**ABSTRACT**

Summary: We present a tool suited for searching for many short nucleotide sequences in large databases, allowing for a predefined number of gaps and mismatches. The commandline-driven program implements a non-deterministic automata matching algorithm on a keyword tree of the search strings. Both queries with and without ambiguity codes can be searched. Search time is short for perfect matches, and retrieval time rises exponentially with the number of edits allowed.

Availability: The C++ source code for PatMaN is distributed under the GNU General Public License and has been tested on the GNU/Linux operating system. It is available from http://bioinf.eva.mpg.de/patman.

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Supplementary information: Supplementary data are available at Bioinformatics online.

**2 METHODS**

**2.1 Usage**

The program accepts several parameters to specify a search. The user can specify both the maximum number of gaps and the total number of edits (gaps+mismatches) allowed in any reported match. Additionally the interpretation of ambiguity codes can be modified. When the ambiguity flag is set, any ambiguous character in the query sequences will be counted as a match if the aligning base is one of the nucleotides represented by the ambiguity code. When the flag is omitted, only the ambiguity code ‘N’ is allowed in the query sequences, and a base aligning to this character will be counted as a mismatch.

Both the query and target sequences must be in FastA format. The output is given in a tab-separated format containing the target and query sequence identifier, the start and end position of the alignment in the target sequence, the number of edits per match.

**2.2 Algorithm**

When initiated, the program begins constructing a single keyword tree of all existing suffix for the sequence represented by the path from the root to the leaf, with the edges representing the bases added, and the leaf node containing the query sequence identifier. If the user sets the ambiguity flag, all possible bases at ambiguous positions are added to the target. If the user does not trigger the ambiguity flag, each base is added only once to the target. The search for occurrences on forward and reverse strands is facilitated by also adding the reverse complement of all query sequences to the same tree. If an outgoing edge is not yet occupied after storing the query sequences, an additional suffix link is set to the longest existing suffix for the sequence represented by the path from the root to the node under consideration. The resulting graph will consist of internal nodes with outgoing edges for all four possible bases and for the ambiguity base ‘N’. This procedure corresponds to the initial processing steps in the

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**REFERENCES**

A well-known algorithm for searching multiple strings was introduced by Aho and Corasick in 1975. Although this approach has previously been implemented to search for restriction enzyme sites (Mount and Conrad, 1986; Smith, 1988), a comprehensive implementation for searches with mismatches and gaps is not available to our knowledge.

We developed PatMaN (Pattern Matching in Nucleotide databases), a tool for performing exhaustive searches to identify all occurrences of a large number of short sequences within a genome-sized database. The program reads sequences in FastA format and reports all hits within the given edit-distance cutoff (i.e. total number of gaps and mismatches). We demonstrate the program’s functionality by aligning Affymetrix HGU95-A microarray probes to the chimpanzee genome.
Aho–Corasick algorithm (for a complete discussion see Navarro and Raffinot [2002]). Figure 1 depicts the resulting data structure for a small input example.

Once the tree is constructed, each sequence in the target database is evaluated base by base and compared to a list of partial matches. Each partial match consists of a node together with the number of mismatches and gaps accumulated. The list is initialized with one element containing the root node of the tree and an edit count of zero. In each iteration of the algorithm, all partial matches are advanced along a perfectly matching outgoing edge. Additional elements are stored for following mismatched edges and for producing all possible gaps, as long as the number of edits remains below the threshold given. If the outgoing edge is a suffix link, the resulting partial match is only included if no mismatch or gap occurred in the part before the suffix. The number of edits needed to align the suffix is stored in the partial match when following a suffix link. Matches are reported when a partial match reaches a leaf node before exceeding the predefined number of allowed edits. The sequence identifier, match coordinates and number of edits are printed.

2.3 Complexity

When ambiguity codes are not interpreted and the query sequences contain only suitable for searching short sequences with a limited number of edit operations. When ambiguity is enabled, both time and space requirements increase exponentially in the number of ambiguity codes used in the patterns.

The time efficiency of the search algorithm is linear in the size of the target database, but depends heavily on the maximum edit distance as well as the average length and number of query sequences. For each additional edit operation, an exponentially increasing number of partial matches must be considered, since neighboring mismatched nodes and all possible gapped alignments are searched along with the perfect matching path through the tree. However, if only perfect matches are searched, the algorithm acts like the Aho–Corasick algorithm, and search time depends solely on the length of the target sequence. Time constraints therefore mean that PatMaN is only suitable for searching short sequences with a limited number of edit operations.

3 RESULTS

We used PatMaN to match 201,807 Affymetrix HGU95-A microarray 25mer probes to the chimpanzee genome (panTro2). The parameters chosen for this evaluation allowed up to one mismatch, but no gaps. The program spent \( \sim 2.5 \) h searching through all chimpanzee chromosomes.

Table 1. HGU95-A probes and Bonobo Reads against Chromosome 22

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Edits</th>
<th>Gaps</th>
<th>Run time</th>
<th>Hits</th>
</tr>
</thead>
<tbody>
<tr>
<td>HGU95-A probes</td>
<td>0</td>
<td>0</td>
<td>0m13.31s</td>
<td>93,225</td>
</tr>
<tr>
<td>HGU95-A probes</td>
<td>1</td>
<td>1</td>
<td>1m51.87s</td>
<td>327,028</td>
</tr>
<tr>
<td>HGU95-A probes</td>
<td>1</td>
<td>1</td>
<td>3m36.92s</td>
<td>496,296</td>
</tr>
<tr>
<td>HGU95-A probes</td>
<td>2</td>
<td>2</td>
<td>1h21m59s</td>
<td>1,843,008</td>
</tr>
<tr>
<td>Bonobo Solexa GAI data</td>
<td>2</td>
<td>2</td>
<td>14h5m50s</td>
<td>14.3 ( \times 10^9 )</td>
</tr>
</tbody>
</table>

\( ^a \)Benchmarking was performed on a 2.2 GHz workstation. Independently of the chosen parameters, \( \sim 260 \) MB RAM were used. \( ^b \)Benchmarking was performed on a 1.8 GHz workstation and 8.6 GB of RAM was used during execution. The dataset contains 2.8 million reads of \( 38 \) bp length of genomic sequence from a Bonobo individual sequenced on the Solexa GAI platform.

4 CONCLUSION

We present a new tool for mapping short sequences to large nucleotide databases. The program does not require target or query database preprocessing and runs rapidly when a search is restricted to small edit distances. While we demonstrate the program’s utility by aligning microarray probes, we anticipate further applications in the near future. In particular, mapping tags generated using next generation resequencing technology will require fast approximate matching to genomes to facilitate large-scale analysis of gene expression.

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Conflict of Interest: none declared.

REFERENCES


