Why people care about spelling

- Misspellings can cause misunderstandings
- Standard spelling makes it easy to organize words & text:
  - e.g., Without standard spelling, how would you look up things in a lexicon or thesaurus?
  - e.g., Optical character recognition software (OCR) can use knowledge about standard spelling to recognize scanned words even for hardly legible input.
- Standard spelling makes it possible to provide a single text, accessible to a wide range of readers (different backgrounds, speaking different dialects, etc.).
- Using standard spelling can make a good impression in social interaction.

Detection vs. Correction

- There are two distinct tasks:
  - error detection = simply find the misspelled words
  - error correction = correct the misspelled words
- e.g., It might be easy to tell that ater is a misspelled word, but what is the correct word? water? later? after?
- Note that detection is a prerequisite for correction.

Error causes

- Keyboard mistypings
- Phonetic errors
- Knowledge problems
- Non-word error detection

Space bar issues

- run-on errors = two separate words become one
  - e.g., the fuzz becomes thefuzz
- split errors = one word becomes two separate items
  - e.g., equalization becomes equali zation
- Note that the resulting items might still be words!
  - e.g., a tollway becomes atoll way
Phonetic errors

- **homophones** = two words which sound the same
  - e.g., read (past tense), cite/site/sight, they’re/their/there
- **Spoonerisms** = switching two letters/sounds around
  - e.g., It’s a tavy grain with biscuit wheels.
- letter/word substitution: replacing a letter (or sequence of letters) with a similar-sounding one
  - e.g., John kracked his nuckles, instead of John cracked his knuckles.

Knowledge problems

- not knowing a word and guessing its spelling (can be phonetic)
  - e.g., sientist
- not knowing a rule and guessing it
  - e.g., Do we double a consonant for ing words? jog → jokking
- knowing something is odd about the spelling, but guessing the wrong thing
  - e.g., typing siscors for the non-regular scissors

Inflection

- A word in English may appear in various guises due to word **inflections** = word endings which are fairly systematic for a given part of speech
  - plural noun ending: the boy + s → the boys
  - past tense verb ending: walk + ed → walked
- This can make spell-checking hard:
  - There are exceptions to the rules: mans, runned
  - There are words which look like they have a given ending, but they don’t: Hans, deed

Productivity

- part of speech change: nouns can be verbified
  - emailed is a common new verb coined after the noun email
- morphological productivity: prefixes and suffixes can be added
  - e.g., I can speak of un-email-able for someone who you can’t reach by email.
- words entering and exiting the lexicon, e.g.:
  - thou, or spleet ‘split’ (Hamlet III.2.10) are on their way out
  - d’oh seems to be entering
non-word error detection is essentially the same thing as word recognition = splitting up "words" into true words and non-words.

How is non-word error detection done?
- using a dictionary (construction and lookup)
- n-gram analysis

Dictionary construction

- Do we include inflected words? i.e., words with prefixes and suffixes already attached.
  - Lookup can be faster
  - But takes more space & doesn't account for new formations (e.g., google → googled)
- Want the dictionary to have only the word relevant for the user = domain-specificity
  - e.g., For most people memorize is a misspelled word, but in computer science this is a technical term
- Foreign words, hyphenations, derived words, proper nouns, and new words will always be problems
  - we cannot predict these words until humans have made them words.
- Dictionary should be dialectically consistent.
  - e.g., include only color or colour but not both

N-gram analysis

An n-gram here is a string of n letters.

a 1-gram (unigram)
at 2-gram (bigram)
ate 3-gram (trigram)
late 4-gram

We can use this n-gram information to define what the possible strings in a language are.
- e.g., po is a possible English string, whereas kvt is not.

This is more useful to correct optical character recognition (OCR) output, but we'll still take a look.

Bigram array

We can define a bigram array = information stored in a tabular fashion.

An example, for the letters k, l, m, with examples in parentheses

<table>
<thead>
<tr>
<th></th>
<th>k</th>
<th>l</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>0</td>
<td>1 (tackle)</td>
<td>1 (Hackman)</td>
</tr>
<tr>
<td>l</td>
<td>1 (elk)</td>
<td>1 (hello)</td>
<td>1 (alms)</td>
</tr>
<tr>
<td>m</td>
<td>0</td>
<td>0</td>
<td>1 (hammer)</td>
</tr>
</tbody>
</table>

The first letter of the bigram is given by the vertical letters (i.e., down the side), the second by the horizontal ones (i.e., across the top).

This is a non-positional bigram array = the array 1's and 0's apply for a string found anywhere within a word (beginning, 4th character, ending, etc.).

Positional bigram array

To store information specific to the beginning, the end, or some other position in a word, we can use a positional bigram array = the array only applies for a given position in a word.

Here's the same array as before, but now only applied to word endings:

<table>
<thead>
<tr>
<th></th>
<th>k</th>
<th>l</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>l</td>
<td>1 (elk)</td>
<td>1 (hall)</td>
<td>1 (elm)</td>
</tr>
<tr>
<td>m</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Having discussed how errors can be detected, we want to know how to correct these misspelled words:

- The most common method is *isolated-word error correction* = correcting words without taking context into account.
- Note: This technique can only handle errors that result in non-words.
- Knowledge about what is a typical error helps in finding correct word.

### Isolated-word error correction methods

- Many different methods are used; we will briefly look at four methods:
  - rule-based methods
  - similarity key techniques
  - probabilistic methods
  - minimum edit distance

- The methods play a role in one of the three basic steps:
  1. Detection of an error (discussed above)
  2. Generation of candidate corrections
     - rule-based methods
     - similarity key techniques
  3. Ranking of candidate corrections
     - probabilistic methods
     - minimum edit distance

### Knowledge about typical errors

- **word length effects**: most misspellings are within two characters in length of original
  - When searching for the correct spelling, we do not usually need to look at words with greater length differences.
- **first-position error effects**: the first letter of a word is rarely erroneous
  - When searching for the correct spelling, the process is sped up by being able to look only at words with the same first letter.

### Rule-based methods

One can generate correct spellings by writing rules:

- **Common misspelling rewritten as correct word**:
  - e.g., hte → the

- **Rules**:
  - based on inflections:
    - e.g., VCing → VCCing, where:
      - \( V \) = letter representing vowel, basically the regular expression \([aeiou] \)
      - \( C \) = letter representing consonant, basically \([b|c|d|f|h|j|k|l|m|n|p|q|r|s|t|v|w|x|y|z] \)
  - based on other common spellings (such as keyboard effects or common transpositions):
    - e.g., CeC → CaC
    - e.g., CiC → Cei

### Similarity key techniques (SOUNDEX)

- **Problem**: How can we find a list of possible corrections?
- **Solution**: Store words in different boxes in a way that puts the similar words together.
- **Example**:
  1. Start by storing words by their first letter (first letter effect), e.g., *punc* starts with the code P.
  2. Then assign numbers to each letter e.g., 0 for vowels, 1 for b, p, f, v (all bilabials), and so forth, e.g., punc → P052
  3. Then throw out all zeros and repeated letters, e.g., P052 → P52.
  4. Look for real words within the same box, e.g., punk is also in the P52 box.

### How is a mistyped word related to the intended?

For ranking errors, it helps to know:

- **types of operations**:
  - *insertion* = a letter is added to a word
  - *deletion* = a letter is deleted from a word
  - *substitution* = a letter is put in place of another one
  - *transposition* = two adjacent letters are switched

Note that the first two alter the length of the word, whereas the second two maintain the same length.
Probabilistic methods

Two main probabilities are taken into account:

- **transition probabilities** = probability (chance) of going from one letter to the next.
  - e.g., What is the chance that a will follow p in English? That u will follow q?
- **confusion probabilities** = probability of one letter being mistaken (substituted) for another (can be derived from a confusion matrix)
  - e.g., What is the chance that q is confused with p?

The Noisy Channel Model

Probabilities can be modeled with the *noisy channel model*

Hypothesized Language: X

Noisy Channel: X → Y

Actual Language: Y

Goal: Recover X from Y

- The noisy channel model has been very popular in speech recognition, among other fields

Thanks to Mike White for the slides on the Noisy Channel Model

Example

Correct Spelling: donald

Transposition: ld → dl

Misspelling: donadl

Goal: Recover correct spelling donald from misspelling donadl (i.e., \( P(\text{donald}|\text{donadl}) \))

Confusion probabilities

- It is impossible to fully investigate all possible error causes and how they interact, but we can learn from watching how often people make errors and where.
- One way is to build a **confusion matrix** = a table indicating how often one letter is mistyped for another correct letter.

<table>
<thead>
<tr>
<th></th>
<th>r</th>
<th>s</th>
<th>t</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>r</td>
<td>12</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>s</td>
<td></td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t</td>
<td>37</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(cf. Kernighan et al 1999)

Noisy Channel Spelling Correction

Incorrect Spelling: donadl

Correct Spelling: donald

Goal: Recover correct spelling X from misspelling Y

- Noisy word: Y = observation (incorrect spelling)
- We want to find the word (X) which maximizes: \( P(X|Y) \), i.e., the probability of X, given that Y has been seen

Conditional probability

\( p(x|y) \) is the probability of x given y

- Let’s say that yogurt appears 20 times in a text of 10,000 words.
  \( \rightarrow p(\text{yogurt}) = 20/10,000 = 0.002 \)
- Now, let’s say frozen appears 50 times in the text, and yogurt appears 10 times after it.
  \( \rightarrow p(\text{yogurt}|\text{frozen}) = 10/50 = 0.20 \)
Bayes Rule

With $X$ as the correct word and $Y$ as the misspelling, $P(X|Y)$ is impossible to calculate directly, so we use:

- $P(Y|X) = \text{the probability of the observed misspelling given the correct word}$
- $P(X) = \text{the probability of the (correct) word occurring anywhere in the text}$

Bayes Rule allows us to calculate $p(X|Y)$ in terms of $p(Y|X)$:

1. **Bayes Rule**: $P(X|Y) = \frac{P(Y|X)P(X)}{P(Y)}$

Finding the Correct Spelling

Goal: for a given misspelling $y$, find correct spelling $x = \arg\max_x \frac{P(y|x)}{P(x)}$

1. List “all” possible candidate corrections, i.e., all words with one insertion, deletion, substitution, or transposition
2. Rank them by their probabilities

Example: calculate for donald

$$Pr(\text{donald}|\text{donald})Pr(\text{donald})$$

and see if this value is higher than for any other possible correction.

Minimum edit distance

- In order to rank possible spelling corrections, it can be useful to calculate the minimum edit distance = minimum number of operations it would take to convert one word into another.
- For example, we can take the following five steps to convert junk to haiku:
  1. junk $\rightarrow$ juk (deletion)
  2. juk $\rightarrow$ huk (substitution)
  3. huk $\rightarrow$ hku (transposition)
  4. hku $\rightarrow$ hiku (insertion)
  5. hiku $\rightarrow$ haiku (insertion)

  But is this the minimum number of steps needed?

Computing edit distances

- To be able to compute the edit distance of two words at all, we need to ensure there is a finite number of steps.
- This can be accomplished by:
  - requiring that letters cannot be changed back and forth a potentially infinite number of times, i.e., we limit the number of changes to the size of the material we are presented with, the two words.
  - Idea: Never deal with a character in either word more than once.

  Result:
  - In the worst case, we delete each character in the first word and then insert each character of the second word.
  - The worst case edit distance for two words is $\text{length}(\text{word1}) + \text{length}(\text{word2})$
Computing edit distances

Using a graph to map out the options

- To calculate minimum edit distance, we set up a **directed, acyclic graph**, a set of nodes (circles) and arcs (arrows).
- Horizontal arcs correspond to deletions, vertical arcs correspond to insertions, and diagonal arcs correspond to substitutions (a letter can be “substituted” for itself).

```
Omit x

Insert y

Substitute x for y
```

Discussion here based on Roger Mitton’s book English Spelling and the Computer.

Computing edit distances

Adding numbers to the example graph

- The graph is **acyclic** = for any given node, it is impossible to return to that node by following the arcs.
- We can add identifiers to the states, which allows us to define a **topological order**:

```
1 p
2 i
3 s
4 o
5 g
6 e
```

Computing edit distances

How to compute the path with the least cost

We want to find the path from the start (1) to the end (20) with the least cost.

- The simple but dumb way of doing it:
  - Follow every path from start (1) to finish (20) and see how many changes we have to make.
  - But this is very inefficient! There are many different paths to check.

Computing edit distances

The smart way to compute the least cost

- The smart way to compute the least cost uses **dynamic programming** = a program designed to make use of results computed earlier
  - We follow the topological ordering.
  - As we go in order, we calculate the least cost for that node:
    - We add the cost of an arc to the cost of reaching the node this arc originates from.
    - We take the minimum of the costs calculated for all arcs pointing to a node and store it for that node.
  - The key point is that we are storing partial results along the way, instead of recalculating everything, every time we compute a new path.

Computing edit distances

An example graph

- Say, the user types in `plog`.
- We want to calculate how far away `peg` is (one of the possible corrections). In other words, we want to calculate the minimum edit distance (or minimum edit cost) from `plog` to `peg`.
- As the first step, we draw the following directed graph:

```
p
1 o
2 g
3 i
4 e
5 a
6 s
7 t
8 9
9 10
```

- Instead of assuming the same cost for all operations, in reality one will use different costs, e.g., for the first character or based on the confusion probability.

```
p
1 o
2 g
3 i
4 e
5 a
6 s
7 t
8 9
9 10
```
Context-dependent word correction

Context-dependent word correction = correcting words based on the surrounding context.

- This will handle errors which are real words, just not the right one or not in the right form.
- Essentially a fancier name for a grammar checker = a mechanism which tells a user if their grammar is wrong.

More on grammar correction

- Semantic errors = errors where the sentence structure sounds okay, but it doesn’t really mean anything.
  - e.g., They are leaving in about fifteen minuets to go to her house.
  ⇒ minuets and minutes are both plural nouns, but only one makes sense here

There are many different ways in which grammar correctors work, two of which we’ll focus on:
- Bigram model (bigrams of words)
- Rule-based model

Rule-based grammar correctors

We can write regular expressions to target specific error patterns. For example:
- To a certain extend, we have achieved our goal.
  - Match the pattern some or certain followed by extend, which can be done using the regular expression some|certain extend
  - Change the occurrence of extend in the pattern to extent.
- Naber (2003) uses 56 such rules to build a grammar corrector which works nearly as well as that in commercial products.

Bigram grammar correctors

We can look at bigrams of words, i.e., two words appearing next to each other.

- Question: Given the previous word, what is the probability of the current word?
  - e.g., given these, we have a lower chance of seeing report than of seeing reports.
  - Since a confusable word (reports) can be put in the same context, resulting in a higher probability, we flag report as a potential error
- But there’s a major problem: we may hardly ever see these reports, so we won’t know its probability.
- Possible Solutions:
  - use bigrams of parts of speech
  - use massive amounts of data and only flag errors when you have enough data to back it up

Beyond regular expressions

- But what about correcting the following:
  - A baseball teams was successful.
  - We should see that A is incorrect, but a simple regular expression doesn’t work because we don’t know where the word teams might show up.
  - A wildly overpaid, horrendous baseball teams were successful. (Five words later; change needed.)
  - A player on both my teams was successful. (Five words later; no change needed.)
- We need to look at how the sentence is constructed in order to build a better rule.
Syntax

- Syntax = the study of the way that sentences are constructed from smaller units.
- There cannot be a “dictionary” for sentences since there is an infinite number of possible sentences:

(3) The house is large.
(4) John believes that the house is large.
(5) Mary says that John believes that the house is large.

There are two basic principles of sentence organization:

- Linear order
- Hierarchical structure (Constituency)

Constituency

- What are the “meaningful units” of a sentence like Many executives eat at really fancy restaurants?
  - Many executives
  - really fancy
  - really fancy restaurants
  - eat at really fancy restaurants
- We refer to these meaningful groupings as constituents of a sentence.

Categories

- We would also like some way to say that Many executives, and really fancy restaurants are the same type of grouping, or constituent, whereas at really fancy restaurants seems to be something else.
- For this, we will talk about different categories
  - Lexical
  - Phrasal

Linear order

- Linear order = the order of words in a sentence.
- A sentence can have different meanings, based on its linear order:

(6) John loves Mary.
(7) Mary loves John.

- Languages vary as to what extent this is true, but linear order in general is used as a guiding principle for organizing words into meaningful sentences.
- Simple linear order as such is not sufficient to determine sentence organization though. For example, we can’t simply say “The verb is the second word in the sentence.”

(8) I eat at really fancy restaurants.
(9) Many executives eat at really fancy restaurants.

Hierarchical structure

- Constituents can appear within other constituents, which can be represented in a bracket form or in a syntactic tree.
- Constituents shown through brackets: [[Many executives] [eat [at [really fancy] restaurants]]]
- Constituents displayed as a tree:

```
   a
  / \  
 b   c
 /   /   e
Many=executives=eat=at=really=fancy=restaurants
```

Lexical categories

- Lexical categories are simply word classes, or what you may have heard as parts of speech. The main ones are:
  - verbs: eat, drink, sleep, ...
  - nouns: gas, food, lodging, ...
  - adjectives: quick, happy, brown, ...
  - adverbs: quickly, happily, well, westward
  - prepositions: on, in, at, to, into, of, ...
  - determiners/articles: a, an, the, this, these, some, much, ...

- Many executives eat at really fancy restaurants.
Determining lexical categories

How do we determine which category a word belongs to?

- **Distribution**: Where can these kinds of words appear in a sentence?
  - e.g., Nouns like mouse can appear after articles ("determiners") like some, while a verb like eat cannot.

- **Morphology**: What kinds of word prefixes/suffixes can a word take?
  - e.g., Verbs like walk can take an ed ending to mark them as past tense. A noun like mouse cannot.

Building a tree

Other phrases work similarly (S = sentence, VP = verb phrase, PP = prepositional phrase, AdjP = adjective phrase):

```
S
  NP
  VP
  PP
```

```
Many executives eat
```

```
at
```

```
AdjP
```

```
really fancy
```

Some other English rules

- NP → Det N (the cat, a house, this computer)
- NP → Det AdjP N (the happy cat, a really happy house)
  - For phrase structure rules, as shorthand parentheses are used to express that a category is optional.
  - We thus can compactly express the two rules above as one rule:
    - NP → Det (AdjP) N
  - Note that this is different and has nothing to do with the use of parentheses in regular expressions.

- AdjP → (Adv) Adj (really happy)
- VP → V (laugh, run, eat)
- VP → V NP (love John, hit the wall, eat cake)
- VP → V NP NP (give John the ball)
- PP → P NP (to the store, at John, in a New York minute)
- NP → NP PP (the cat on the stairs)

Phrase Structure Rules

- We can give rules for building these phrases. That is, we want a way to say that a determiner and a noun make up a noun phrase, but a verb and an adverb do not.

  **Phrase structure rules** are a way to build larger constituents from smaller ones.

  - e.g., S → NP VP
    - A sentence (S) constituent is composed of a noun phrase (NP) constituent and a verb phrase (VP) constituent. [hierarchy]
    - The NP must precede the VP. [linear order]

Phrase Structure Rules and Trees

With every phrase structure rule, you can draw a tree for it.

```
PP

to

Det

N

the

store
```

Phraseal categories

What about phraseal categories?

- What other phrases can we put in place of The joggers in a sentence such as the following?
  - The joggers ran through the park.
- Some options:
  - Susan
  - students
  - you
  - most dogs
  - some children
  - a huge, lovable bear
  - my friends from Brazil
  - the people that we interviewed

Since all of these contain nouns, we consider these to be *noun phrases*, abbreviated with NP.
Properties of Phrase Structure Rules

- **generative** = a schematic strategy that describes a set of sentences completely.
- **potentially (structurally) ambiguous** = have more than one analysis
  
  (10) We need more intelligent leaders.
  
  (11) Paraphrases:
  a. We need leaders who are more intelligent.
  b. Intelligent leaders? We need more of them!
- **recursive** = property allowing for a rule to be reapplied (within its hierarchical structure).
  
  e.g., \( NP \rightarrow NP \) \( PP \rightarrow P \) \( NP \)
  
  • The property of recursion means that the set of potential sentences in a language is infinite.

Pushdown automata

**Pushdown automaton** = the computational implementation of a context-free grammar.

It uses a **stack** (its memory device) and has two operations:
- **push** = put an element onto the top of a stack.
- **pop** = take the topmost element from the stack.

This has the property of being **Last In First Out (LIFO)**.

Consider a rule like \( PP \rightarrow P \) \( NP \)

- Push \( NP \) onto the stack
- Push \( P \) onto it
- If you find a preposition (e.g., on), pop \( P \) off of the stack
  - Now, the next thing you need is an \( NP \) ... when you find that, pop \( NP \) and push \( PP \) onto the stack

Writing grammar correction rules

So, with context-free grammars, we can now write some correction rules, which we will just sketch here.

- **A baseball teams were successful.**
  - A followed by PLURAL NP: change A \( \rightarrow \) The
- **John at the pizza.**
  - The structure of this sentence is NP PP, but that doesn’t make up a whole sentence.
  - We need a verb somewhere.

Context-free grammars

A **context-free grammar** (CFG) is essentially a collection of phrase structure rules.

- It specifies that each rule must have:
  - a left-hand side (LHS): a single **non-terminal** element = (phrasal and lexical) categories
  - a right-hand side (RHS): a mixture of non-terminal and **terminal** elements = actual words
- A CFG tries to capture a natural language completely.

Why “context-free”? Because these rules make no reference to any context surrounding them. i.e. you can’t say \( PP \rightarrow P \) \( NP \) when there is a verb phrase (VP) to the left.

Parsing

Using these context-free rules and something like a pushdown automaton, we can get a computer to **parse** a sentence = assign a structure to a sentence.

There are many, many parsing techniques out there.

- **top-down**: build a tree by starting at the top (i.e. \( S \rightarrow NP \) \( VP \)) and working down the tree.
- **bottom-up**: build a tree by starting with the words at the bottom and working up to the top.

Dangers of spelling and grammar correction

- The more we depend on spelling correctors, the less we try to correct things on our own. But spell checkers are not 100%
- A study at the University of Pittsburgh found that students made **more** errors (in proofreading) when using a spell checker!

<table>
<thead>
<tr>
<th>use checker</th>
<th>high SAT scores (16 errors)</th>
<th>low SAT scores (17 errors)</th>
</tr>
</thead>
<tbody>
<tr>
<td>no checker</td>
<td>5 errors</td>
<td>12.3 errors</td>
</tr>
</tbody>
</table>

(cf., [http://www.wired.com/news/business/0,1367,58058,00.html](http://www.wired.com/news/business/0,1367,58058,00.html))
A Poem on the Dangers of Spell Checkers

Michael Livingston

Eye halve a spelling chequer
It came with my pea sea.
It plainly marques four my revue
Miss steaks eye kin knot sea.
Eye strike a key and type a word
And weight four it two say
Weather eye am wrong ear write
It shows me strait a weigh.
As soon as a mist ache is maid
It nose bee fore two long
And eye can put the error rite
Its rare lea ever wrong.
Eye have run this poem threw it
I am shore your pleased two no
Its letter perfect awl the weigh
My chequer tolled me sew.

References