CS4330: Combinatorial Methods in Bioinformatics

Read error correction using K-mers

Wong Limsoon

Acknowledgement: This set of slides were adapted from Ken Sung's



Errors in reads greatly increase complexity of genome assembly

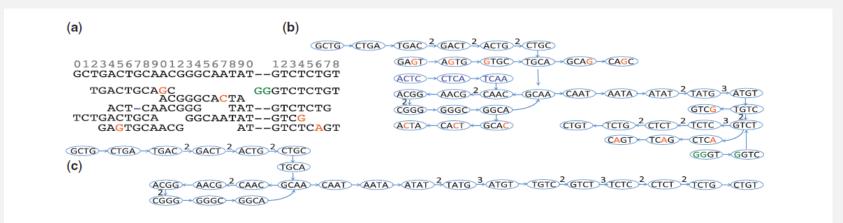


Fig. 1 An example of NGS data and its de Bruijn graph. The short stretches of sequences in (a) are the reads generated from an NGS platform, while the long sequence is the reference. The reference is often unknown but, for ease of illustration, it is shown here to demonstrate substitutions (coloured in orange), insertions (green) or deletions (light blue) errors. There is no '-' in the real-life reference and sequenced reads, but it is shown here also for better understanding. (b) The de Bruijn graph constructed from all the short sequences in (a) with a k-mer size of 4. (c) is the simplified error-corrected version of the de Bruijn graph of (b). The numbers along the edges represent their multiplicities

The error-containing de Bruijn graph (b) is much more complicated than the error-free graph (c)

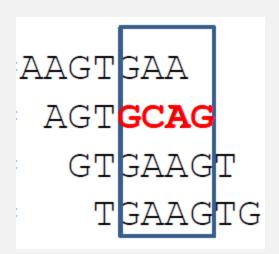
L. Zhao et al., "MapReduce for accurate error correction of next-generation sequencing data", *Bioinformatics* 33(23):3844-3851, 2017

Reads containing low-freq K-mers are much more likely to have errors

When a genome is sampled at high coverage, any K-mer in the genome can be expected to appear in many reads

For any K-mer t, let freq(t) = # of reads containing t or its reverse complement

If freq(t) is small, it is likely that some error has occurred in the reads containing t



Reads containing low-frequency K-mers are likely to contain sequencing errors

Reads with errors greatly increase complexity of genome assembly

We should discard these reads and not use them in genome assembly, no?



Solid K-mers

A K-mer t is said to be solid wrt a set of sequencing reads \mathcal{R} if freq(t) > M, where M is a given threshold

Solid K-mers are considered reliable due to their high frequency within the set of sequencing reads

Example

Read set,
AAGTGAA

AGTGCAG

GTGAAGT

TGAAGTG

K-mer t is solid if freq(t) > M

E.g., M = 2, the solid K-mers are:
AAGT, ACTT, AGTG
CACT, TGAA, TTCA

4-mer	freq(t)
AAGT	3
ACTT	3
AGTG	3
CACT	3
CTTC	2
CTGC	1
GAAG	2
GCAC	1
GCAG	1
GTGA	2
GTGC	1
TCAC	2
TGAA	3
TGCA	2
TTCA	3

The read error correction problem

Given a set of reads 2

Let 7 = the set of all correct K-mers in the genome
7 is often approximated by solid K-mers in \mathbb{R} in practice

A read R is a 7-string if every K-mer in R is in 7

Objective: Convert every read R ∈ ₽ to R' by the minimum # of mutations such that R' is a 7-string

Read set, \nearrow AAGTGAA
AGTGCAG
GTGAAGT
TGAAGTG

7 = solid K-mers, freq>1

AAGT, ACTT, AGTG

CACT, TGAA, TTCA,

CTTC, GAAG, GTGA,

TCAC, TGCA

Which reads in *₹* are *7*-strings?

Can you convert the non 7-string reads to 7-strings using min # of mutations?

Read set, \nearrow AAGTGAA
AGTGCAG
GTGAAGT
TGAAGTG

7 = solid K-mers, freq>2
AAGT, ACTT, AGTG
CACT, TGAA, TTCA

Which reads in *₹* are 7-strings?

Can you convert the non 7-string reads to 7-strings using min # of mutations?

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Recursive spectra alignment

```
For a read R, find \min_{t \in \mathcal{T}} \text{dist}(|R|,t) \text{ where dist}(i,t) = \begin{cases} \text{minimum edit distance betw R[1..i] and} \\ \text{any 7-string that ends at K-mer t} \end{cases}
```

Assume no indel error in first k bases of R

Let
$$\rho(x,y) = 0$$
 if $x = y$ and $\rho(x,y) = 1$ if $x \neq y$

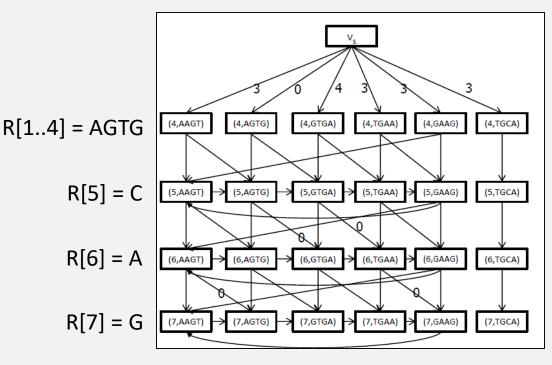
b • t[1..K-1])

The "dependency graph" is cyclic but non-negative

```
R = AGTGCAG
T = \{ AAGT, AGTG, 
    GAAG, GTGA,
    TGAA, TGCA }
```

(mis)match = slant edge delete = vertical edge insert = horizontal edge

Recurrence: min $_{b \in \{A,C,G,T\}}$ dist(i – 1, b • t[1..K-1]) + $\rho(R[i],t[K])$ match dist(i,t) = min dist(i - 1, t) + 1delete $\min_{b \in \{A,C,G,T\}} dist(i, b \cdot t[1..K-1]) + 1$ insert



R[7] = G

Spectra alignment via "shortest path" of dependency graph

Key lemma

 $dist(i,t) = length of shortest path from v_s to (i,t)$

...Construct dependency graph; find shortest path from v_s to (|R|,t) for some $t \in 7$

The dependency graph has O(|R| |7|) nodes and edges

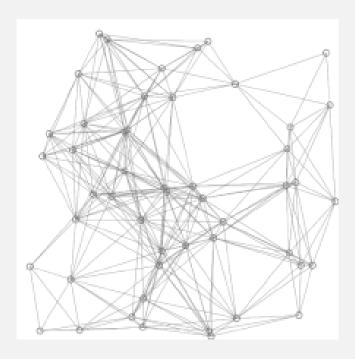
- ∴ Complexity of graph construction = O(|R| |7|)
- \therefore Complexity of shortest path finding = O(|R| |7|)

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Dijkstra's shortest path algorithm

```
function Dijkstra(Graph, source):
         for each vertex v in Graph.Vertices:
 3
              dist[v] \leftarrow INFINITY
              prev[v] \leftarrow UNDEFINED
              add v to Q
          dist[source] ← 0
 8
         while Q is not empty:
10
              u \leftarrow \text{vertex in } Q \text{ with min dist[u]}
              remove u from O
11
12
              for each neighbor v of u still in Q:
13
14
                   alt \leftarrow dist[u] + Graph.Edges(u, v)
                   if alt < dist[v]:</pre>
15
                        dist[v] \leftarrow alt
16
                        prev[v] \leftarrow u
17
18
19
          return dist[], prev[]
```



Source: Wikipedia

Example

R = AGTGCAG

 $T = \{ AAGT, AGTG,$

GAAG, GTGA,

TGAA, TGCA }

R[1..4] = AGTG

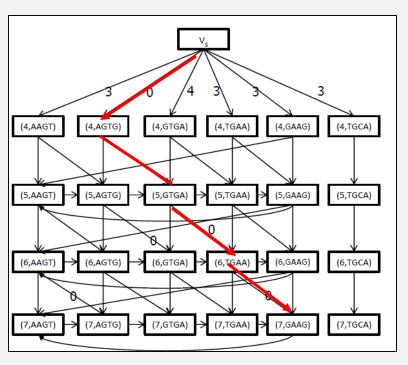
Min path length = 1 Corrected read = AGTGAAG

$$R[5] = C$$

R[6] = A

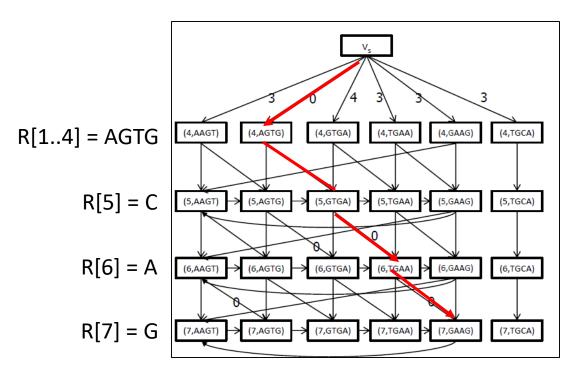
$$R[7] = G$$

Recurrence: min $_{b \in \{A,C,G,T\}}$ dist(i – 1, b • t[1..K-1]) + $\rho(R[i],t[K])$ match dist(i - 1, t) + 1dist(i,t) = min delete $\min_{b \in \{A,C,G,T\}} dist(i, b \cdot t[1..K-1]) + 1$ insert



$$\begin{aligned} \text{Recurrence:} & & \\ & \text{dist}(i,t) = \text{min} \\ & & \\ & & \\ & \text{dist}(i-1,t) + 1 \\ & & \\ & \text{min} \\ & & \\ & \\ & \text{dist}(i-1,t) + 1 \\ & & \\ & \text{min} \\ & \\ & \\ & \text{b} \in \{A,C,G,T\} \\ & \text{dist}(i,b \bullet t[1..K-1]) + 1 \end{aligned} \end{aligned}$$

Discuss the good, the bad, & the ugly of read error correction by spectra alignment





of solid K-mers in human genome

n = size of Bloom filter m = # of elements inserted $\epsilon = false positive rate$

- ~4.2 billion K-mers have freq = 1; assumed error K-mers
- ~2.8 billion K-mers have freq > 1; assumed solid K-mers

Optimal size of Bloom filter is n = -2.08 m (ln ϵ) bits

$$n = -2.08 \ (2.8 \ x \ 10^9) \ (ln \ \epsilon)$$

$$\approx 40 \ x \ 10^9 \ bits \approx 5 \ GB \ at \ \epsilon = 0.01\%$$

$$\approx 54 \ x \ 10^9 \ bits \approx 6.7 \ GB \ at \ \epsilon = 0.001\%$$

$$\approx 54 \ x \ 10^9 \ bits \approx 6.7 \ GB \ at \ \epsilon = 0.001\%$$

Can use Bloom filter to keep solid K-mers for correcting read errors for human genome

Many modern & popular read error correction tools rely on K-mer counting & **Bloom filter**

1. Quake: https://pubmed.ncbi.nlm.nih.gov/21114842

- Description: Quake is a k-mer based error correction tool that uses a combination of read overlapping and k-mer counting to correct sequencing errors.
- 2. Musket: https://pubmed.ncbi.nlm.nih.gov/23202746
 - Description: Musket is a k-mer based error correction tool that uses a probabilistic model to correct sequencing errors in short-read data.
- 3. Bless: https://pubmed.ncbi.nlm.nih.gov/24451628
 - Description: Bless is a k-mer based error correction tool that employs a Bloom filter to correct errors in Illumina sequencing reads.
- 4. Lighter: https://pubmed.ncbi.nlm.nih.gov/25398208
 - Description: Lighter is a k-mer based error correction tool designed for large-scale sequencing data. It uses a lightweight algorithm for fast error correction.

Check out Lighter especially. It does not do K-mer counting.

A simple approach to Bloom filter-based read error correction

Keep solid K-mers in a Bloom filter H

For a read R, mark all positions R[i.. i + K - 1] as solid if R[i.. i + K - 1] is found in H

If a position R[i] is not solid, replace R[i] by b ∈ {A,C,G,T} provided some of the following is found in H:

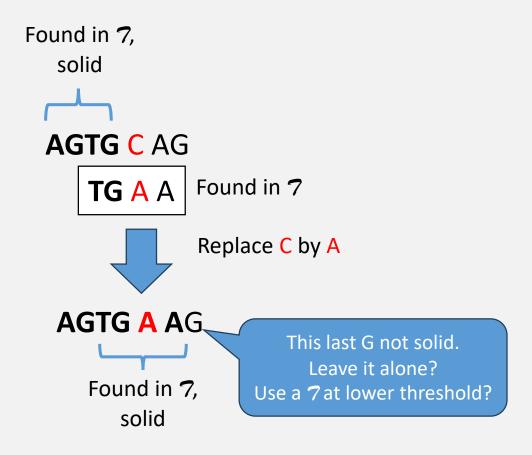
$$b \cdot R[i + 1 ... i + K - 1]$$

 $R[i - K ... i - 1] \cdot b$
 $R[i - j ... i - 1] \cdot b \cdot R[i + 1 ... i + K - j - 1], where $1 \le j \le K$$

If more non-solid positions, repeat the last step

Example

```
R = AGTGCAG
```



Sometimes different "b" can be substituted, and hits found in H

How do you select the more likely one?

A simple approach to Bloom filter-based read error correction

Keep solid K-mers in a Bloom filter H

For a read R, mark all positions R[i.. i + K - 1] as solid if R[i.. i + K - 1] is found in H

If a position R[i] is not solid, replace R[i] by $b \in \{A,C,G,T\}$ provided some of the following is found in H:

$$R[i - K ... i - 1] \cdot b$$

$$R[i - j ... i - 1] \bullet b \bullet R[i + 1 ... i + K - j - 1]$$
, where $1 \le j \le K$

If more non-solid positions, repeat the last step

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Reminder: Low-frequency K-mers may not be errors

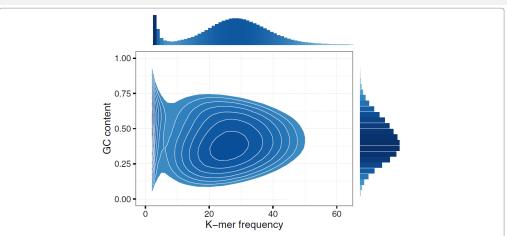


Fig. 3 A relation between *k*-mer frequency and GC-content. The bottom left panel shows the smoothed scatter plot between *k*-mer frequency and GC-content, the top left is the distribution of *k*-mer frequency, and the bottom right is the distribution of GC-content. It is clear that GC-content *k*-mers have relatively low frequency. The data shown in this example is obtained from the H. chromosome 14 with *k*-mer size of 25

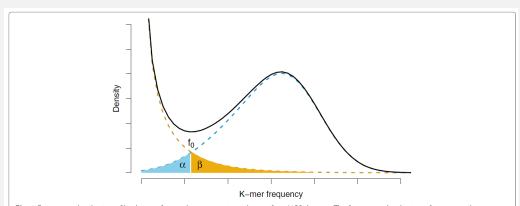


Fig. 1 Frequency distribution of both error-free and error-containing k-mers for a NGS data set. The frequency distribution of erroneous k-mers is represented by the dash orange line, while the distribution of the correct ones is shown as the dash sky-blue line. The solid black line is the distribution of all the k-mers. The α -labeled area is the proportion of correct k-mers having frequency less than f_0 , while the β -labeled area is the proportion of erroneous k-mers having frequency greater than f_0

Zhao et al., Mining statistically-solid k-mers for accurate NGS error correction, *BMC Genomics* 19(S10):912, 2018

At freq > 1 Error K-mer TGCA ∈ 7

At freq > 2Valid K-mer GAAG ∉ 7

How to make 7 contain less error K-mers and include more valid Kmers?

Read set, ₹ **AAGTGAA AGTGCAG GTGAAGT TGAAGTG** 7 = solid K-mers, freq>1 AAGT, ACTT, AGTG CACT, TGAA, TTCA, CTTC, GAAG, GTGA, TCAC, TGCA 7 = solid K-mers, freq>2 AAGT, ACTT, AGTG CACT, TGAA, TTCA

4-mer	freq(t)
AAGT	3
ACTT	3
AGTG	3
CACT	3
CTTC	2
CTGC	1
GAAG	2
GCAC	1
GCAG	1
GTGA	2
GTGC	1
TCAC	2
TGAA	3
TGCA	2
TTCA	3

State of the art in read error correction, ZEC

Btw, MEC is me ©

Table 1 The data sets that are used for evaluating the performance of error correction models

Data set	Genome name	Genome size (bp)	Error rate (%)	Read length (bp)	Coverage	Number of reads	Insert length	ls sythetic
R1	S. aueus	2,821,361	1.28	101	46.3 x	1,294,104	180	No
R2	R. sphaeroides	4,603,110	1.08	101	45.0×	2,050,868	180	No
R3	H. chromosome 14	88,218,286	0.52	101	41.8×	36,504,800	155	No
R4	B. impatiens	249,185,056	0.86	124	150.8×	303,118,594	400	No
S1	H. chromosome 14	88,218,286	0.97	101	41.8×	36,504,800	180	Yes
S2	B. impatiens	249,185,056	0.98	124	150.8×	303,118,594	400	Yes

Metrics that are considered include gain, recall, precision and per base error rate (pber). Gain is defined as (TP-FP)/(TP+FN), recall is TP/(TP+FN), precision is TP/(TP+FP) and pber is N^e/N , where TP stands for the number of corrected bases that are truly erroneous bases, FP represents the number of corrected bases that are not sequencing errors intrinsically, FN is the number of erroneous bases that remain untouched, N^e is the number of erroneous bases and N is the total number of bases. Among these metrics, F is the most informative.

All experiments are carried out on a cluster having eight Intel Xeon E7 CPUs and 1Tb RAM. Each CPU has eight cores.

Regarding the running speed, this algorithm is linearly scaled. Since locating each k-mer in a bit vector is O(1) pertaining to time complexity by using hash, this algorithm is pretty fast. For instance, based on our computing power, it only takes 387 s to construct the bit vectors and calculate the z-scores of all the k-mers of R4—the largest data set.

Zhao et al., BMC Genomics 19(S10):912, 2018

Table 2 Error-correction performance comparison between ZEC, Lighter, Racer, BLESS2, Musket, BFC, SGA and MEC

R1 ZEC 0.908 0.912 0.996 0.102 Lighter 0.839 0.845 0.994 0.163 Racer 0.760 0.822 0.929 0.190 RLESS2 0.189 0.409 0.650 0.879 Musket 0.499 0.628 0.830 0.448 SGA 0.746 0.815 0.992 0.202 BFC 0.753 0.817 0.927 0.196 MEC 0.909 0.911 0.998 0.102 TEC 0.584 0.663 0.894 0.537 Lighter 0.226 0.329 0.762 1.076 Racer 0.364 0.450 0.839 0.780 RLESS2 0.318 0.405 0.806 0.890 Musket 0.265 0.364 0.786 0.984 SGA 0.331 0.423 0.822 0.843 BFC 0.306 0.400 0.811 0.893 MEC 0.570 0.631 0.912 0.541 RS ZEC 0.802 0.923 0.884 0.087 Lighter 0.445 0.764 0.706 0.256 Racer 0.562 0.814 0.764 0.196 RLESS2 0.130 0.641 0.556 0.438 Musket 0.533 0.802 0.749 0.211 SGA 0.567 0.818 0.765 0.194 BFC 0.603 0.833 0.783 0.176 MEC 0.788 0.852 0.930 0.117 RA ZEC 0.746 0.833 0.905 0.137 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 Racer 0.313 0.541 0.703 0.484 Racer 0.313 0.541 0.703 0.486 Racer 0.318 0.935 0.982 0.056 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.486 Racer 0.318 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 Racer 0.889 0.916 0.964 0.071 Racer 0.889 0.991 0.966 0.889 0.201 SGA 0.810 0.865 0.940 0.117 SGA 0.810 0.865 0.940 0.117 SGA 0.810 0.866 0.903 0.961 0.081 Racer 0.882 0.916 0.964 0.071 Racer 0.889 0.9916 0.962 0.063 Racer 0.882 0.916 0.964 0.071 Racer 0.866 0.903 0.961 0.081 Racer 0.168 0.408 0.630 0.720 Racer 0.168 0.408 0.630 0	2	,,,,,						
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BLESS2 0.189 0.409 0.650 0.879 Musket 0.499 0.628 0.830 0.448 SGA 0.746 0.815 0.922 0.202 BFC 0.753 0.817 0.927 0.196 MEC 0.909 0.911 0.998 0.102 TEZ ZEC 0.584 0.663 0.894 0.537 Lighter 0.226 0.329 0.762 1.076 Racer 0.364 0.450 0.839 0.786 Musket 0.265 0.364 0.786 0.896 Musket 0.265 0.364 0.786 0.896 MEC 0.570 0.631 0.912 0.541 Racer 0.306 0.400 0.811 0.893 MEC 0.570 0.631 0.912 0.541 Racer 0.562 0.814 0.764 0.706 0.256 Racer 0.562 0.814 0.764 0.196 BLESS2 0.130 0.641 0.556 0.438 Musket 0.533 0.802 0.749 0.211 SGA 0.567 0.801 0.833 0.783 0.176 MEC 0.788 0.852 0.930 0.117 SGA 0.567 0.808 0.852 0.930 0.117 Racer 0.126 0.408 0.591 0.688 Racer 0.126 0.408 0.591 0.688 BLESS2 -0.517 0.118 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.886 BFC 0.195 0.457 0.636 0.607 MEC 0.791 0.851 0.934 0.130 SGA 0.567 0.806 0.809 0.201 SGA 0.567 0.806 0.809 0.201 SGA 0.567 0.808 0.959 0.056 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 SGA 0.510 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.636 MEC 0.899 0.916 0.998 0.065 SGA 0.810 0.865 0.940 0.117 SGA 0.810 0.866 0.903 0.961 0.081 BFC 0.866 0.903 0.961 0.081 BFC 0.866 0.903 0.961 0.081 SGA 0.810 0.865 0.940 0.117 SGA 0.810 0.865 0.940 0.117 Racer 0.882 0.916 0.964 0.071 Racer 0.883 0.894 0.956 0.1099 Racer 0.884 0.899 0.916 0.982 0.066 Rac		Lighter	0.839	0.845	0.994	0.163		
Musket 0.499 0.628 0.830 0.448 SGA 0.746 0.815 0.922 0.202 BFC 0.753 0.817 0.927 0.196 MEC 0.909 0.911 0.998 0.102 ZEC 0.584 0.663 0.894 0.537 Lighter 0.226 0.329 0.762 1.076 Racer 0.364 0.450 0.839 0.780 Musket 0.265 0.364 0.786 0.994 SGA 0.331 0.423 0.822 0.843 BFC 0.306 0.400 0.811 0.893 MEC 0.570 0.631 0.912 0.541 Racer 0.562 0.814 0.764 0.706 0.256 Racer 0.562 0.814 0.764 0.196 BLESS2 0.130 0.641 0.556 0.438 Musket 0.533 0.802 0.749 0.211 SGA 0.567 0.818 0.765 0.194 BFC 0.603 0.833 0.783 0.174 MEC 0.788 0.852 0.930 0.117 R4 ZEC 0.746 0.833 0.905 0.137 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.809 MEC 0.795 0.806 0.809 0.923 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 Racer 0.882 0.916 0.964 0.071 Racer 0.882 0.916 0.964 0.071 SGA 0.810 0.865 0.940 0.117 SGA 0.810 0.805 0.940 0.117 SGA 0.810 0.805 0.940 0.117 SGA 0.810 0.805 0.940 0.1		Racer	0.760	0.822	0.929	0.190		
SGA 0.746 0.815 0.922 0.202 BFC 0.753 0.817 0.927 0.196 MEC 0.909 0.911 0.998 0.102 TEC 0.584 0.663 0.894 0.537 Lighter 0.226 0.329 0.762 1.076 Racer 0.364 0.450 0.839 0.760 BLESS2 0.318 0.405 0.806 0.890 Musket 0.265 0.364 0.786 0.984 SGA 0.331 0.423 0.822 0.843 BFC 0.306 0.400 0.811 0.893 MEC 0.570 0.631 0.912 0.541 Lighter 0.445 0.764 0.706 0.256 Racer 0.562 0.814 0.764 0.196 BLESS2 0.130 0.641 0.556 0.438 Musket 0.533 0.802 0.749 0.211 SGA 0.567 0.818 0.765 0.194 BFC 0.603 0.833 0.783 0.176 MEC 0.788 0.852 0.930 0.117 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 BLESS2 0.130 0.641 0.703 0.484 BFC 0.517 0.018 0.003 0.484 BLESS2 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 SGA 0.541 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 BFC 0.866 0.329 0.548 0.891 BFC 0.866 0.329 0.562 0.866 BFC 0.853 0.342 0.562 0.866 BFC 0.853 0.342 0.562 0.866 BFC 0.853 0.342 0.562 0.866		BLESS2	0.189	0.409	0.650	0.879		
BFC 0.753 0.817 0.927 0.196 MEC 0.909 0.911 0.998 0.102 F2 ZEC 0.584 0.663 0.894 0.537 Lighter 0.226 0.329 0.762 1.076 Racer 0.364 0.450 0.839 0.780 BLESS2 0.318 0.405 0.806 0.890 Musket 0.265 0.364 0.786 0.984 SGA 0.331 0.423 0.822 0.843 BFC 0.306 0.400 0.811 0.893 MEC 0.570 0.631 0.912 0.541 Lighter 0.445 0.764 0.706 0.256 Racer 0.562 0.814 0.764 0.196 BLESS2 0.130 0.641 0.556 0.438 Musket 0.533 0.802 0.749 0.211 SGA 0.567 0.818 0.765 0.194 BFC 0.603 0.833 0.783 0.176 MFC 0.788 0.852 0.930 0.117 EACH O.746 0.833 0.905 0.137 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 SGA 0.542 0.690 0.823 0.289 SGA 0.542 0.690 0.823 0.289 SGA 0.542 0.690 0.823 0.289 SGA 0.542 0.690 0.823 0.280 SGA 0.542 0.690 0.807 0.320 SGA 0.542 0.690 0.807 0.308 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 SI ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 SGA 0.810 0.865 0.940 0.115		Musket	0.499	0.628	0.830	0.448		
MEC 0.909 0.911 0.998 0.102		SGA	0.746	0.815	0.922	0.202		
R2 ZEC 0.584 0.663 0.894 0.537 Lighter 0.226 0.329 0.762 1.076 Racer 0.364 0.450 0.839 0.780 BLESS2 0.318 0.405 0.806 0.890 Musker 0.265 0.364 0.786 0.984 SGA 0.331 0.423 0.822 0.843 BFC 0.306 0.400 0.811 0.893 MEC 0.570 0.631 0.912 0.541 Racer 0.562 0.814 0.764 0.076 0.256 Racer 0.562 0.814 0.764 0.196 0.196 BLESS2 0.130 0.641 0.556 0.438 Musket 0.533 0.802 0.749 0.211 SGA 0.567 0.818 0.765 0.194 BFC 0.603 0.833 0.783 0.176 MEC 0.748 0.852 0.930 <		BFC	0.753	0.817	0.927	0.196		
Lighter 0.226 0.329 0.762 1.076 Racer 0.364 0.450 0.839 0.760 BLESS2 0.318 0.405 0.806 0.890 Musker 0.265 0.364 0.786 0.984 SGA 0.331 0.423 0.822 0.843 BFC 0.306 0.400 0.811 0.893 MEC 0.570 0.631 0.912 0.541 R3 ZEC 0.802 0.923 0.884 0.087 Lighter 0.445 0.764 0.706 0.256 Racer 0.562 0.814 0.764 0.196 BLESS2 0.130 0.641 0.556 0.438 Misket 0.533 0.802 0.749 0.211 SGA 0.567 0.818 0.765 0.194 BFC 0.603 0.833 0.783 0.176 MEC 0.788 0.852 0.930 0.117 R4 ZEC 0.746 0.833 0.905 0.137 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 SGA 0.542 0.690 0.823 0.280 BFC 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 SGA 0.810 0.8065 0.940 0.117 SGA		MEC	0.909	0.911	0.998	0.102		
Racer 0.364 0.450 0.839 0.780 BLESS2 0.318 0.405 0.806 0.890 Musker 0.265 0.364 0.786 0.984 SGA 0.331 0.423 0.822 0.843 BFC 0.306 0.400 0.811 0.893 MEC 0.570 0.631 0.912 0.541 R3 ZEC 0.802 0.923 0.884 0.087 BLESS2 0.130 0.641 0.764 0.196 BLESS2 0.130 0.641 0.556 0.438 Musker 0.533 0.802 0.749 0.211 SGA 0.567 0.818 0.765 0.194 BFC 0.603 0.833 0.783 0.176 MEC 0.788 0.852 0.930 0.117 R4 ZEC 0.746 0.833 0.905 0.137 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musker 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musker 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 SGA 0.810 0.	R2	ZEC	0.584	0.663	0.894	0.537		
BLESS2 0.318 0.405 0.806 0.890 Musket 0.265 0.364 0.786 0.984 SGA 0.331 0.423 0.822 0.843 BFC 0.306 0.400 0.811 0.893 MEC 0.570 0.631 0.912 0.541 R3 ZEC 0.802 0.923 0.884 0.087 Lighter 0.445 0.764 0.706 0.256 Racer 0.562 0.814 0.764 0.196 BLESS2 0.130 0.641 0.556 0.438 Musket 0.533 0.802 0.749 0.211 SGA 0.567 0.818 0.765 0.194 BFC 0.603 0.833 0.783 0.176 MEC 0.788 0.852 0.930 0.117 R4 ZEC 0.746 0.833 0.905 0.137 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 S1 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 Racer 0.882 0.916 0.964 0.071 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 SGA 0.810 0.865 0.940 0.956 0.109 SGA 0.957 0.957 0.958 0.958 0.		Lighter	0.226	0.329	0.762	1.076		
Musket 0.265 0.364 0.786 0.984 SGA 0.331 0.423 0.822 0.843 BFC 0.306 0.400 0.811 0.893 MEC 0.570 0.631 0.912 0.541 R3 ZEC 0.802 0.923 0.884 0.087 Lighter 0.445 0.764 0.706 0.256 Racer 0.562 0.814 0.764 0.196 BLESS2 0.130 0.641 0.556 0.438 Musket 0.533 0.802 0.749 0.211 SGA 0.567 0.818 0.765 0.194 BFC 0.603 0.833 0.783 0.176 MEC 0.788 0.852 0.930 0.117 R4 ZEC 0.746 0.833 0.905 0.137 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 S1 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 Racer 0.882 0.916 0.964 0.071 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 SGA 0.810 0.865 0.940 0.117 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 SZ ZEC 0.853 0.894 0.956 0.109 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86 BFC 0.151 0.822 0.920 0.15		Racer	0.364	0.450	0.839	0.780		
SGA 0.331 0.423 0.822 0.843 BFC 0.306 0.400 0.811 0.893 MEC 0.570 0.631 0.912 0.541 R3 ZEC 0.802 0.923 0.884 0.087 Lighter 0.445 0.764 0.706 0.256 Racer 0.562 0.814 0.764 0.196 BLESS2 0.130 0.641 0.556 0.438 Musket 0.533 0.802 0.749 0.211 SGA 0.567 0.818 0.765 0.194 BFC 0.603 0.833 0.783 0.176 MEC 0.788 0.852 0.930 0.117 R4 ZEC 0.746 0.833 0.905 0.137 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 S1 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 Racer 0.882 0.916 0.964 0.071 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86 BFC 0.751 0.822 0.920 0.15		BLESS2	0.318	0.405	0.806	0.890		
BFC 0.306 0.400 0.811 0.893 MEC 0.570 0.631 0.912 0.541 R3 ZEC 0.802 0.923 0.884 0.087 Lighter 0.445 0.764 0.706 0.256 Racer 0.562 0.814 0.764 0.196 BLESS2 0.130 0.641 0.556 0.438 Musket 0.533 0.802 0.749 0.211 SGA 0.567 0.818 0.765 0.194 BFC 0.603 0.833 0.783 0.176 MEC 0.788 0.852 0.930 0.117 R4 ZEC 0.746 0.833 0.905 0.137 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 S1 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 SGA 0.810 0.865 0.940 0.117 SGA 0.810 0.865 0.940 0.956 0.109 SGA 0.810 0.865 0.940 0.961 0.081		Musket	0.265	0.364	0.786	0.984		
MEC 0.570 0.631 0.912 0.541 R3 ZEC 0.802 0.923 0.884 0.087 Lighter 0.445 0.764 0.706 0.256 Racer 0.562 0.814 0.764 0.196 BLESS2 0.130 0.641 0.556 0.438 Musket 0.533 0.802 0.749 0.211 SGA 0.567 0.818 0.765 0.194 BFC 0.603 0.833 0.783 0.176 MEC 0.788 0.852 0.930 0.117 R4 ZEC 0.746 0.833 0.905 0.137 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 S1 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86 BFC 0.751 0.822 0.920 0.15		SGA	0.331	0.423	0.822	0.843		
R3 ZEC 0.802 0.923 0.884 0.087 Lighter 0.445 0.764 0.706 0.256 Racer 0.562 0.814 0.764 0.196 BLESS2 0.130 0.641 0.556 0.438 Musket 0.533 0.802 0.749 0.211 SGA 0.567 0.818 0.765 0.194 BFC 0.603 0.833 0.783 0.176 MEC 0.788 0.852 0.930 0.117 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607		BFC	0.306	0.400	0.811	0.893		
Lighter 0.445 0.764 0.706 0.256 Racer 0.562 0.814 0.764 0.196 RLESS2 0.130 0.641 0.556 0.438 Musket 0.533 0.802 0.749 0.211 SGA 0.567 0.818 0.765 0.194 REC 0.788 0.852 0.930 0.117 R4 ZEC 0.746 0.833 0.905 0.137 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 RLESS2 -0.517 0.018 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 RFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 S1 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 SGA 0.810 0.865 0.940 0.117 RFC 0.899 0.916 0.982 0.063 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Racer 0.168 0.408 0.630 0.720 RLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86 RFC 0.751 0.822 0.920 0.15		MEC	0.570	0.631	0.912	0.541		
Racer 0.562 0.814 0.764 0.196 BLESS2 0.130 0.641 0.556 0.438 Musket 0.533 0.802 0.749 0.211 SGA 0.567 0.818 0.765 0.194 BFC 0.603 0.833 0.783 0.176 MEC 0.788 0.852 0.930 0.117 R4 ZEC 0.746 0.833 0.905 0.137 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 S1 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.868 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86 BFC 0.751 0.822 0.920 0.15	R3	ZEC	0.802	0.923	0.884	0.087		
BLESS2 0.130 0.641 0.556 0.438 Musket 0.533 0.802 0.749 0.211 SGA 0.567 0.818 0.765 0.194 BFC 0.603 0.833 0.783 0.176 MEC 0.788 0.852 0.930 0.117 R4 ZEC 0.746 0.833 0.905 0.137 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 S1 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86		Lighter	0.445	0.764	0.706	0.256		
Musket 0.533 0.802 0.749 0.211 SGA 0.567 0.818 0.765 0.194 BFC 0.603 0.833 0.783 0.176 MEC 0.788 0.852 0.930 0.117 R4 ZEC 0.746 0.833 0.905 0.137 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 S1 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86		Racer	0.562	0.814	0.764	0.196		
SGA 0.567 0.818 0.765 0.194 BFC 0.603 0.833 0.783 0.176 MEC 0.788 0.852 0.930 0.117 R4 ZEC 0.746 0.833 0.905 0.137 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musker 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 S1 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musker 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musker 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86		BLESS2	0.130	0.641	0.556	0.438		
BFC 0.603 0.833 0.783 0.176 MEC 0.788 0.852 0.930 0.117 R4 ZEC 0.746 0.833 0.905 0.137 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86		Musket	0.533	0.802	0.749	0.211		
MEC 0.788 0.852 0.930 0.117 R4 ZEC 0.746 0.833 0.905 0.137 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 S1 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86		SGA	0.567	0.818	0.765	0.194		
R4 ZEC 0.746 0.833 0.905 0.137 Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 S1 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.865 0.940 0.117 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081		BFC	0.603	0.833	0.783	0.176		
Lighter 0.126 0.408 0.591 0.688 Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86		MEC	0.788	0.852	0.930	0.117		
Racer 0.313 0.541 0.703 0.484 BLESS2 -0.517 0.018 0.003 0.862 Musker 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musker 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musker 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86	R4	ZEC	0.746	0.833	0.905	0.137		
BLESS2 -0.517 0.018 0.003 0.862 Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 S1 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86		Lighter	0.126	0.408	0.591	0.688		
Musket 0.502 0.660 0.807 0.320 SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 S1 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86		Racer	0.313	0.541	0.703	0.484		
SGA 0.542 0.690 0.823 0.289 BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86		BLESS2	-0.517	0.018	0.003	0.862		
BFC 0.195 0.457 0.636 0.607 MEC 0.705 0.806 0.889 0.201 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86		Musket	0.502	0.660	0.807	0.320		
MEC 0.705 0.806 0.889 0.201 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86		SGA	0.542	0.690	0.823	0.289		
S1 ZEC 0.918 0.935 0.982 0.056 Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musker 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86 BFC 0.751 0.822 0.920 0.15 <td></td> <td>BFC</td> <td>0.195</td> <td>0.457</td> <td>0.636</td> <td>0.607</td>		BFC	0.195	0.457	0.636	0.607		
Lighter 0.791 0.851 0.934 0.130 Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86		MEC	0.705	0.806	0.889	0.201		
Racer 0.882 0.916 0.964 0.071 BLESS2 0.634 0.740 0.875 0.243 Musker 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86	S1	ZEC	0.918	0.935	0.982	0.056		
BLESS2 0.634 0.740 0.875 0.243 Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86		Lighter	0.791	0.851	0.934	0.130		
Musket 0.819 0.871 0.944 0.111 SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.61 SGA 0.075 0.342 0.562 0.86 BFC 0.751 0.822 0.920 0.11		Racer	0.882	0.916	0.964	0.071		
SGA 0.810 0.865 0.940 0.117 BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86 BFC 0.751 0.822 0.920 0.13		BLESS2	0.634	0.740	0.875	0.243		
BFC 0.866 0.903 0.961 0.081 MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musker 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86 BFC 0.751 0.822 0.920 0.13		Musket	0.819	0.871	0.944	0.111		
MEC 0.899 0.916 0.982 0.063 S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86 BFC 0.751 0.822 0.920 0.13		SGA	0.810	0.865	0.940	0.117		
S2 ZEC 0.853 0.894 0.956 0.109 Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musker 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.86 BFC 0.751 0.822 0.920 0.15		BFC	0.866	0.903	0.961	0.081		
Lighter 0.058 0.329 0.548 0.891 Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.6: SGA 0.075 0.342 0.562 0.86 BFC 0.751 0.822 0.920 0.1:		MEC	0.899	0.916	0.982	0.063		
Racer 0.168 0.408 0.630 0.720 BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.63 SGA 0.075 0.342 0.562 0.88 BFC 0.751 0.822 0.920 0.15	S2	ZEC	0.853	0.894	0.956	0.109		
BLESS2 0.311 0.509 0.719 0.54 Musket 0.232 0.453 0.672 0.65 SGA 0.075 0.342 0.562 0.86 BFC 0.751 0.822 0.920 0.15		Lighter	0.058	0.329	0.548	0.891		
Musket 0.232 0.453 0.672 0.6: SGA 0.075 0.342 0.562 0.8: BFC 0.751 0.822 0.920 0.1:		Racer	0.168	0.408	0.630	0.720		
SGA 0.075 0.342 0.562 0.86 BFC 0.751 0.822 0.920 0.15		BLESS2	0.311	0.509	0.719	0.54		
BFC 0.751 0.822 0.920 0.15		Musket	0.232	0.453	0.672	0.63		
		SGA	0.075	0.342	0.562	0.86		
MEC 0.840 0.887 0.050 0.11		BFC	0.751	0.822	0.920	0.15		
WELL 0.049 0.007 0.939 0.11		MEC	0.849	0.887	0.959	0.12		



Good to read

Spectra alignment

M. Chaisson et al, "Fragment assembly with short reads", *Bioinformatics* 20(13):2067-2074, 2004. https://pubmed.ncbi.nlm.nih.gov/15059830/

ZEC

L. Zhao et al., "Mining statistically-solid k-mers for accurate NGS error correction", *BMC Genomics* 19(S10):912, 2018. https://doi.org/10.1186/s12864-018-5272-y

Lighter

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Good to read

Musket

Y. Liu et al., "Musket: A multistage k-mer spectrum-based error corrector for Illumina sequence data", *Bioinformatics* 29(3):308-315, 2013. https://pubmed.ncbi.nlm.nih.gov/23202746/

MEC

L. Zhao et al., "MapReduce for accurate error correction of next-generation sequencing data", *Bioinformatics* 33(23):3844-3851, 2017. https://pubmed.ncbi.nlm.nih.gov/28205674/

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