

Making the Most of Ancient DNA

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Why Study Ancient DNA



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Specification
and
Properties of
the Data

Common
Approaches
to String
Alignments

Evaluation of
the New
Approach

Conclusion &
Future Work



Source: www.sciencemag.org

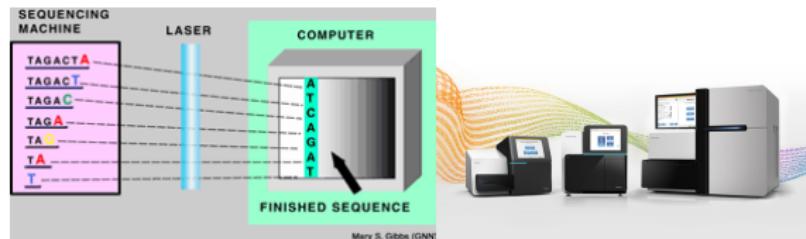
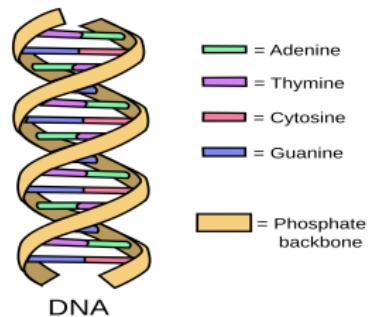
What is a DNA Sequence

- Let X be a sequence of λ random variables.

$$X = \{X_1, X_2, \dots, X_\lambda\}$$

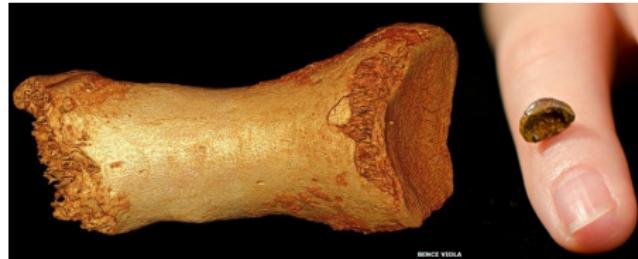
which takes the values from the alphabet $\{A, C, G, T\}$.

- e.g. ACGGCTAACGTAGATACAGCTCGCA



Source: medivizor.com
<http://www.genomenewsnetwork.org>

What is Ancient DNA



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Let lowercase $x = \{x_1, x_2, \dots, x_\lambda\}$ represent a specific DNA sequence.

- e.g. ATTGTTACAGATATT

Characteristics

- Hard to retrieve.
- Short molecule ≤ 50 bp.
- *Post-Mortem* damage: deamination (substitutions of C→T).
- Microbial contamination.

Source: Meyer M, et al. Science 2012 &
<http://www.ourdailyread.com/2014/02/>

Sequencing Ancient DNA

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 Ancient DNA (aDNA)	 Microbial DNA
 Present-day human DNA	 aDNA damage



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DNA Similarity



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- DNA sequences may have changed from a common ancestor through various reasons:

- Change of a letter

ACGCTATGCA
ACC**TATGCA**

- Insertion of a letter

ACGCTATGC-A
ACGCTATGC**TA**

- Deletion of a letter

ACGCTA**TGCA**
ACGCT-TGCA

- A few mutations make sequences different, but still “similar” and we are looking for these similarities.



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DNA Sequence Alignment



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- Alignment to the reference genome to identify the molecules we are interested in.
- Approximate pattern matching.
- e.g.

S_1 : **ACGCTATAGCA**
 S_2 : **CGATGAC**

A plausible alignment of S_1 and S_2 :

S_1 : **ACGCTATAGCA-**
 S_2 : **-CG--AT-G-AC**

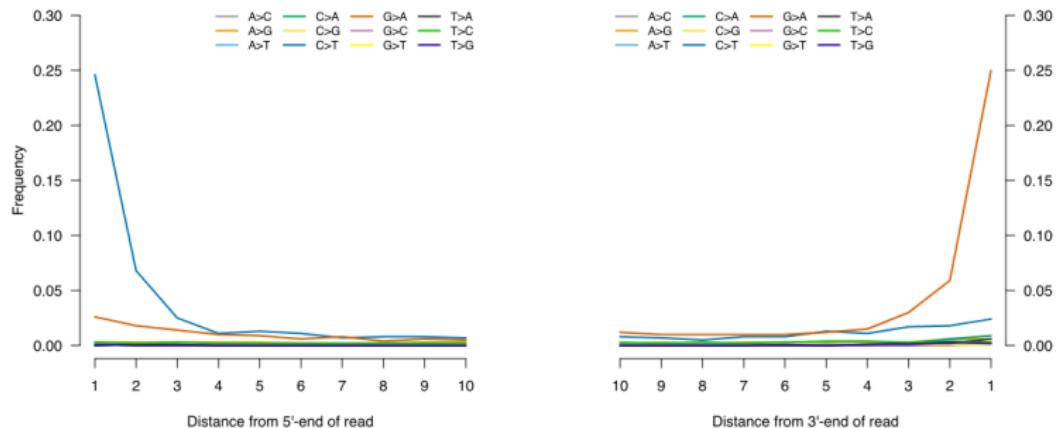
Post-Mortem Deamination Damage

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A high nucleotide misincorporation rate of thymine(T) in place of cytosine(C) near the ends of ancient DNA reads.

Source:
<http://mitosuite.com/example/results.html>



What Sort of Alignment?



■ Global alignment:

S_1 : ACCGTCGCTACTGCTGT CAGATCGCTCATCGCATACTGTCT
 S_2 : ACCGTGTA CAGATCGCTCATC~~ATCGC~~AGTCGATAGCCTGTCT

■ Local alignment:

S_1 : ACCGTCGCTACTGCTGTC~~AGATCGCTCA~~GTTCGATCTG
 S_2 : GTCTGTCAG~~AGATCGCTCA~~TCGCATACTGTCTCGTCC

■ Semi-Global alignment:

S_1 : ACCGTCGCTACTGCTGTC~~AGATCGCTCA~~GTTCGCTGTCAAGTCACT
 S_2 : AGATCGCTCA



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Scoring an Alignment

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- The alignment score is the sum of all the scores of paired aligned characters plus the gap scores.
- e.g. substitution matrix

$S(S_{1i}, S_{2j})$	A	C	G	T
A	1	-1	-1	-1
C	-1	1	-1	-1
G	-1	-1	1	-1
T	-1	-1	-1	1

If $g = -1$

$$\begin{array}{l} S_1 : \quad C \quad C \quad G \quad A \quad - \quad T \quad A \\ S_2 : \quad T \quad C \quad G \quad - \quad C \quad T \quad A \end{array}$$

we score it by:

$$\begin{aligned} S(C, T) + S(C, C) + S(G, G) + 2g + S(T, T) + S(A, A) \\ -1 + 1 + 1 - 1 - 1 + 1 + 1 = 1 \end{aligned}$$



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How to Find the Optimal Alignment?

- Simple approach: Compute and score all possible alignments.

There are:

$$\binom{2n}{n} = \frac{(2n)!}{(n!)^2} \simeq \frac{2^{2n}}{\sqrt{2\pi n}}$$

global alignments.

- Time complexity $\mathcal{O}(2^{2n})$.
- Dynamic programming
 - Calculate the best alignment of all prefixes of the sequences instead of best alignment of the two sequences.
 - Time complexity $\mathcal{O}(n^2)$.



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Overview of BWA Aligner

- Based on FM-index. (Burrows-Wheeler Transform plus auxiliary data structures) which enables fast matching.
- Fast and moderate memory footprint (<4GB).
- Backtracking algorithm with heuristics.
- Seed heuristic.
- Does not take deamination into consideration.



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Why is a New Aligner Needed?

■ Alignment 1:

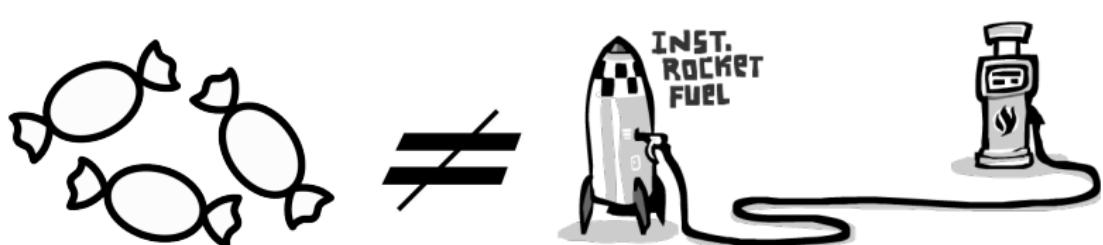
A**CCC****A****C****T****C****T****A****C****C****T****C****A****T****C****G****A****C****C**
A**T****T****T****A****C****T****C****T****A****C****C****T****C****A****T****C****G****A****T****T**

■ Alignment 2:

A**CC****C****A****C****T****C****T****A****C****C****T****C****A****T****C****G****A****C****C**
C**CC****C****T****G****T****T****A****C****C****A****C****T****C****G****A****C****C**

R-Candy: New Aligner for Ancient DNA

- Aligns ultra-short reads of length $\leq 35\text{bp}$.
- Copes with high levels of specific damage expected in ancient DNA.



Source: <http://www.5ideas.in>



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Overview of R-Candy's Algorithm

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- Based on FM-index (Burrows-Wheeler Transform plus auxiliary data structures) which enables fast matching.
- Backtracking on FM-index.
- Implements a model for damage expected on ancient DNA.
- Tailored for short reads of ancient DNA.



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Test Data



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- To compare sensitivity of R-Candy to BWA aligner.
 - Simulated modern and ancient DNA reads originated from a simulated genome.
- To roll out possible artifacts of genome simulation.
 - Simulated modern and ancient DNA reads originated from a real genome.
- To evaluate the rate of false positive alignments.
 - Simulated random reads as stands for exogenous DNA.

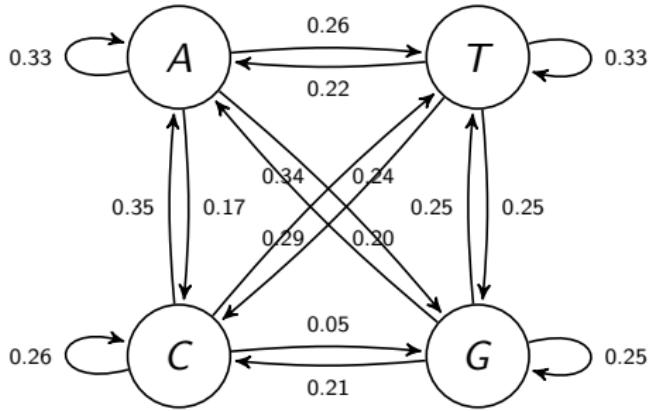
Genome Simulation

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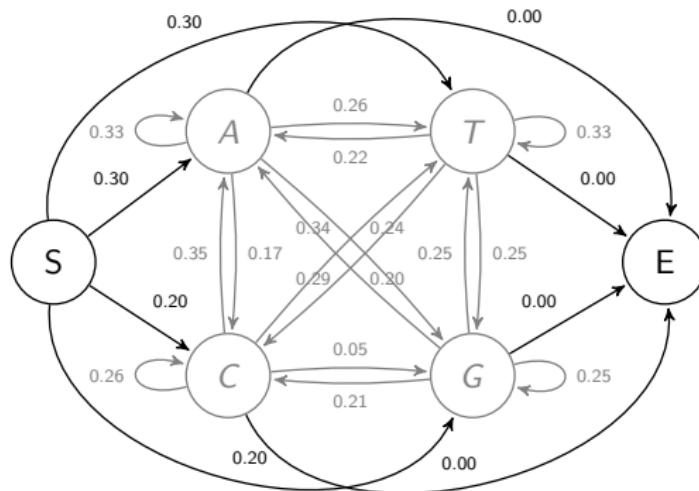
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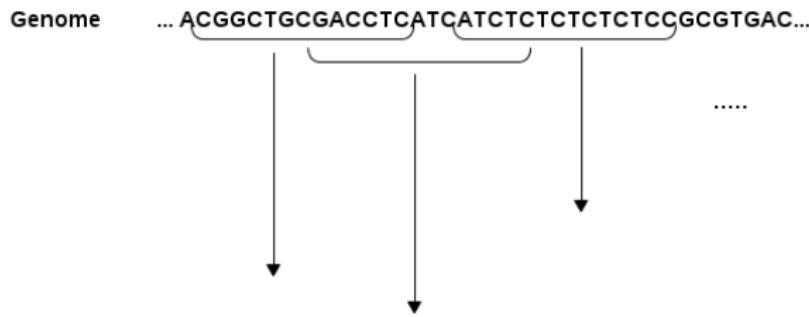
Trained 1st order Markov chain based on the human reference genome.

1st Order Markov Chain



Trained 1st Order Markov-Chain based on the human reference genome with start and end states

Read Simulation (Cont.)

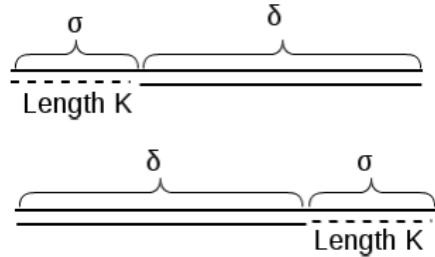
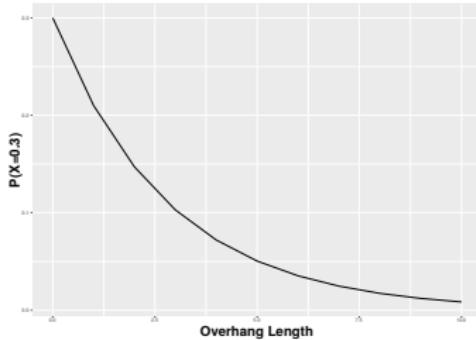


Reads.sam

```
Genomic_0 0 Simulated_Genome 8657611 0 * * 0 0 CGGCTGACCTCATCT  
Genomic_1 0 Simulated_Genome 1668761 0 * * 0 0 TGACGGGTCGTTCA
```

Read Simulation (Cont.)

- **Divergence:** different divergence rates are simulated by a given number of mismatches per read.
- **Deamination damage:** based on deamination parameters (overhang (σ) and double stranded (δ) deamination rates plus the probability of being in overhangs) provided by users.



Read Simulation (Cont.)

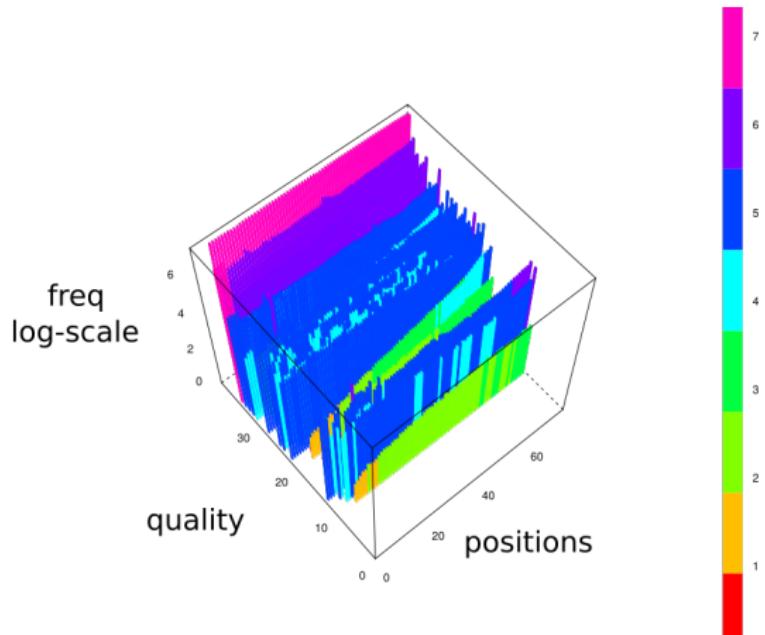
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- **Sequencing error:** specific types of errors introduced by the sequencing machine based on the distribution of quality scores on an actual sequencing run.





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Read Simulation (Cont.)

	Divergence	Deamination Damage	Sequencing Error
Modern DNA	✓		✓
Ancient DNA	✓	✓	✓
Exogenous DNA		✓	✓

Evaluation Criteria

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■ Mapping accuracy:

$$\text{Sensitivity (TPR)} = \frac{\# TP}{\# TP + \# FN}$$

$$\text{Specificity (TNR)} = \frac{\# TN}{\# TN + \# FP}$$



- **Throughput:** the number of mapped reads per second.
- **Memory footprint:** required memory for indexing, processing and storing.



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Evaluation Scenarios

	DNA Reads		Aligned To		Parameters	
	Modern	Ancient	Simulated Genome	Real Genome	Default (No Deamination)	Ancient
MSD	✓		✓		✓	
MRD	✓			✓	✓	
MSA	✓		✓			✓
MRA	✓			✓		✓
ASA		✓	✓			✓
ARA		✓		✓		✓

M = Modern/Fresh DNA

A = Ancient DNA/parameters

S = Simulated genome

R = Real genome

D = Default parameters

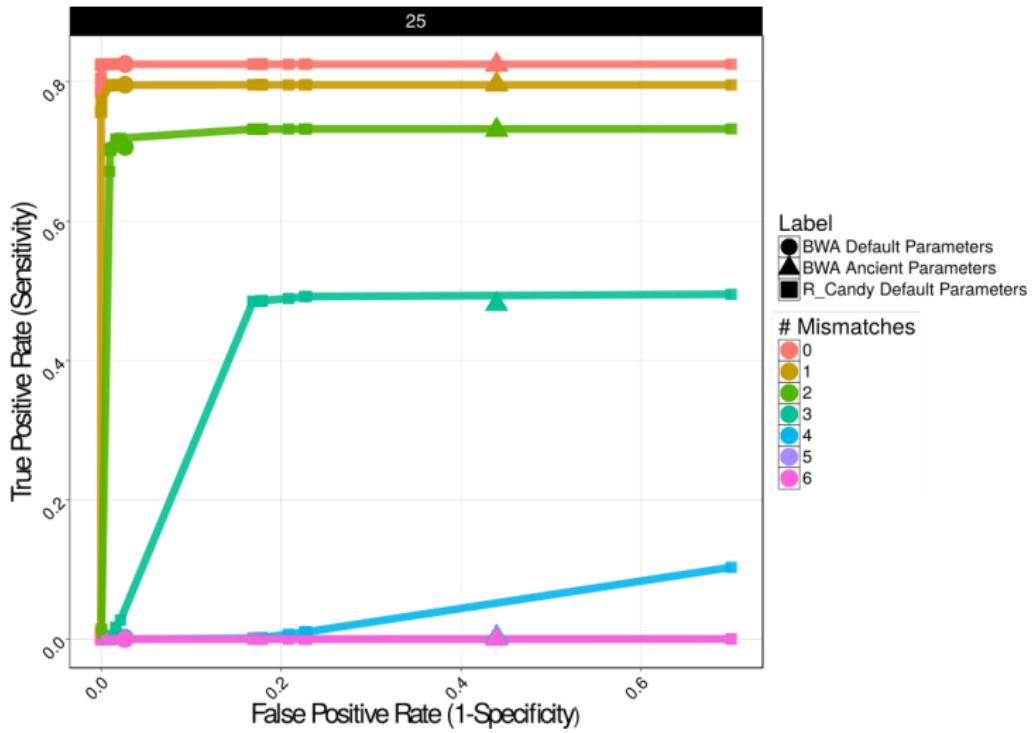
ROC Curve

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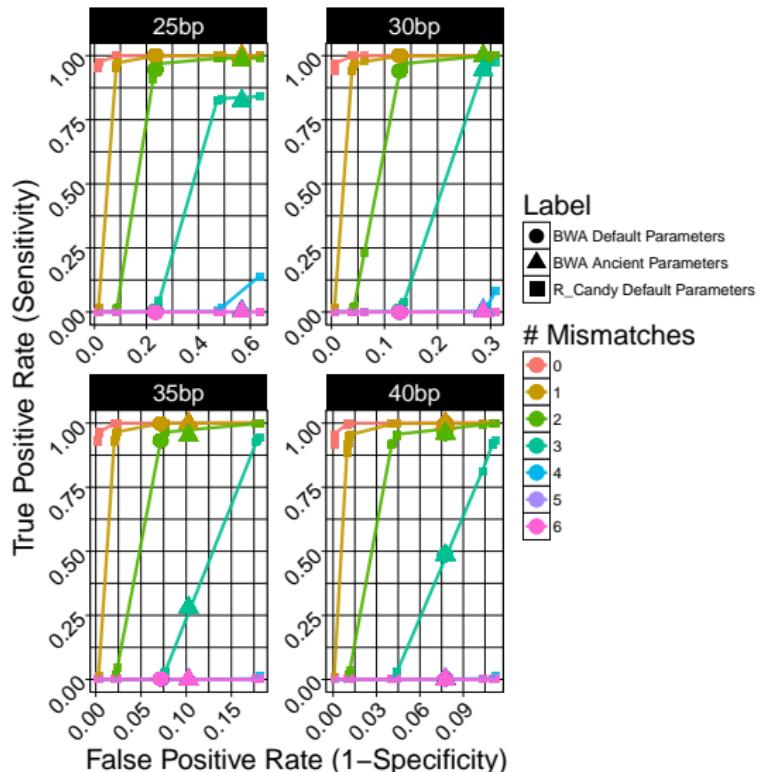
Modern DNA Simulated Genome, Default Parameters

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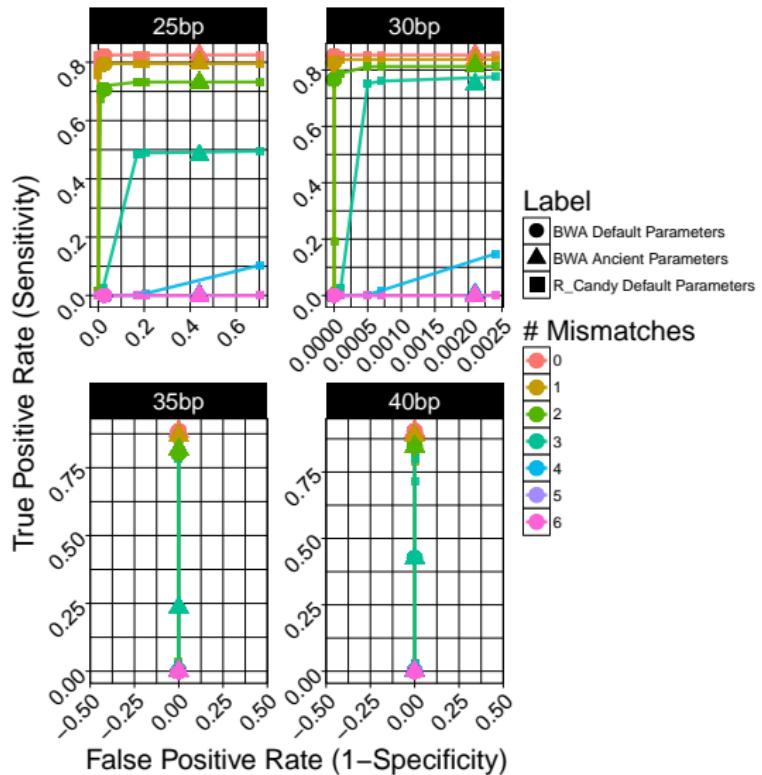
Modern DNA Human Ref Genome, Default Parameters

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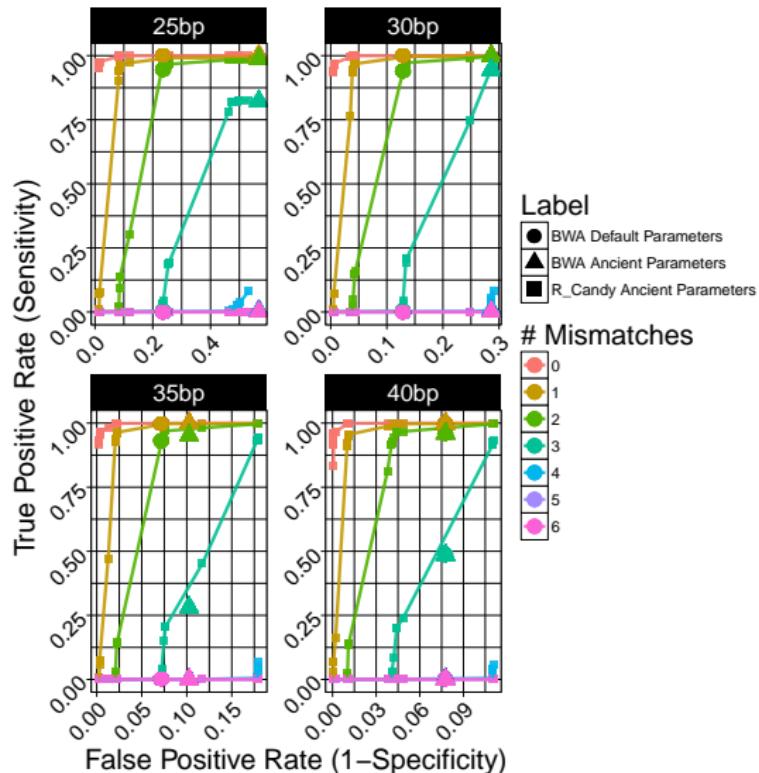
Modern DNA Simulated Genome, Ancient Parameters

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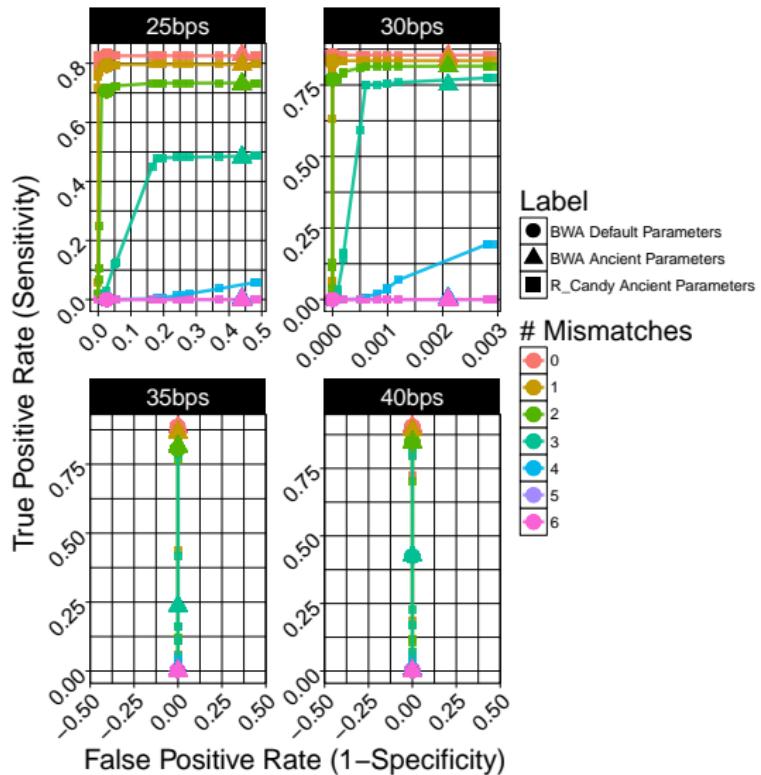
Modern DNA Human Ref Genome, Ancient Parameters

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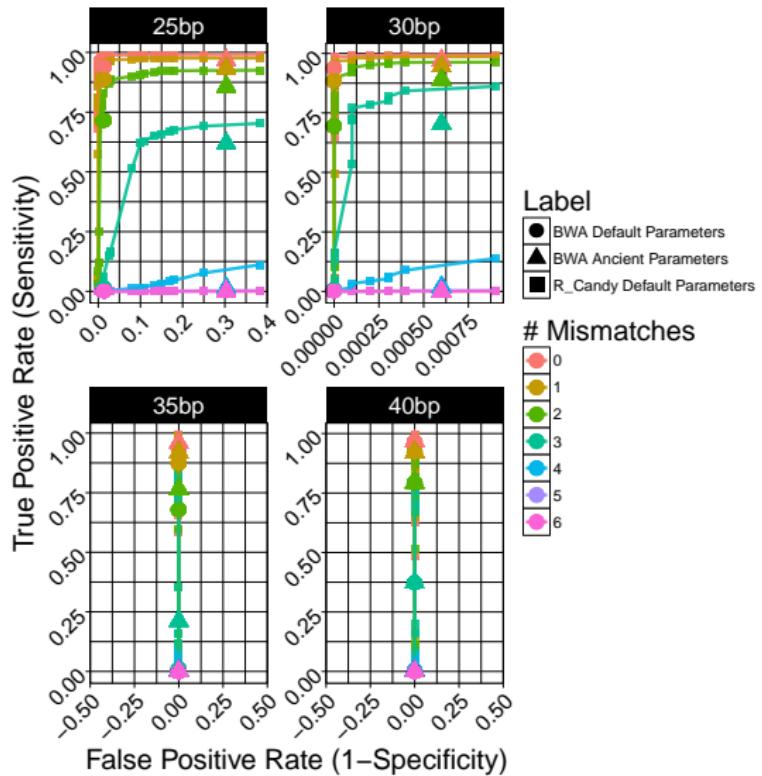
Ancient DNA Simulated Genome, Ancient Parameters

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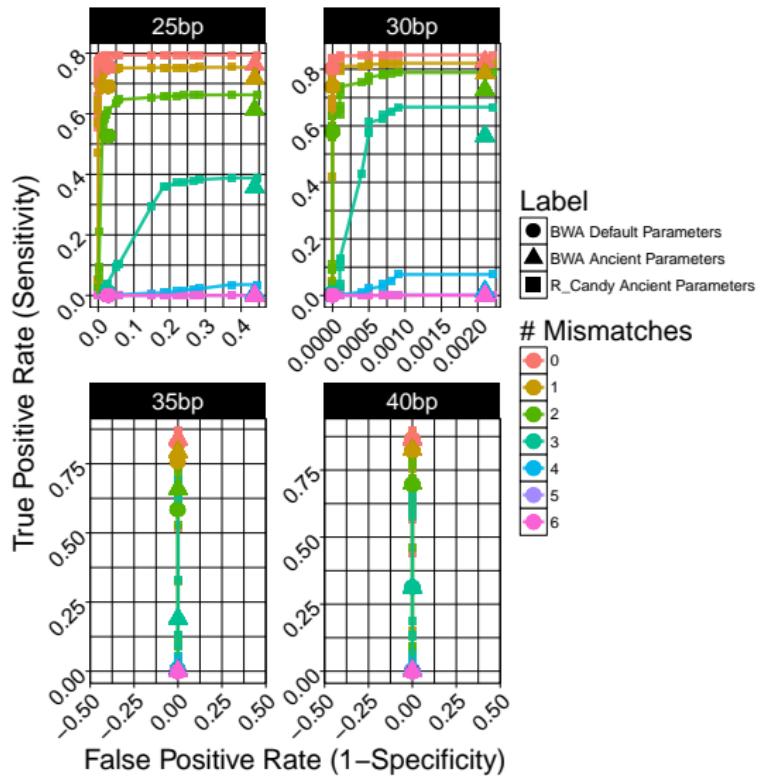
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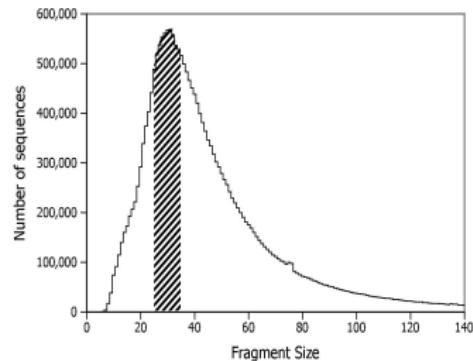
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- R-Candy reduces the minimum read length that can be used for ancient DNA alignment from 35 bp to about 25 bp.



- Can be used to align both ancient and modern DNA.
- Memory efficient (4 GB).
- Very low throughput rate (speed) therefore unusable in the case of big-data.

Source: Meyer M, et al. Nature 2013



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Future Work

- Different search algorithm starting from the middle part of the reads.
- Requires a different index structure (Bi-directional Wavelet Tree).
- Enable a seed strategy where the middle part of a read would serve as seed.
- Dynamic programming with a Full-Text index might extend the usefulness of R-Candy to longer reads.



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Acknowledgement

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Udo Stenzel



Janet Kelso



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Availability



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R-Candy: <https://bitbucket.org/ustenzel/r-candy>.

readSim:(genome and read simulator)

<https://github.com/Homa1127/simulateGenome.git>.



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R-Candy's Speed Performance

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Type	Read length	Speed BWA default (reads/s)	Speed BWA ancient (reads/s)	Speed R-Candy ancient (reads/s)
Genomic	25	222	34	1.79
Genomic	30	526	52	2.22
Genomic	35	625	434	2.26
Genomic	40	500	357	2.45
exogenous	25	147	13	1.68
exogenous	30	217	42	2.19
exogenous	35	232	153	1.67
exogenous	40	178	144	3.10

The alignment speed for ancient reads aligned to the human reference genome.



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R-Candy's Memory Usage

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Type	Read length	BWA default memory usage (MB)	BWA ancient memory usage (MB)	R-Candy memory usage (MB)
Genomic	25	945	947	1181
Genomic	30	945	949	1182
Genomic	35	945	945	1183
Genomic	40	945	945	1181
exogenous	25	945	947	814
exogenous	30	945	947	815
exogenous	35	945	945	825
exogenous	40	945	945	828

The alignment speed for ancient reads aligned to the human reference genome.



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Scoring Matrix for ancient DNA

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$$\begin{pmatrix} 1 - 3\epsilon & \epsilon & \epsilon + p_G - 4\epsilon p_G & \epsilon \\ \epsilon & 1 - 3\epsilon - p_C + 4\epsilon p_C & \epsilon & \epsilon \\ \epsilon & \epsilon & 1 - 3\epsilon - p_G + 4\epsilon p_G & \epsilon \\ \epsilon & \epsilon + p_C - 4\epsilon p_C & \epsilon & 1 - 3\epsilon \end{pmatrix}$$