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Succinct De Bruijn graphs

Implementation report

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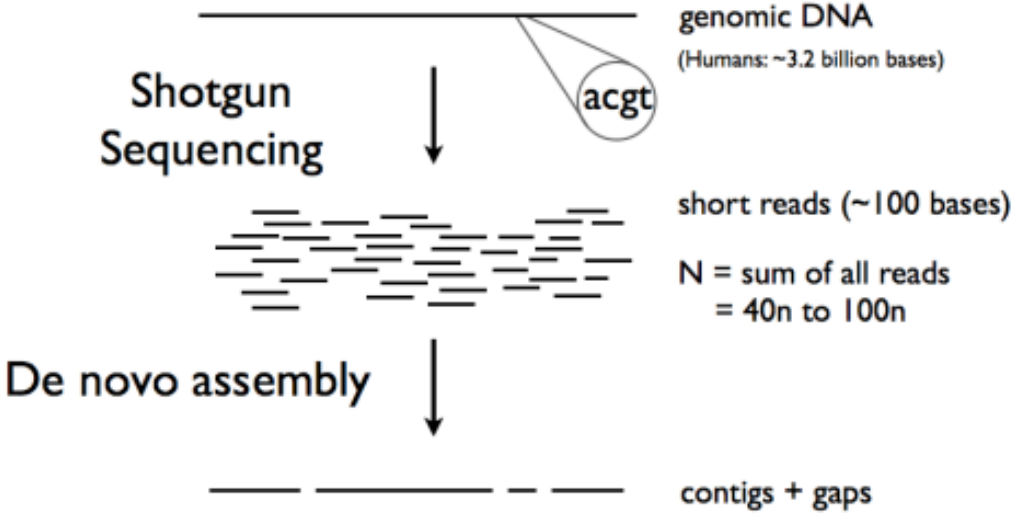
"Succint de Bruijn Graphs" by Bowe et al. (2012)

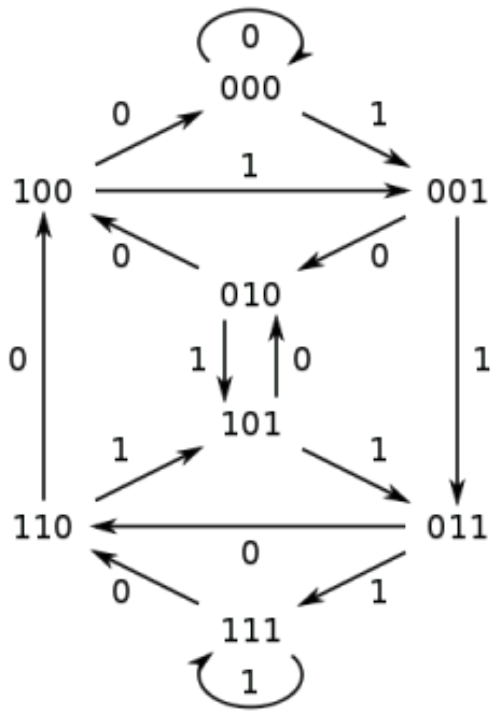
New succinct de Bruijn graph representation for k-mers in a DNA sequence using $(2 + \log \sigma)m + o(m)$ bits (so $4m + o(m)$ for DNA).

- Summary of the main ideas of the paper
- C++ implementation of the BOSS data structure
- Analysis of memory usage and construction time



- $|\Sigma|^k$ distinct nodes, corresponding to all possible sequences.
- Directed edges between overlapping nodes.

- De novo assembly of reads.

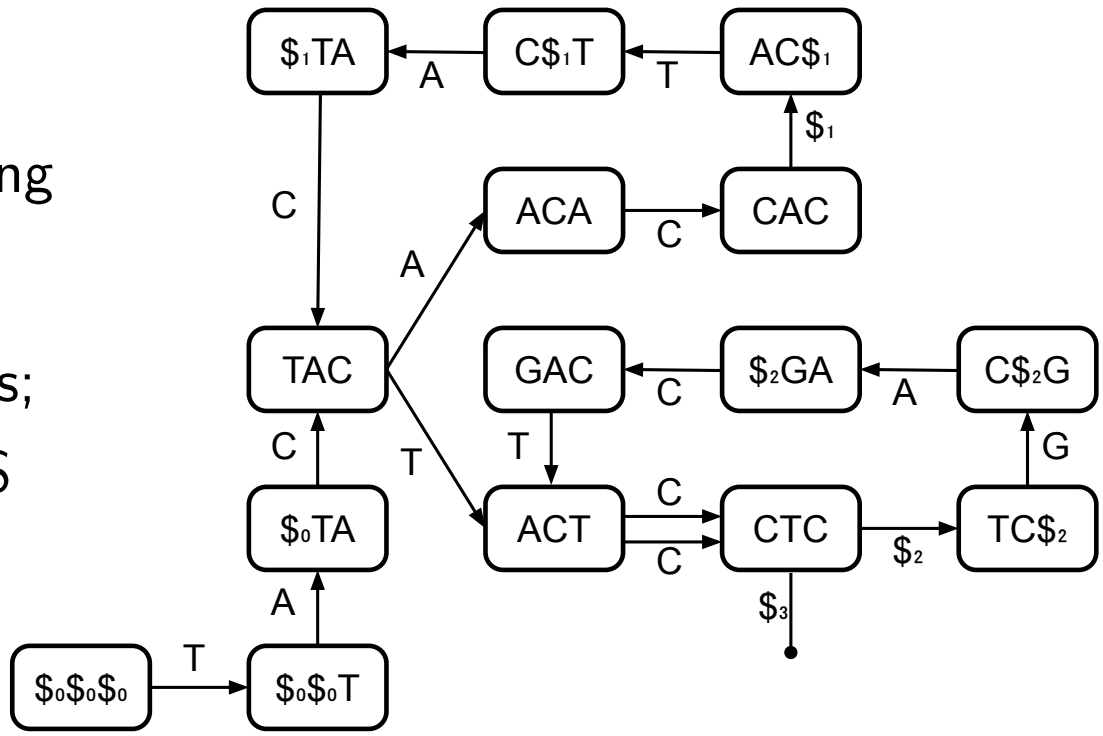


Alex Bowe. *Succinct de Bruijn Graphs*. July 2013

Objective

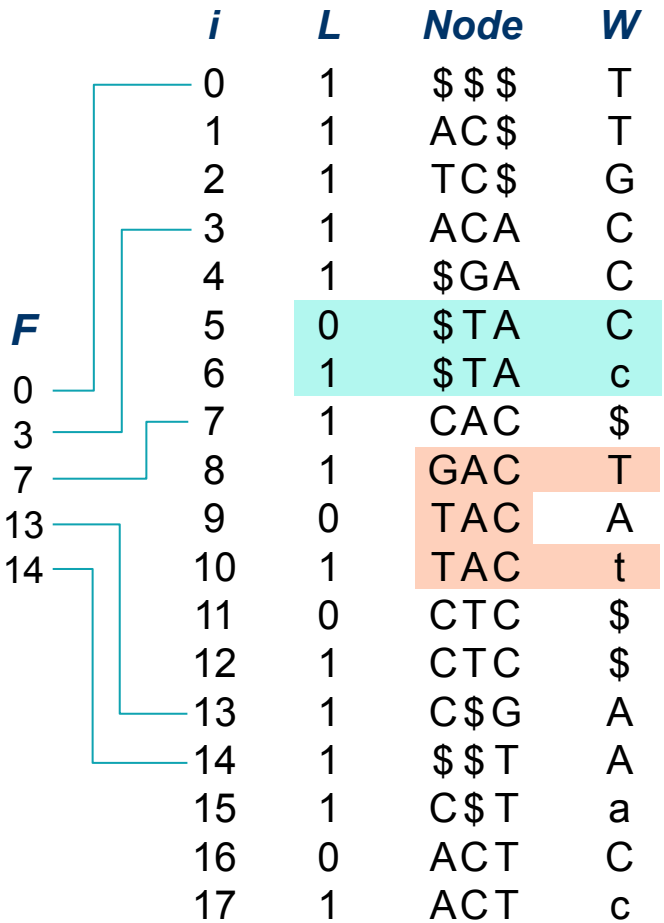
Construction of the k-dimensional dBg of a string T of lenght N:

- At most $N - k + 1$ nodes;
- k terminator characters \$ at the head;
- Different reads are followed by a \$ and concatenated.



$T =$"$\$_0\$_0\$_0$TACAC$\$_1$TACTC$\$_2$GACTC$\$_3$"

Theoretical construction



	i	L	Node	W
	0	1	$$$	T
	1	1	AC$	T
	2	1	TC$	G
	3	1	ACA	C
	4	1	$GA	C
	5	0	$TA	C
	6	1	$TA	c
	7	1	CAC	$
	8	1	GAC	T
	9	0	TAC	A
	10	1	TAC	t
	11	0	CTC	$
	12	1	CTC	$
	13	1	C$G	A
	14	1	$$T	A
	15	1	C$T	a
	16	0	ACT	C
	17	1	ACT	c

F
0
3
7
13
14

First step: taking every <node, edge> pair and sorting them in colex order.

Then, the proposed representation is composed of the following three elements:

- a string W of lenght m over alphabet Σ;
- a bitvector L of lenght m;
- an array F of length $|\Sigma|$.

For a total of $m + m \log(2\sigma + 1) + o(m)$ bits.

- First step: creation of a CSA using the Succinct Data Structure Library (SDSL) $\Longrightarrow$ suffix sorting, label extraction, W, F

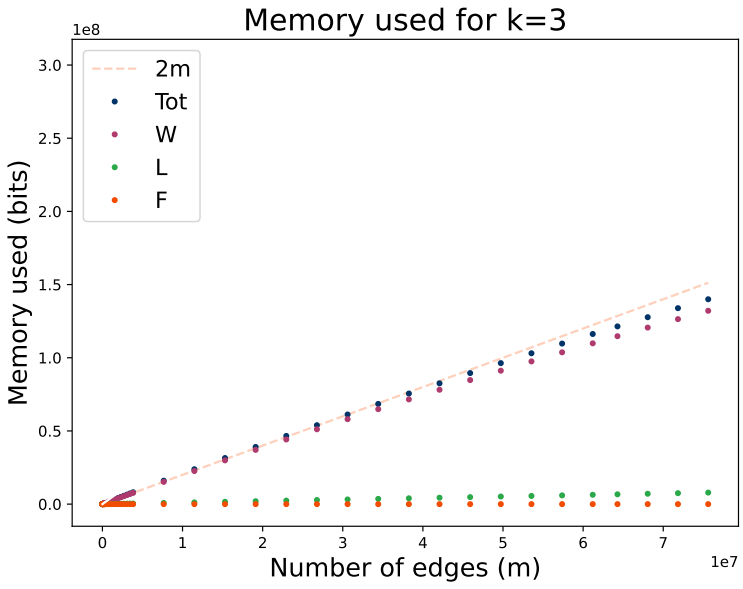
i	SA	ISA	PSI	LF	BWT	T[SA[i]...SA[i]-1]
0	20	14	14	1	$	$CTCAG$CTCAT$CACAT$$$
1	19	19	0	2	$	$$CTCAG$CTCAT$CACAT$$
2	18	11	1	3	$	$$$CTCAG$CTCAT$CACAT$
3	17	7	2	17	T	$$$$CTCAG$CTCAT$CACAT
4	11	16	10	18	T	$CACAT$$$$CTCAG$CTCAT
5	5	5	15	16	G	$CTCAT$CACAT$$$$CTCAG
6	13	15	12	10	C	ACAT$$$$CTCAG$CTCAT$C
⋮	⋮	⋮	⋮	⋮	⋮	⋮

C 0 1 6 10 16 17 21

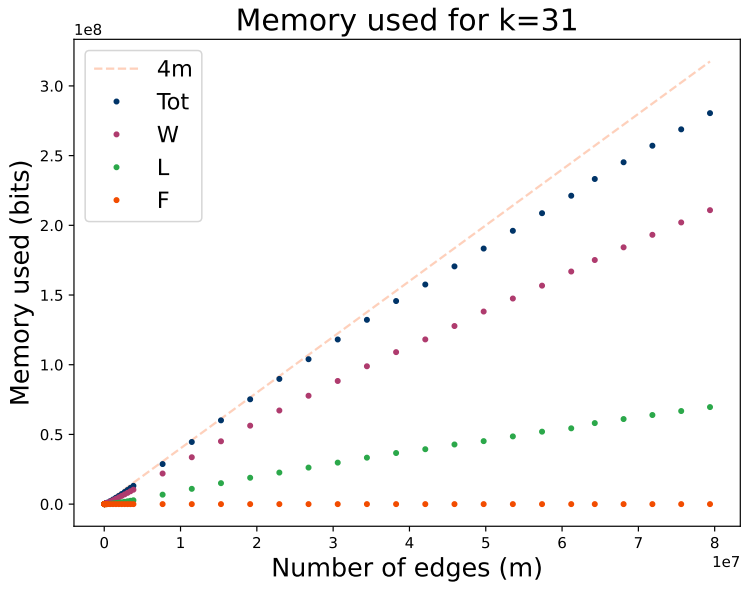
- Second step: for loop $\Longrightarrow$ label extraction, creation of L, flags for the characters of W

- Third step: compression of data structures
  - W $\Longrightarrow$ Wavelet Tree which occupies $mH_0(W) + 2\sigma \log m$.
  - L $\Longrightarrow$ RRR bitvector which occupies $mH_0(L) + o(m)$ bits.
  - F $\Longrightarrow$ compressed with the function $sdsl :: util :: bit\_compress(F)$

Operation	Description	Time
outdegree(v)	Returns number of outgoing edges from node V.	$\mathcal{O}(1)$
outgoing(v,c)	From node V, follows the edge labeled by symbol c.	$\mathcal{O}(1)$
label(v)	Returns the label of node v.	$\mathcal{O}(k)$
index(s)	Returns the index of k-mer s if present.	$\mathcal{O}(k)$
indegree(v)	Returns the number of incoming edges to node v	$\mathcal{O}(1)$
incoming(v,c)	Returns predecessor node starting with c that has an edge to node v	$\mathcal{O}(k \log \sigma)$

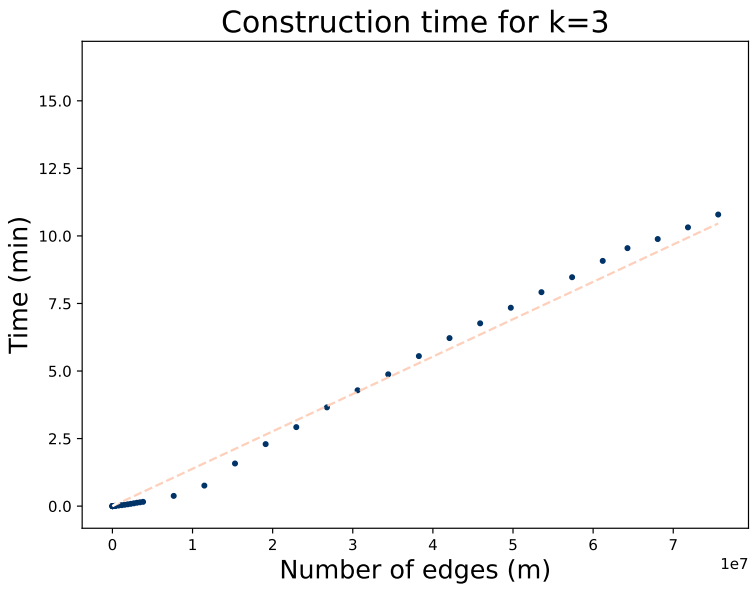


Number of bits for $k = 3$

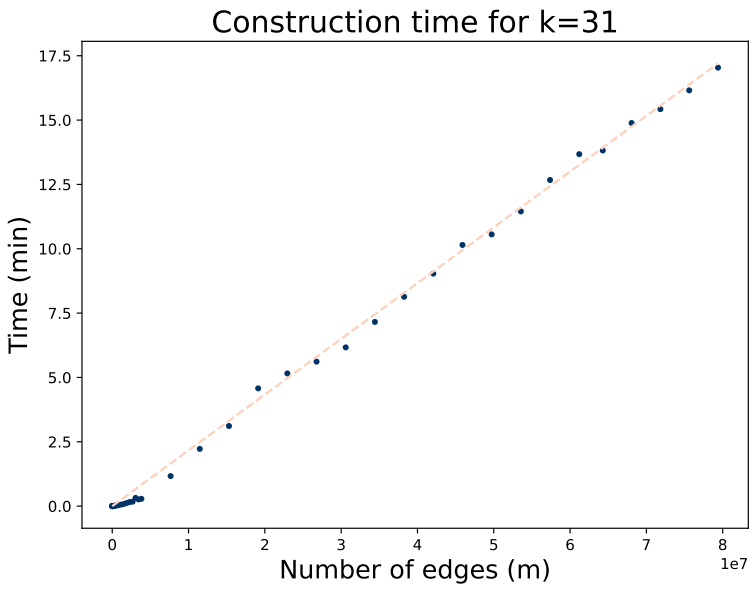


Number of bits for $k = 31$

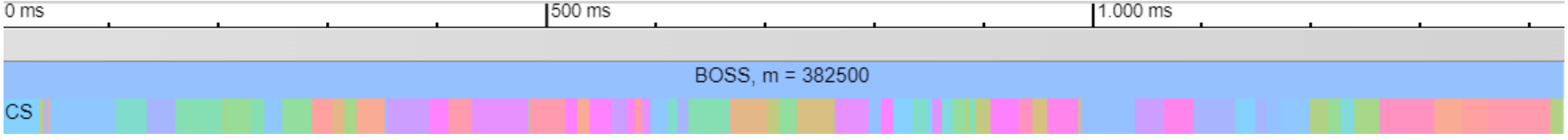
- The number of bits used depends on $H_0(L)$ and on $H_0(W)$ and thus it changes depending on the value of k and the input string.



Construction time for $k = 3$



Construction time for $k = 31$



Breakdown of timing for $k = 3$, $m = 382500$

Results

- We have described a novel approach to representing de Bruijn graphs efficiently, while alsosupporting a full suite of navigation operations quickly.
- The total space is a theoretical $4m$ bits for DNA. Using specially modified indexes we can further lower this value.

Further work

- The data structure can be constructed in $\mathcal{O}(Nk)$ time.
- We can think of reducing the construction time by parallelizing the for loop, which ends up being the most time consuming part of the algorithm.

[1] Alex Bowe. *Succinct de Bruijn Graphs*. July 2013. URL: https://www.alexbowe.com/succinct-debruijn-graphs/ (visited on 09/01/2024).

[2] Alex Bowe et al. "Succinct de Bruijn Graphs". In: *Algorithms in Bioinformatics, Volume 7534 of Lecture Notes in Computer Science* (Sept. 2012), pp. 225–235. DOI: 10.1007/978-3-642-33122-0_18.

[3] Rayan Chikhi. "A Tale of Optimizing the Space Taken by de Bruijn Graphs". In: *Connecting with Computability*. Cham: Springer International Publishing, 2021, pp. 120–134.

[4] Simon Gog et al. "From Theory to Practice: Plug and Play with Succinct Data Structures". In: *13th International Symposium on Experimental Algorithms, (SEA 2014)*. 2014, pp. 326–337.