

BFC: correcting Illumina sequencing errors

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Associate Editor: Dr. Inanc Birol

ABSTRACT

Summary: BFC is a free, fast and easy-to-use sequencing error corrector designed for Illumina short reads. It uses a non-greedy algorithm but still maintains a speed comparable to implementations based on greedy methods. In evaluations on real data, BFC appears to correct more errors with fewer overcorrections in comparison to existing tools. It particularly does well in suppressing systematic sequencing errors, which helps to improve the base accuracy of *de novo* assemblies.

Availability and implementation: <https://github.com/lh3/bfc>

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1 INTRODUCTION

Error correction is a process to fix sequencing errors on a sequence read by using other overlapping reads that do not contain the errors. Many *de novo* assemblers, in particular short-read assemblers for large genomes, use error correction to reduce the complexity of the assembly graph such that the graph can be fitted to limited RAM. Error correction was first expressed as the *spectral alignment problem* (Pevzner et al., 2001), whereby we take a set of trusted k -mers and attempt to find a sequence with minimal corrections such that each k -mer on the corrected sequence is trusted. The majority of error correctors are based on this idea and take a greedy approach to solving this problem approximately. They make a correction based on the local sequence context and do not revert the decision. We worried that the greedy strategy might affect the accuracy given reads from a repeat-rich diploid genome, so derived a new non-greedy algorithm that explores larger search space in attempt to achieve higher accuracy.

2 METHODS

Algorithm 1 is the key component of BFC. It defines a *state* of correction as a 4-tuple (i, W, C, p) , which consists of the position i of the preceding base, the last $(k-1)$ -mer W ending at i , the set C of previous corrected positions and bases (called a *solution*) up to i , and the penalty p of solution C . BFC keeps all possible states in a priority queue \mathcal{Q} . At each iteration, it retrieves the state (i, W, C, p) with the lowest penalty p (line 1) and adds a new state $(i + 1, W[1, k - 2] \circ a, C', p')$ if a is the read base or $W \circ a$ is a trusted k -mer. If the first k -mer in S is error free and we disallow untrusted k -mers by removing line 3, this algorithm finds the optimal solution to the spectral alignment problem. Chaisson et al. (2004) have described a more general non-greedy algorithm. Its strict form is not implementable in practice. The heuristic adaptation is loosely similar to ours without line 3.

It is possible to modify Algorithm 1 to correct insertion and deletion errors (INDELs) by augmenting the set of the “next bases” at line 2 to:

$$\mathcal{N} = \{(j, a) | j \in \{i - 1, i\}, a \in \{A, C, G, T\}\} \cup \{(i, \epsilon)\}$$

Algorithm 1: Error correction for one string in one direction

Input: k -mer size k , set \mathcal{H} of trusted k -mers, and one string S

Output: Set of corrected positions and bases changed to

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Function CORRECTERRORS( $k, \mathcal{H}, S$ ) begin
     $\mathcal{Q} \leftarrow \text{HEAPINIT}()$   $\triangleright \mathcal{Q}$  is a priority queue
     $\text{HEAPPUSH}(\mathcal{Q}, (k - 2, S[0, k - 2], \emptyset, 0))$   $\triangleright 0$ -based strings
    while  $\mathcal{Q}$  is not empty do
1       $(i, W, C, p) \leftarrow \text{HEAPPOPBEST}(\mathcal{Q})$   $\triangleright$  current best state
       $i \leftarrow i + 1$ 
      if  $i = |S|$  then return  $C$   $\triangleright$  reaching the end of  $S$ 
2       $\mathcal{N} \leftarrow \{(i, A), (i, C), (i, G), (i, T)\}$   $\triangleright$  set of next bases
      foreach  $(j, a) \in \mathcal{N}$  do  $\triangleright$  try all possible next bases
           $W' \leftarrow W \circ a$   $\triangleright$  “o” concatenates strings
          if  $i = j$  and  $a = S[j]$  then  $\triangleright$  no correction
              if  $W' \in \mathcal{H}$  then  $\triangleright$  good read base; no penalty
                   $\text{HEAPPUSH}(\mathcal{Q}, (j, W'[1, k - 1], C, p))$ 
              else  $\triangleright$  bad read base; penalize
                   $\text{HEAPPUSH}(\mathcal{Q}, (j, W'[1, k - 1], C, p + 1))$ 
3          else if  $W' \in \mathcal{H}$  then  $\triangleright$  make a correction with penalty
4               $\text{HEAPPUSH}(\mathcal{Q}, (j, W'[1, k - 1], C \cup \{(j, a)\}, p + 1))$ 

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In this set, (i, a) substitutes a base at position i , (i, ϵ) deletes the base and $(i - 1, a)$ inserts a base a before i . We have not implemented this INDEL-aware algorithm because such errors are rare in Illumina data.

The worst-case time complexity of Algorithm 1 is exponential in the length of the read. In implementation, we use a heuristic to reduce the search space by skipping line 4 if the base quality is 20 or higher (Q20) and the k -mer ending at it is trusted, or if five bases or two Q20 bases have been corrected in the last 10bp window. If function CORRECTERRORS still takes too many iterations before returning, it stops the search and claims the read uncorrectable.

Given a read, BFC finds the longest substring on which each k -mer is trusted. It then extends the substring to both ends of the read with Algorithm 1. If a read does not contain any trusted k -mers, BFC exhaustively enumerates all k -mers one-mismatch away from the first k -mer on the read to find a trusted k -mer. It marks the read uncorrectable if none or multiple trusted k -mers are found this way.

We provided two related implementations of Algorithm 1, BFC-bf and BFC-ht. BFC-bf uses KMC2 (Deorowicz et al., 2015) to get exact k -mers counts and then keeps k -mers occurring three times or more in a blocked bloom filter (Putze et al., 2007). BFC-ht uses a combination of bloom filter and in-memory hash table to derive approximate k -mer counts (Melsted and Pritchard, 2011) and counts of k -mers consisting of Q20 bases. We modified Algorithm 1 such that missing trusted high-quality k -mers incurs an extra penalty. This supposedly helps to correct systematic sequencing errors which are recurrent but have lower base quality.

Table 1. Performance of error correction

Prog.	<i>k</i>	Time	RAM	Perfect	Chim.	Better	Worse
raw data	–	–	–	2.40M	12.4k	–	–
BFC-bf	31	7h32m	23.3G	3.01M	13.1k	783k	9.2k
BFC-bf	55	4h41m	23.3G	3.05M	11.8k	819k	11.4k
BFC-ht	31	7h15m	83.5G	3.03M	13.6k	816k	10.8k
BFC-ht	55	5h51m	67.9G	3.05M	11.7k	830k	9.0k
BLESS	31	6h31m	22.3G	2.91M	13.1k	674k	20.8k
BLESS	55	5h09m	22.3G	3.01M	11.5k	775k	10.3k
Bloocoo	31	5h52m	4.0G	2.88M	14.1k	764k	31.5k
Fermi2	29	17h14m	64.7G	3.00M	17.7k	849k	42.8k
Lighter	31	5h12m	13.4G	2.98M	13.0k	756k	30.1k
Musket	27	21h33m	77.5G	2.94M	22.5k	790k	36.3k
SGA	55	48h40m	35.6G	3.01M	12.1k	755k	12.8k

445 million pairs of ~150bp reads were downloaded from BaseSpace, under the sample “NA12878-L7” of project “HiSeq X Ten: TruSeq Nano (4 replicates of NA12878)”, and were corrected together. On a subset of two million randomly sampled read pairs, the original and the corrected sequences were mapped to hs37d5 (<http://bit.ly/GRCh37d5>) with BWA-MEM (Li, 2013). A read is said to become *better* (or *worse*) if the best alignment of the corrected sequence has more (or fewer) identical bases to the reference genome than the best alignment of the original sequence. The table gives *k*-mer size (maximal size used for Bloocoo, fermi2, Lighter and Musket), the wall-clock *time* when 16 threads are specified if possible, the peak *RAM* measured by GNU time, number of corrected reads mapped *perfectly*, number of *chimeric* reads (i.e. reads with parts mapped to different places), number of corrected reads becoming *better* and the number of reads becoming *worse* than the original reads. For each metric, the best tool is highlighted in the bold fontface.

3 RESULTS AND DISCUSSIONS

We evaluated BFC along with BLESS-v0p23 (Heo et al., 2014), Bloocoo-1.0.4 (Drezen et al., 2014), fermi2-r175 (Li, 2012), Lighter-20150123 (Song et al., 2014), Musket-1.1 (Liu et al., 2013) and SGA-0.9.13 (Simpson and Durbin, 2012). We ran the tools on a Linux server with 20 cores of Intel E5-2660 CPUs and 128GB RAM. Precompiled binaries are available through <http://bit.ly/biobin> and the command lines were shown in Table S2. Notably, BLESS only works with uncompressed files. Other tools were provided with gzip’d FASTQ.

On human data (Table 1), BFC has similar performance to other error correctors that use greedy algorithms. It tends to correct more errors without introducing new errors, potentially due to its non-greedy and quality-aware algorithm.

BFC also works well with assemblers (Table 2). It should be noted that the short reads were sequenced from the Bristol N2 strain, the same as the *C. elegans* reference genome. We expect to see few alignment break points and base-level differences. Extended discussions on the results can be found in Supplementary Notes.

ACKNOWLEDGEMENT

Funding: NHGRI U54HG003037; NIH GM100233

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Table 2. Effect on *de novo* assembly

Program	Scaffold NG50 (kb)	Contig aligned-N50 (kb)	Alignment break points	Potential FP SNP
raw data	31.6 / 29.9	14.8 / 20.2 / 4.9	352 / 157 / 29	1568 / 334
BFC-bf	33.7 / 33.7	17.3 / 22.8 / 7.6	341 / 173 / 33	3334 / 668
BFC-ht	34.8 / 34.2	17.3 / 22.9 / 9.1	314 / 176 / 31	1397 / 374
BLESS	33.6 / 31.7	15.4 / 20.7 / 8.0	351 / 165 / 28	1744 / 414
Bloocoo	34.5 / 33.7	17.1 / 22.6 / 6.2	340 / 177 / 32	3128 / 480
Fermi2	33.8 / 33.7	16.8 / 22.6 / 8.9	333 / 174 / 32	1444 / 396
Lighter	34.6 / 33.6	16.6 / 22.4 / 7.9	329 / 180 / 34	3011 / 651
Musket	33.4 / 32.2	16.0 / 21.2 / 8.2	338 / 181 / 30	1940 / 617
SGA	34.4 / 33.4	16.7 / 22.4 / 6.6	360 / 163 / 32	3107 / 495

33.8 million pairs of 100bp *C. elegans* reads were downloaded from SRA under accession SRR065390, corrected using *k*-mer length 23 and then assembled with Velvet-1.2.10 (Zerbino and Birney, 2008; velvetg option ‘-exp_cov auto -cov_cutoff auto -ins_length 250’ with *k*-mer length 61), ABySS-1.5.2 [Simpson et al., 2009; abyss-pe option ‘k=67 q=0 s=500 n=5’ taken from Simpson and Durbin (2012)] and fermikit-0.9 (fermi2.pl option ‘-Es100m’). For Velvet and ABySS, contigs were derived by splitting scaffolds at contiguous ‘N’ bases longer than 5bp. In the table, each row gives the NG50 of Velvet/ABYSS scaffolds longer than 200bp, the aligned N50 of Velvet/ABYSS/fermi2 contigs longer than 200bp, the number of contig alignment break points with >200bp flanking sequences and the number of false positive unfiltered/filtered fermikit SNPs as compared to freebayes-0.9.20 calls (Garrison and Marth, 2012; option ‘-experimental-gls’). BFC and fermi2 were tuned to work with fermikit for human variant calling before this evaluation while others were not.