller edit distance than by *q*.
- We now require a weight matrix as input.
- Modify dynamic programming to handle weights

Using edit distance for spelling correction

- Given query, first enumerate all character sequences within a preset (possibly weighted) edit distance
- Intersect this set with our list of “correct” words
- Then suggest terms in the intersection to the user.
- $\rightarrow$ exercise in the next slide

Exercise

1. Compute Levenshtein distance matrix for OSLO – SNOW
2. What are the Levenshtein editing operations that transform *cat* into *catcat*?

		s	n	o	w
	0	1 1	2 2	3 3	4 4
o	1 1				
s	2 2				
l	3 3				
o	4 4				

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	1	2						
		1	2	?						
s		**2**								
		2								
l		**3**								
		3								
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2						
		1	2	**1**						
s		**2**								
		2								
l		**3**								
		3								
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	2	3				
		1	2	**1**	2	?				
s		**2**								
		2								
l		**3**								
		3								
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3				
		1	2	**1**	**2**	**2**				
s		**2**								
		2								
l		**3**								
		3								
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	2	4		
		1	2	**1**	**2**	**2**	3	?		
s		**2**								
		2								
l		**3**								
		3								
o		**4**								
		4								

		s	n	o	w
	0	**1** **1**	**2** **2**	**3** **3**	**4** **4**
o	**1** **1**	**1** 2 2 **1**	**2** 3 **2** **2**	**2** 4 3 **2**	
s	**2** **2**				
l	**3** **3**				
o	**4** **4**				

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	3	?
s		**2**								
		2								
l		**3**								
		3								
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**								
		2								
l		**3**								
		3								
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	1	2						
		2	3	?						
l		**3**								
		3								
o		**4**								
		4								

		s	n	o	w
	0	**1** **1**	**2** **2**	**3** **3**	**4** **4**
o	**1** / **1**	**1** 2 / 2 **1**	**2** 3 / **2** **2**	**2** 4 / 3 **2**	4 5 / **3** **3**
s	**2** / **2**	**1** 2 / 3 **1**			
l	**3** / **3**				
o	**4** / **4**				

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	2	3				
		2	3	**1**	2	?				
l		**3**								
		3								
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3				
		2	3	**1**	**2**	**2**				
l		**3**								
		3								
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	3	3		
		2	3	**1**	**2**	**2**	3	?		
l		**3**								
		3								
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**		
		2	3	**1**	**2**	**2**	**3**	**3**		
l		**3**								
		3								
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	3	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	?
l		**3**								
		3								
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**								
		3								
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	2						
		3	4	?						
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**						
		3	4	**2**						
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**	2	3				
		3	4	**2**	3	?				
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**	**2**	3				
		3	4	**2**	3	**2**				
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**	**2**	3	3	4		
		3	4	**2**	3	**2**	3	?		
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**	**2**	3	**3**	4		
		3	4	**2**	3	**2**	**3**	**3**		
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**	**2**	3	**3**	4	4	4
		3	4	**2**	3	**2**	**3**	**3**	4	?
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**	**2**	3	**3**	4	**4**	**4**
		3	4	**2**	3	**2**	**3**	**3**	**4**	**4**
o		**4**								
		4								

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**	**2**	3	**3**	4	**4**	**4**
		3	4	**2**	3	**2**	**3**	**3**	**4**	**4**
o		**4**	4	3						
		4	5	?						

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**	**2**	3	**3**	4	**4**	**4**
		3	4	**2**	3	**2**	**3**	**3**	**4**	**4**
o		**4**	4	**3**						
		4	5	**3**						

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**	**2**	3	**3**	4	**4**	**4**
		3	4	**2**	3	**2**	**3**	**3**	**4**	**4**
o		**4**	4	**3**	3	3				
		4	5	**3**	4	?				

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**	**2**	3	**3**	4	**4**	**4**
		3	4	**2**	3	**2**	**3**	**3**	**4**	**4**
o		**4**	4	**3**	**3**	**3**				
		4	5	**3**	4	**3**				

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**	**2**	3	**3**	4	**4**	**4**
		3	4	**2**	3	**2**	**3**	**3**	**4**	**4**
o		**4**	4	**3**	**3**	**3**	2	4		
		4	5	**3**	4	**3**	4	?		

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**	**2**	3	**3**	4	**4**	**4**
		3	4	**2**	3	**2**	**3**	**3**	**4**	**4**
o		**4**	4	**3**	**3**	**3**	**2**	4		
		4	5	**3**	4	**3**	4	**2**		

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**	**2**	3	**3**	4	**4**	**4**
		3	4	**2**	3	**2**	**3**	**3**	**4**	**4**
o		**4**	4	**3**	**3**	**3**	**2**	4	4	5
		4	5	**3**	4	**3**	4	**2**	3	?

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**	**2**	3	**3**	4	**4**	**4**
		3	4	**2**	3	**2**	**3**	**3**	**4**	**4**
o		**4**	4	**3**	**3**	**3**	**2**	4	4	5
		4	5	**3**	4	**3**	4	**2**	**3**	**3**

		s	n	o	w
	0	**1** **1**	**2** **2**	**3** **3**	**4** **4**
o	**1** / **1**	**1** 2 / 2 **1**	**2** 3 / **2** **2**	**2** 4 / 3 **2**	4 5 / **3** **3**
s	**2** / **2**	**1** 2 / 3 **1**	**2** 3 / **2** **2**	**3** **3** / **3** **3**	**3** 4 / 4 **3**
l	**3** / **3**	3 **2** / 4 **2**	**2** 3 / 3 **2**	**3** 4 / **3** **3**	**4** **4** / **4** **4**
o	**4** / **4**	4 **3** / 5 **3**	**3** **3** / 4 **3**	**2** 4 / 4 **2**	4 5 / **3** **3**

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**	**2**	3	**3**	4	**4**	**4**
		3	4	**2**	3	**2**	**3**	**3**	**4**	**4**
o		**4**	4	**3**	**3**	**3**	**2**	4	4	5
		4	5	**3**	4	**3**	4	**2**	**3**	**3**

How do I read out the editing operations that transform OSLO into SNOW?

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**	**2**	3	**3**	4	**4**	**4**
		3	4	**2**	3	**2**	**3**	**3**	**4**	**4**
o		**4**	4	**3**	**3**	**3**	**2**	4	4	5
		4	5	**3**	4	**3**	4	**2**	**3**	**3**

cost	operation	input	output
1	insert	*	w

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**	**2**	3	**3**	4	**4**	**4**
		3	4	**2**	3	**2**	**3**	**3**	**4**	**4**
o		**4**	4	**3**	**3**	**3**	**2**	4	4	5
		4	5	**3**	4	**3**	4	**2**	**3**	**3**

cost	operation	input	output
0	(copy)	o	o
1	insert	*	w

		s	n	o	w
	/ **0**	/ **1** **1**	/ **2** **2**	/ **3** **3**	/ **4** **4**
o	**1** / **1**	**1** 2 / 2 **1**	**2** 3 / **2** **2**	**2** 4 / 3 **2**	4 5 / **3** **3**
s	**2** / **2**	**1** 2 / 3 **1**	**2** 3 / **2** **2**	**3** **3** / **3** **3**	**3** 4 / 4 **3**
l	**3** / **3**	3 **2** / 4 **2**	**2** 3 / 3 **2**	**3** 4 / **3** **3**	**4** **4** / **4** **4**
o	**4** / **4**	4 **3** / 5 **3**	**3** **3** / 4 **3**	**2** 4 / 4 **2**	4 5 / **3** **3**

cost	operation	input	output
1	replace	l	n
0	(copy)	o	o
1	insert	*	w

			s		n		o		w	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
o		**1**	**1**	2	**2**	3	**2**	4	4	5
		1	2	**1**	**2**	**2**	3	**2**	**3**	**3**
s		**2**	**1**	2	**2**	3	**3**	**3**	**3**	4
		2	3	**1**	**2**	**2**	**3**	**3**	4	**3**
l		**3**	3	**2**	**2**	3	**3**	4	**4**	**4**
		3	4	**2**	3	**2**	**3**	**3**	**4**	**4**
o		**4**	4	**3**	**3**	**3**	**2**	4	4	5
		4	5	**3**	4	**3**	4	**2**	**3**	**3**

cost	operation	input	output
0	(copy)	s	s
1	replace	l	n
0	(copy)	o	o
1	insert	*	w

		s	n	o	w
	0	1 1	2 2	3 3	4 4
o	1 / 1	1 2 / 2 1	2 3 / 2 2	2 4 / 3 2	4 5 / 3 3
s	2 / 2	1 2 / 3 1	2 3 / 2 2	3 3 / 3 3	3 4 / 4 3
l	3 / 3	3 2 / 4 2	2 3 / 3 2	3 4 / 3 3	4 4 / 4 4
o	4 / 4	4 3 / 5 3	3 3 / 4 3	2 4 / 4 2	4 5 / 3 3

cost	operation	input	output
1	delete	o	*
0	(copy)	s	s
1	replace	l	n
0	(copy)	o	o
1	insert	*	w

			c		a		t		c		a		t	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**	**5**	**5**	**6**	**6**
c		**1**	**0**	2	2	3	3	4	**3**	5	5	6	6	7
		1	2	**0**	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**	**5**	**5**
a		**2**	2	**1**	**0**	2	2	3	3	4	**3**	5	5	6
		2	3	**1**	2	**0**	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
t		**3**	3	**2**	2	**1**	**0**	2	2	3	3	4	**3**	5
		3	4	**2**	3	**1**	2	**0**	**1**	**1**	**2**	**2**	**3**	**3**

			c		a		t		c		a		t	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**	**5**	**5**	**6**	**6**
c		**1**	**0**	2	2	3	3	4	**3**	5	5	6	6	7
		1	2	**0**	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**	**5**	**5**
a		**2**	2	**1**	**0**	2	2	3	3	4	**3**	5	5	6
		2	3	**1**	2	**0**	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
t		**3**	3	**2**	2	**1**	**0**	2	2	3	3	4	**3**	5
		3	4	**2**	3	**1**	2	**0**	**1**	**1**	**2**	**2**	**3**	**3**

cost	operation	input	output
1	insert	*	c
1	insert	*	a
1	insert	*	t
0	(copy)	c	c
0	(copy)	a	a
0	(copy)	t	t

			c		a		t		c		a		t	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**	**5**	**5**	**6**	**6**
c		**1**	**0**	2	2	3	3	4	**3**	5	5	6	6	7
		1	2	**0**	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**	**5**	**5**
a		**2**	2	**1**	**0**	2	2	3	3	4	**3**	5	5	6
		2	3	**1**	2	**0**	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
t		**3**	3	**2**	2	**1**	**0**	2	2	3	3	4	**3**	5
		3	4	**2**	3	**1**	2	**0**	**1**	**1**	**2**	**2**	**3**	**3**

cost	operation	input	output
0	(copy)	c	c
1	insert	*	a
1	insert	*	t
1	insert	*	c
0	(copy)	a	a
0	(copy)	t	t

		c	a	t	c	a	t
	/ **0**	/ **1** **1**	/ **2** **2**	/ **3** **3**	/ **4** **4**	/ **5** **5**	/ **6** **6**
c	**1** / **1**	**0** 2 / 2 **0**	2 3 / **1** **1**	3 4 / **2** **2**	**3** 5 / **3** **3**	5 6 / **4** **4**	6 7 / **5** **5**
a	**2** / **2**	2 **1** / 3 **1**	**0** 2 / 2 **0**	2 3 / **1** **1**	3 4 / **2** **2**	**3** 5 / **3** **3**	5 6 / **4** **4**
t	**3** / **3**	3 **2** / 4 **2**	2 **1** / 3 **1**	**0** 2 / 2 **0**	2 3 / **1** **1**	3 4 / **2** **2**	**3** 5 / **3** **3**

cost	operation	input	output
0	(copy)	c	c
0	(copy)	a	a
1	insert	*	t
1	insert	*	c
1	insert	*	a
0	(copy)	t	t

			c		a		t		c		a		t	
		0	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**	**5**	**5**	**6**	**6**
c		**1**	**0**	2	2	3	3	4	**3**	5	5	6	6	7
		1	2	**0**	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**	**5**	**5**
a		**2**	2	**1**	**0**	2	2	3	3	4	**3**	5	5	6
		2	3	**1**	2	**0**	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
t		**3**	3	**2**	2	**1**	**0**	2	2	3	3	4	**3**	5
		3	4	**2**	3	**1**	2	**0**	**1**	**1**	**2**	**2**	**3**	**3**

cost	operation	input	output
0	(copy)	c	c
0	(copy)	a	a
0	(copy)	t	t
1	insert	*	c
1	insert	*	a
1	insert	*	t

Outline

Spelling correction

- Isolated spell correction
  - Based on edit distance. How is this done?
  - *k*-gram indexes. Next few slides.
- Context-sensitive spelling correction
  - Hit-based algorithm
  - Language models

k-gram indexes for spelling correction

- Enumerate all *k*-grams in the query term
- Example: bigram index, misspelled word *bordroom*
- Bigrams: *bo, or, rd, dr, ro, oo, om*
- Use the *k*-gram index to retrieve "correct" words that match query term *k*-grams
- Threshold by number of matching *k*-grams
- E.g., only vocabulary terms that differ by at most 3 *k*-grams

k-gram indexes for spelling correction: *bordroom*

$$\begin{tikzcd}
\boxed{\text{BO}} \arrow[r] & \boxed{\text{aboard}} \arrow[r] & \boxed{\text{about}} \arrow[r] & \boxed{\text{boardroom}} \arrow[r] & \boxed{\text{border}} \\
\boxed{\text{OR}} \arrow[r] & \boxed{\text{border}} \arrow[r] & \boxed{\text{lord}} \arrow[r] & \boxed{\text{morbid}} \arrow[r] & \boxed{\text{sordid}} \\
\boxed{\text{RD}} \arrow[r] & \boxed{\text{aboard}} \arrow[r] & \boxed{\text{ardent}} \arrow[r] & \boxed{\text{boardroom}} \arrow[r] & \boxed{\text{border}}
\end{tikzcd}$$

Context-sensitive spelling correction

- Our example was: *an asteroid that fell form the sky*
- How can we correct *form* here?
- One idea: hit-based spelling correction
  - Retrieve "correct" terms close to each query term
  - for *flew form munich*: *flea* for *flew*, *from* for *form*, *munch* for *munich*
  - Now try all possible resulting phrases as queries with one word "fixed" at a time
  - Try query *"flea form munich"*
  - Try query *"flew from munich"*
  - Try query *"flew form munch*"
  - The correct query *"flew from munich"* has the most hits.
- Suppose we have 7 alternatives for *flew*, 20 for *form* and 3 for *munich*, how many "corrected" phrases will we enumerate?

Context-sensitive spelling correction

- The “hit-based” algorithm we just outlined is not very efficient.
- More efficient alternative: look at the query log, i.e., a “collection” of queries, not documents
- Even more efficient: build a language model to predict the misspelled word. We will talk about this later in the course.

General issues in spelling correction

- User interface
  - automatic vs. suggested correction
  - *Did you mean* only works for one suggestion.
  - What about multiple possible corrections?
  - Tradeoff: simple vs. powerful UI
- Cost
  - Spelling correction is potentially expensive.
  - Avoid running on every query?
  - Maybe just on queries that match few documents.
  - Guess: Spelling correction of major search engines is efficient enough to be run on every query.

- Nice discussion of Google's spell checker: `http://norvig.com/spell-correct.html`
- (Do not read after the "How it Works" title. We will revisit this when we look at language models!)

Soundex

- Soundex is the basis for finding phonetic (as opposed to orthographic) alternatives.
- We won't cover this algorithm!

Take-away

- Tolerant retrieval: What to do if there is no exact match between query term and document term
- Wildcard queries
- Spelling correction