Fast Approximate String Matching with Finite Automata

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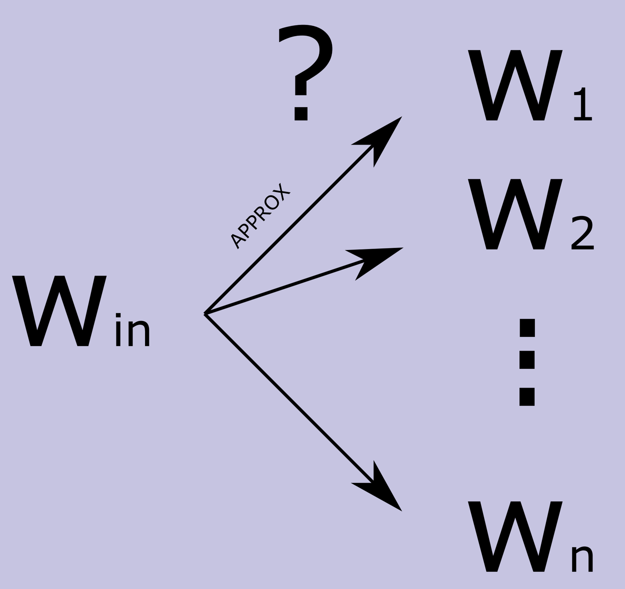
The problem

The problem addressed here is a classic search problem: given a word w_{in} not found in a list W, which word in W most closely resembles w_{in}?

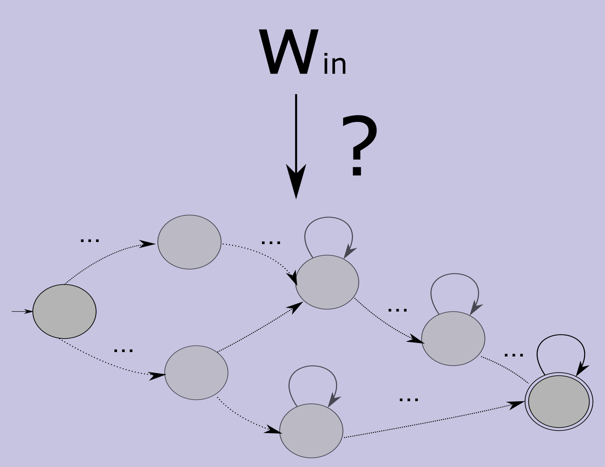


This can be costly using standard edit distance calculations for several reasons:

- If the size of the list W is large, we cannot practically calculate a 'distance' between every word on the list and our candidate word to find the solution
- The list W may be infinite: we may have a grammar that models unlimited compounding and affixing and thus allows infinitely long words
- We may want to use complex distance metrics to define the similarity between two words

An alternate formulation

Instead of considering a list W to find approximate matches for a word w_{in} we consider finding the words in a finite-state automaton $\mathcal{A}$ that most closely resemble w_{in}.



Generalizing the problem has a number of potential advantages:

- Any finite list W can be converted into a deterministic finite state automaton
- A finite state automaton can encode an infinite number of words
- Morphological analyzers are often designed to be finite-state transducers (FSTs). It is trivial, given a morphological FST, to extract an automaton that encodes all the legal words in the language

Applying A*-search to the problem

We apply the classic A-* search algorithm to the problem. In effect, we match letters in w_{in} against arcs in the automaton $\mathcal{A}$ taking into account the possibility of insertion, deletion and substitution. For each step and node expansion in the search space we recalculate the score $f = g + h$, where g is the accumulated cost so far, and h our heuristic guess of the future score. We maintain nodes in a priority queue and iteratively expand the one with the cheapest f and keep going until we find a solution.

Heuristics

The most important question when doing first-best/A*-type search strategies is the heuristic h used to decide the node expansion strategy. The requirements on h are basically:

- h must be consistent (never overestimates the remaining cost)
- h must be fast to calculate
- additional data needed to calculate h must take up little space

For this algorithm, several experiments with different heuristics h were made, and we settled for a strategy where:

- We precalculate for each state in the automaton $\mathcal{A}$, what symbols can *possibly* be encountered on future paths starting from that state
- The path length is variable from $1 \ldots \infty$
- Whenever we need to calculate h in the search we compare the number of symbols *different* in the word remainder vs. the symbols stored in the state

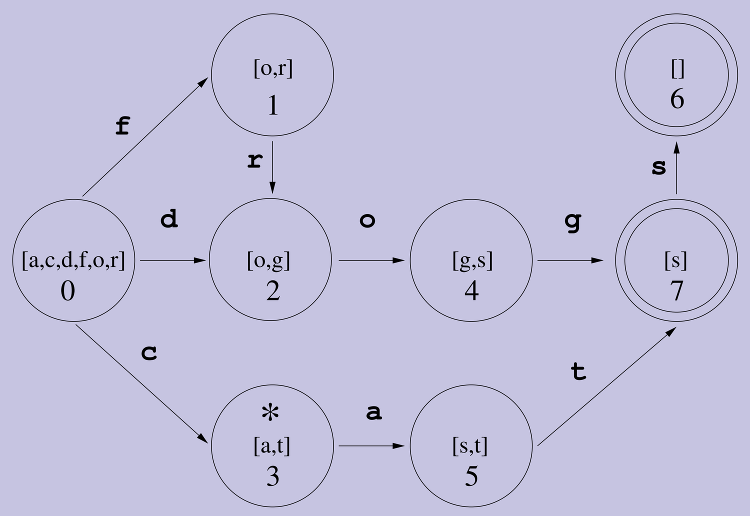


FIGURE 1: *Automaton where every state contains the possible symbols that can be encountered 2 steps ahead.*

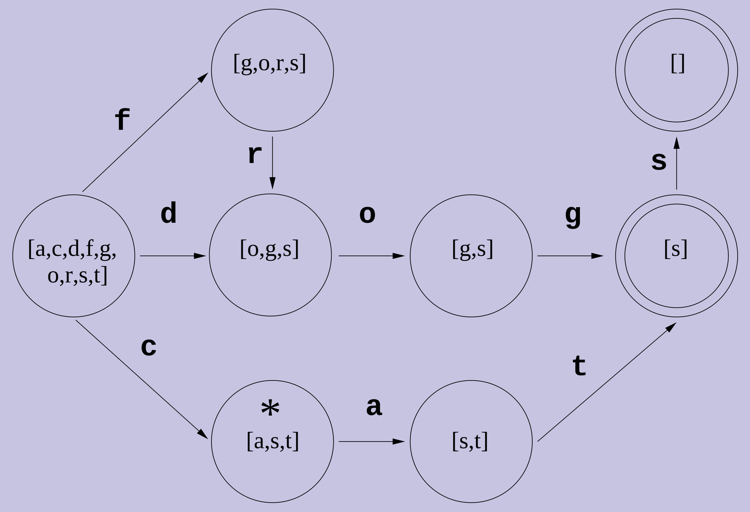


FIGURE 2: *Automaton where every state contains the possible symbols that can be encountered ∞ steps ahead.*

Choosing a heuristic

Since several different h (varying with lookahead length) were available, we conducted experiments to find an overall reliable strategy. Most results were similar to that of table 1.

	h_0	h_1	h_2	h_3	h_4	h_5
NI	6092	1892	1548	1772	1904	622
NE	3295	1143	909	1049	1193	89

TABLE 1: *Average number of nodes inserted and nodes expanded using 5 strategies, tested with random misspellings against a wide-coverage Spanish dictionary/morphology encoded as an automaton.*

h_0 : no heuristic (i.e. h = 0 always)

h_1 : $n = \infty$ (we only use the ∞ lookahead)

h_2 : $n = 2$

h_3 : $n = 3$

h_4 : $n = 4$

h_5 : $n = \text{MAX}(h_1, h_2)$ (also, ties in priority queue broken depending on value of pos)

Example & Results

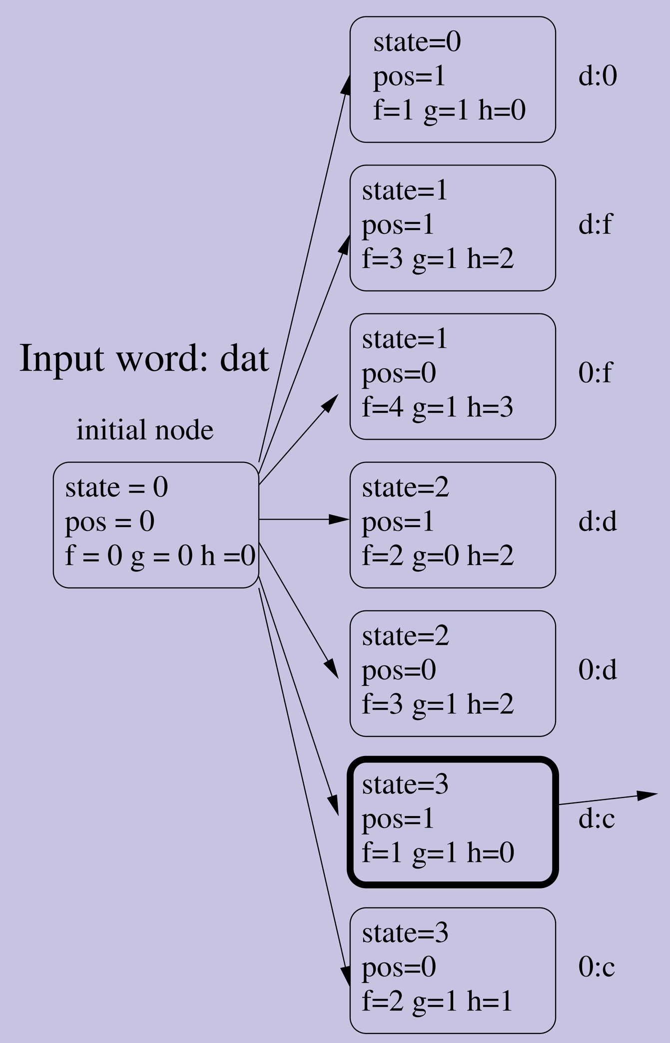


FIGURE 3: *Illustration of A*-search against the word **dat** and the automaton in figure 2.*

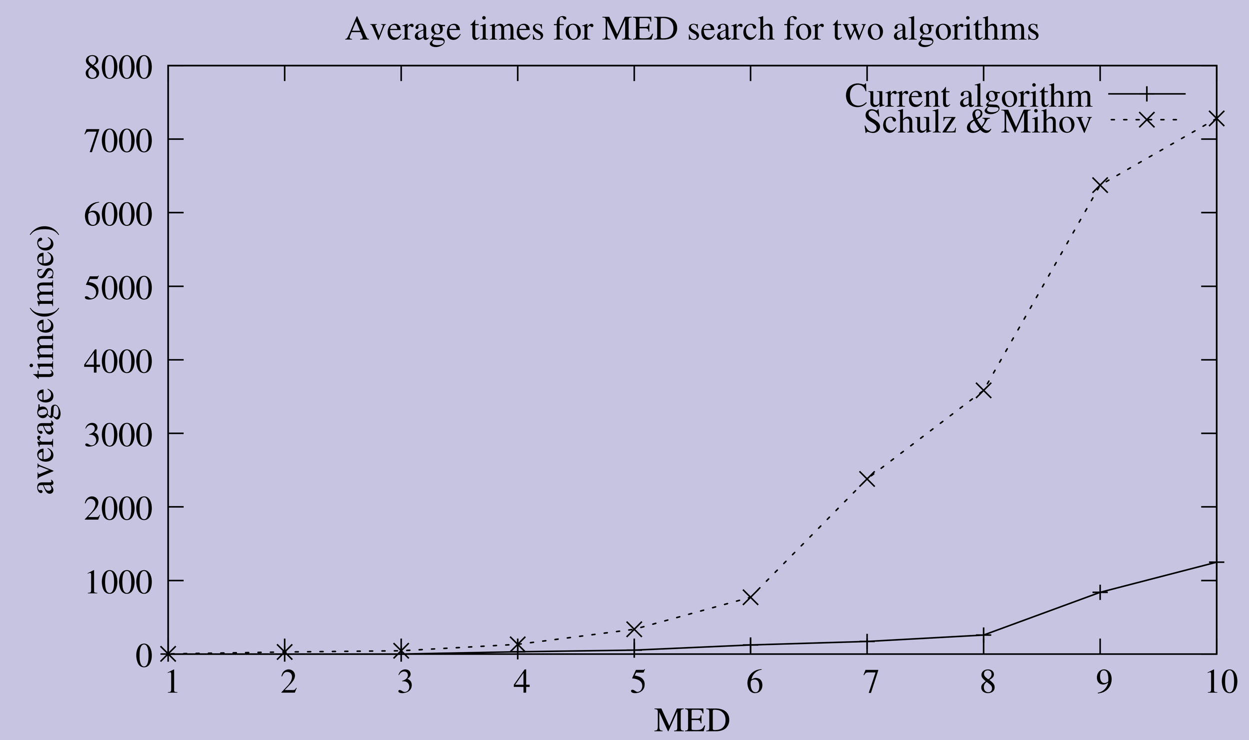


FIGURE 4: *Comparison against Schulz & Mihov's algorithm for 1,000 random words, 100 of each edit distance between 0 and 10; words taken from the FreeLing Spanish dictionary and randomly perturbed.*

Conclusions

- A*-search works well for approximate string matching with the relatively simple heuristic presented here
- The algorithm has been implemented and is included in the freely available finite-state toolkit *foma*, found at `http://foma.sf.net`.
- Additional features that have been implemented (also in *foma*) include the possibility of specifying context-dependent confusion matrices to specify different costs for different types of substitutions, deletions and insertions, depending on the environment where they occur