Spell Checker

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Spelling Correction

Spelling correction is an integral part of modern writing, ranging from **texting** and **emailing** to document creation and **web searches**. Despite their ubiquity, modern spell correctors aren't perfect, as evidenced by "autocorrect-gone-wrong" scenarios.

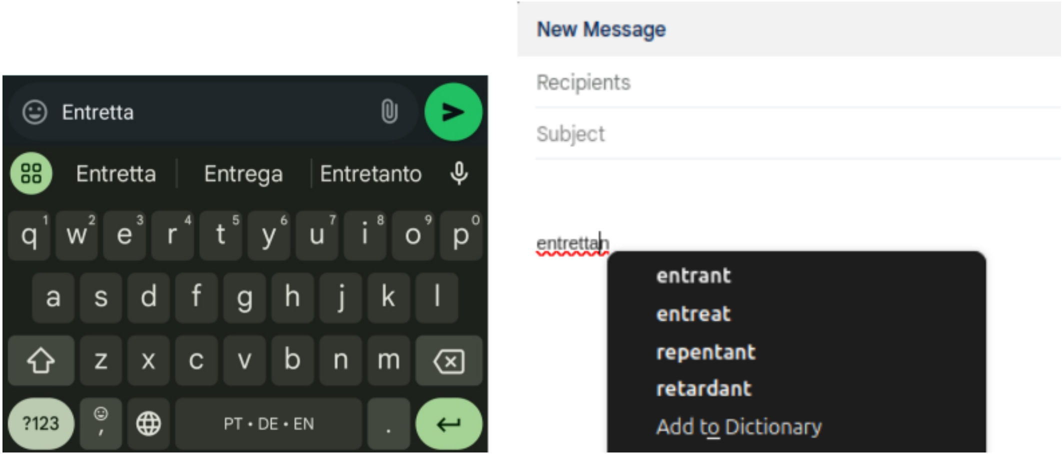


Figure 1: Spell checker.

Applications of Spell Checking

- Text Writing
- Automated and Information Systems
    - Data Entry Systems
    - Search and Information Retrieval
    - Optical Character Recognition (OCR)
    - Chatbots
    - Translation Systems

Automatic Spelling Correction Task

1. detection of an error;
2. generation of correction candidates;
3. ranking of candidate corrections;
4. perform automatic correction.

Perspectives in Spelling Correction

1. Non-Word Spelling Correction
   - Detects and corrects errors where the **word does not exist** in the dictionary. Example:
     - Input: `speling`
     - Correction: `spelling`

2. Real-Word Spelling Correction
   - Detects and corrects errors where the **word exists** but is contextually wrong. Example:
     - Input: `I no what to do.`
     - Correction: `I know what to do.`

Error Sources in Spelling

1. Typographical Errors:
   - May change with input devices (physical or virtual keyboard, or OCR system) and environment conditions.
   - Insertion: `speeling` → `spelling`
   - Deletion: `spelng` → `spelling`
   - Substitution: `spolling` → `spelling`
   - Transposition: `spelilng` → `spelling`
   - Diacritical marking: `naive` → `naïve`
2. Homophone Errors:
   - Homophones: `their` / `there`
   - Near-homophones: `accept` / `except`
3. Grammatical Errors:
   - among / between
4. Cross Word Boundary Errors:
   - maybe / may be

Notable Algorithms and Tools

- **Soundex** (1918): Phonetic algorithm that maps similar-sounding names.

```
Stephen → S315, Perez  → P620, Juice  → J200, Robert → R163
Steven  → S315, Powers → P620, Juicy  → J200, Rupert → R163
Stefan  → S315, Price  → P620, Juiced → J230, Rubin  → R150
```

- **Shannon (1948)**: A Mathematical Theory of Communication.

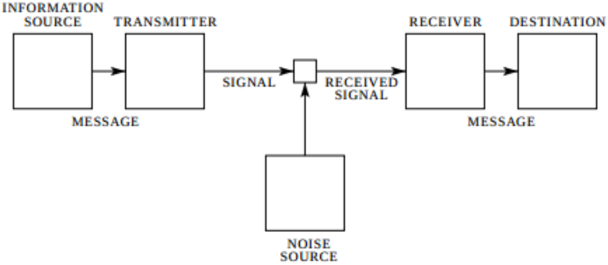


Fig. 1—Schematic diagram of a general communication system.

Figure 2: Noisy Channel.

- **Shannon (1950)**: Introduction of n-gram models in text analysis.

Figure 3: Word prediction is mean?

- **Blair (1960)**: Early algorithm for spelling error correction.
- **Damerau–Levenshtein** distance (1964, 1966): A string metric for measuring the edit distance between two sequences.

		S	u	n	d	a	y
	0	1	2	3	4	5	6
S	1	0	1	2	3	4	5
a	2	1	1	2	3	3	4
t	3	2	2	2	3	4	4
u	4	3	2	3	3	4	5
r	5	4	3	3	4	4	5
d	6	5	4	4	3	4	5
a	7	6	5	5	4	3	4
y	8	7	6	6	5	4	3

delete a

delete t

replace r with n

Figure 4: How many operations does it take to turn Saturday into Sundat?

The Levenshtein distance between two strings a, b (of length $|a|$ and $|b|$ respectively) is given by

$$\operatorname{lev}(a,b) = \begin{cases} |a| & \text{if } |b| = 0, \\ |b| & \text{if } |a| = 0, \\ \operatorname{lev}\big(\operatorname{tail}(a), \operatorname{tail}(b)\big) & \text{if } \operatorname{head}(a) = \operatorname{head}(b), \\ 1 + \min \begin{cases} \operatorname{lev}\big(\operatorname{tail}(a), b\big) & \text{deletion} \\ \operatorname{lev}\big(a, \operatorname{tail}(b)\big) & \text{insertion} \\ \operatorname{lev}\big(\operatorname{tail}(a), \operatorname{tail}(b)\big) & \text{replacement} \end{cases} & \text{otherwise} \end{cases}$$

Damerau-Levenshtein distance: also allows transposition of adjacent symbols.

Operations are expensive and language dependent: e.g. as of version 16.0, Unicode defines a total of 98682 Chinese characters.

- **BK-Trees** (1973): Efficient search for near matches using Levenshtein distance.
  - An arbitrary element a is selected as root node.
  - The k-th subtree is recursively built of all elements b such that $d(a, b) = k$.
  - Search idea: restrict the exploration of the tree to nodes that can only improve the best candidate found so far (use triangle inequality).

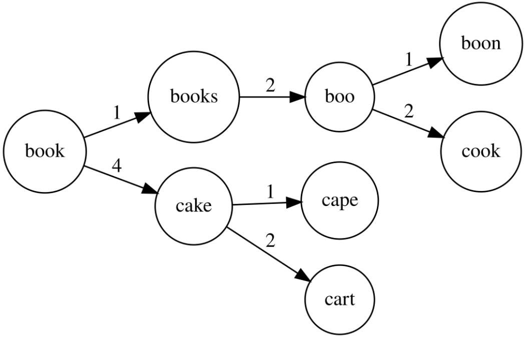
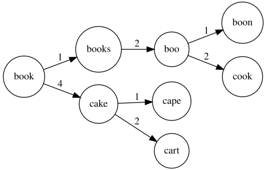


Figure 5: Burkhard-Keller Tree.

Search for w = 'cool'



1 $d_u = d(w,u) = d(\text{'cool'}, \text{'book'}) = 2$, set $d_{\text{best}} = 2$;

2 v = 'books', $|d_{uv} - d_u| = |1 - 2| = 1 < d_{\text{best}}$, then select v;

3 v = 'cake', $|d_{uv} - d_u| = |4 - 2| = 2 \nless d_{\text{best}}$, do not select v;

4 $d_u = d(w,u) = d(\text{'cool'}, \text{'books'}) = 3$, $d_u \nless d_{\text{best}}$;

5 $d_u = d(w,u) = d(\text{'cool'}, \text{'boo'}) = 2$, $d_u \nless d_{\text{best}}$;

6 v = 'boon', $|d_{uv} - d_u| = |2 - 1| = 1 < d_{\text{best}}$, then select v;

7 v = 'cook', $|d_{uv} - d_u| = |2 - 2| = 0 < d_{\text{best}}$, then select v;

8 $d_u = d(w,u) = d(\text{'cool'}, \text{'cook'}) = 1$, $d_u < d_{\text{best}}$, set $d_{\text{best}} = 1$;

9 $d_u = d(w,u) = d(\text{'cool'}, \text{'boon'}) = 2$, $d_u \nless d_{\text{best}}$;

10 'cook' is returned as the answer with $d_{\text{best}} = 1$.

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  - Error detection only.

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  - Hashing (discarding 60% of the remaining bits);

    Examples of hashing functions:
    1. Shift-and-Add: $h = (h << 1) + \text{char}\%m$
    2. Multiplicative Hashing: $h = (a \cdot h + \text{char})\%m$ (with a typically 31 or 33)
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  - Words were represented by 16-bit machine words;
  - Bloom filter;
  - False Positives.

- **Metaphone** (1990), Double Metaphone (2000), Metaphone 3 (2009): Extracts phonetic information for better matching.
  - Set of rules to improves on the Soundex algorithm.
  - `Smith → SM0, [SM0, XMT]`, `Schmidt → SXMTT, [XMT, SMT]`,
  - `Taylor → TLR, [TLR]`, `Taylor → EFNS, [AFNS]`,
  - `Roberts → RBRTS, [RPRTS]`
  - `spelling → SPLNK, [SPLNK]`, `speling → SPLNK, [SPLNK]`, `speeling → SPLNK, [SPLNK]`, `sprlling → SPRLNK, [SPRLNK]`

- **Noisy Channel Model (Kernighan et al., 1990 and Mays et al., 1991)**: Combined prior and likelihood models.

In the noisy channel model, we imagine that the surface form we see is actually a "distorted" form of an original word passed through a noisy channel. The decoder passes each hypothesis through a model of this channel and picks the word that best matches the surface noisy word. (Jurafsky and Martin, 2024)

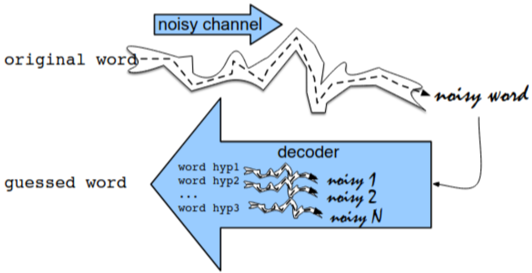

Figure 6: Noisy Channel Model

This noisy channel model is a kind of **Bayesian inference**.

Out of all possible words in the vocabulary V we want to find the word w such that $P(w|x)$ is highest.

$$\hat{w} = \arg\max_{w \in V} P(w|x)$$

Using Bayes: $P(x, w) = P(w|x)P(x) = P(x|w)P(w)$,

$$\hat{w} = \arg\max_{w \in V} \frac{P(x|w)P(w)}{P(x)} = \arg\max_{w \in V} \underbrace{P(x \mid w)}_{\substack{\text{channel model} \\ \text{or likelihood}}} \underbrace{P(w)}_{\text{prior}}$$

$$\hat{w} = \arg\max_{w \in V} (\log P(x \mid w) + \log P(w))$$

function NOISY CHANNEL SPELLING(*word* x, *dict* D, lm, *editprob*) **returns** *correction*

if $x \notin D$
  candidates, edits $\leftarrow$ All strings at edit distance 1 from x that are $\in D$, and their edit
  for each c, e in candidates, edits
    channel $\leftarrow$ editprob(e)
    prior $\leftarrow$ lm(c)
    $score[c] = \log channel + \log prior$
  return $\operatorname{argmax}_c \; score[c]$

Figure 7: Noisy channel model for spelling correction for unknown words (Jurafsky and Martin, 2024).

Example

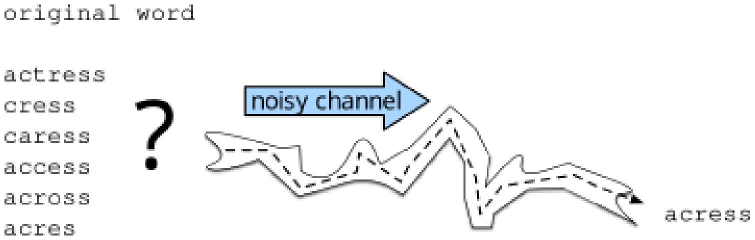

Figure 8: Example: misspelling acress.

		Transformation			
Error	Correction	Correct Letter	Error Letter	Position (Letter #)	Type
acress	actress	t	—	2	deletion
acress	cress	—	a	0	insertion
acress	caress	ca	ac	0	transposition
acress	access	c	r	2	substitution
acress	across	o	e	3	substitution
acress	acres	—	s	5	insertion
acress	acres	—	s	4	insertion

Figure 9: Candidate corrections for the misspelling acress and the transformations that would have produced the error (after Kernighan et al. (1990)). "—" represents a null letter. (Jurafsky and Martin, 2024)

w	count(w)	p(w)
actress	9,321	.0000231
cress	220	.000000544
caress	686	.00000170
access	37,038	.0000916
across	120,844	.000299
acres	12,874	.0000318

Figure 10: Language model from the 404,253,213 words in the Corpus of Contemporary English (COCA) (Jurafsky and Martin, 2024).

Error model

- A perfect model would need all sorts of factors: who the typist was, whether the typist was left-handed or right-handed, and so on.
- We can get a pretty reasonable estimate of $P(x|w)$ just by looking at **local context**: the identity of the correct letter itself, the misspelling, and the surrounding letters.
- Confusion Matrices:
  - `del[x, y]: count(xy typed as x)`
  - `ins[x, y]: count(x typed as xy)`
  - `sub[x, y]: count(x typed as y)`
  - `trans[x, y]: count(xy typed as yx)`

sub[X, Y] = Substitution of X (incorrect) for Y (correct)

Y (correct)

X	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
a	0	0	7	1	342	0	0	2	118	0	1	0	0	3	76	0	0	1	35	9	9	0	1	0	5	0
b	0	0	9	9	2	2	3	1	0	0	0	5	11	5	0	10	0	0	2	1	0	0	8	0	0	0
c	6	5	0	16	0	9	5	0	0	0	1	0	7	9	1	10	2	5	39	40	1	3	7	1	1	0
d	1	10	13	0	12	0	5	5	0	0	2	3	7	3	0	1	0	43	30	22	0	0	4	0	2	0
e	388	0	3	11	0	2	2	0	89	0	0	3	0	5	93	0	0	14	12	6	15	0	1	0	18	0
f	0	15	0	3	1	0	5	2	0	0	0	3	4	1	0	0	0	6	4	12	0	0	2	0	0	0
g	4	1	11	11	9	2	0	0	0	1	1	3	0	0	2	1	3	5	13	21	0	0	1	0	3	0
h	1	8	0	3	0	0	0	0	0	0	2	0	12	14	2	3	0	3	1	11	0	0	2	0	0	0
i	103	0	0	0	146	0	1	0	0	0	0	6	0	0	49	0	0	0	2	1	47	0	2	1	15	0
j	0	1	1	9	0	0	1	0	0	0	0	2	1	0	0	0	0	0	5	0	0	0	0	0	0	0
k	1	2	8	4	1	1	2	5	0	0	0	0	5	0	2	0	0	0	6	0	0	0	4	0	0	3
l	2	10	1	4	0	4	5	6	13	0	1	0	0	14	2	5	0	11	10	2	0	0	0	0	0	0
m	1	3	7	8	0	2	0	6	0	0	4	4	0	180	0	6	0	0	9	15	13	3	2	2	3	0
n	2	7	6	5	3	0	1	19	1	0	4	35	78	0	0	7	0	28	5	7	0	0	1	2	0	2
o	91	1	1	3	116	0	0	0	25	0	2	0	0	0	0	14	0	2	4	14	39	0	0	0	18	0
p	0	11	1	2	0	6	5	0	2	9	0	2	7	6	15	0	0	1	3	6	0	4	1	0	0	0
q	0	0	1	0	0	0	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
r	0	14	0	30	12	2	2	8	2	0	5	8	4	20	1	14	0	0	12	22	4	0	0	1	0	0
s	11	8	27	33	35	4	0	1	0	1	0	27	0	6	1	7	0	14	0	15	0	0	5	3	20	1
t	3	4	9	42	7	5	19	5	0	1	0	14	9	5	5	6	0	11	37	0	0	2	19	0	7	6
u	20	0	0	0	44	0	0	0	64	0	0	0	0	2	43	0	0	4	0	0	0	0	2	0	8	0
v	0	0	7	0	0	3	0	0	0	0	0	1	0	0	1	0	0	0	8	3	0	0	0	0	0	0
w	2	2	1	0	1	0	0	2	0	0	1	0	0	0	0	7	0	6	3	3	1	0	0	0	0	0
x	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0
y	0	0	2	0	15	0	1	7	15	0	0	0	2	0	6	1	0	7	36	8	5	0	0	1	0	0
z	0	0	0	7	0	0	0	0	0	0	0	7	5	0	0	0	0	2	21	3	0	0	0	0	3	0

Figure 11: Confusion matrix for spelling errors (Kernighan et al., 1990).

Estimating the channel model

$$P(x|w) = \begin{cases} \frac{\text{del}[x_{i-1}, w_i]}{\text{count}[x_{i-1} w_i]}, & \text{if deletion} \\ \frac{\text{ins}[x_{i-1}, w_i]}{\text{count}[w_{i-1}]}, & \text{if insertion} \\ \frac{\text{sub}[x_i, w_i]}{\text{count}[w_i]}, & \text{if substitution} \\ \frac{\text{trans}[w_i, w_{i+1}]}{\text{count}[w_i w_{i+1}]}, & \text{if transposition} \end{cases}$$

Candidate Correction	Correct Letter	Error Letter	x|w	P(x|w)
actress	t	-	c|ct	.000117
cress	-	a	a|#	.00000144
caress	ca	ac	ac|ca	.00000164
access	c	r	r|c	.000000209
across	o	e	e|o	.0000093
acres	-	s	es|e	.0000321
acres	-	s	ss|s	.0000342

Figure 12: Channel model for acress; the probabilities are taken from the `del[]`, `ins[]`, `sub[]`, and `trans[]` confusion matrices as shown in Kernighan et al. (1990).

Final probabilities for each of the potential corrections

Candidate Correction	Correct Letter	Error Letter	x|w	P(x|w)	P(w)	10^9*P(x|w)P(w)
actress	t	-	c|ct	.000117	.0000231	2.7
cress	-	a	a|#	.00000144	.000000544	0.00078
caress	ca	ac	ac|ca	.00000164	.00000170	0.0028
access	c	r	r|c	.000000209	.0000916	0.019
across	o	e	e|o	.0000093	.000299	2.8
acres	-	s	es|e	.0000321	.0000318	1.0
acres	-	s	ss|s	.0000342	.0000318	1.0

Figure 13: Computation of the ranking for each candidate correction, using the language model shown earlier and the error model. The final score is multiplied by 10^9 for readability (Jurafsky and Martin, 2024).

Unfortunately, the algorithm was wrong here; the writer's intention becomes clear from the context: . . . was called a "stellar and versatile ***acress*** *whose combination of sass and glamour has defined her . . . ". The surrounding words make it clear that actress and not across was the intended word.* (Jurafsky and Martin, 2024)

Using the *Corpus of Contemporary American English* to compute bigram probabilities for the words *actress* and *across* in their context using add-one smoothing, we get the following probabilities:

$$P(\text{actress}|\text{versatile}) = .000021$$
$$P(\text{across}|\text{versatile}) = .000021$$
$$P(\text{whose}|\text{actress}) = .0010$$
$$P(\text{whose}|\text{across}) = .000006$$

Multiplying these out gives us the language model estimate for the two candidates in context:

$$P(\text{versatile actress whose}) = .000021 \times .0010 = 210 \times 10^{-10}$$
$$P(\text{versatile across whose}) = .000021 \times .000006 = 1 \times 10^{-10}$$

Jurafsky, D., & Martin, J. H. (2024). *Speech and Language Processing*.

Kernighan, M. D. et al. (1990). *A spelling correction program based on a noisy channel model*.

Mays, E. et al. (1991). *Context based spelling correction*.

- Noisy Channel Model
  - Correct (Unix, 1990): Takes inputs from SPELL rejected words and provides candidates. Operations: Insertion, Deletion, Substitution, Reversal. Uses error probabilities.

- **Aspell** (2000): Combines spelling and phonetic correction.
  - Hashing for Spell Checking: Efficient candidate lookup using hash tables.
  - Metaphone Algorithm: Handles phonetic corrections by matching words that sound similar.
  - Ispell's Near Miss Strategy:
    - Focuses on edit distance 1 to reduce the search space.
    - Early Dictionary Filtering: Prunes invalid candidates during generation.

Example - Handling Homophones in Aspell

- Misspelled word `ther`
- Candidates: `there`, `their`, `they're`

1. Metaphone
   - The Metaphone algorithm transforms words into phonetic codes based on pronunciation.
   - Phonetic codes for the candidate words:
     - `there` → `0R`
     - `their` → `0R`
     - `they're` → `0R`
   - Homophones share the same code (`0R`).

2. Workflow:
   - Input: Misspelled word `ther`.
   - Step 1: Generate candidates using **edit distance 2 or less**:
     - Candidates: `there`, `their`, `thee`, `thor`, `her`, `the`, `they're`.
   - Step 2: Compute Metaphone codes for all candidates:
     - Candidates phonetically similar to `ther` (`0R`) rank higher: `there`, `their`, `thor`, `they're`.
   - Step 3: Rank and suggest based on:
     - Word frequency, Edit distance, Phonetic Similarity, Error Likelihood.
3. Limitations:
   - Metaphone matches words by sound but lacks **contextual understanding**.
   - Example:
     - Input: *"I went to ther house."*
     - Suggestions: `thee`, `their`, `there`, `therm`, `the`, `her`, `Thar`, `Thea`, `Thor`, `Thur`.
     - Aspell cannot infer the correct word (`their`) without considering the sentence's context.

GNU Aspell

- **Hunspell** (2002): Morphological analyzer with affix rules and phonetic matching.

Key Features:

- Morphological Analysis:
  - Supports complex languages with rich morphology (e.g., Hungarian, Turkish, Finnish).
  - Handles word roots, prefixes, and suffixes using affix rules.
- Dictionary System:
  - Two components:
    1. Dictionary File: Contains root forms of words.
    2. Affix File: Defines rules for combining roots with prefixes/suffixes.
- Levenshtein Distance:
  - Uses *edit distance* to generate and rank candidate corrections.
- Phonetic Matching:
  - Uses a table-driven phonetic transcription algorithm borrowed from Aspell. It is useful for languages with not pronunciation based orthography.
- n-gram similarity:
  - Improve suggestions.

- Multilingual Support:
  - Available for 98 languages with extensive dictionaries.

Applications:

- Integrated into tools like LibreOffice, Firefox, and Chrome for multilingual spell checking.
- Supports custom dictionaries for specialized fields (e.g., medical, legal).

Hunspell at GitHub

- **Norvig**'s Algorithm (2007): Uses Damerau-Levenshtein distance to generate candidates.

Key Features:

- Eit Distance:
  - Generates all possible words within a given edit distance (e.g., 1 or 2) from the misspelled word.
  - Handles insertion, deletion, substitution, and transposition.
- Dictionary Lookup:
  - Filters candidates by validating them against a word dictionary.
- Ranking:
  - Ranks valid candidates based on:
    - Word Frequency: More frequent words are prioritized.
    - Likelihood of Errors: Based on the Noisy Channel Model (optional).

How to Write a Spelling Corrector

- **Neural-Based Models**: Leverage deep learning for advanced error detection and correction.

Key Techniques in Spelling Correction

The Noisy Channel Model

- **Bayesian Inference**:
  Finds the word (w) that maximizes (P(w|x)):

$$\hat{w} = \arg\max_{w \in V} P(x|w)P(w)$$

- **Components**:
  - **Prior Probability**: (P(w)) (from n-grams like unigrams, bigrams, etc.)
  - **Error Model**: (P(x|w)) (using confusion matrices).

Confusion Matrix Examples:

- **Deletion**: (del[x, y])
- **Insertion**: (ins[x, y])
- **Substitution**: (sub[x, y])
- **Transposition**: (trans[x, y])

Lexical Similarity Metrics

1. **Levenshtein Distance** (Edit Distance):
   Minimal number of insertions, deletions, and replacements to transform one word into another.
2. **Jaro Similarity**:
   Measures similarity based on matching characters and transpositions.
3. **Keyboard Distance**:
   Considers physical proximity of keys.
4. **Phonetic Matching**:
   Algorithms like Soundex and Metaphone to identify similar-sounding words.

Probabilistic Models

- **Example**:

  Correction for real-word spelling errors.

  Input: `Only two of thew apples`

  Candidates: `two of the`, `two of threw`, `two of thaw`, etc.

  Use trigram probabilities (e.g., ($P(\text{the}|\text{two of}) = 0.476012$)).

Neural Networks and Deep Learning

- Models like RNNs, Transformers, and LSTMs learn patterns from large datasets.

Real-World Spelling Correction

- Input: Sentence with an error.
- Output: Highest-probability correction based on:
  1. Language Model (($P(W)$))
  2. Channel Model (($P(x|W)$)).

Domain-Specific Spell Checkers

1. Medical
   - MedSpell: a medical spelling and autocorrect application
   - OpenMedSpel (open-source)
2. Programming
   - CodeSpell: designed primarily for checking misspelled words in source code
3. Learning
   - Kidspell: A child-oriented, rule-based, phonetic spellchecker
4. Accessibility
   - Real Check: A Spellchecker for Dyslexia
5. Custom Dictionaries
   - Hunspell and Aspell: Add specialized vocabularies

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