

Genome assemblies

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B2
v2021



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Lecture outline

- Introduction
- Assembly algorithm overview
- Long read technologies
- Scaffolding
 - Chromosome conformation capture
- Case studies

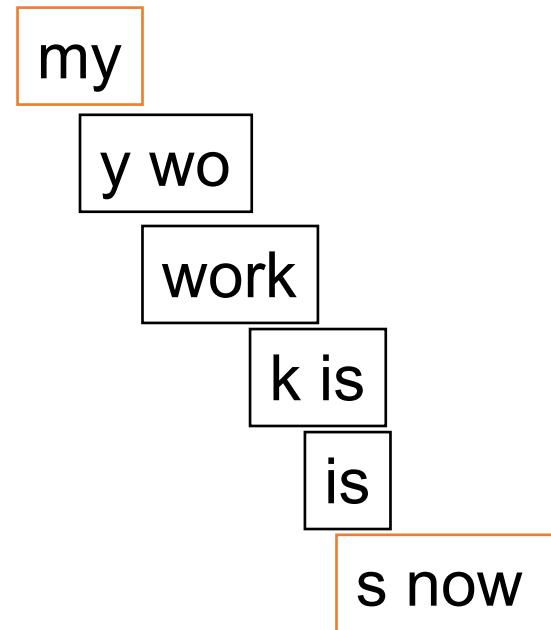
Problem

We accidentally printed my five copies of “Origin of Species”, and shredded into pieces



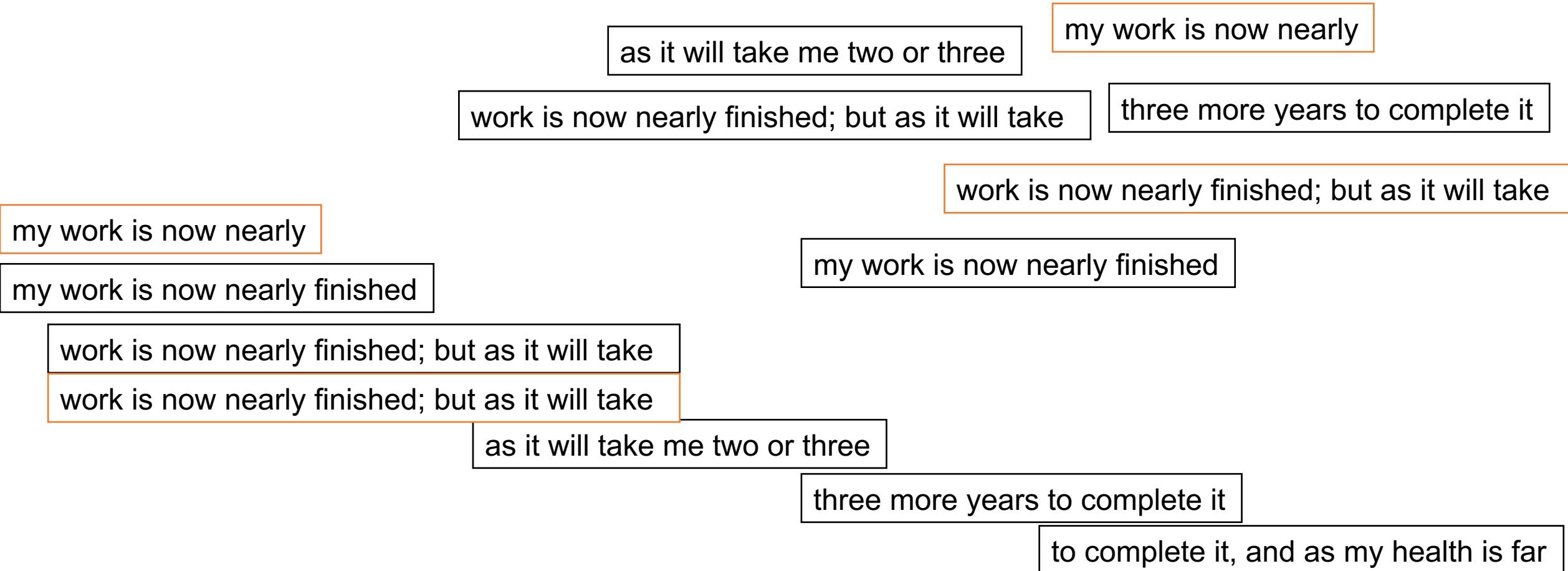
my work is now nearly finished; but as it will take me two or three more years to complete it, and as my health is far from strong, I have been urged to publish this Abstract. I have more especially been induced to do this, as Mr Wallace, who is now studying the natural history of the Malay archipelago, has arrived at almost exactly the same general conclusions that I have on the origin of species. Last year he sent to me a memoir on this subject, with a request that I would forward it to Sir Charles Lyell, who sent it to the Linnean Society, and it is published in the third volume of the journal of that Society. Sir C. Lyell and Dr Hooker, who both knew of my work -- the latter having read my sketch of 1844 -- honoured me by thinking it advisable to publish, with Mr Wallace's excellent memoir, some brief extracts from my manuscripts.

Assembly = Piecing the pieces together



my work is now

Long shredded pieces (read) = easier assembly

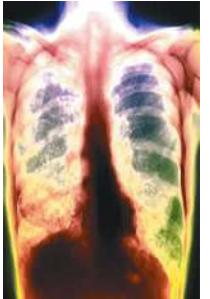


my work is now nearly finished; but as it will take me two or three more years to complete it, and as my health is far

Why sequence a genome?

Genomics advance our understanding of organisms across tree of life

pathogens



TB



model



model



model

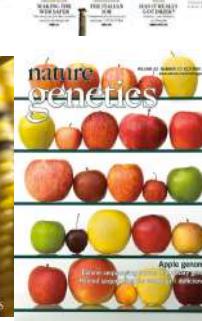
NGS

nature



Science

nature



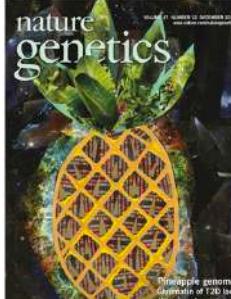
nature genetics



Blood fluke



Tapeworms



nature genetics



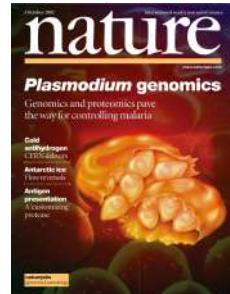
Science

1996



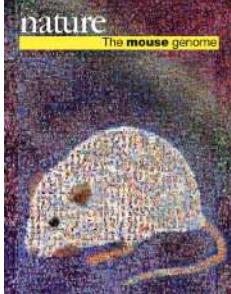
S. cerevisiae
model

1997



Plasmodium
pathogens

1998



model

1999



model

2000



model

2001



Phytophthora infestans
(potato blight)

2002



Black death
(potato blight)

2005



model

2006



model

2007

2008

2009

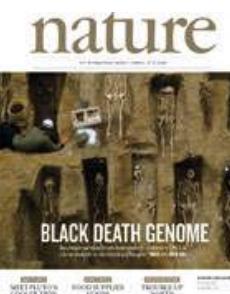
2010

2011

2012

2013

2014

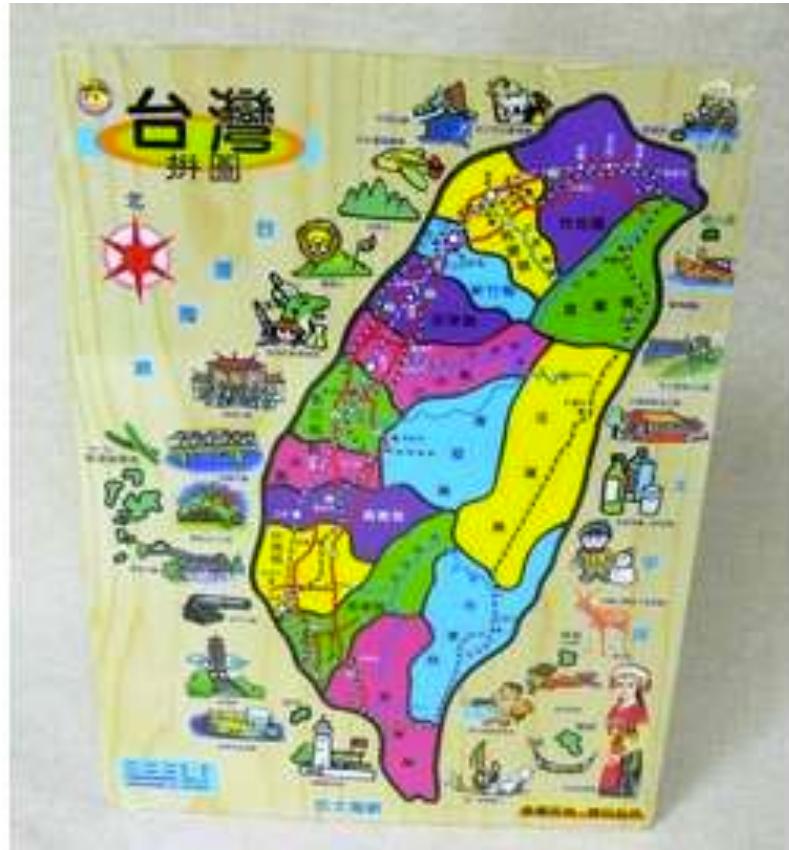


pathogens

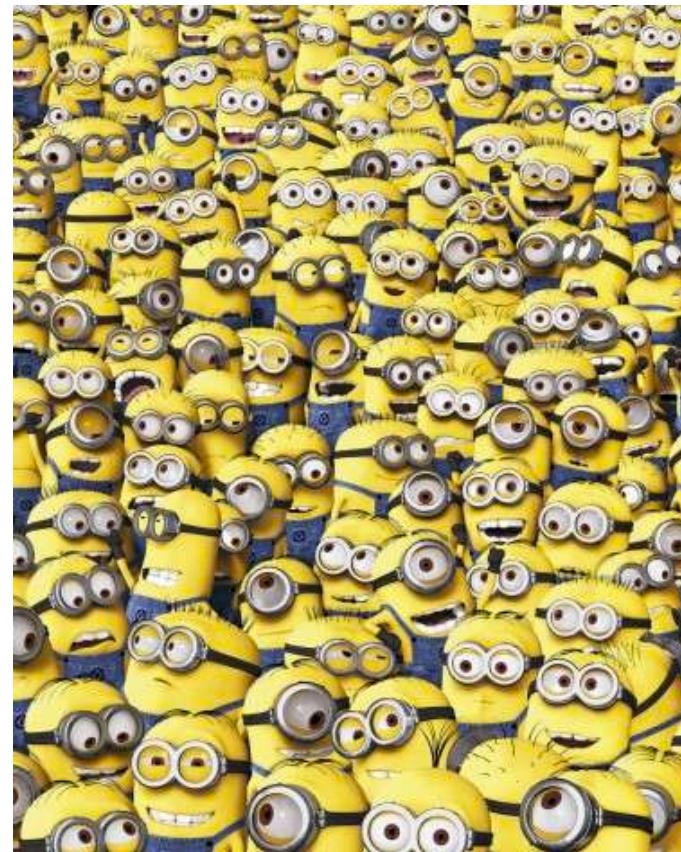


pathogens

Assemble a genome is hard



Less complicated

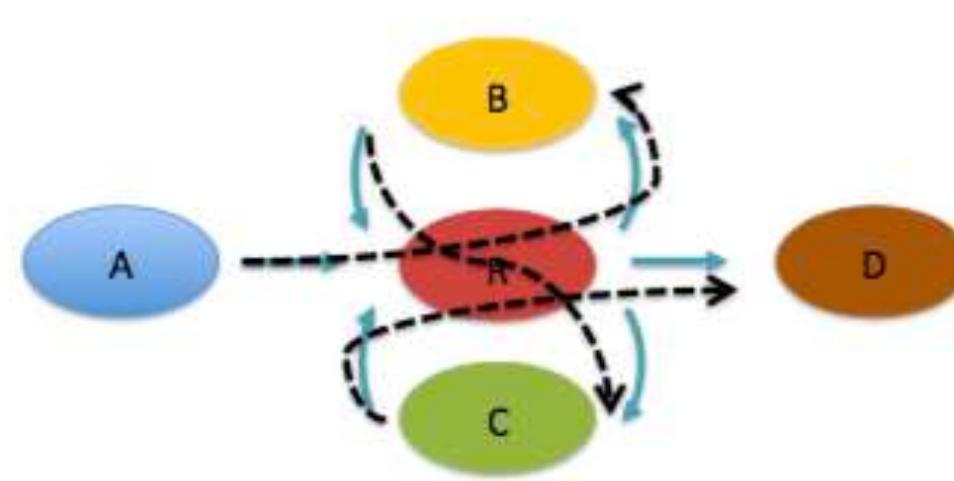


Complicated



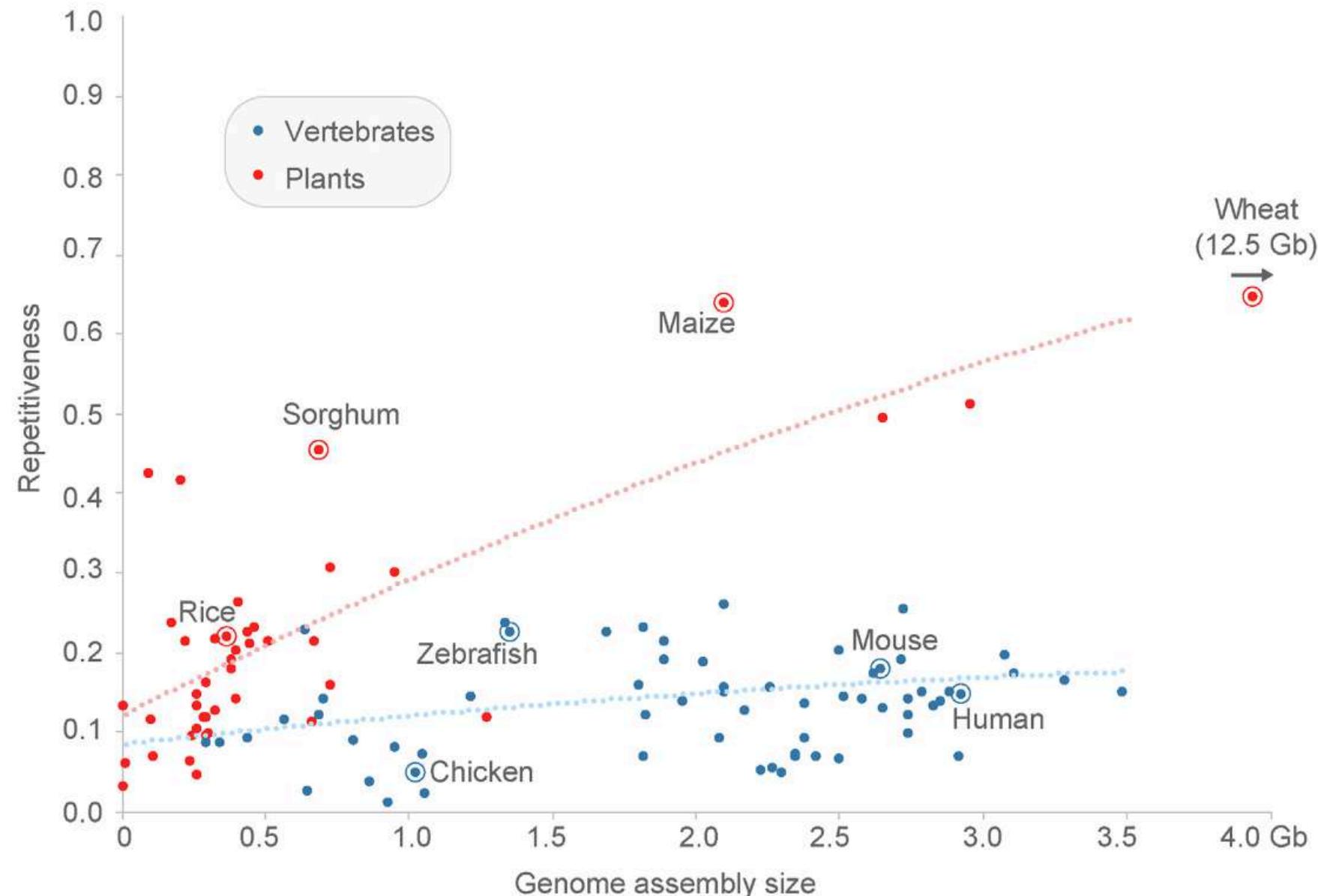
Repeats

You can't 100% resolve repeats unless you have your sequence length > repeat



Credit: Michael Schatz

Repeat content of plant and vertebrate genomes



Largest genome ever recorded: 149Gb



Organism Type	Organism Name	Approximate Genome size, in number of nucleotides ("letters")	Number of protein-coding genes
Bacterium	Nasuia deltocephalinicola, a tiny bacterium that lives inside an insect [3]	112,000 (0.112 million) * currently the smallest known bacterial genome	137
Bacterium	Escherichia coli [2]	4,600,000 (4.6 million)	5,000
Plant	Arabidopsis thaliana	135,000,000 (135 million)	27,416
Mammal	Homo sapiens, Humans	3,000,000,000 (3 billion)	20,000 [5]
Plant	Norway Spruce	19,000,000,000 (19 billion)	28,000
Plant	Paris japonica, a rare Japanese flower [4]	149,000,000,000 (149 billion) * currently the largest known genome	unknown

Actually not too far off...

Article

Giant lungfish genome elucidates the conquest of land by vertebrates

k-mers (Extended Data Fig. 2). We ascertained the high completeness of the 37-Gb assembly by observing that 88.2% of the DNA and 84% of the RNA sequencing (RNA-seq) reads aligned to the genome, which gives an estimated total genome size of 43 Gb (about 30% larger than the axolotl⁸). This matches the *k*-mer value but is smaller than that predicted by flow cytometry (52 Gb⁹) and Feulgen photometry (75 Gb¹⁰).

QC and understand your data before assembly

Conversation:

Jason, we don't know why our assembly is not as good as yours. We have about 90X of Mate pair data..

Email 2 weeks later:

Dear Jason,

I run the Trimmomatic analysis for the raw data of mate-pair libraries (10kL2_1, 10kL7_1, 15kL3_1 and 15kL8_4 as examples) with a custom adapter file containing mate-pair adapter sequences (junction and external adaptors, you may find them in the attached technote pdf file) and found **that over 80% reads of the library were dropped out.**

Always be careful of contamination

Evidence for extensive horizontal gene transfer from the draft genome of a tardigrade

Thomas C. Boothby^{a,1}, Jennifer R. Tenlen^{a,2}, Frank W. Smith^a, Jeremy R. Wang^{a,b}, Kiera A. Patanella^a, Erin Osborne Nishimura^a, Sophia C. Tintori^a, Qing Li^c, Corbin D. Jones^a, Mark Yandell^c, David N. Messina^d, Jarret Glasscock^d, and Bob Goldstein^a

17.5 % HGT

^aDepartment of Biology, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599; ^bDepartment of Genetics, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599; ^cEccles Institute of Human Genetics, University of Utah, Salt Lake City, UT 84112; and ^dCofactor Genomics, St. Louis, MO 63110

Edited by W. Ford Doolittle, Dalhousie University, Halifax, Canada, and approved September 28, 2015 (received for review May 28, 2015)

No evidence for extensive horizontal gene transfer in the genome of the tardigrade *Hypsibius dujardini*

Georgios Koutsovoulos^a, Sujai Kumar^a, Dominik R. Laetsch^{a,b}, Lewis Stevens^a, Jennifer Daub^a, Claire Conlon^a, Habib Maroon^a, Fran Thomas^a, Aziz A. Aboobaker^c, and Mark Blaxter^{a,1}

0.4 % HGT

^aInstitute of Evolutionary Biology, University of Edinburgh, Edinburgh EH9 3FL, United Kingdom; ^bThe James Hutton Institute, Dundee DD2 5DA, United Kingdom; and ^cDepartment of Zoology, University of Oxford, Oxford OX1 3PS, United Kingdom

Edited by W. Ford Doolittle, Dalhousie University, Halifax, Canada, and approved March 1, 2016 (received for review January 8, 2016)

Always be careful of contamination

ARTICLE

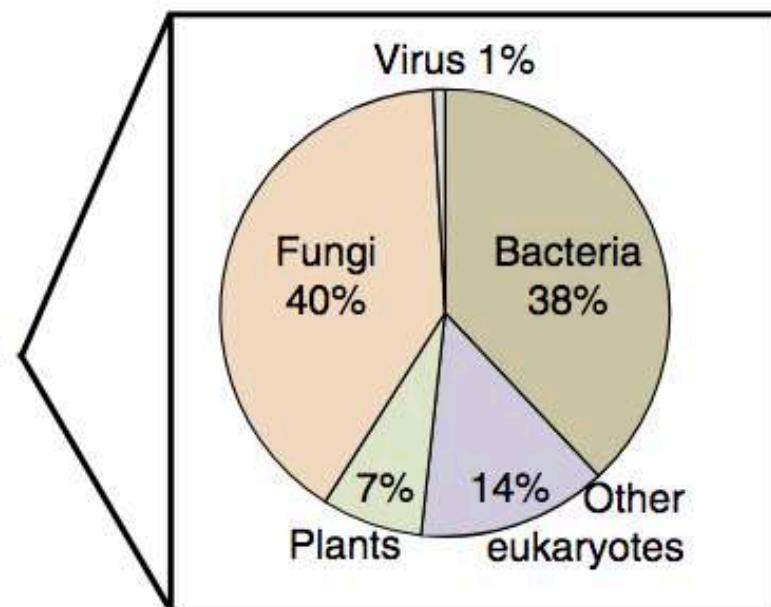
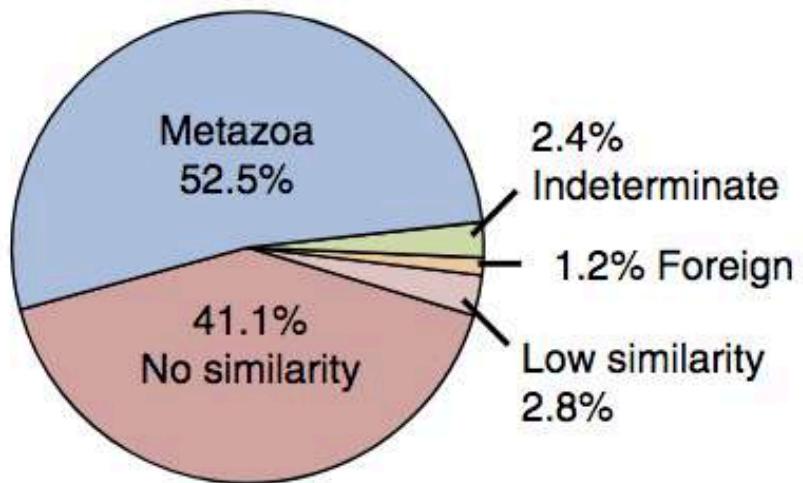
Received 21 Jun 2015 | Accepted 3 Aug 2016 | Published 20 Sep 2016

DOI: 10.1038/ncomms12808

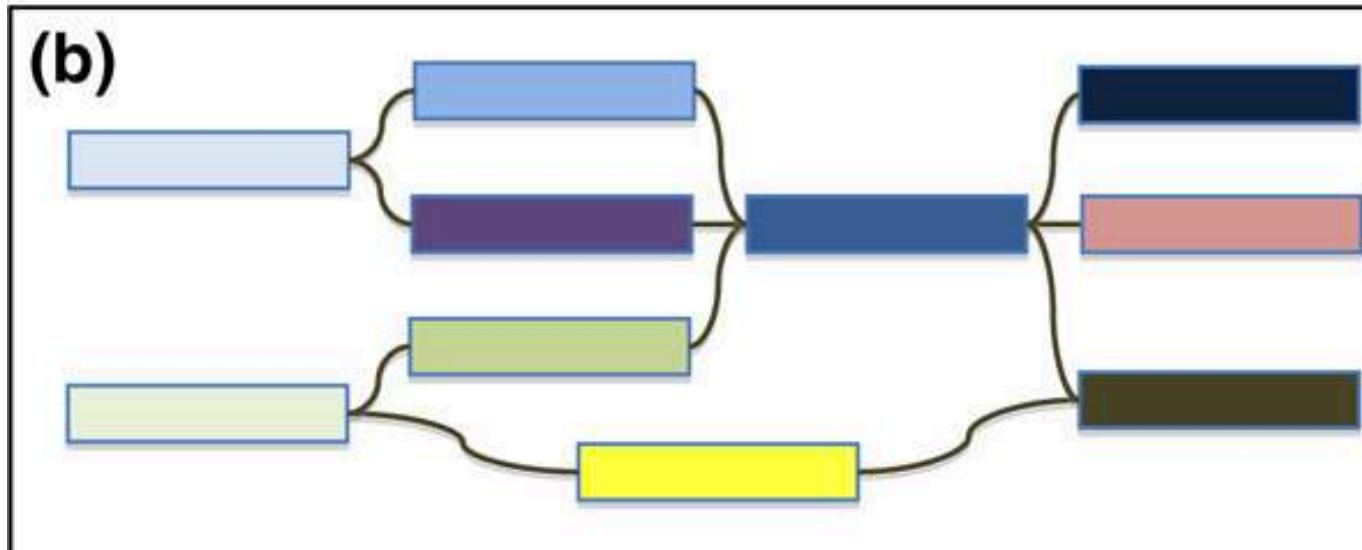
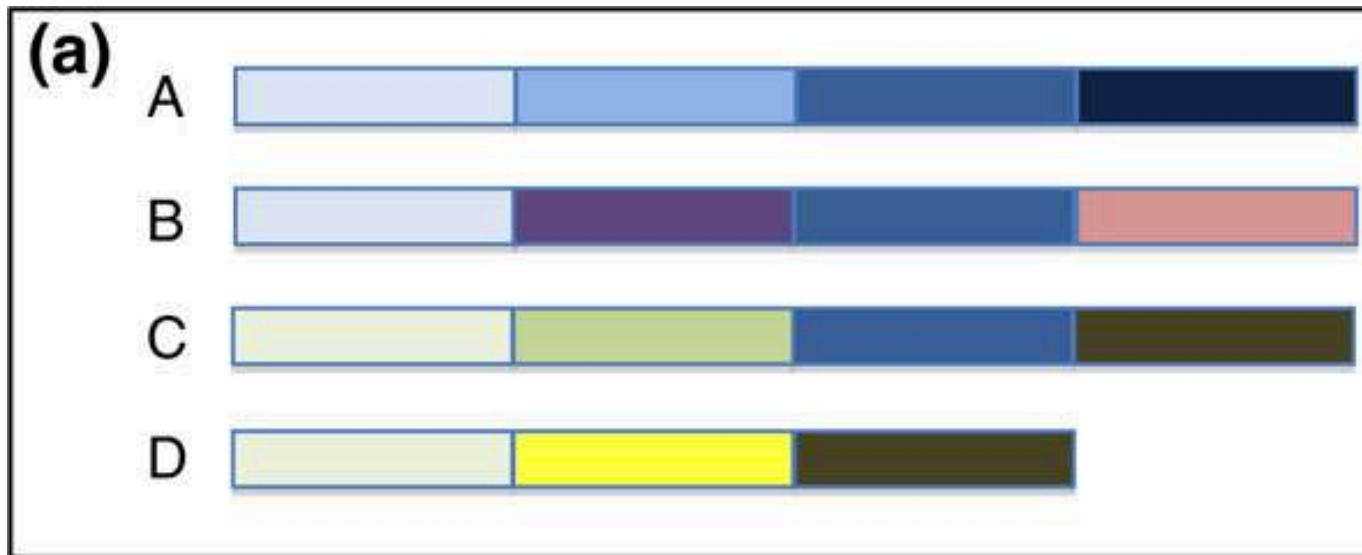
OPEN

Extremotolerant tardigrade genome and improved radiotolerance of human cultured cells by tardigrade-unique protein

c



Ploidy, heterozygosity and the assembly graph



Assembly process

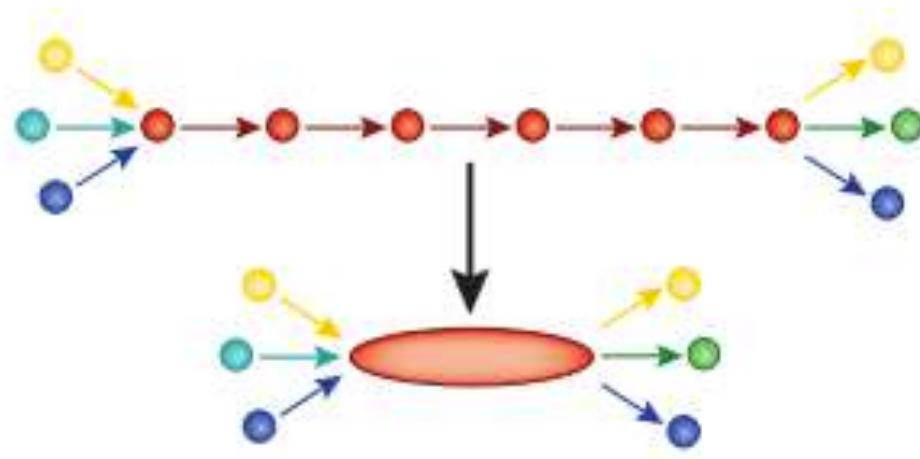
1. Fragment DNA and sequence



2. Find overlaps between reads

...AGCCTAGACCTACA**GGATGCGCGACACGT**
GGATGCGCGACACGTCGCATATCCGGT...

3. Assemble overlaps into contigs



4. Assemble contigs into scaffolds



Which program to choose?

EULER-SR	WhatsHap	GARM	SOAPdenovo		SSPACE	HaploMerger		mip
A5	Telescooper	Contrail	fermi	GABenchToB	QSRA	Opera	RAMPART	
SSAKE	SWAP-Assembler	Newbler	AutoAssemblyD	HapCompass	Dazzler	PCAP	Platanus	Arapan
TIGR	Mapsembler 2	ALLPATHS-LG	VICUNA	Edena	CLC	PERGA	Forge	SHEAR
gapfiller	CloudBrush	REAPR	Ray	Tedna	TIGRA	Amos	KmerGenie	
Arachne	MIRA	dipSPAdes	MetAMOS	Geneious	SeqMan NGen	Nesoni	ATAC	
SCARPA	Celera	VCAKE	GAM	PASHA	bambus2	MetaVelvet-SL	Quast	
GRIT	IDBA	Trinity	MHAP	Hapsembler	GAML	Sequencher	BESST	GGAKE
Phrap	MaSuRCA	HiPGA	PADENA	SeqPrep	Phusion	SGA	PE-Assembler	
CGAL	Curtain	SWiPS	KGBAssembler	Metassembler				
Pipeline	Pilot	SHRAP	Taipan	SILP3	IDBA-MTP	HGAP	PRICE	Pilon
OMACC	Anchor	Omega	SUTTA	ABySS	HyDA-Vista	SR-ASM	Velvet	Enly
SOPRA	iMetAMOS	DNAexus		Ragout	SPAdes	Atlas		FRCBam
DNA Dragon	CABOG	SAGE		Cerulean	Monument	SAT-Assembler		
FALCON	SuccinctAssembly	SHORTY		SHARCGS	GAGM	ngsShoRT	ABBA	
	GigAssembler			PBJelly	DecGPU	Khmer	GenoMiner	ELOPER

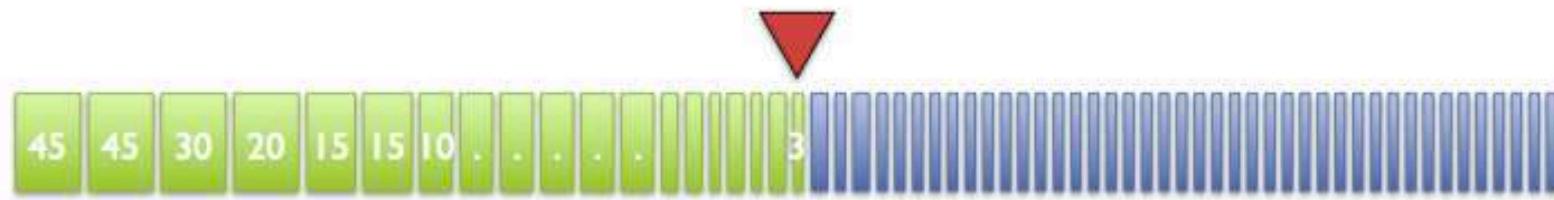
Contiguity (good) is a genome? N50

Definition: 50% of genome in contigs/scaffolds of length **N50 bp** or greater



N50 size = 30 kbp

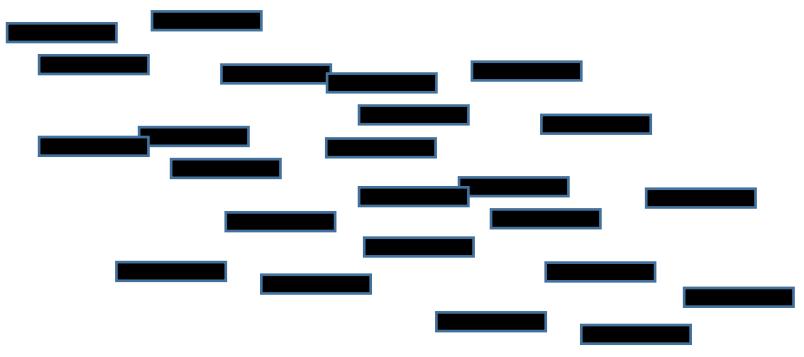
sorted



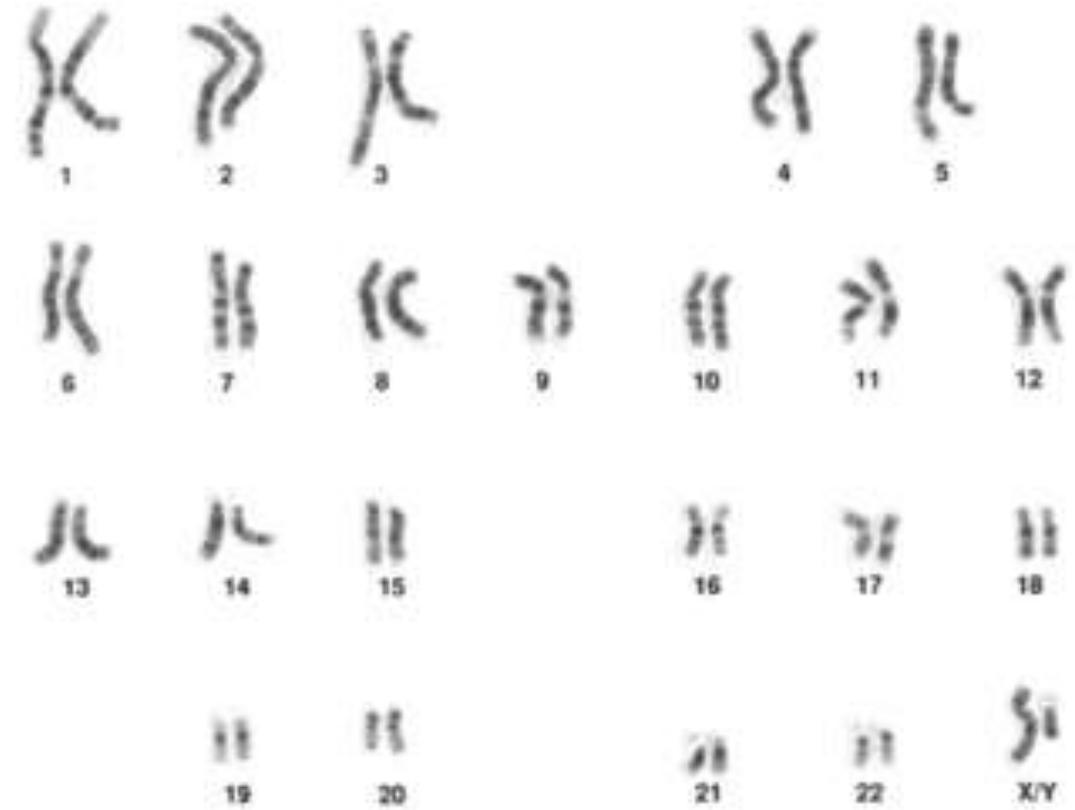
N50 size = 3 kbp

Credit: Michael Schatz

Most assemblies are fragmented



!=

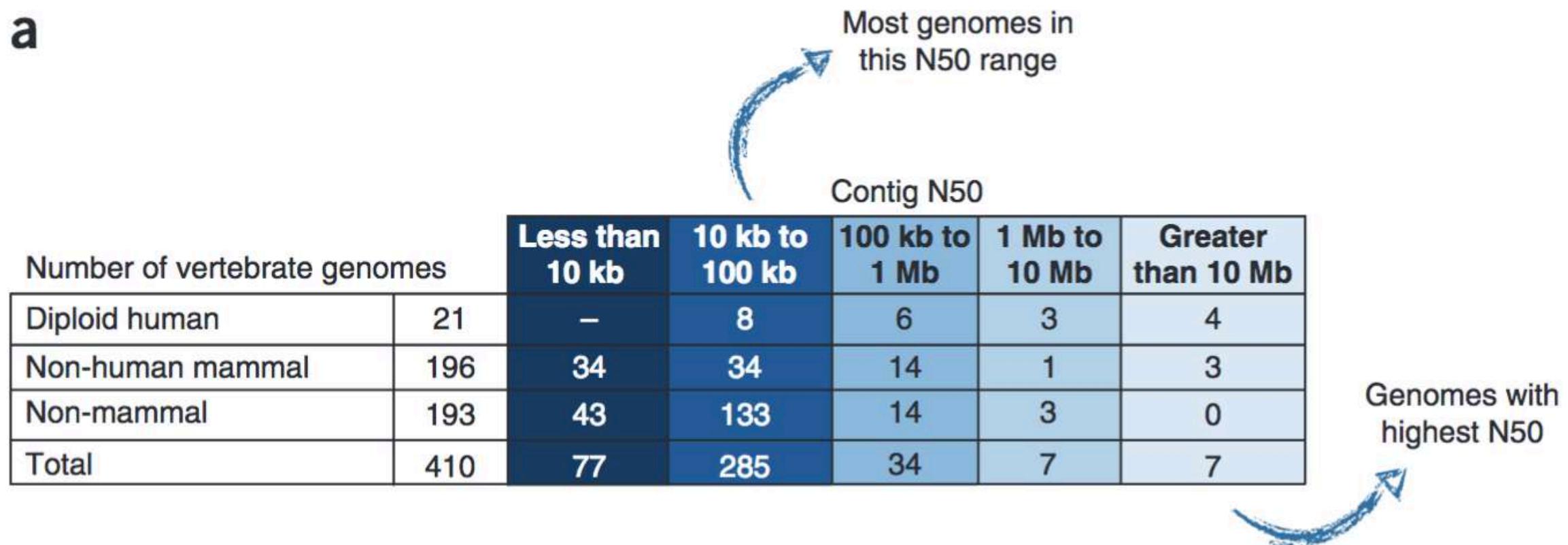


Contigs

chromosomes

Statistics for current GenBank assemblies.

a



Why do we need a good assembly?

It is easier to analyse

10000 pieces vs. 23 pieces (chromosomes)

Allows more accurate representation of genes locations on genome

Is gene A close to gene B? On the same chromosome?

Transposon dynamics

Missing in most assemblies (located in NNNNNNNNNN gaps)

Responsibility to contribute to your community

Do you want others to work on the same genome / species as well?

Bottom line:

It's really no point to do one if you can't produce an accurate and useful assembly

Assembly qualities

	Whole Genome Representation	Sequence Status	Genes	Usability
1	Incomplete for non-repetitive regions	Small scaffolds and contigs	Incomplete genes	Markers development
2	Complete for non-repetitive regions	Medium scaffolds and contigs	Complete but 1-2 genes/contig	Gene mining
3	Complete for non-repetitive regions	Large scaffolds and contigs	Several dozens of genes/contig	Microsynteny
4	Complete for almost the whole genome	Pseudomolecules	Hundreds of genes/contig	Any (Synteny, Candidate gene by QTLs)
5	Complete genome	Pseudomolecules	Thousands of genes/contig	

Credit: Aureliano Bombarely

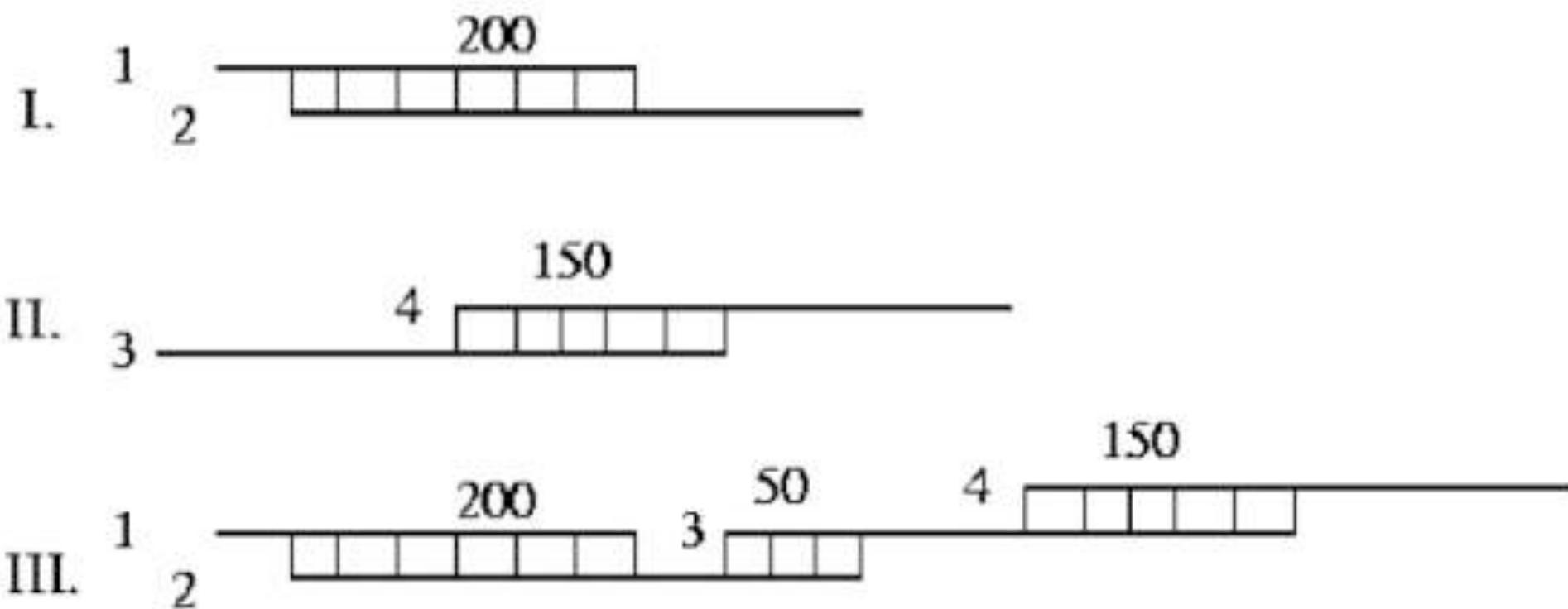
Assembly algorithms

Approaches

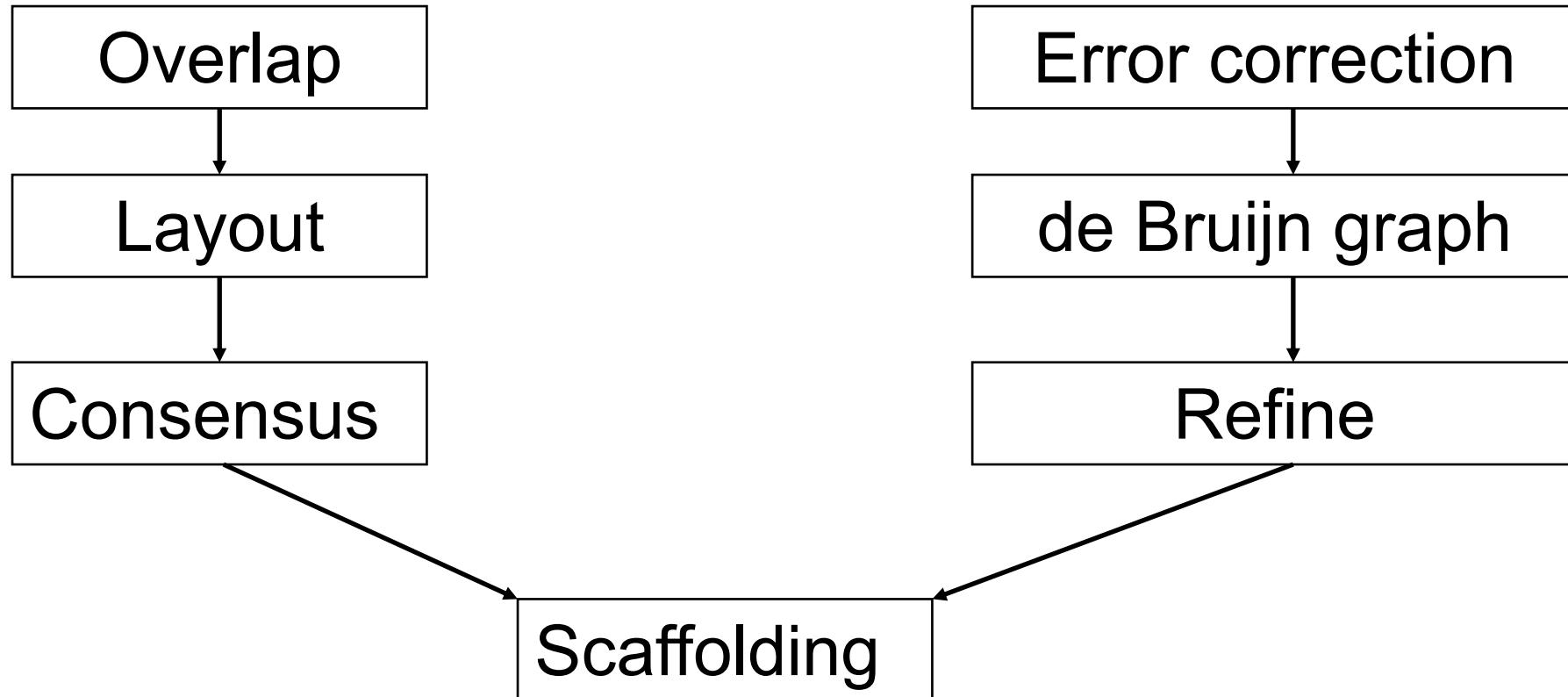
- Greedy extension
 - only mentioned for historical reasons
- Overlap – Layout – Consensus (**OLC**) assembly: 'traditional' and well established method, but challenging to implement at each stage
 - Most "old" and "newest" assemblies were produced using this approach
- de Bruijn graph (**DBG**) assembly

Greedy extension

- Oldest and not really useful in most cases

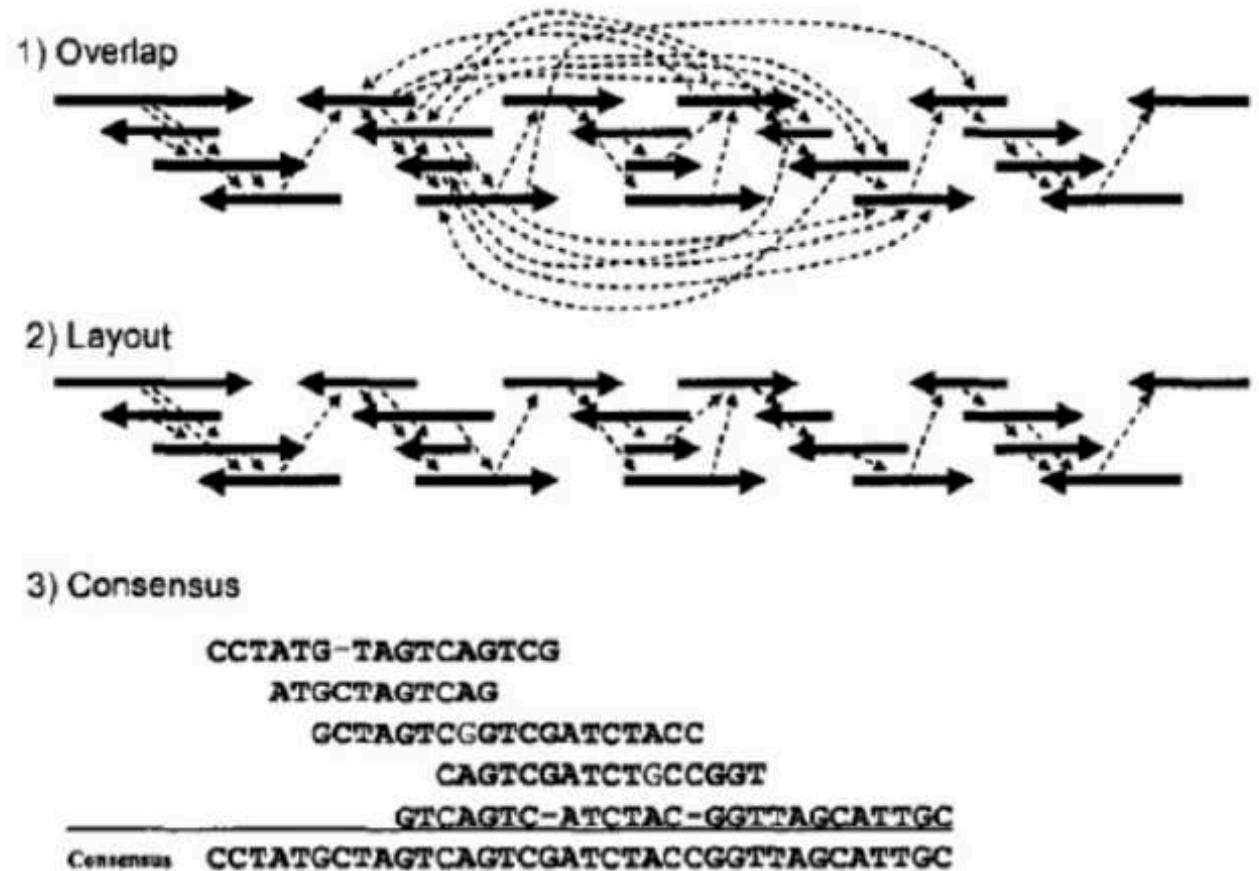


OLC and DBG assemblers



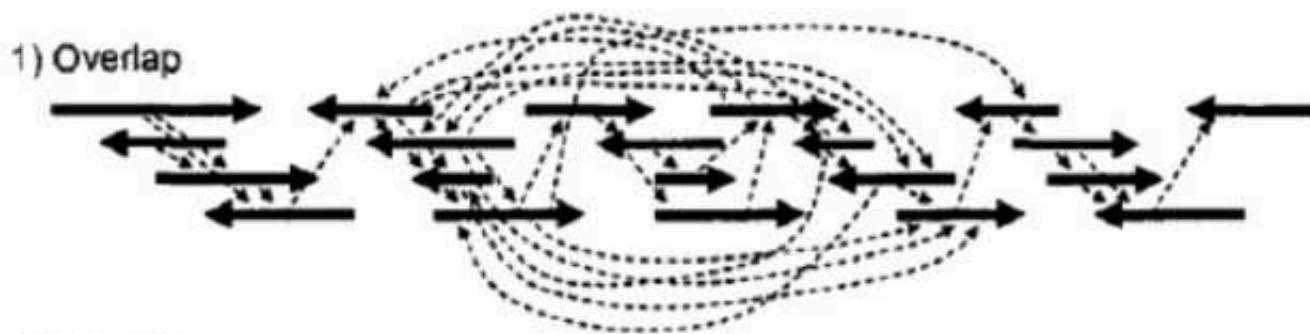
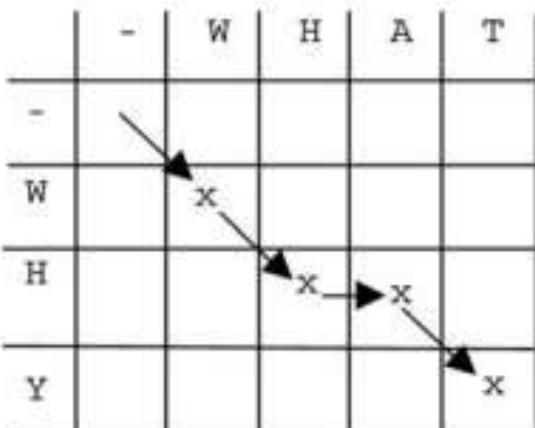
OLC approach

- Pairwise alignment of all reads to find **overlaps**
- **Layout** the reads to decide which read align to which
- Get **consensus** by joining join the read sequences, merging overlaps
- All three are challenging



Overlap

- All vs. all pairwise alignment
 - Smith-Waterman? Blast? Kmer based? Suffix tree? Dynamic programming?
- Computationally very intensive but can be parallelised
 - Need lots of CPUs!
 - Batch1 align Batch 1 in 1st CPU
 - Batch1 align Batch 2 in 2nd CPU

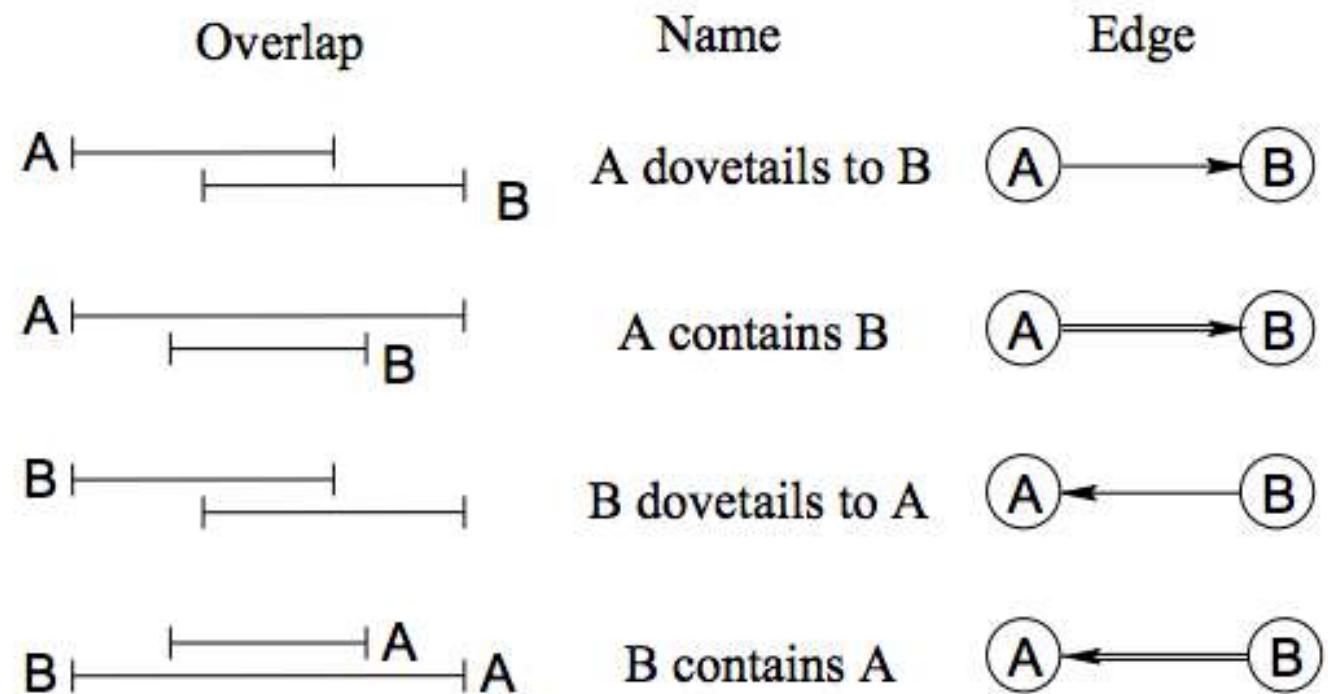


Computational Example 8.1: Pseudocode for overlap alignment

```
Input sequences A, B  
Set  $O_{i,0} = O_{0,j} = 0$  for all  $i, j$   
for  $i = 1$  to  $n$   
    for  $j = 1$  to  $m$   
         $O_{i,j} = \max\{O_{i-1,j} - \delta, O_{i-1,j-1} + s(a_i, b_j), O_{i,j-1} - \delta\}$   
    end  
end  
Best overlap =  $\max\{O_{i,m}, O_{n,j}; 1 \leq i \leq n, 1 \leq j \leq m\}$ 
```

Build overlap graph

- It's common practice to represent them in **graphs**
- The actual overlaps are the edges
- Now we create the genome assembly graph



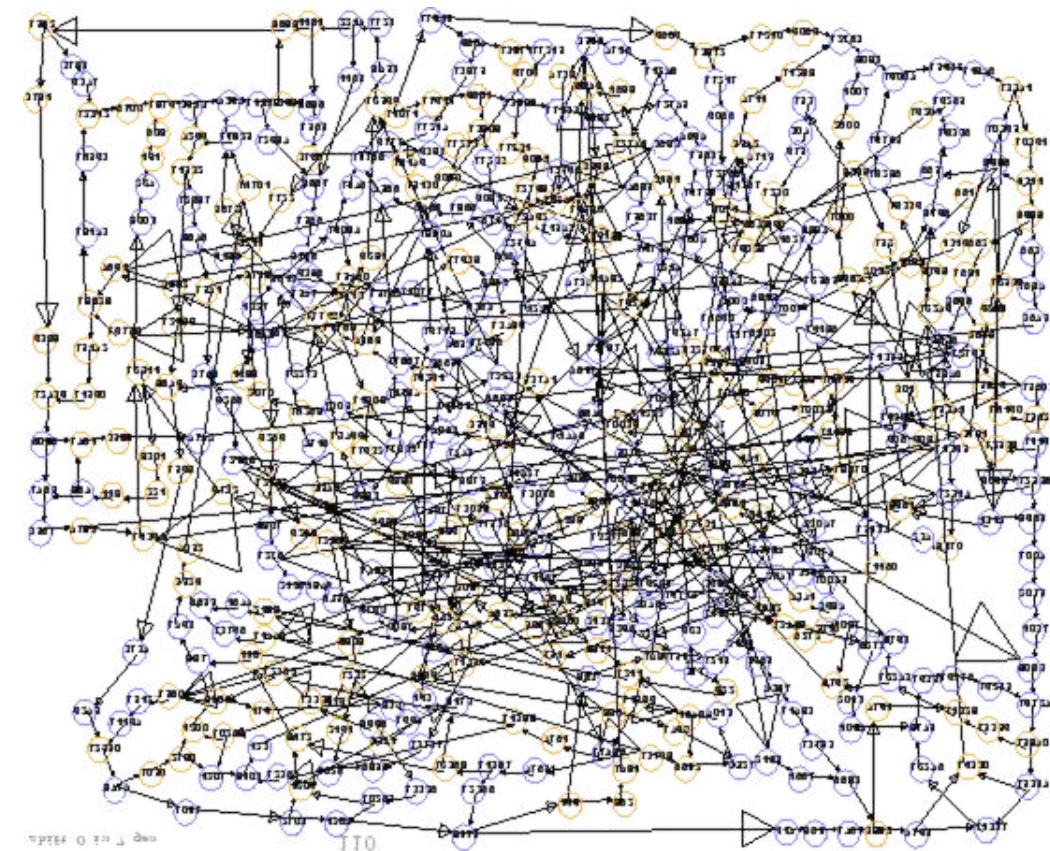
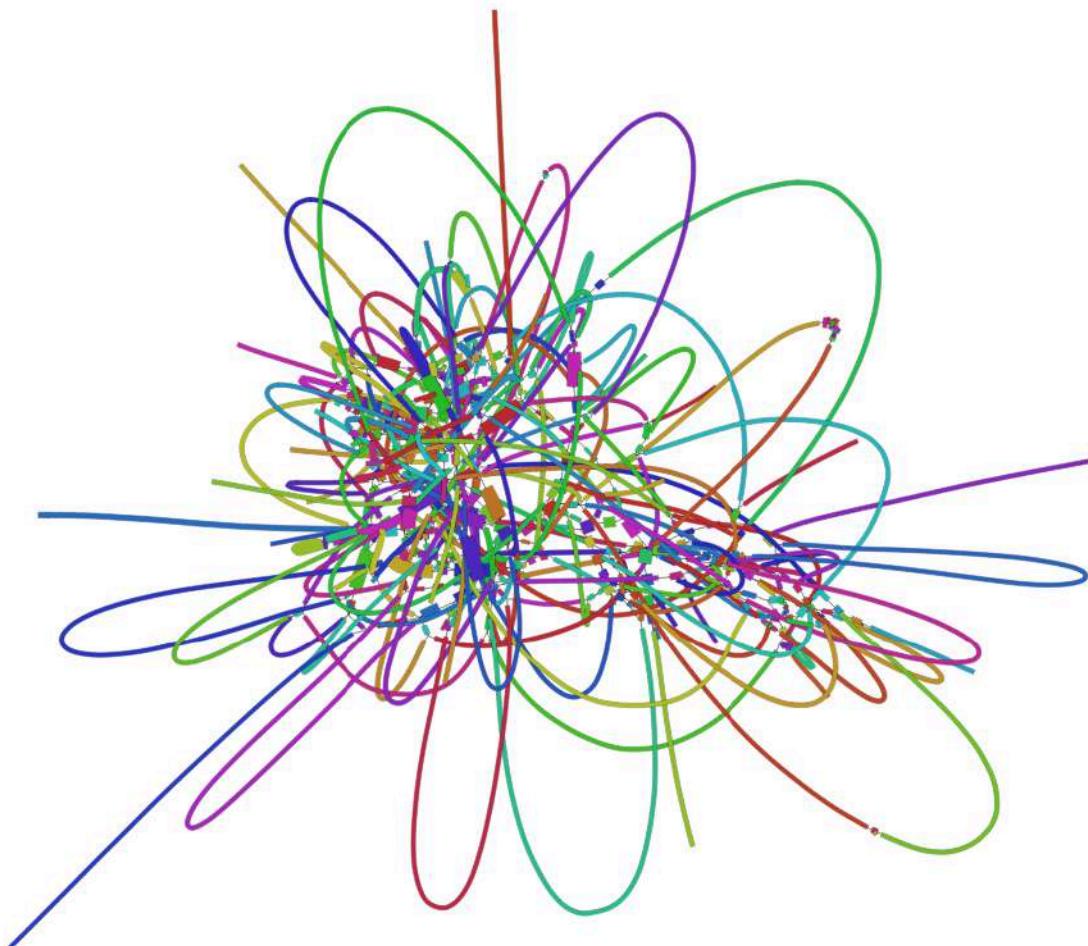
my work is now nearly finished

work is now nearly finished; but as it will take

my work is now nearly finished

work is now nearly finished; but as it will take

Some assembly graph can be complicated...



<http://rrwick.github.io/Bandage/images/screenshots/screenshot02.png>

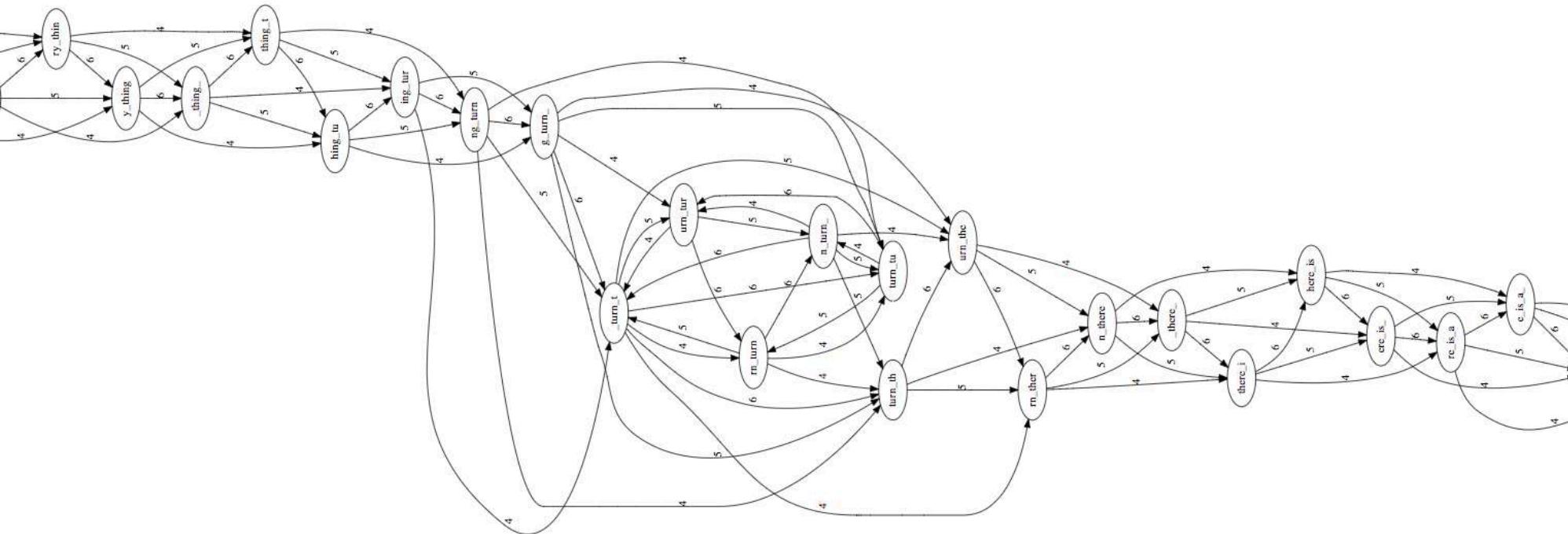
Layout

Overlap graph is big and messy. Contigs don't "pop out" at us.

Below: part of the overlap graph for

[to_every_thing_turn_turn_turn_there_is_a_season](#)

$l = 4, k = 7$



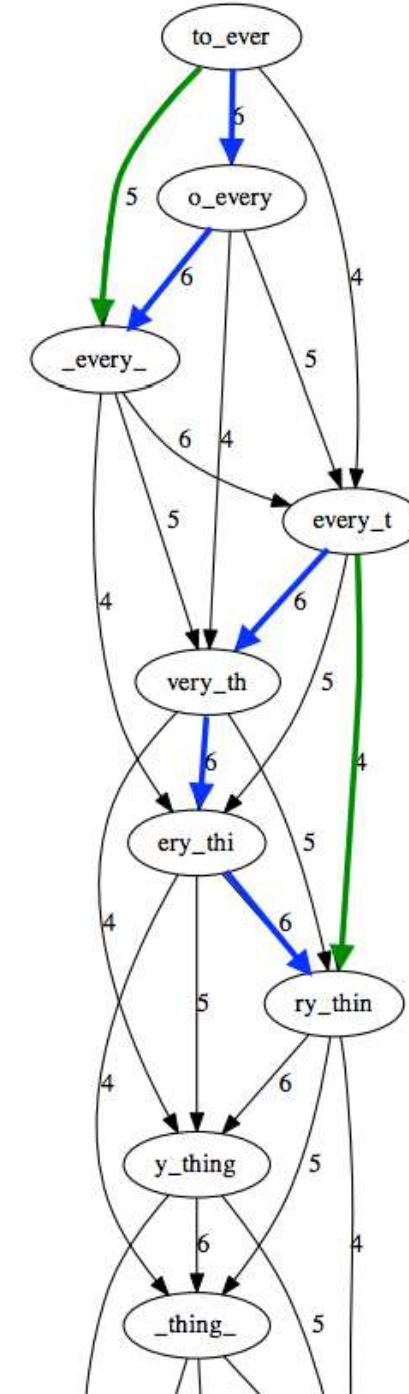
Layout

Order the reads into a consistent manner

Anything redundant about this part of overlap graph?

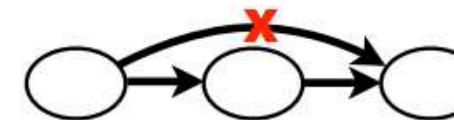
Some edges can be inferred from other edges

E.g., green edge can be inferred from blue

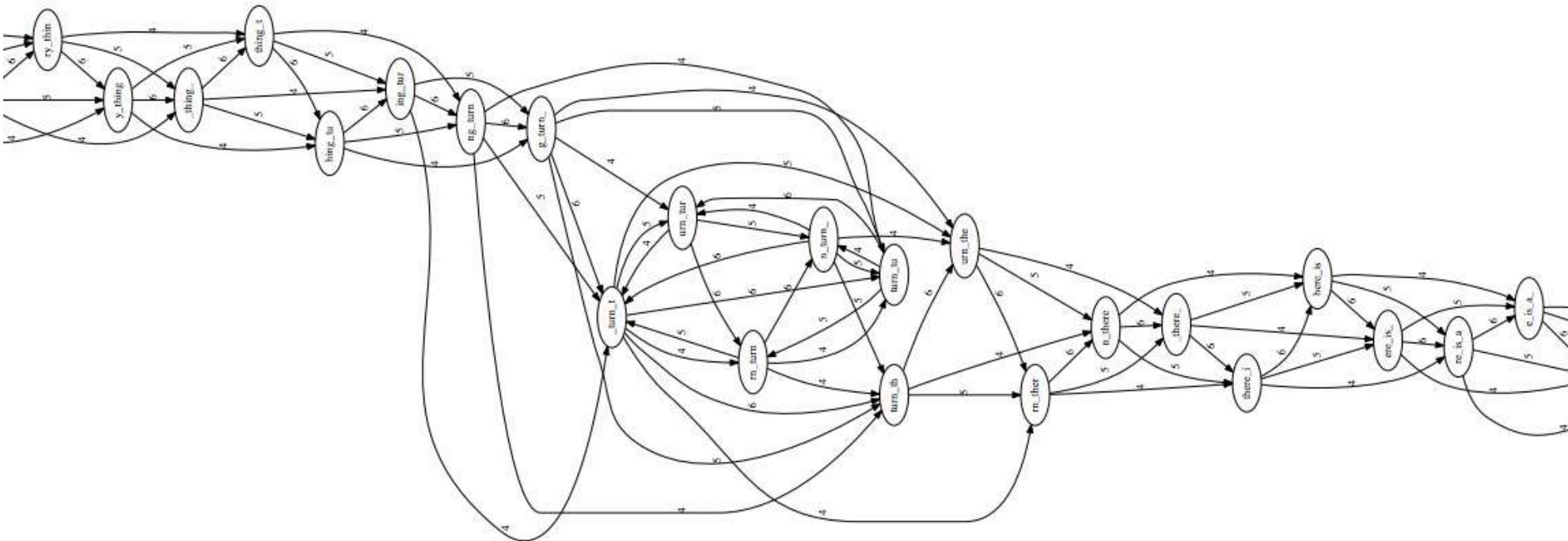


Layout

Remove transitively-inferrible edges, starting with edges that skip one node:

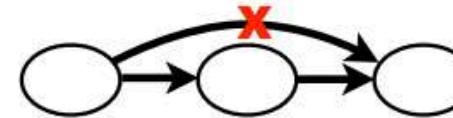


Before:

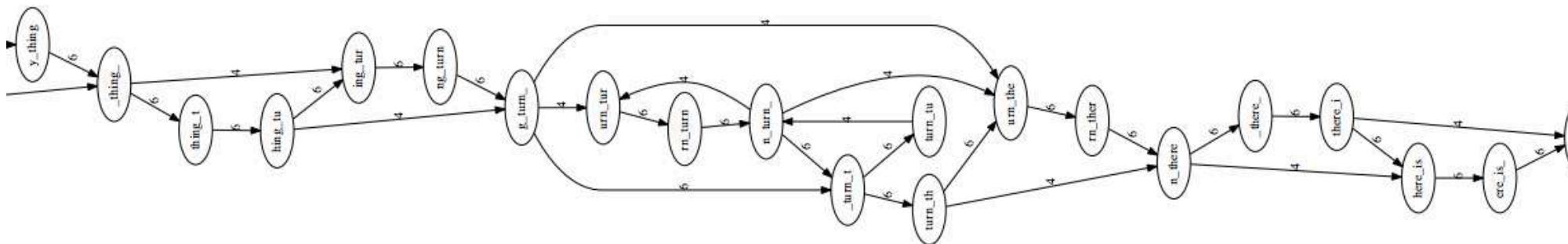


Layout

Remove transitively-inferrible edges, starting with edges that skip one node:



After:

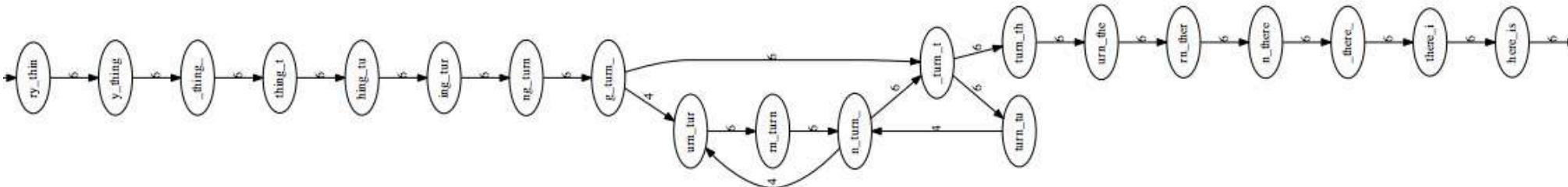


Layout

Remove transitively-inferrible edges, starting with edges that skip one or two nodes:

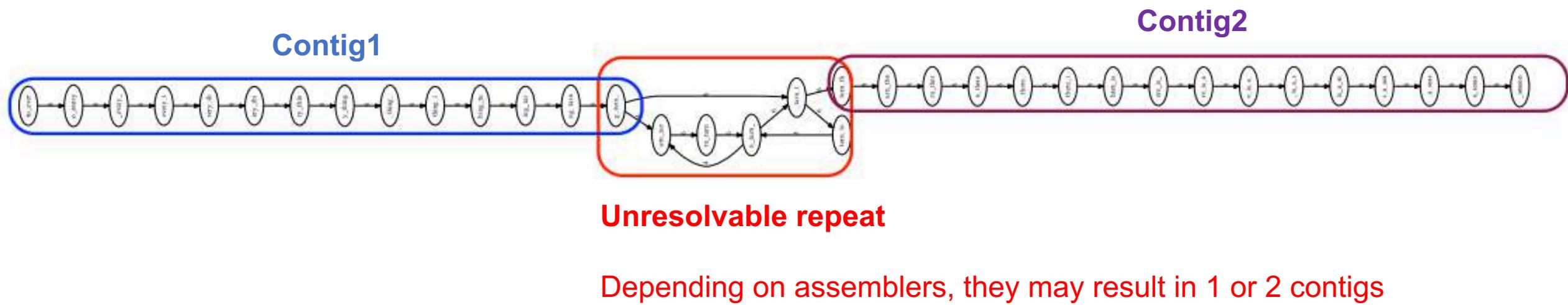


After:



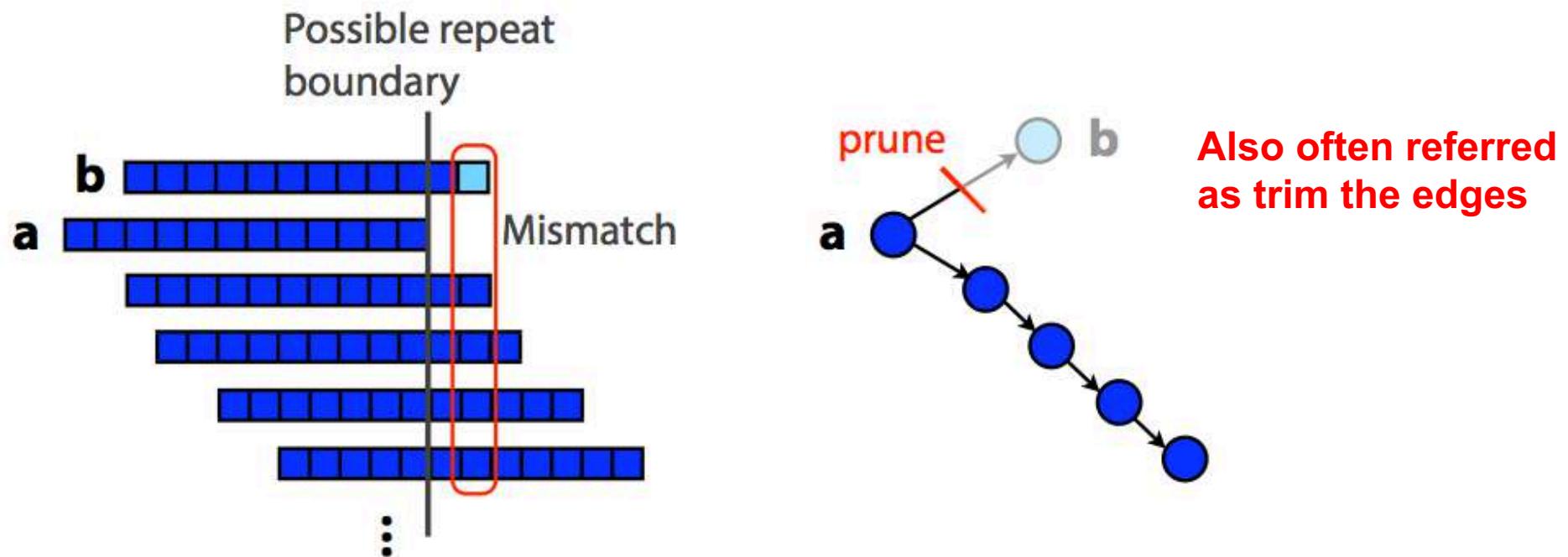
Even simpler

Layout



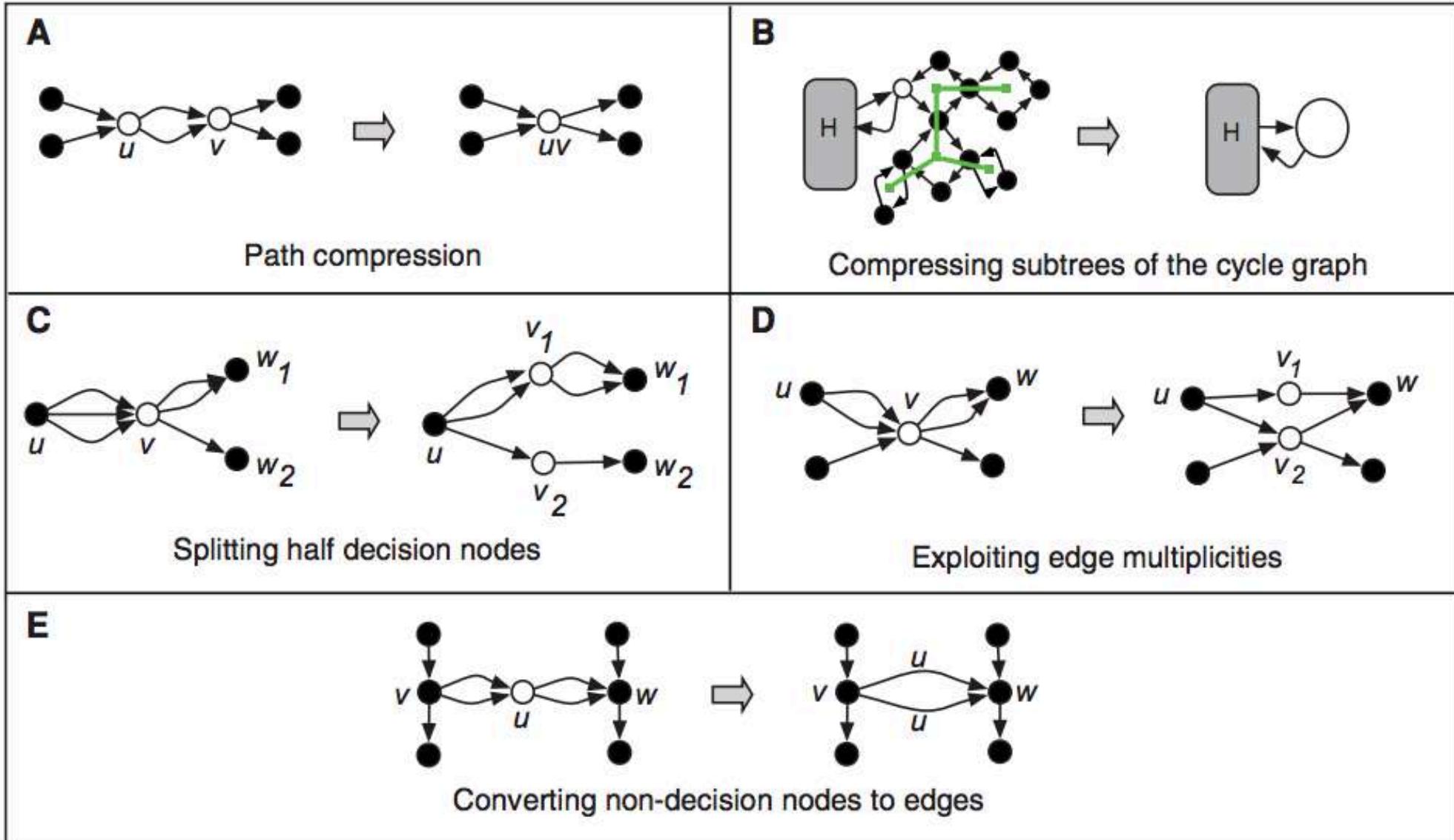
Layout – can we do more?

In practice, layout step also has to deal with spurious subgraphs, e.g. because of sequencing error



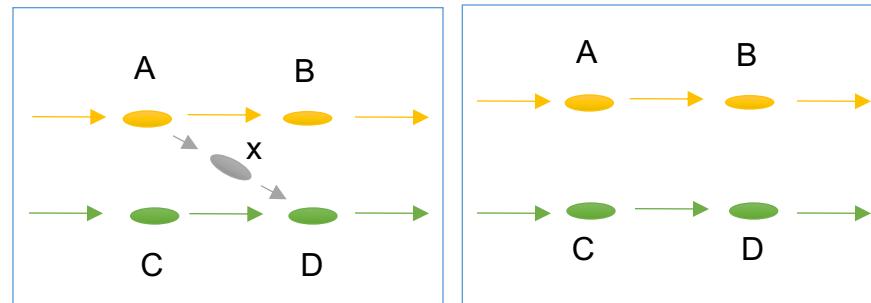
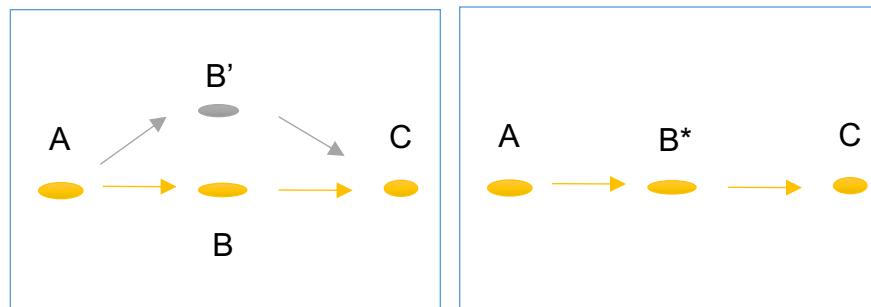
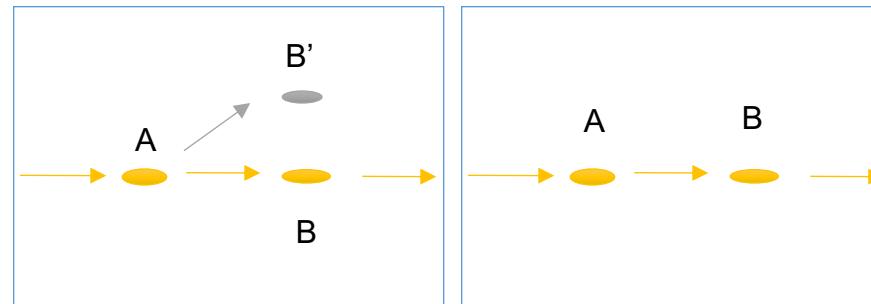
Mismatch could be due to sequencing error or repeat. Since the path through **b** ends abruptly we might conclude it's an error and prune **b**.

Usefulness of graph transformation



Error correction in graph

- Errors at end of read
 - Trim off ‘dead-end’ tips
- Errors in middle of read
 - Pop Bubbles
- Chimeric Edges
 - Clip short, low coverage nodes



Consensus

TAGATTACACAGATTACTGA TTGATGGCGTAA CTA
TAGATTACACAGATTACTGACTT GATGGCGTAA ACTA
TAG TTACACAGATTATTGACTT CATGGCGTAA CTA
TAGATTACACAGATTACTGACTT GATGGCGTAA CTA
TAGATTACACAGATTACTGACTT GATGGCGTAA CTA

↓ ↓ ↓ ↓
TAGATTACACAGATTACTGACTT GATGGCGTAA CTA



Take reads that make up a contig and line them up

Take *consensus*, i.e. majority vote

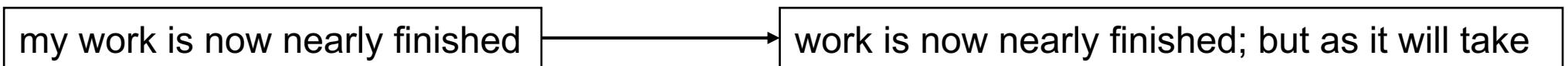
At each position, ask: what nucleotide (and/or gap) is here?

Complications: (a) sequencing error, (b) ploidy

Say the true genotype is AG, but we have a high sequencing error rate and only about 6 reads covering the position.

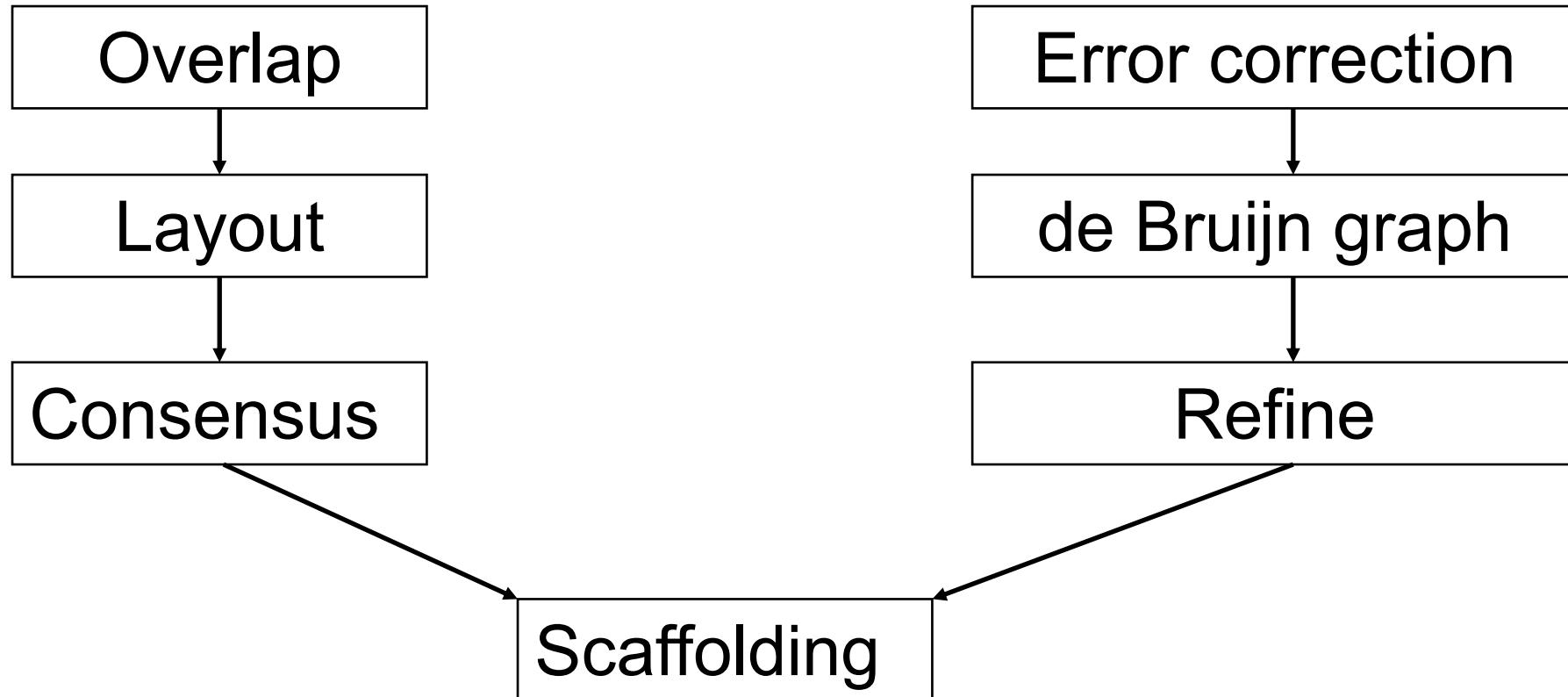
OLC Assemblers

- Mostly used in the Sanger sequencing era
 - Celera, Phusion, PCAP, Arachne
- Disadvantages of OLC
 - Computing overlaps is slow
 - 5 billion reads -> takes **400 years** to compute overlaps if 1 million overlap per second
 - Overlap graph is big and complicated
 - One node per read
 - Number of edges grows superlinearly with number of reads



- When 2nd generation dataset first arrived
 - Millions and millions of reads
 - Short read length – difficult to build sufficient overlap

OLC and DBG assemblers



k-mer

"k-mer" is a substring of length k

$S:$ **GGCGATTCA**T TCG

A 4-mer of S : **ATTC**

All 3-mers of S :

GGC
GCG
CGA
GAT
ATT
TTC
TCA
CAT
ATC
TCG

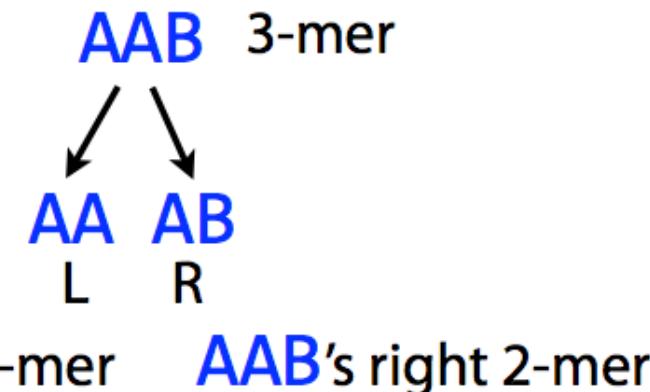
mer: from Greek meaning "part"

De Bruijn graph

We start with a collection of reads of **3bp** from the reference genome **AAABBBA**

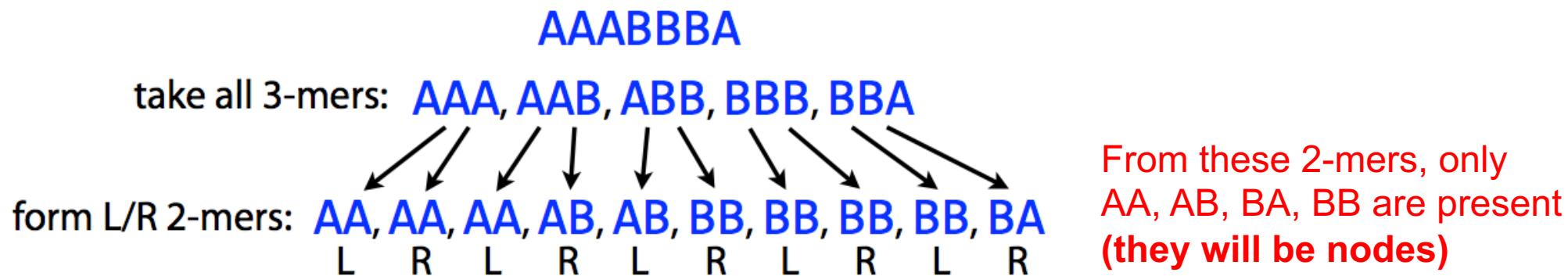
AAA, AAB, ABB, BBB, BBA

AAB is a k -mer ($k = 3$). **AA** is its *left* $k-1$ -mer, and **AB** is its right $k-1$ -mer.



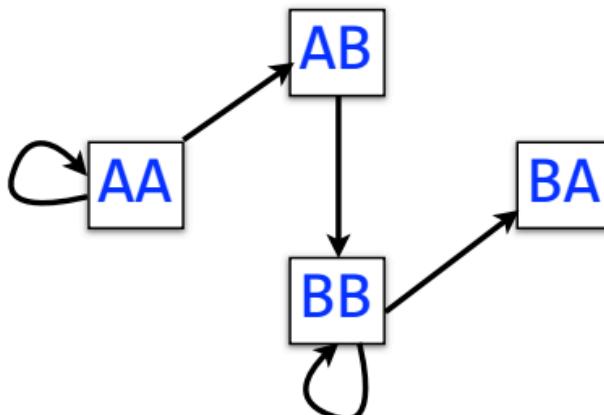
De Bruijn graph

Take each length-3 input string and split it into two overlapping substrings of length 2. Call these the *left* and *right* 2-mers.



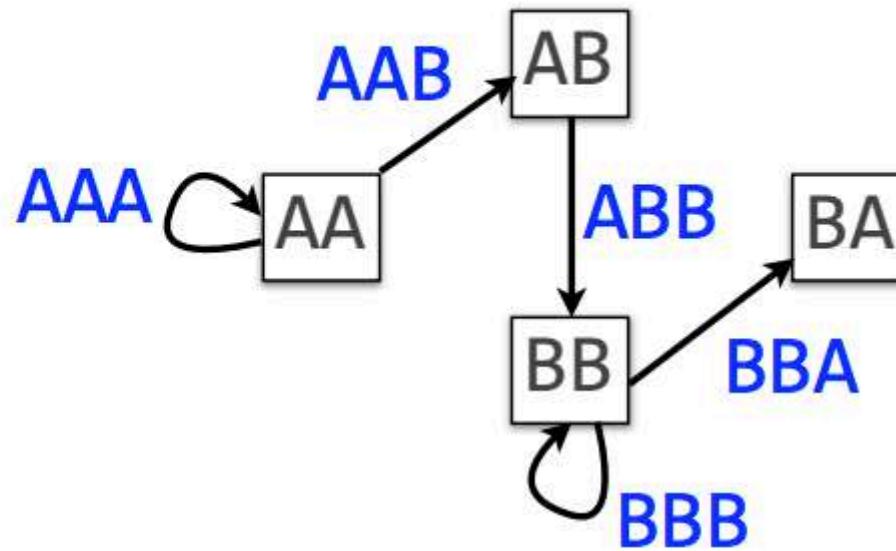
Let 2-mers be nodes in a new graph. Draw a directed edge from each left 2-mer to corresponding right 2-mer:

So AAB will be AA → AB



Each *edge* in this graph corresponds to a length-3 input string

De Bruijn graph



How do we get contigs from the graph?

Intuitively we walk and visited all edges and node of the graph, but how?

An edge corresponds to an overlap (of length $k-2$) between two $k-1$ mers.
More precisely, it corresponds to a **k -mer** from the input.

De Bruijn graph is a directed multigraph

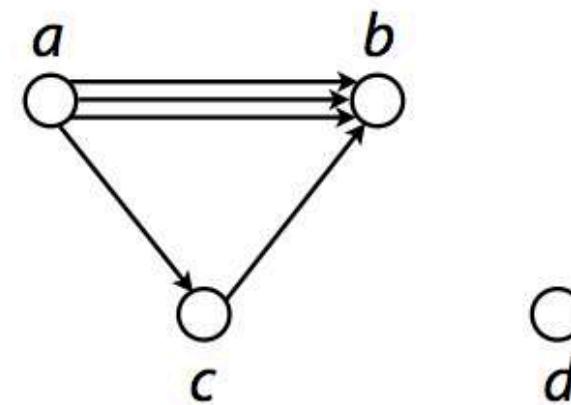
Directed **multigraph** $G(V, E)$ consists of set of vertices, V and **multiset** of *directed edges*, E

Otherwise, like a directed graph

Node's *indegree* = # incoming edges

Node's *outdegree* = # outgoing edges

De Bruijn graph is a directed multigraph



$$V = \{ a, b, c, d \}$$

$$E = \{ (a, b), (a, b), (a, b), (a, c), (c, b) \}$$

Repeated

Eulerian walk definitions and statement

1.A **directed graph** is a *graph* in which each edge has a direction, usually represented as an arrow from a node v to a node w .

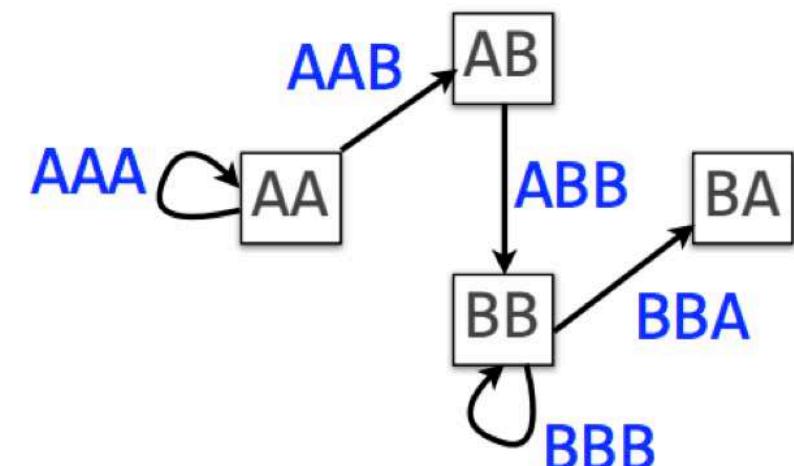
Yes

2.Graph is connected if each node can be reached by some other node.

Yes

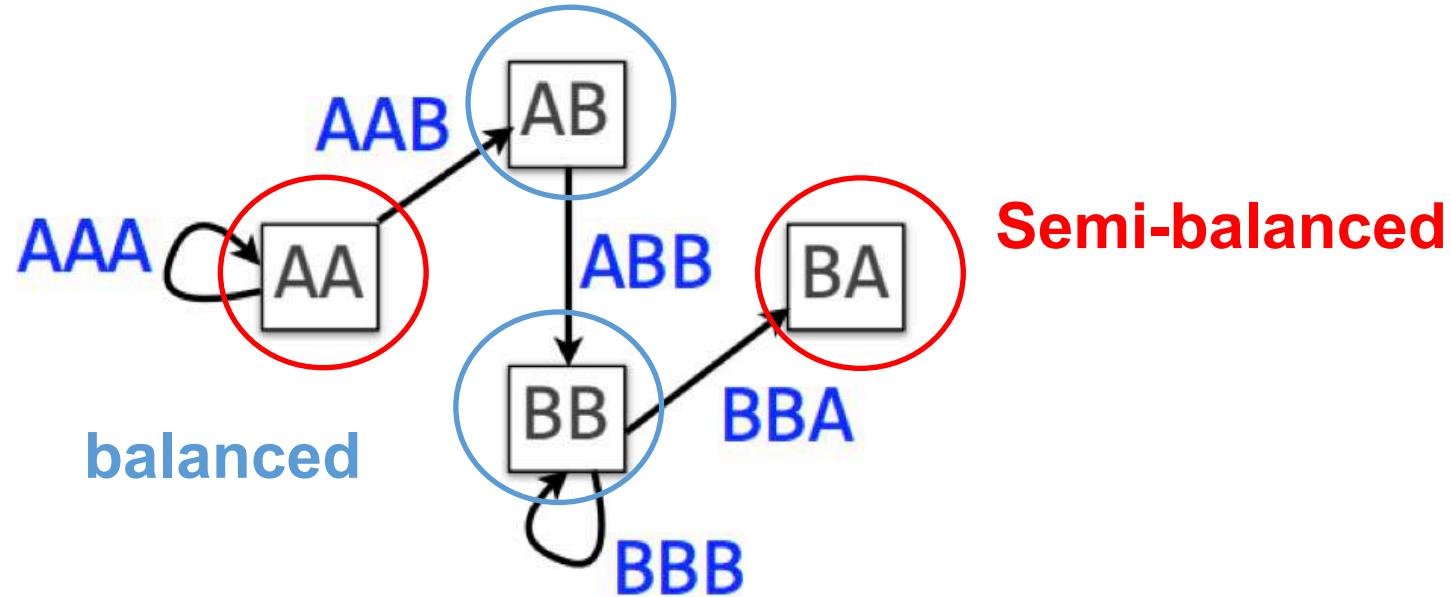
3.Node is **balanced** if indegree equals outdegree. Node is **semi-balanced** if indegree differs from outdegree by 1

4.A directed, connected graph is Eulerian if and only if it has **at most 2 semi-balanced nodes** and all other nodes are balanced



Eulerian walk definitions and statement

A **directed, connected graph** is Eulerian if and only if **it has at most 2 semi-balanced nodes and all other nodes are balanced**



Is it Eulerian? Yes

Argument 1: $\text{AA} \rightarrow \text{AA} \rightarrow \text{AB} \rightarrow \text{BB} \rightarrow \text{BB} \rightarrow \text{BA}$

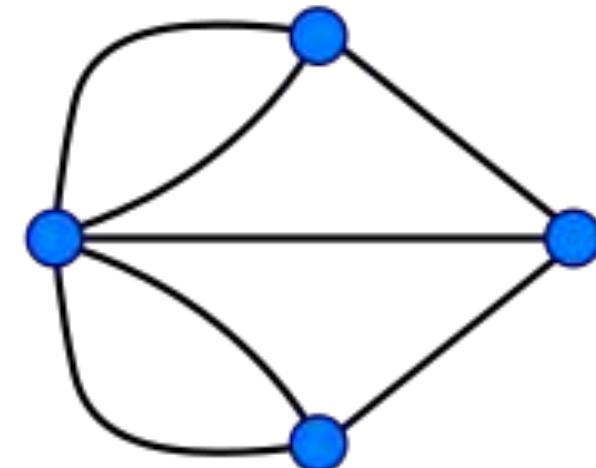
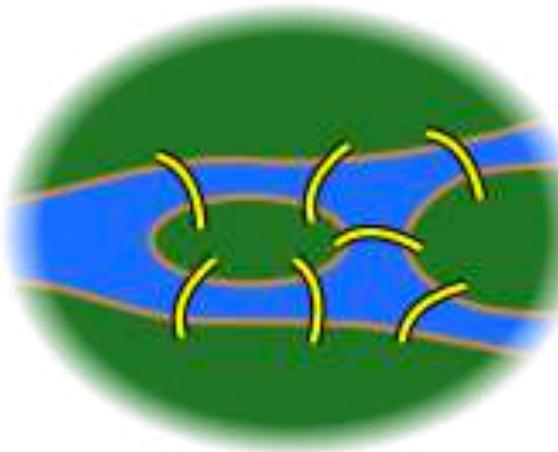
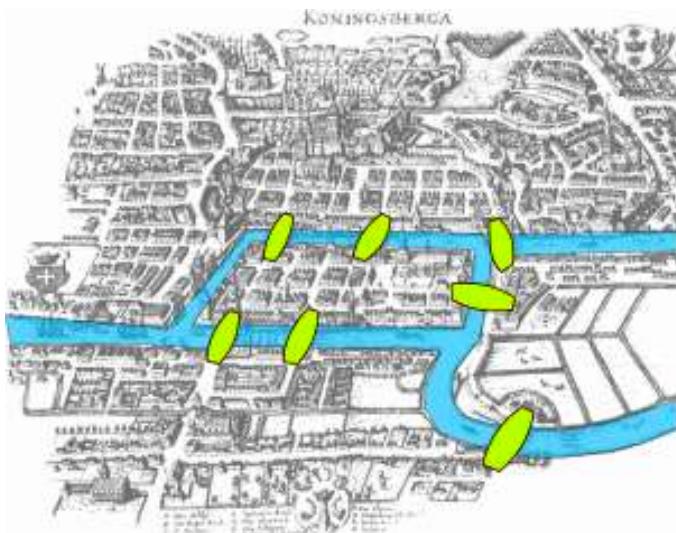
Argument 2: AA and BA are semi-balanced, AB and BB are balanced

Then we can search for Eulerian path from the graph:
Eulerian walk visits each edge exactly once ****

Eulerian walk

In [graph theory](#), an **Eulerian trail** (or **Eulerian path**) is a [trail](#) in a graph which visits every [edge](#) exactly once. Similarly, an **Eulerian circuit** or **Eulerian cycle** is an Eulerian trail which starts and ends on the same [vertex](#). They were first discussed by [Leonhard Euler](#) while solving the famous [Seven Bridges of Königsberg](#) problem in 1736. Mathematically the problem can be stated like this:

Given the graph in the image, is it possible to construct a path (or a [cycle](#), i.e. a path starting and ending on the same vertex) which visits each edge exactly once?



PS. This graph is
Not Eulerian

De Bruijn graph

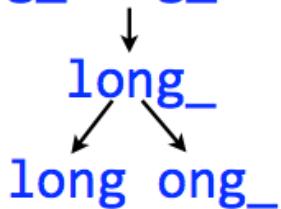
A procedure for making a De Bruijn graph
for a genome

Assume *perfect sequencing* where each length- k
substring is sequenced exactly once with no errors

Pick a substring length k : 5

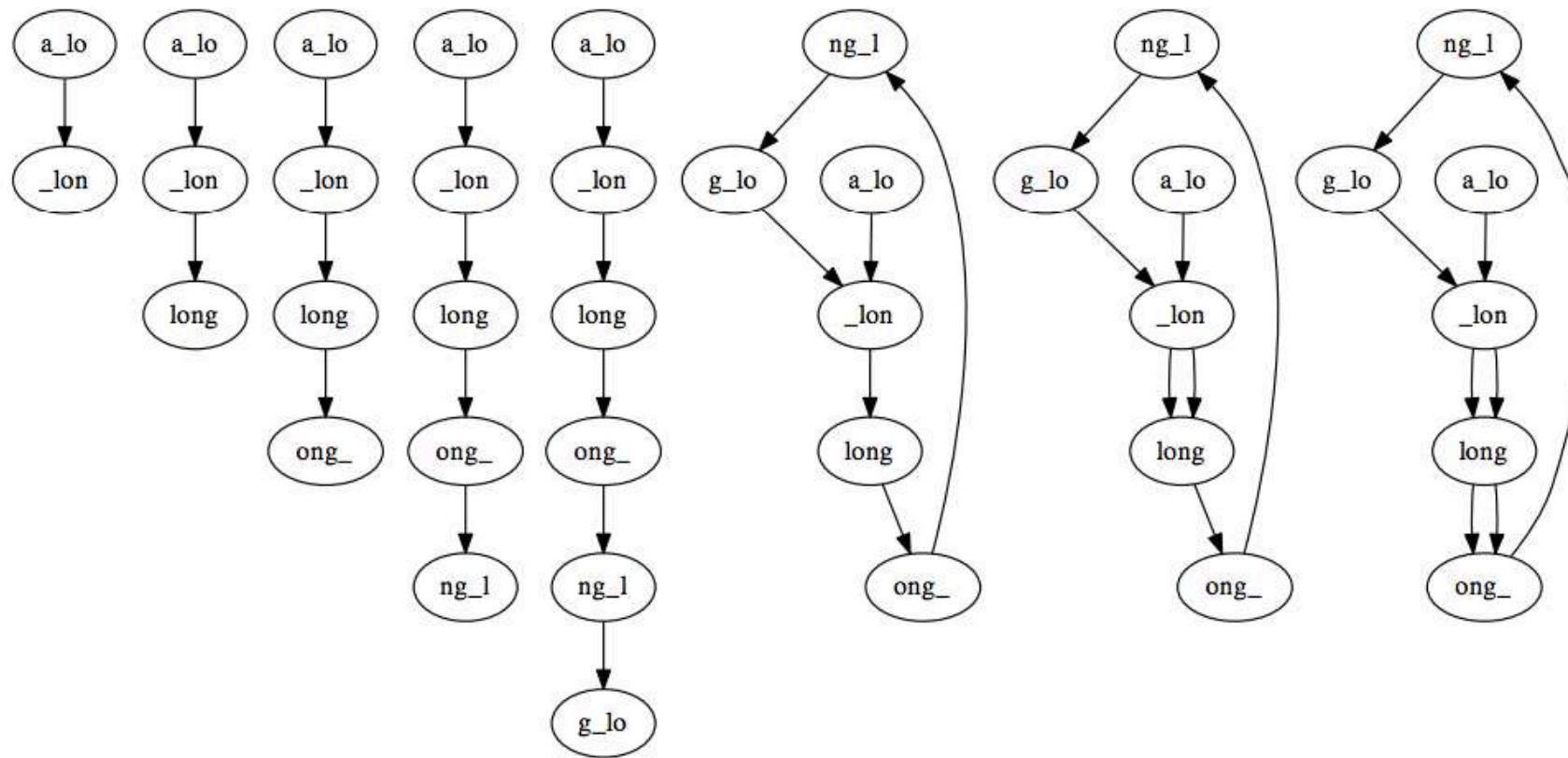
Start with an input string: a_long_long_long_time

Take each k mer and split
into left and right $k-1$ mers



Add $k-1$ mers as nodes to De Bruijn graph
(if not already there), add edge from left $k-1$
mer to right $k-1$ mer

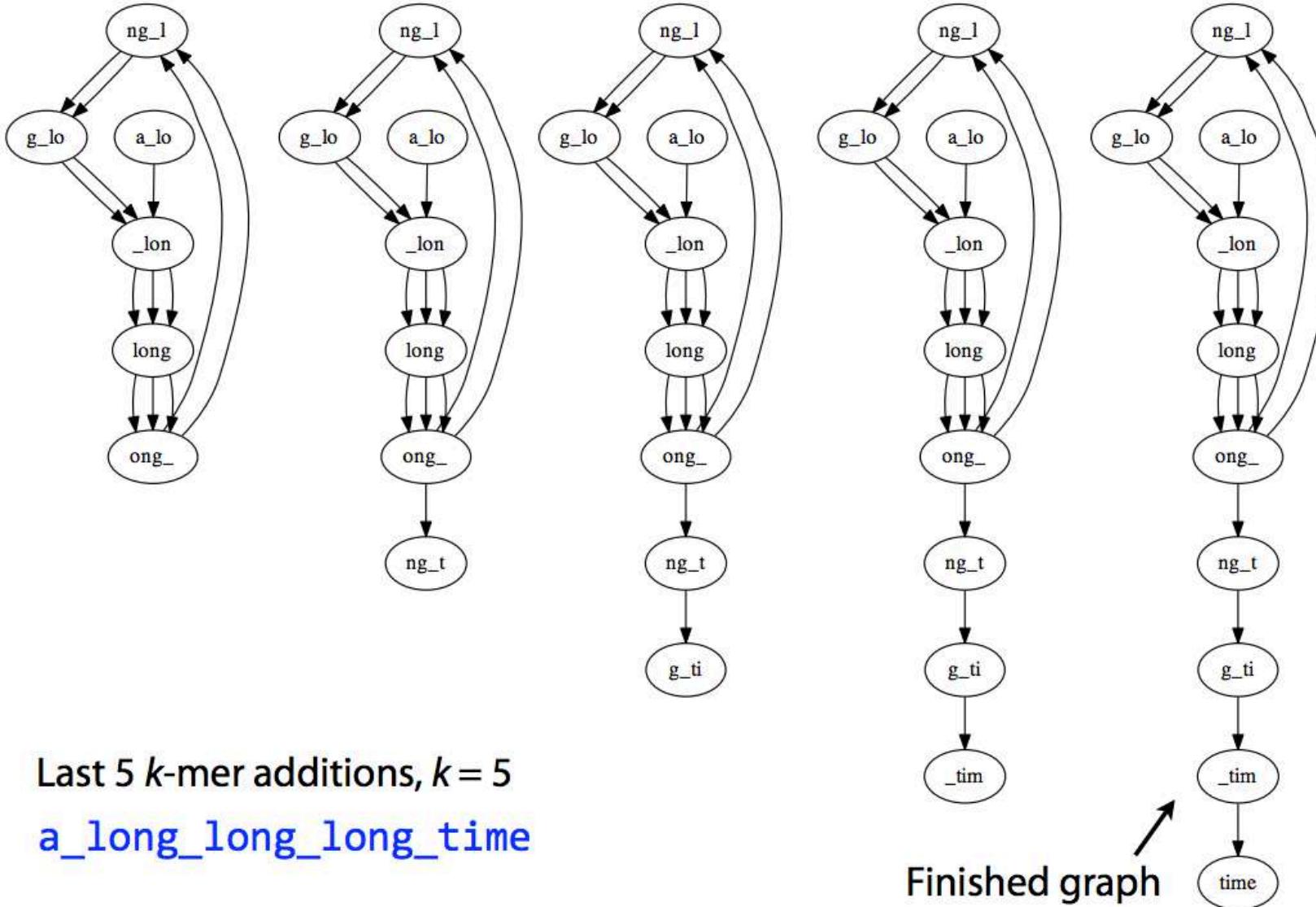
De Bruijn graph



First 8 k -mer additions, $k = 5$

a_long_long_long_time

De Bruijn graph



Last 5 k -mer additions, $k = 5$
a_long_long_long_time

Finished graph

De Bruijn graph

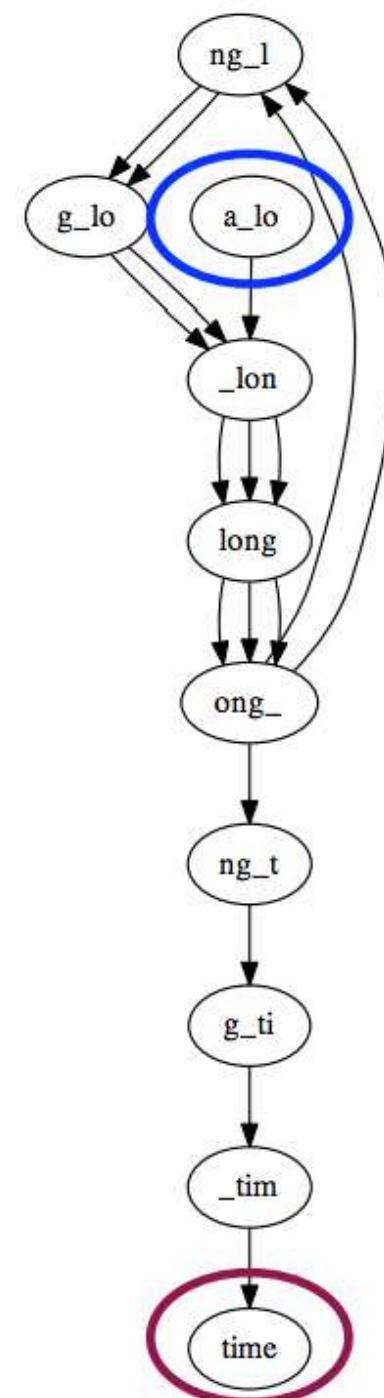
With perfect sequencing, this procedure always yields an Eulerian graph. Why?

Node for k -1-mer from **left end** is semi-balanced with one more outgoing edge than incoming *

Node for k -1-mer at **right end** is semi-balanced with one more incoming than outgoing *

Other nodes are balanced since # times k -1-mer occurs as a left k -1-mer = # times it occurs as a right k -1-mer

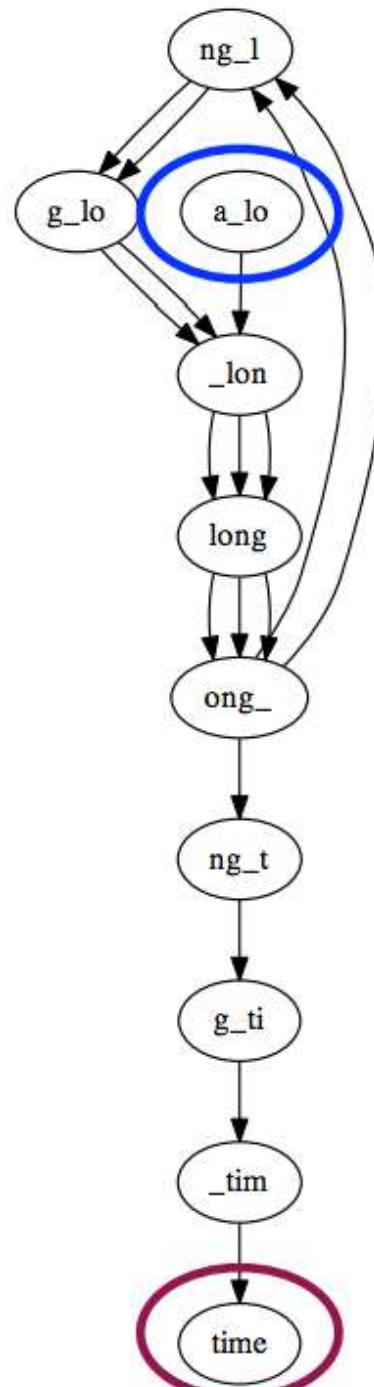
* Unless genome is circular



De Bruijn graph with actual data

Assuming perfect sequencing, procedure yields graph with Eulerian walk that can be found efficiently.

We saw cases where Eulerian walk corresponds to the original superstring. Is this always the case?



When k-mer is repeat

No: graph can have multiple Eulerian walks, only one of which corresponds to original superstring

Right: graph for **ZABCDABEFABY**, $k=3$

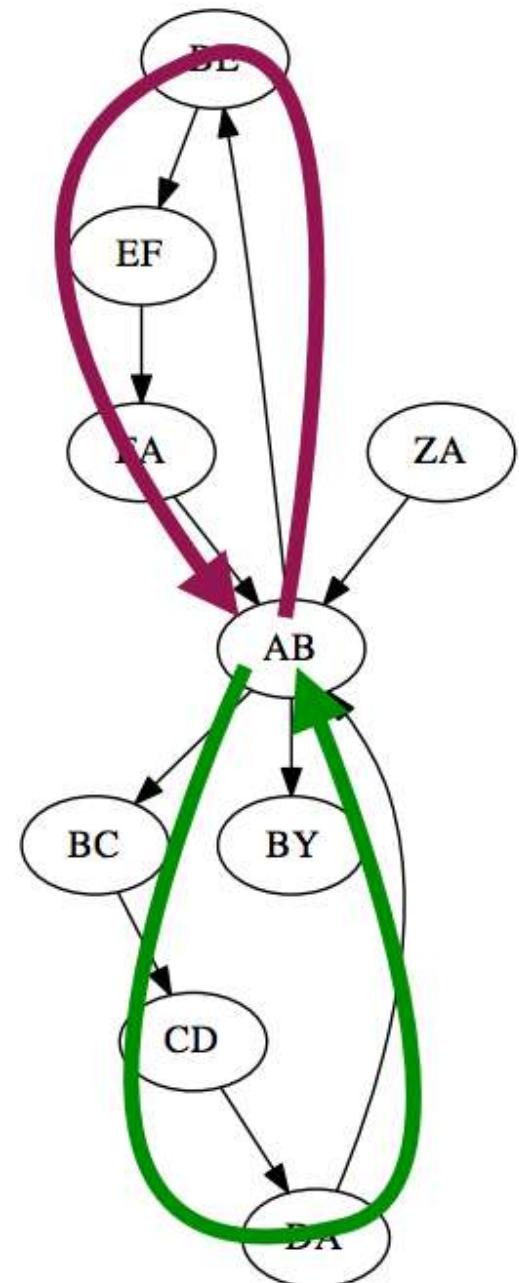
Alternative Eulerian walks:

ZA → **AB** → **BE** → **EF** → **FA** → **AB** → **BC** → **CD** → **DA** → **AB** → **BY**

ZA → **AB** → **BC** → **CD** → **DA** → **AB** → **BE** → **EF** → **FA** → **AB** → **BY**

These correspond to two edge-disjoint directed cycles joined by node **AB**

AB is a repeat: **ZABCDABEFABY**



When k-mer is repeat (in practice)

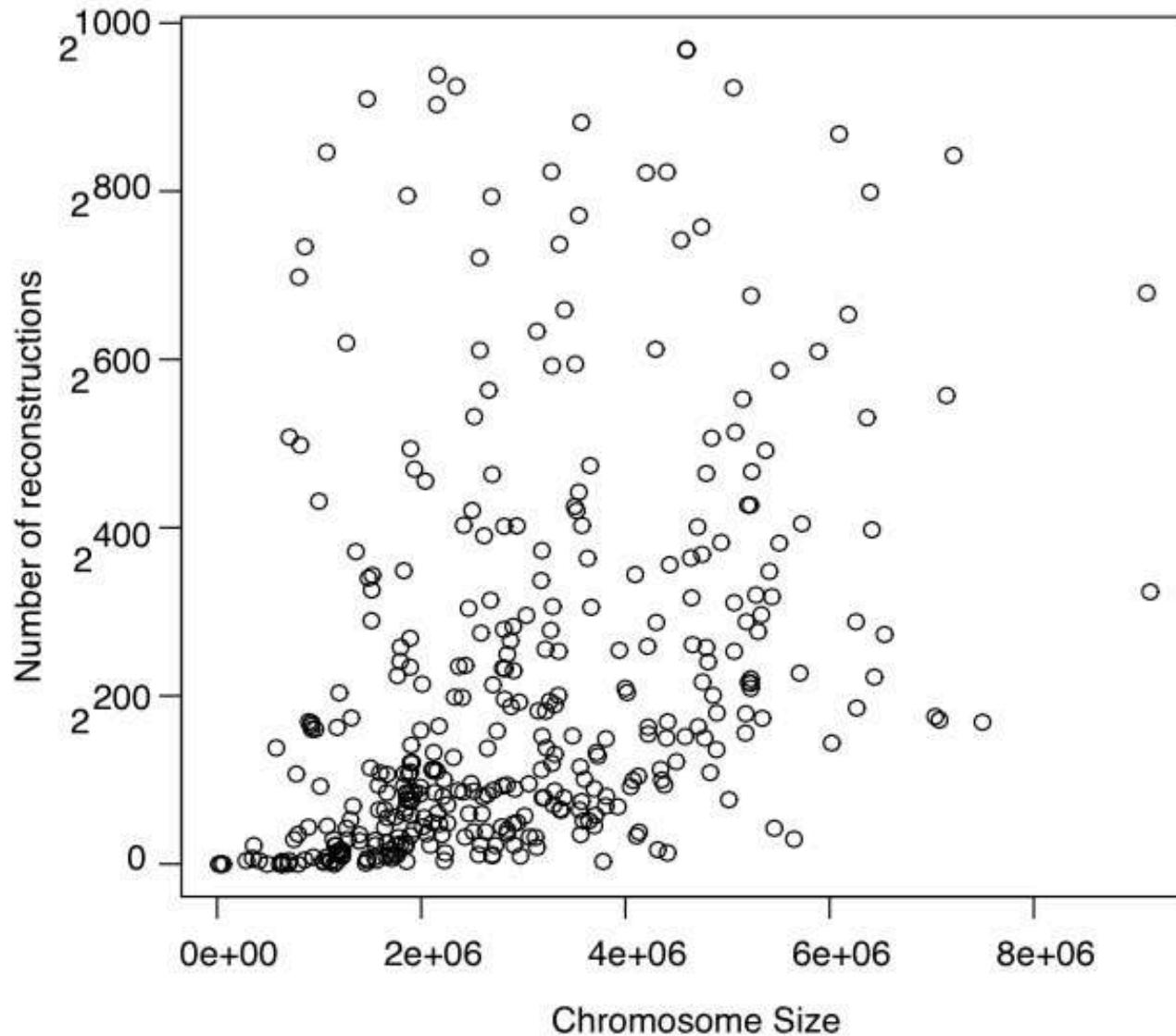


Figure 2 Number of words consistent with genome graphs. The

Impact of changing kmer size

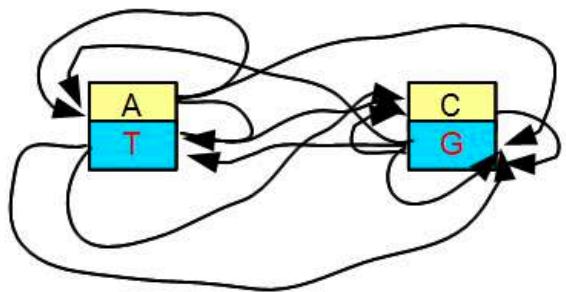
sequence

ATGGAAAGTCGCGGAATC

1mers

A
T
G
G
A
A
G
T
C
G
C
G
G
A
A
T
C

de Bruijn graph



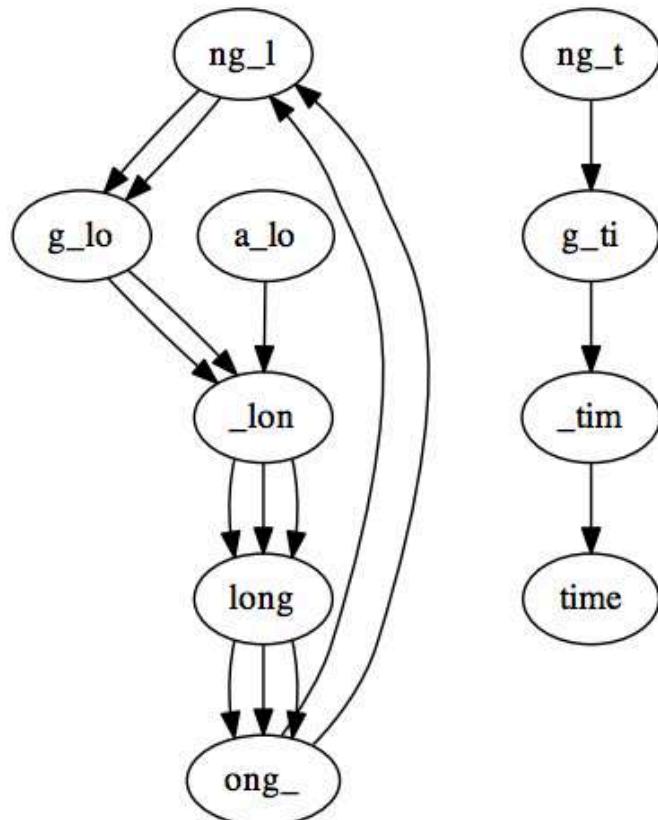
Example of a kmer of 1 basically means A,C,T,G are all repeats..

Larger kmer will span more small repeat less than kmer size, but likely to have less overlap

Low coverage = disconnected graph

Gaps in coverage can lead to *disconnected* graph

Graph for `a_long_long_long_time`, $k=5$ but *omitting* `ong_t`:



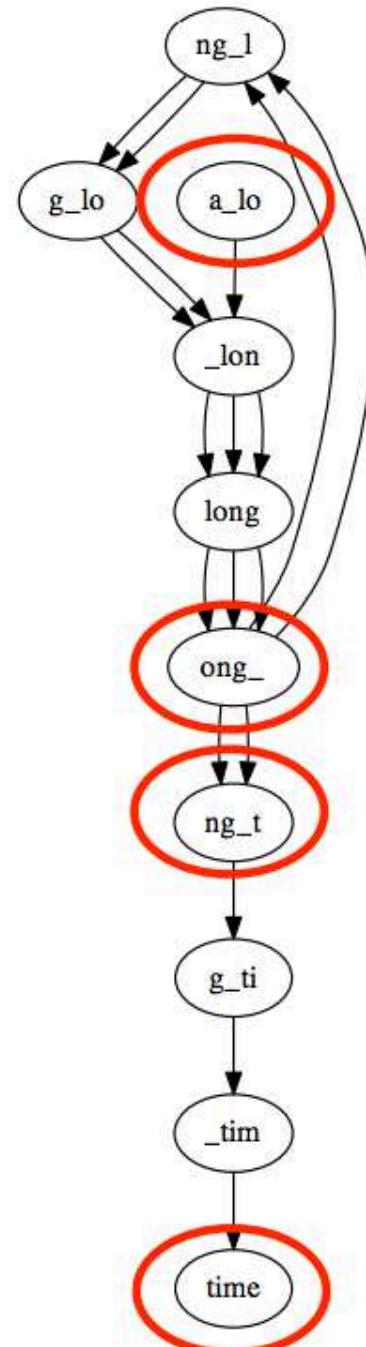
Connected components are individually Eulerian, overall graph is not

Coverage difference = not Eulerian

Differences in coverage also lead to non-Eulerian graph

Graph for `a_long_long_long_time`,
 $k = 5$ but with extra copy of `ong_t`:

Graph has 4 semi-balanced nodes,
isn't Eulerian



De Bruijn graph

Gaining assembly as Eulerian walk is appealing, not many practical cases impede this:

- Uneven coverage, sequencing errors, make graph non-Eulerian
- Repeats produces many possible walks

But there is one major advantage of De Bruijn graph over OLC

- Computationally efficient

Efficiency

Assume you have 5 billion reads to assemble

- Not uncommon nowadays in some plant species

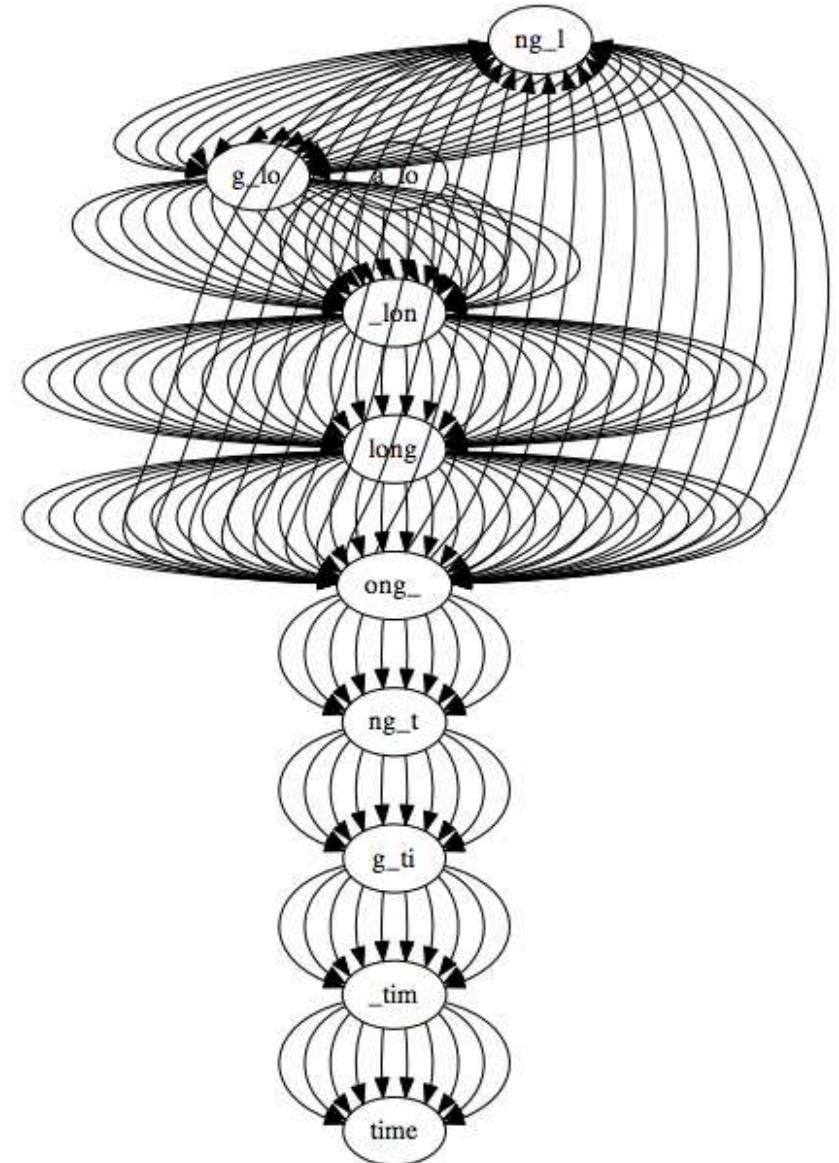
OLC: 12.5 quadrillion overlaps to compute first

Even 1 million overlap per sec will equate to **400 years**

DBG: depends on genome size

Size of De Bruijn graph depends on genome size

Usually ~50X paired end reads in coverage



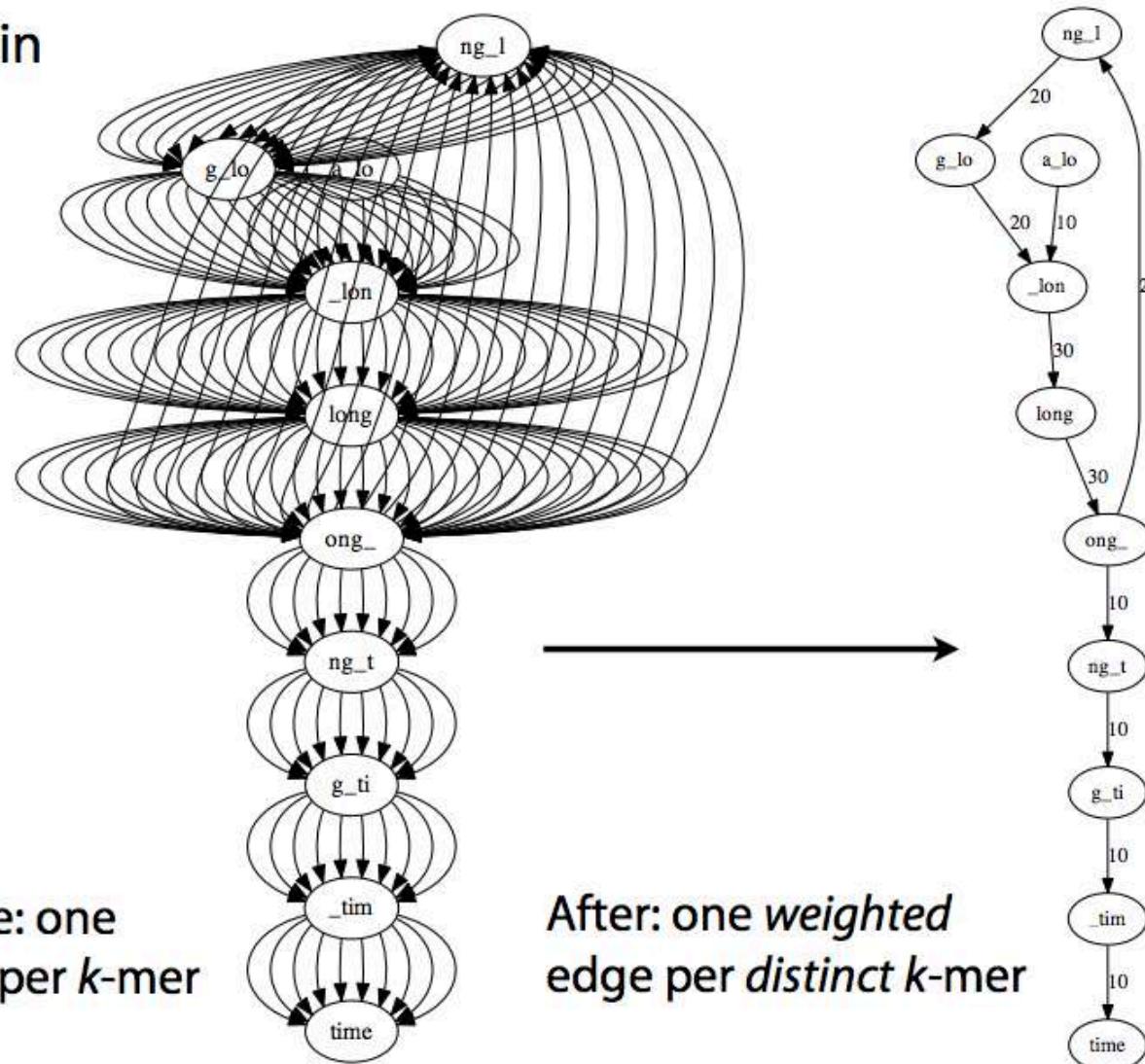
Size of De Bruijn graph depends on genome size

Same edge might appear in dozens of copies; let's use edge *weights* instead

Weight = # times k-mer occurs

Using weights, there's one *weighted* edge for each *distinct* k-mer

Before: one edge per k-mer



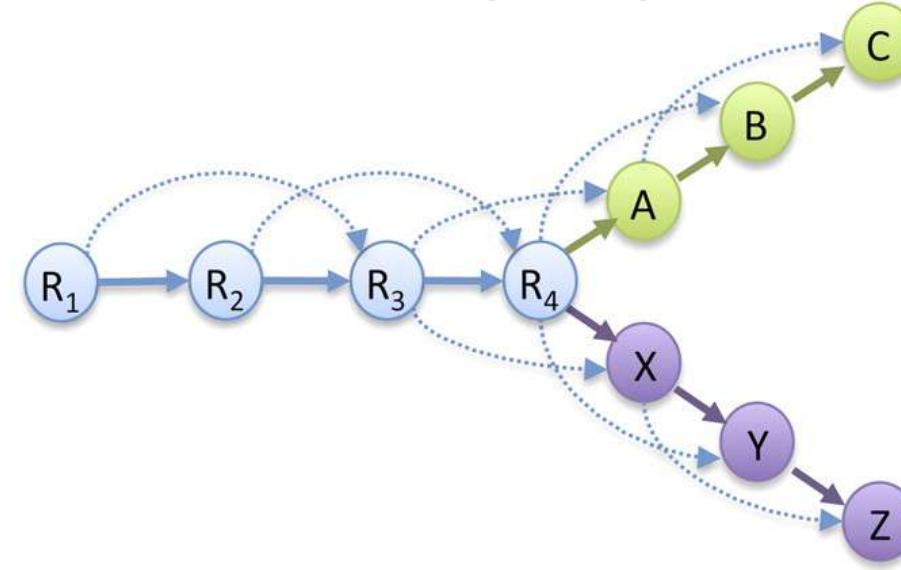
After: one *weighted* edge per *distinct* k-mer

Summary

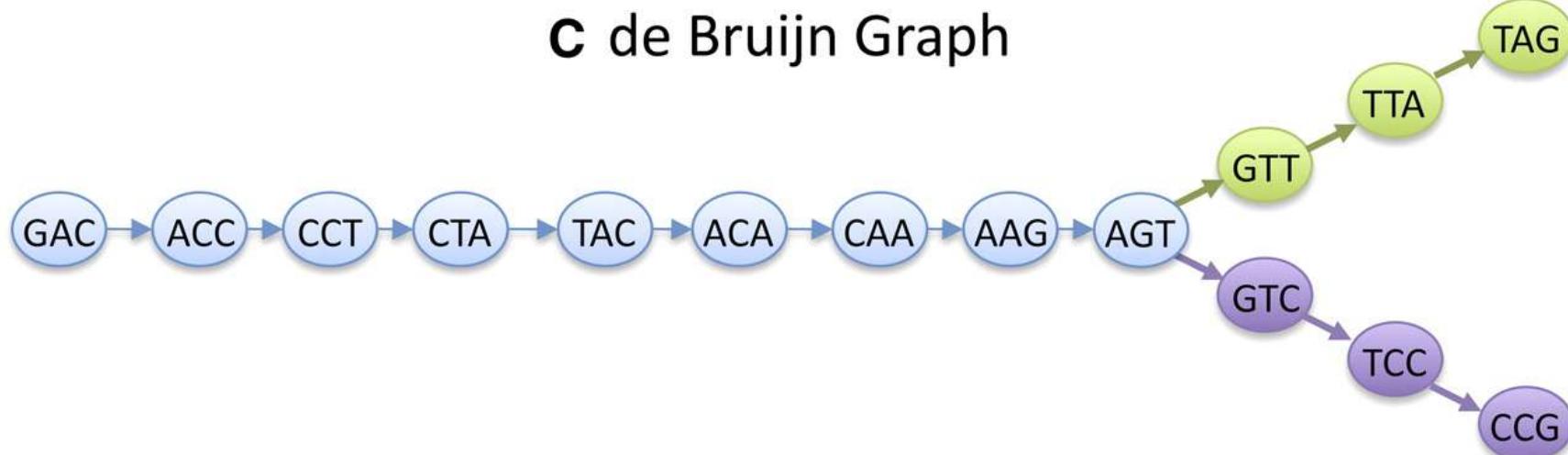
A Read Layout

R ₁ :	GACCTACA
R ₂ :	ACCTACAA
R ₃ :	CCTACAAAG
R ₄ :	CTACAAGT
A:	TACAAGTT
B:	ACAAGTTA
C:	CAAGTTAG
X:	TACAAGTC
Y:	ACAAGTCC
Z:	CAAGTCCG

B Overlap Graph



C de Bruijn Graph



Summary

Advantage of DBG:

Time to build based on Genome size (G) or total length of reads (N)

For OLC: time to build overlap graph is based on number of reads

But:

DBG not flexible: only overlap of **fixed length** (=kmer)
can't solve repeat with repeat > kmer

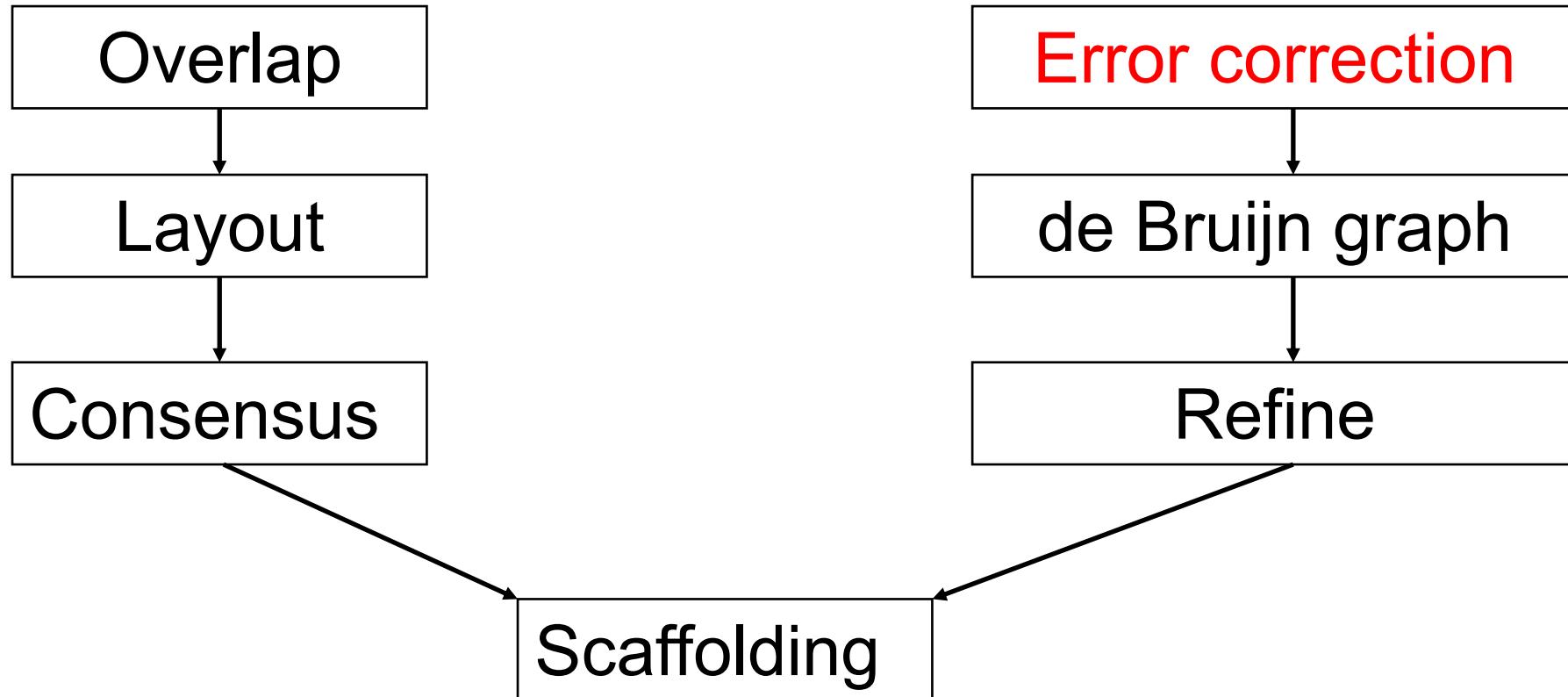
Read information is lost: All reads are split into kmers.
(A lot of work on later DBG assemblers are put in this)

Tradeoff between DBG and OLC needed

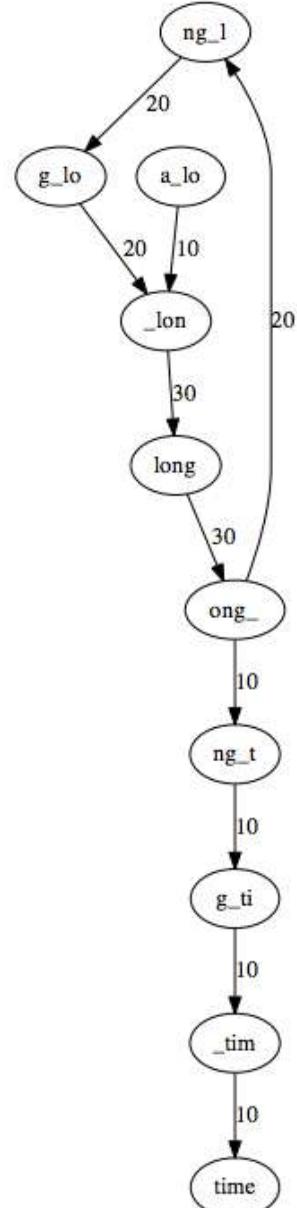
Some improve over existing approach: Spades

Some combine both: Maserca

OLC and DBG assemblers



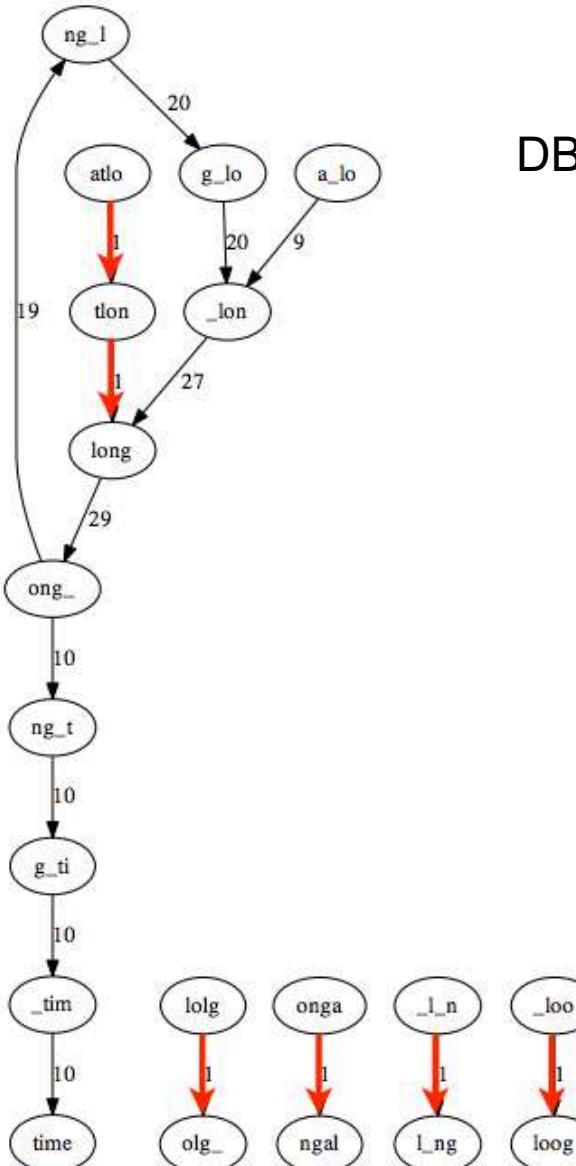
Error in graphs



DBG from perfect reads (10X)

As you can see all weighted edges have high coverage

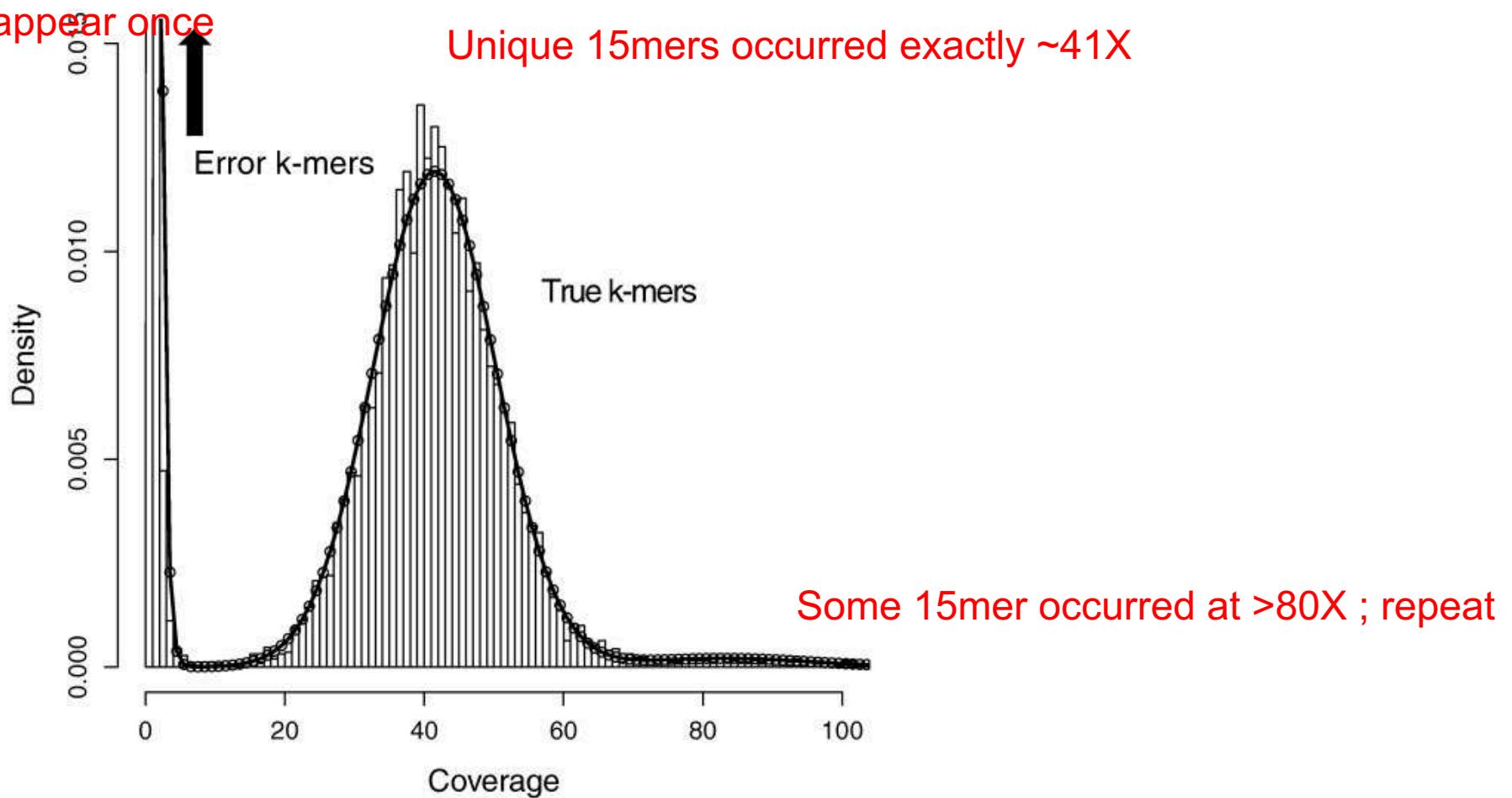
Some higher than the other; this is obviously repeat



DBG from reads with some errors

Kmer coverage

Indeed most erroneous kmer
has kmer appear once



The mean and variance for true k-mers are 41 and 77 suggesting that a coverage bias exists as the variance is almost twice the theoretical 41 suggested by the Poisson distribution

Choosing the right kmer

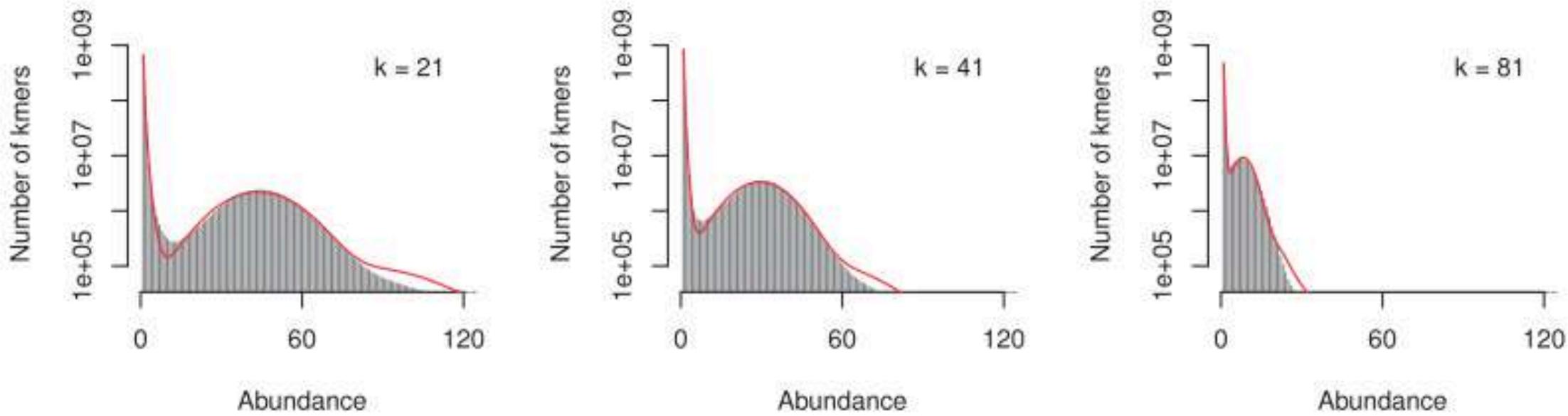


Fig. 2. The abundance histograms for *chr14* with k values of 21, 41 and 81 (on a y log scale). Each plot also shows a curve corresponding to the optimized statistical model (haploid)

Error correction: rationale

Idea: errors tend to turn frequent k -mers to infrequent k -mers, so corrections should do the reverse

Say we have a collection of reads where each distinct 8-mer occurs an average of ~10 times, and we have the following read:

Read: GCGTATTACGCGTCTGGCCT (20 nt)

8-mers:	
GCGTATTA:	8
CGTATTAC:	8
GTATTACG:	9
TATTACGC:	9
ATTACGCG:	9
TTACGCGT:	12
TACGCGTC:	9
ACGCGTCT:	8
CGCGTCTG:	10
GCGTCTGG:	10
CGTCTGGC:	11
GTCTGGCC:	9
TCTGGCCT:	8

times each 8-mer occurs in the dataset.
"k-mer count profile"

All 8-mer counts are around the average, suggesting read is error-free

Error correction: rationale

Suppose there's an **error**

Read: GCGTACTACGCGTCTGGCCT

GCGTACTA:	1	Below average
CGTACTAC:	3	
GTACTACG:	1	
TACTACGC:	1	
ACTACGCG:	2	
CTACGCGT:	1	
TACGCGTC:	9	Around average
ACGCGTCT:	8	
CGCGTCTG:	10	
GCGTCTGG:	10	
CGTCTGGC:	11	
GTCTGGCC:	9	
TCTGGCCT:	8	

k-mer count profile has corresponding stretch of below-average counts

Error correction: rationale

k-mer count profiles when errors are in different parts of the read:

GCGTACTACGCGTCTGGCCT

GCGTACTA: 1

CGTACTAC: 3

GTACTACG: 1

TACTACGC: 1

ACTACGCG: 2

CTACGCGT: 1

TACGCGTC: 9

ACCGTCT: 8

CGCGTCTG: 10

GCGTCTGG: 10

CGTCTGGC: 11

GTCTGGCC: 9

TCTGGCCT: 8

GCGTATTACACGTCTGGCCT

GCGTATTA: 8

CGTATTAC: 8

GTATTACA: 1

TATTACAC: 1

ATTACACG: 1

TTACACGT: 1

TACACGTC: 1

ACACGTCT: 2

CACGTCTG: 1

GCGTCTGG: 10

CGTCTGGC: 11

GTCTGGCC: 9

TCTGGCCT: 8

GCGTATTACGCGTCTGGTCT

GCGTATTA: 8

CGTATTAC: 8

GTATTACG: 9

TATTACGC: 9

ATTACGCG: 9

TTACGCGT: 12

TACGCGTC: 9

ACCGTCT: 8

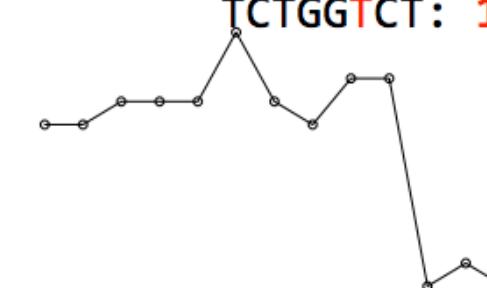
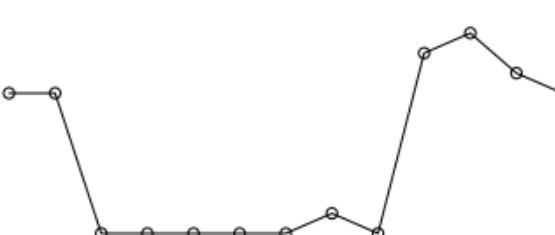
CGCGTCTG: 10

GCGTCTGG: 10

CGTCTGGT: 1

GTCTGGTC: 2

TCTGGTCT: 1



Localize error and correct

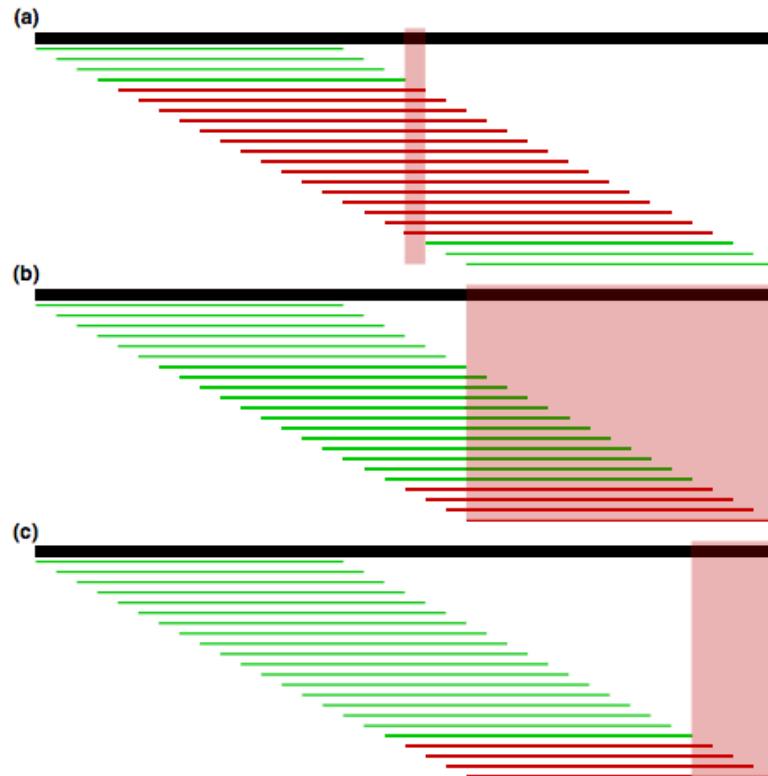
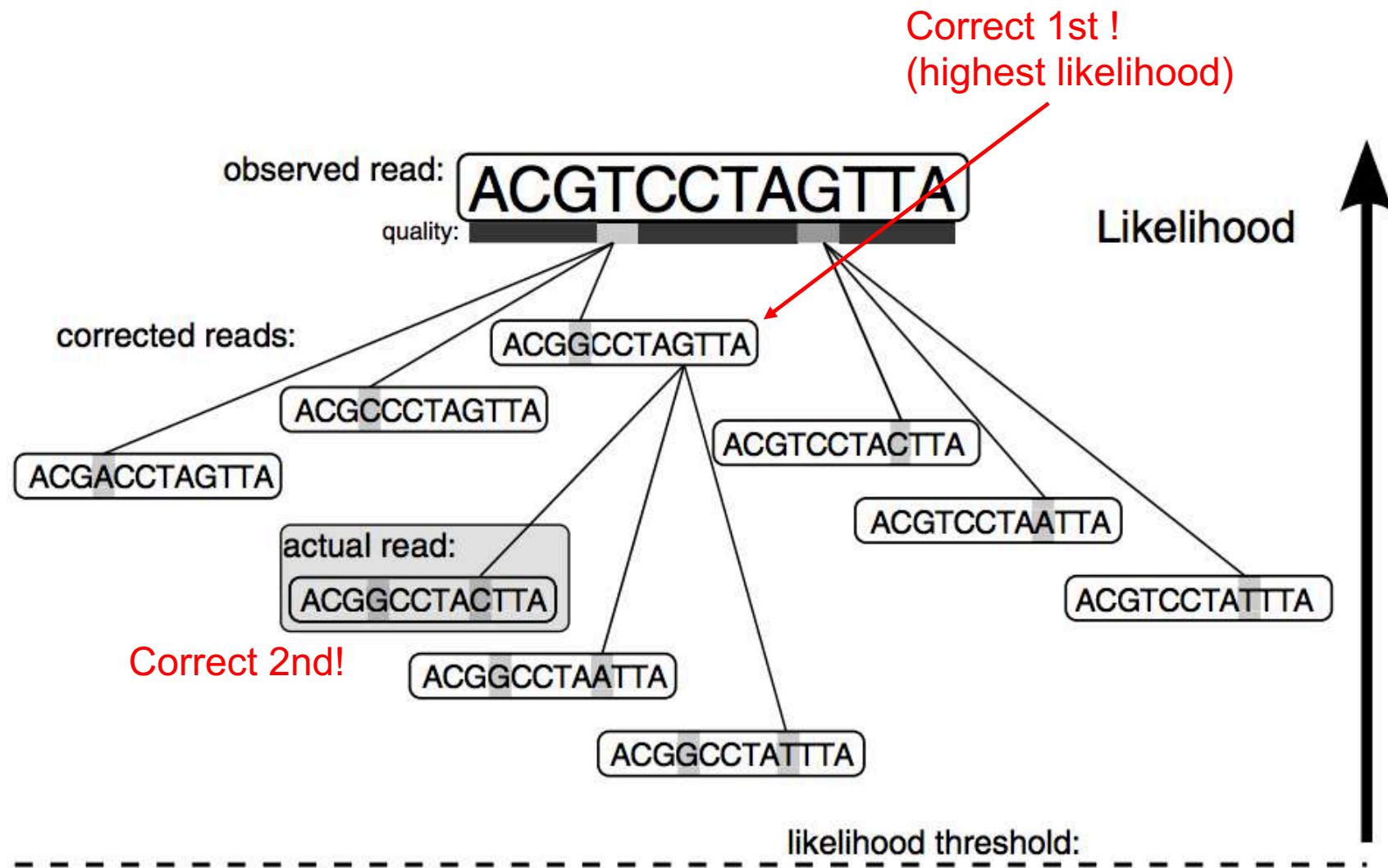


Figure 4 Localize errors. Trusted (green) and untrusted (red) 15-mers are drawn against a 36 bp read. In (a), the intersection of the untrusted k -mers localizes the sequencing error to the highlighted column. In (b), the untrusted k -mers reach the edge of the read, so we must consider the bases at the edge in addition to the intersection of the untrusted k -mers. However, in most cases, we can further localize the error by considering all bases covered by the right-most trusted k -mer to be correct and removing them from the error region as shown in (c).



Velvet: first de Bruijn graph assembler

- Cited 8812 times
- Still being used in some metagenomics dataset

Resource

Velvet: Algorithms for de novo short read assembly using de Bruijn graphs

Daniel R. Zerbino and Ewan Birney¹

EMBL-European Bioinformatics Institute, Wellcome Trust Genome Campus, Hinxton, Cambridge CB10 1SD, United Kingdom

We have developed a new set of algorithms, collectively called “Velvet,” to manipulate de Bruijn graphs for genomic sequence assembly. A de Bruijn graph is a compact representation based on short words (k -mers) that is ideal for high coverage, very short read (25–50 bp) data sets. Applying Velvet to very short reads and paired-ends information only, one can produce contigs of significant length, up to 50-kb N50 length in simulations of prokaryotic data and 3-kb N50 on simulated mammalian BACs. When applied to real Solexa data sets without read pairs, Velvet generated contigs of ~8 kb in a prokaryote and 2 kb in a mammalian BAC, in close agreement with our simulated results without read-pair information. Velvet represents a new approach to assembly that can leverage very short reads in combination with read pairs to produce useful assemblies.

[Supplemental material is available online at www.genome.org. The code for Velvet is freely available, under the GNU Public License, at <http://www.ebi.ac.uk/~zerbino/velvet>.]

Summary

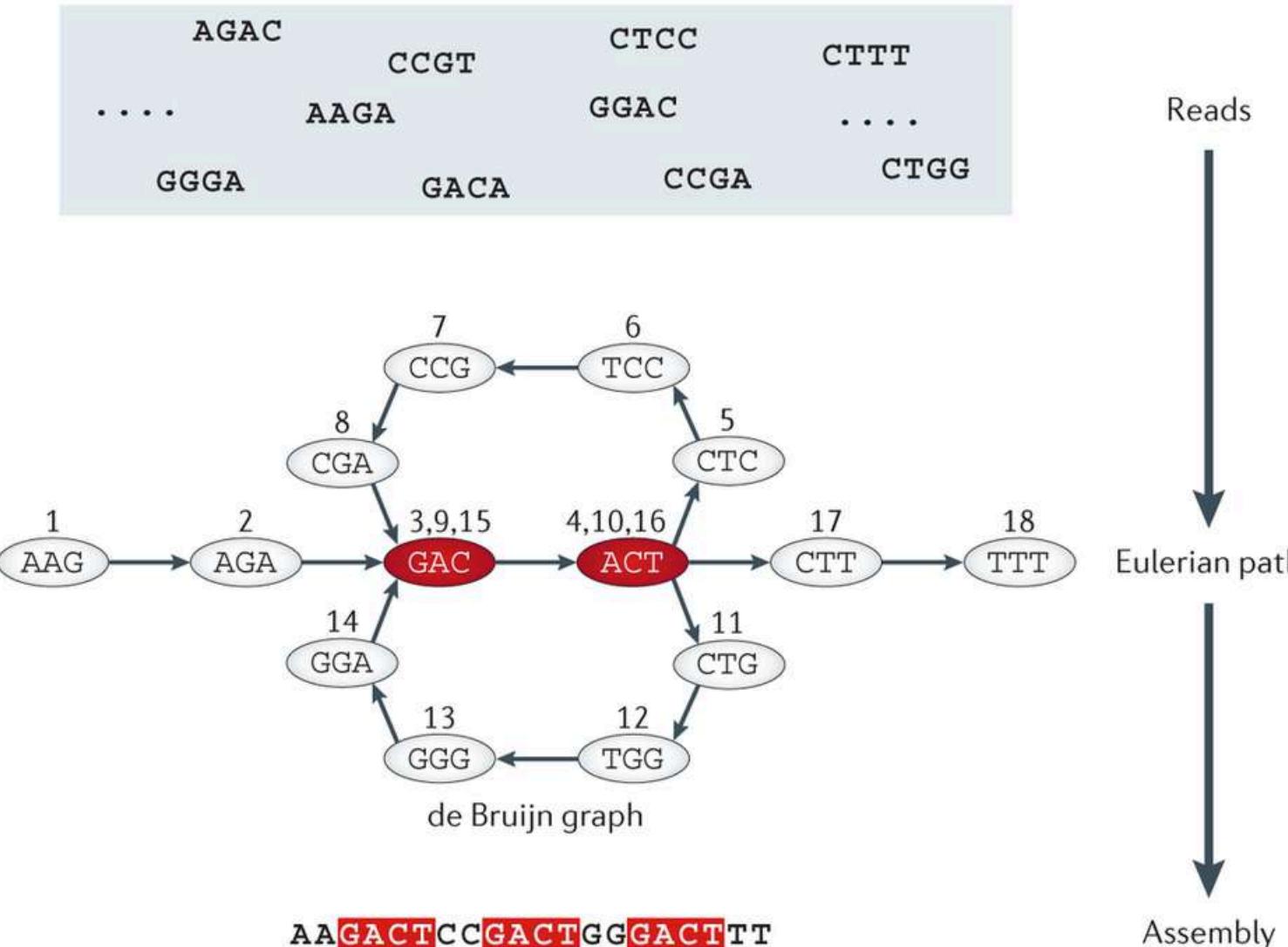
Error correction will **definitely** improve assembly

But, for it to work well:

- Sequenced coverage should be high enough

- Choose kmer wisely otherwise we can't distinguish erroneous kmer from frequent kmers

Summary I



Summary II

a

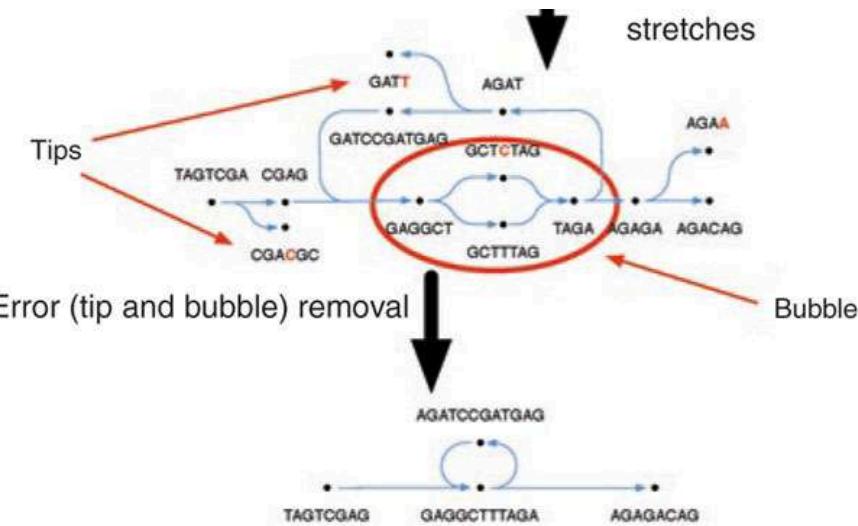
TAGTCGAGGCTTAGATCCGATGAGGCTTAGAGACAG
AGTCGAG CTTAGA CGATGAG CTTAGA
GTCGGG TTAGATC ATGAGGC GAGACAG
GAGGCTC ATCCGAT AGGCTT GAGACAG
AGTCGAG TAGATCC ATGAGGC TAGAGAA
TAGTCGA CTTAGA CCGATGA TTAGAGA
CGAGGCT AGATCCG TGAGGCT AGAGACA
TAGTCGA GCTTTAG TCCGATG GCTCTAG
TOGACGC GATCCGA GAGGCTT AGAGACA
TAGTCGA TTAGATC GATGAGG TTTAGAG
GTCGAGG TCTAGAT ATGAGGC TAGAGAC
AGGCTT ATCCGAT AGGCTT GAGACAG
AGTCGAG TTAGATT ATGAGGC AGAGACA
GGCTTA TCCGATG TTTAGAG
CGAGGCT TAGATCC TGAGGCT GAGACAG
AGTCGAG TTTAGATC ATGAGGC TTTAGAGA
GAGGCTT GATCCGA GAGGCTT GAGACAG

1. Sequencing
(for example, Solexa or 454)

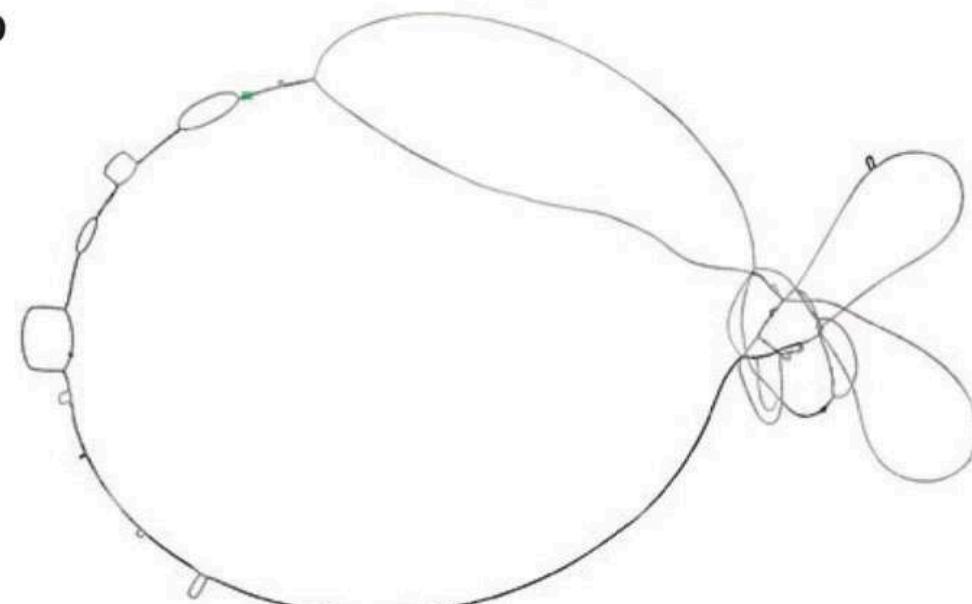
2. Hashing

Linear stretches
GATT (1x)
TGAG (9x) ATGA (8x) GATG (5x) CGAT (6x) CCGA (7x) TCCG (7x) ATCC (7x) GATC (8x) AGAT (8x)
CGAG (8x) GAGG (16x) AGGC (16x) GGCT (16x) GGCT (11x)
CGAC (1x) GACG (1x) AGCG (1x)
TAGT (3x) AGTC (7x) GTCG (9x) TCGA (10x)
GCTC (2x) CTCT (1x) TCTA (2x) CTAG (2x)
GCTT (8x) CTTT (8x) TTTA (8x) TTAG (12x)
TAGA (16x) AGAG (9x) GAGA (12x) AGAC (9x) GACA (8x) ACAG (5x)

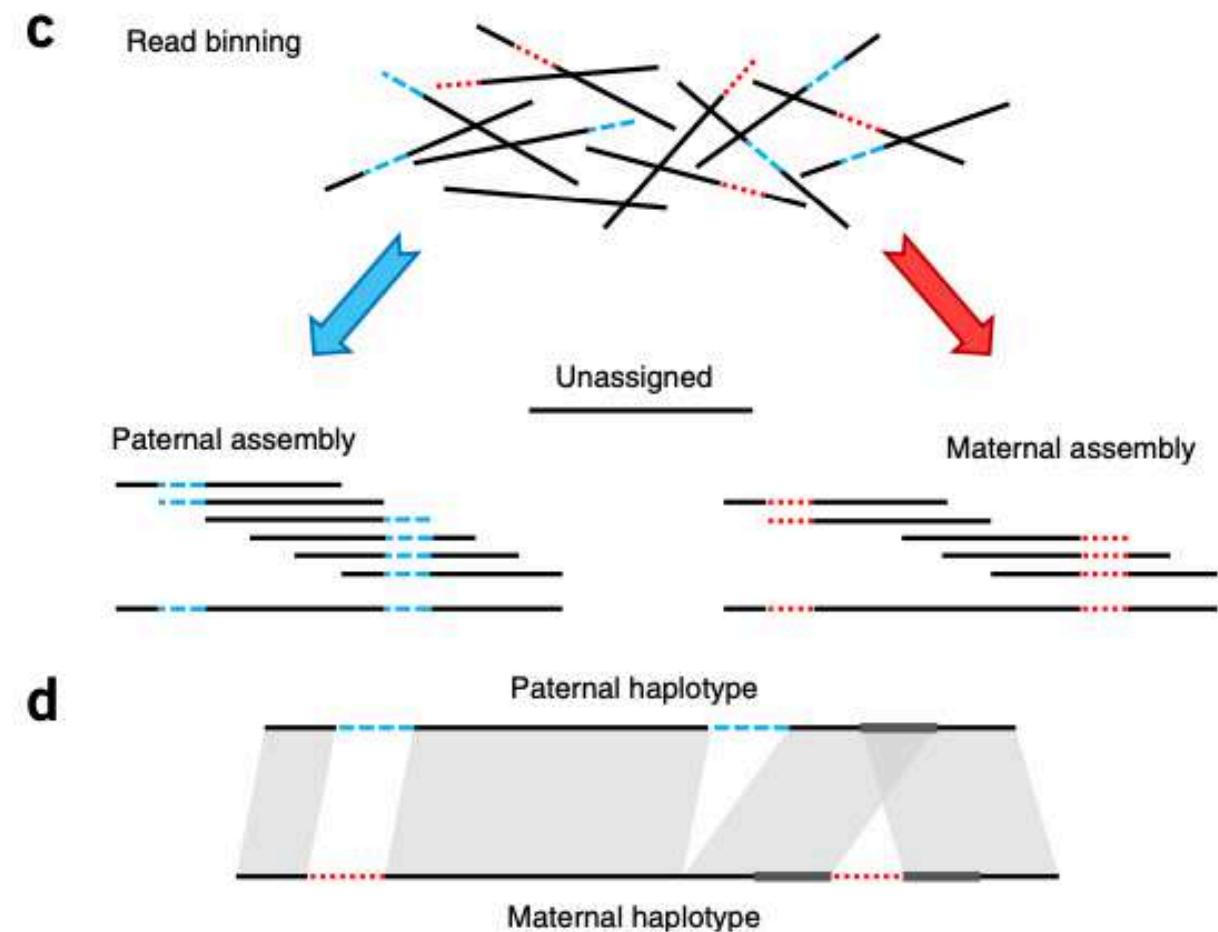
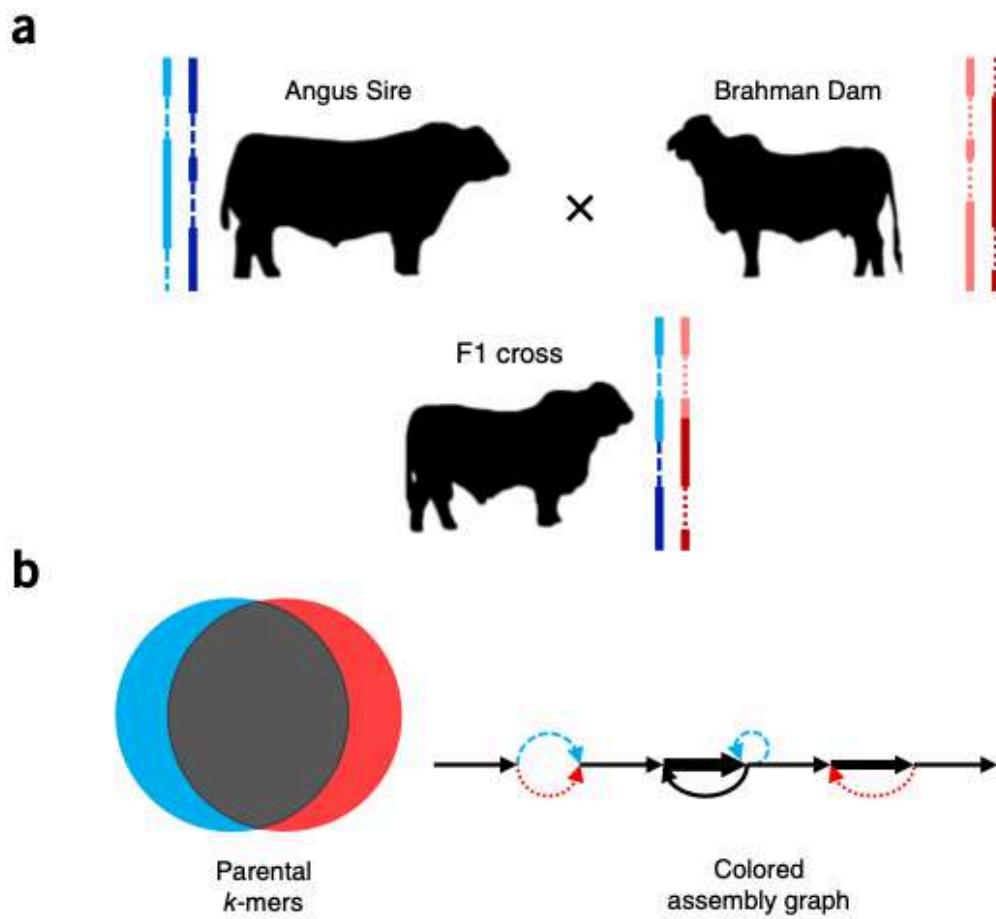
3. Simplification of linear
stretches



b



Trio binning



Binning (in metagenomics ; trios)

Keyword: MAG (metagenome-assembled genomes)

Advantage of metagenomics approach

Better classification with Increasing number of complete genomes

Focus on whole genome based phylogeny (whole genome phlyotyping)

- Advantages

No amplification bias like in 16S/ITS

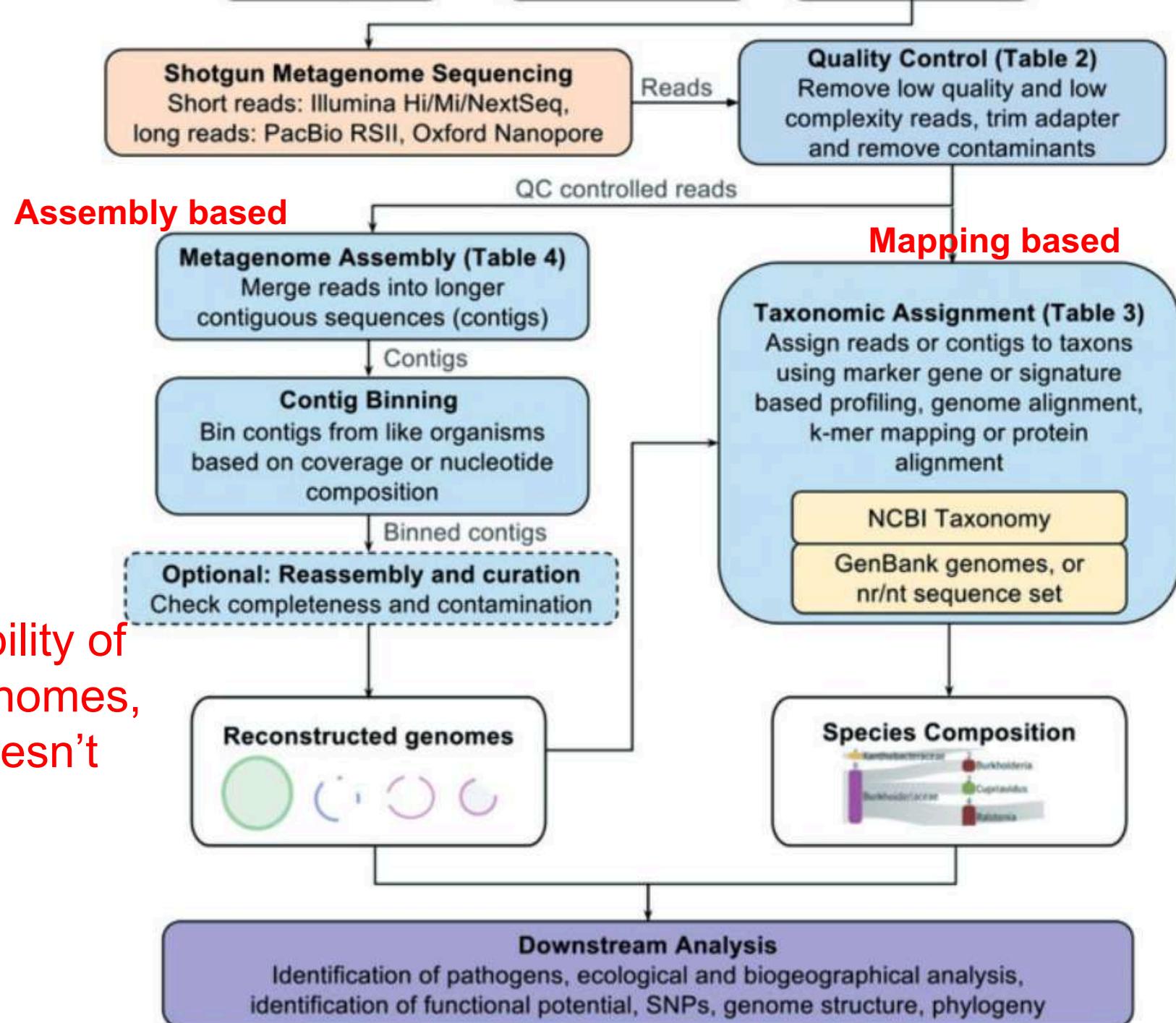
Issues

Poor sampling beyond eukaryotic diversity

Assembly of metagenomes is **challenging** due to uneven coverage

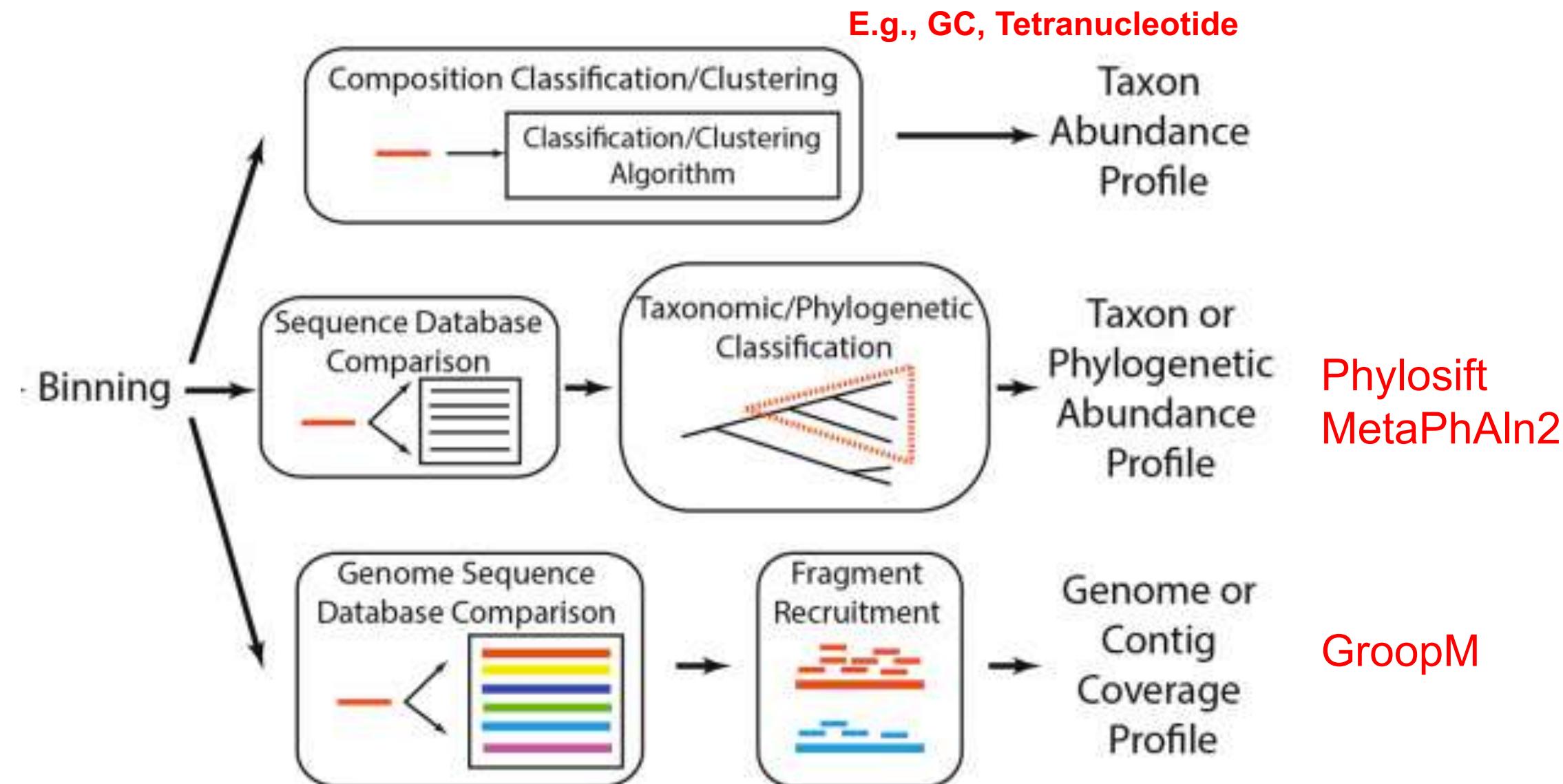
Requires **high** depth of coverage

Overall workflow

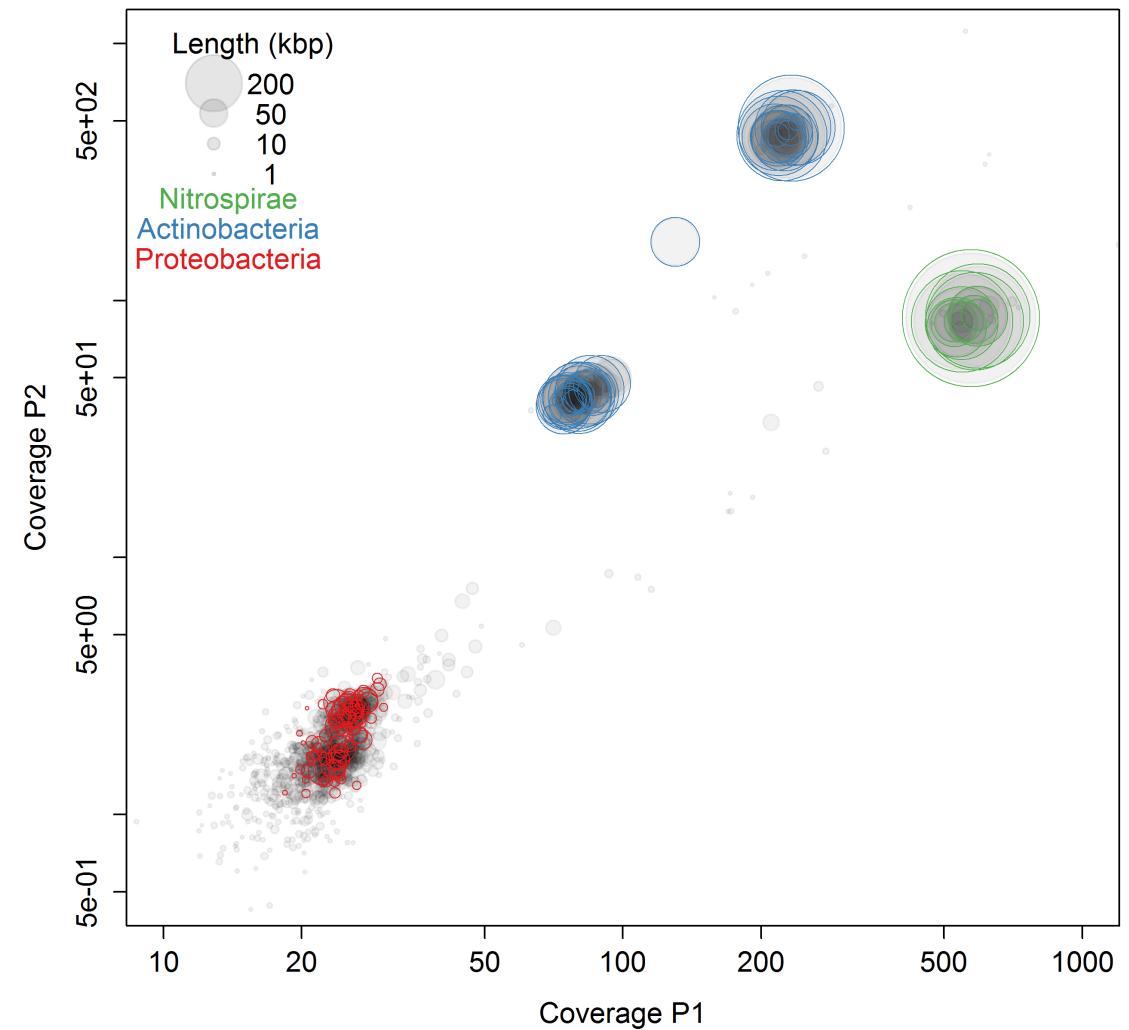
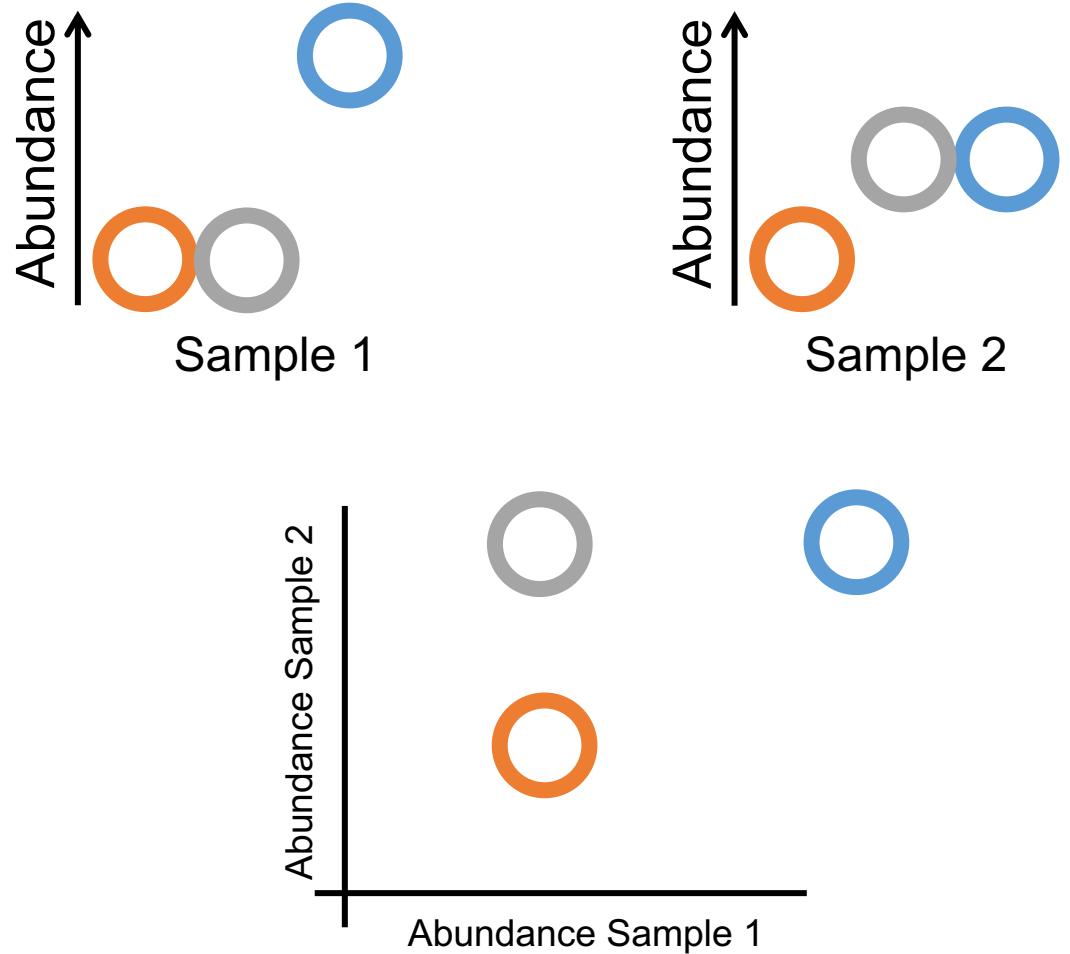


With the increase availability of reference sequenced genomes, probably one day one doesn't require assembly of metagenomes

Binning methods



Example of binning based on differential coverage



Binning methods: A combination of

Classification based on **sequence composition**:

Advantage : all reads can be categorised into bins

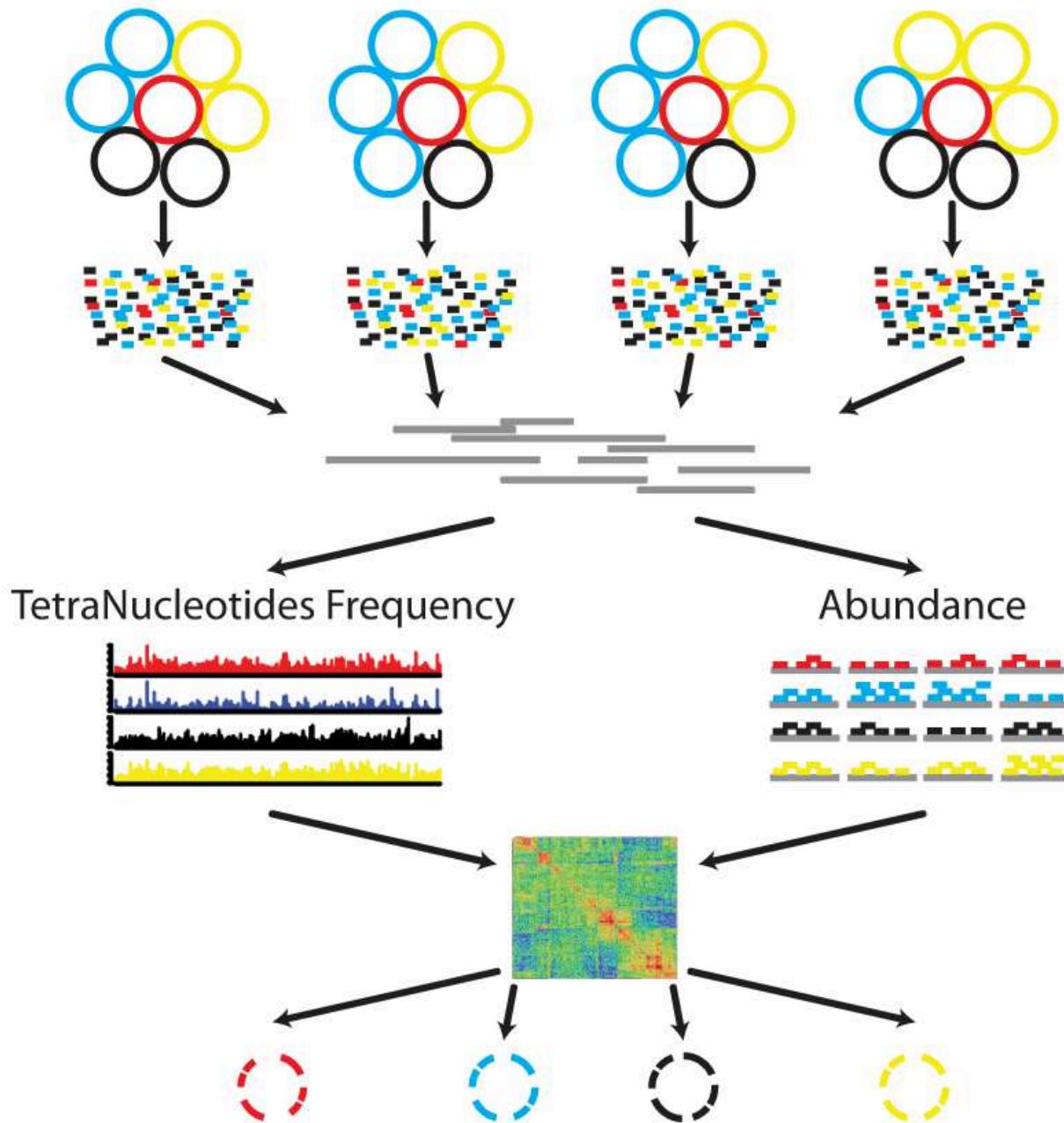
Disadvantage: no taxonomy / function of the bins.

Classification based on **sequence similarity (of known genes)**

Advantage: One can determine taxonomy and function of reads.

Disadvantage: reads with similarity can not be classified .

Metabat



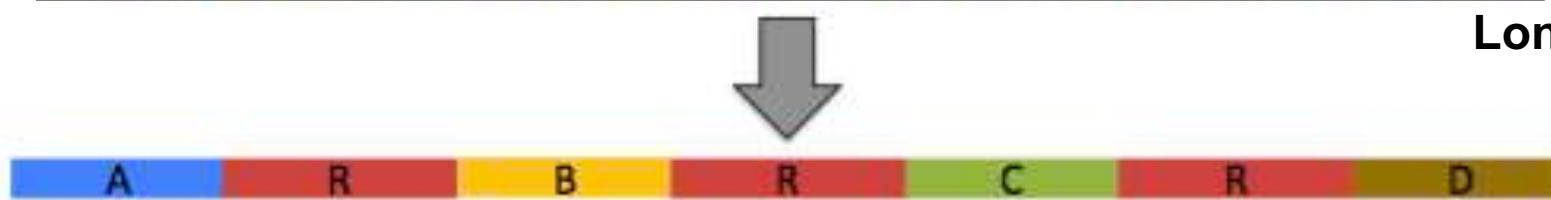
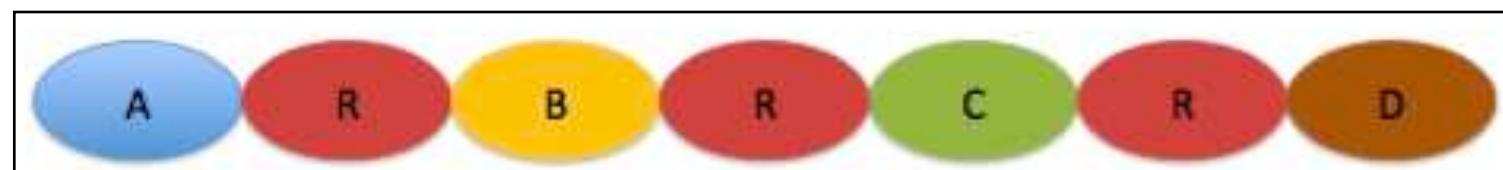
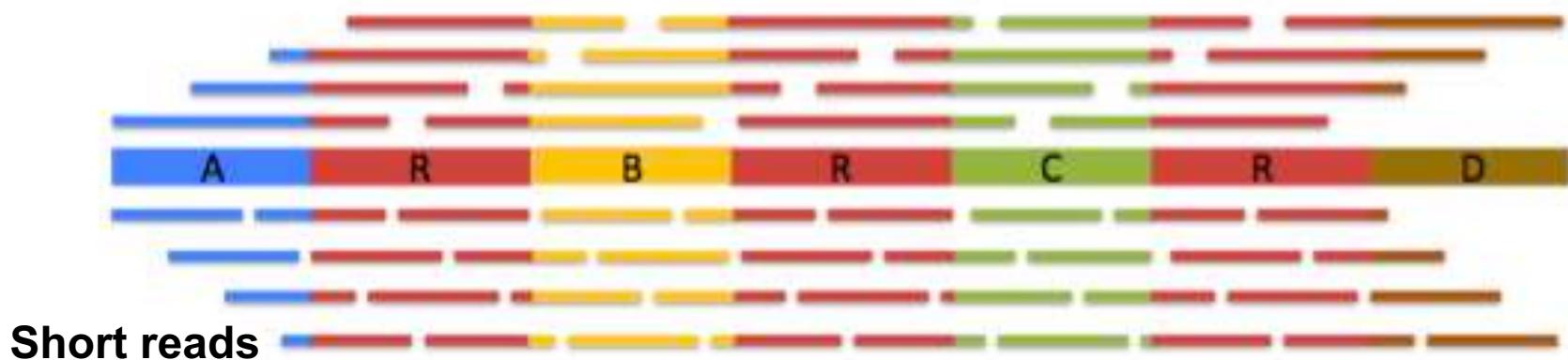
Preprocessing

- 1 Samples from multiple sites or times
- 2 Metagenome libraries
- 3 Initial de-novo assembly using the combined library

MetaBAT

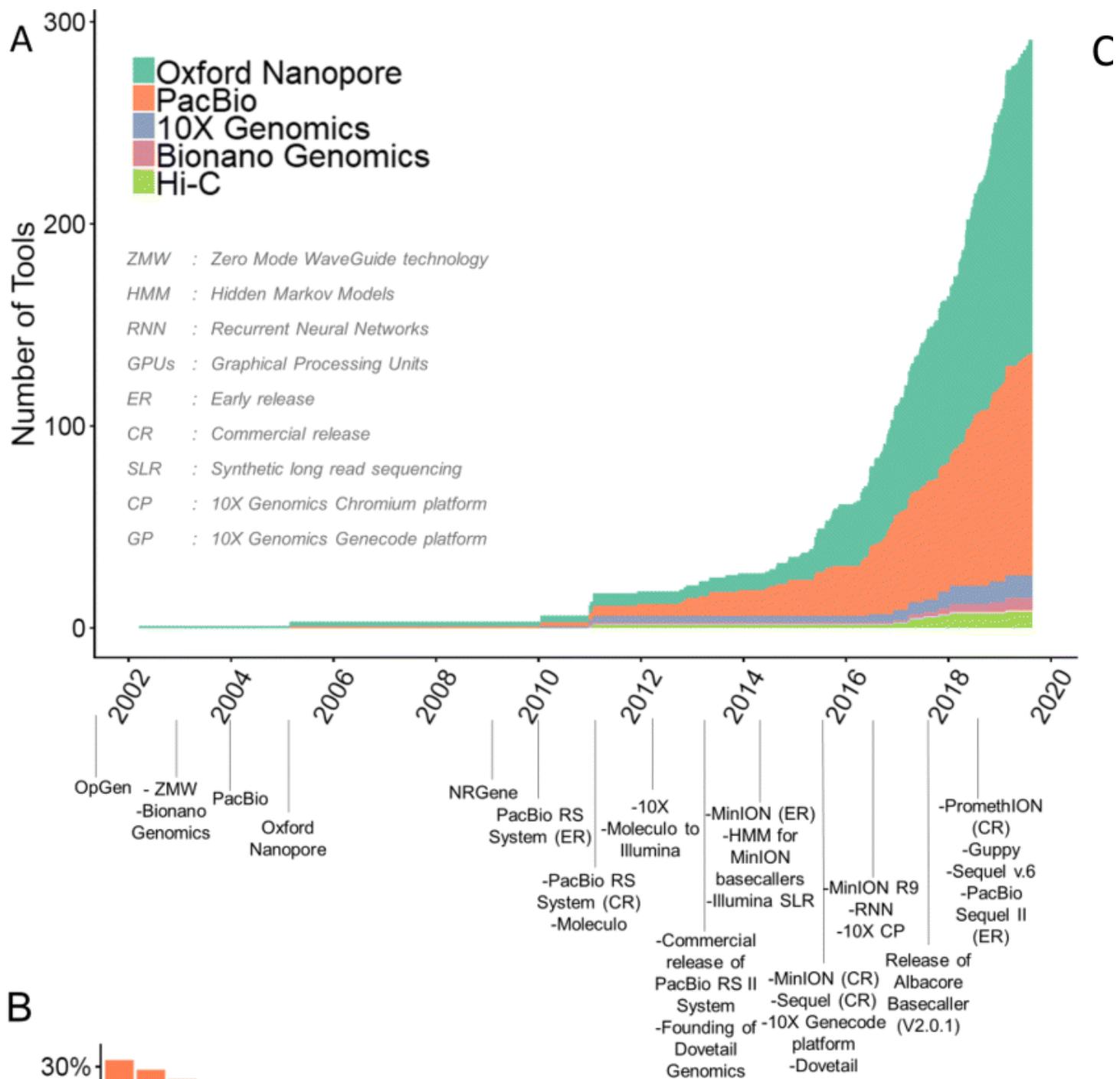
- 4 Calculate TNF for each contig
- 5 Calculate Abundance per library for each contig
- 6 Calculate the pairwise distance matrix using pre-trained probabilistic models
- 7 Forming genome bins iteratively

Long read technologies



Credit: Michael Schatz

New tools continue to be developed



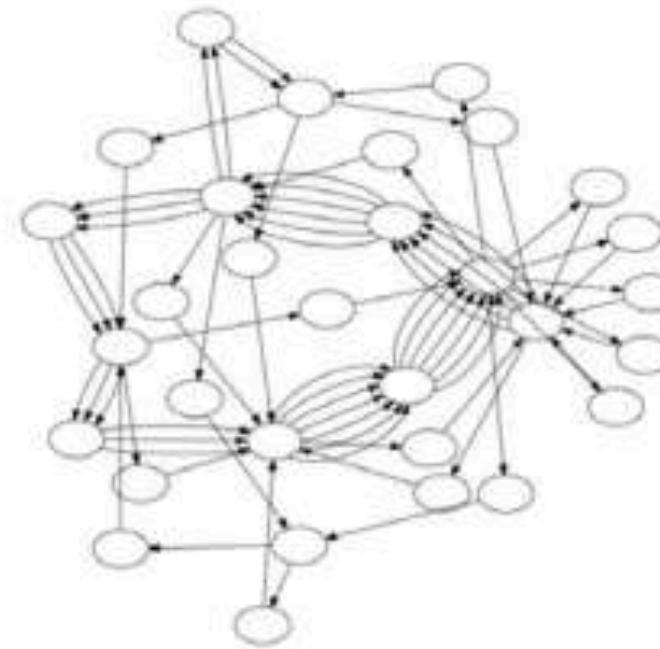
Simpler graphs

(a)



K=100
Contigs=98

(b)



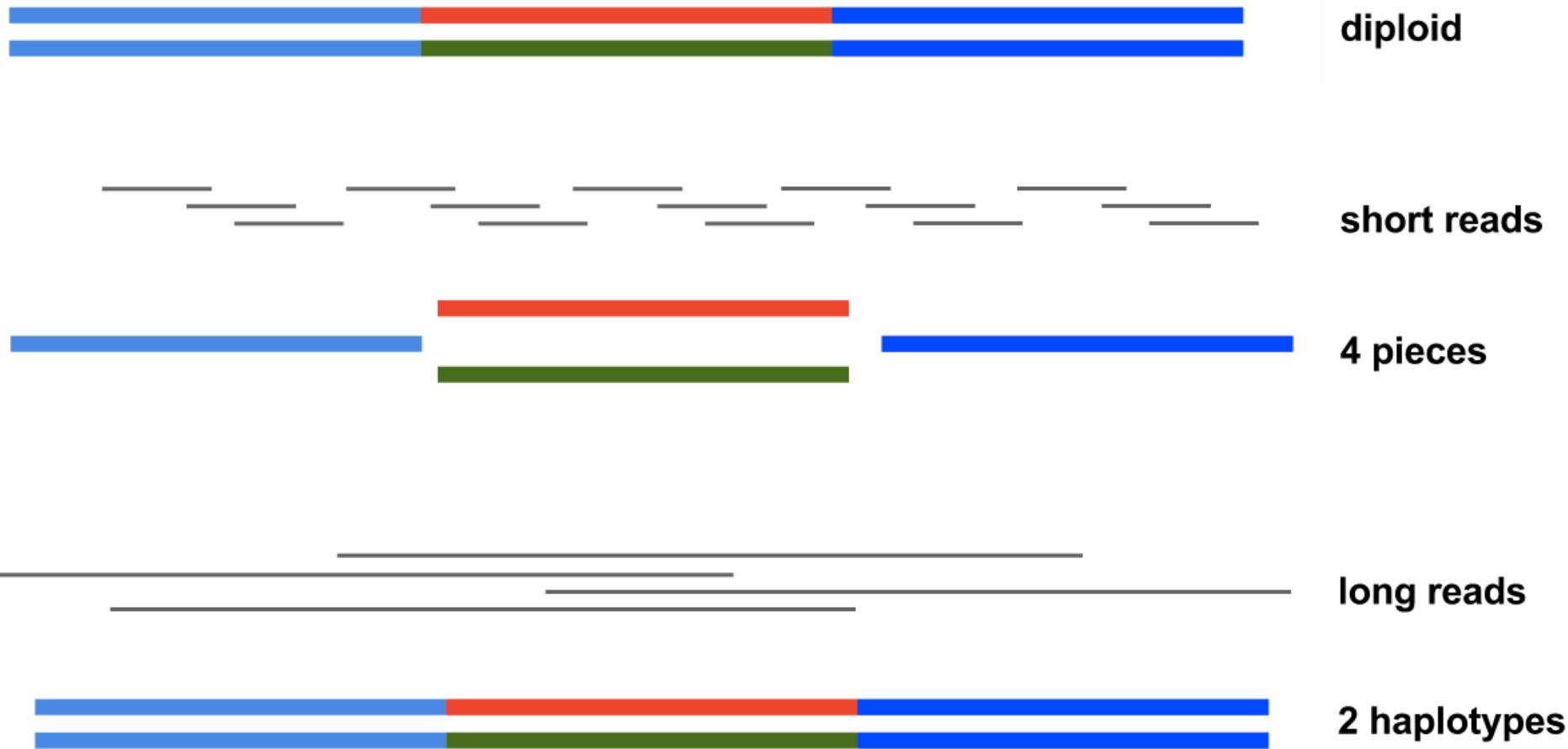
K=1,000
Contigs=31

(c)



K=5,000
Contigs=1

Long reads can also resolve haplotypes (with sufficient coverage)



HiFi reads

Start with high-quality double stranded DNA



Ligate SMRTbell adapters and size select



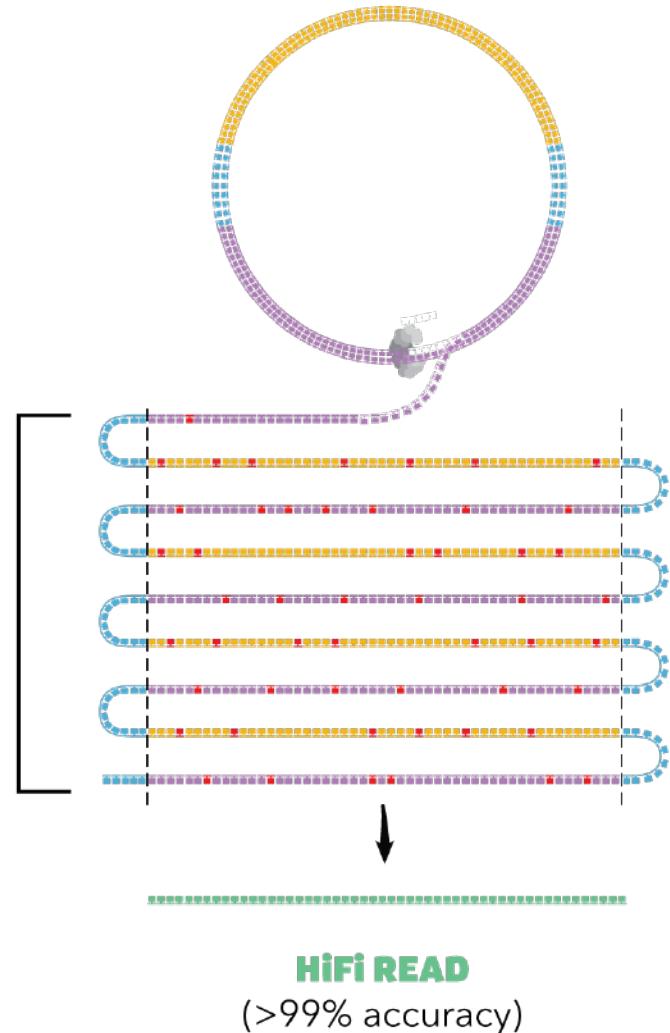
Anneal primers and bind DNA polymerase



Circularized DNA is sequenced in repeated passes

The polymerase reads are trimmed of adapters to yield subreads

Consensus is called from subreads





Miten Jain @mitenjain · Mar 11

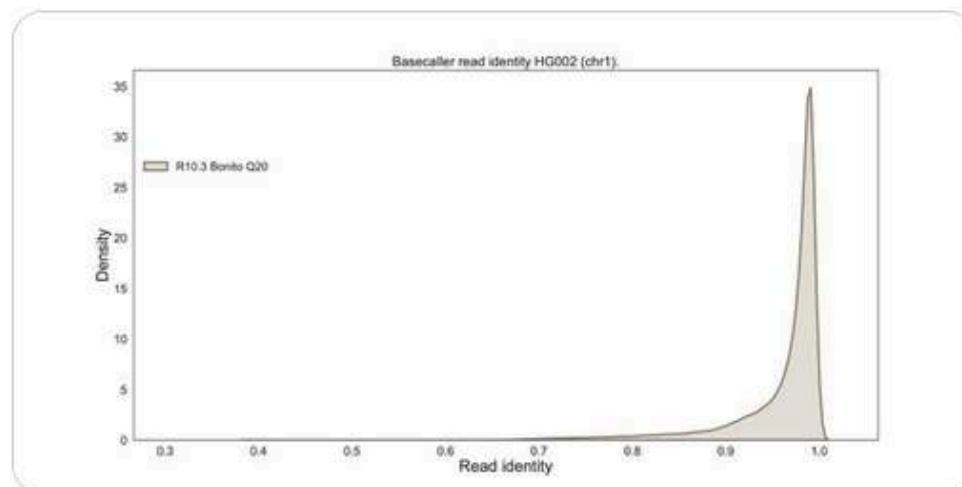
...

Impressive numbers on human genome @nanopore data using Q20 early-access chemistry.

PEPPER-Margin-DeepVariant achieves amazing, precisionFDA level, performance (F1 scores >0.996) with modest coverage

@kishwarshafin @BenedictPaten @pichuan @acarroll_ATG

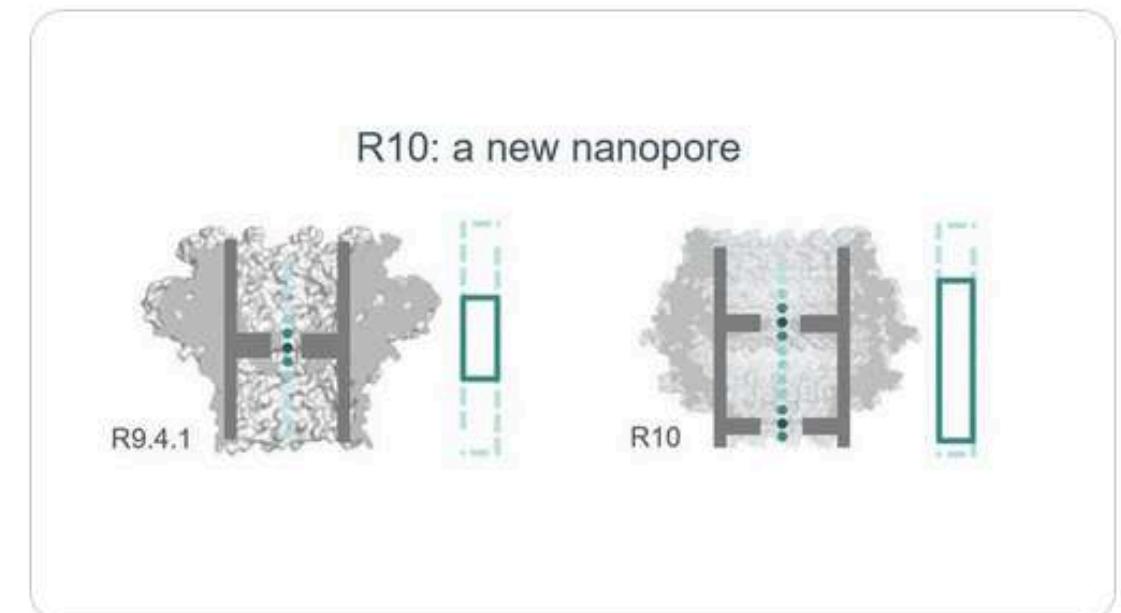
[biorxiv.org/content/10.1101/2021.03.08.480312](https://www.biorxiv.org/content/10.1101/2021.03.08.480312)...



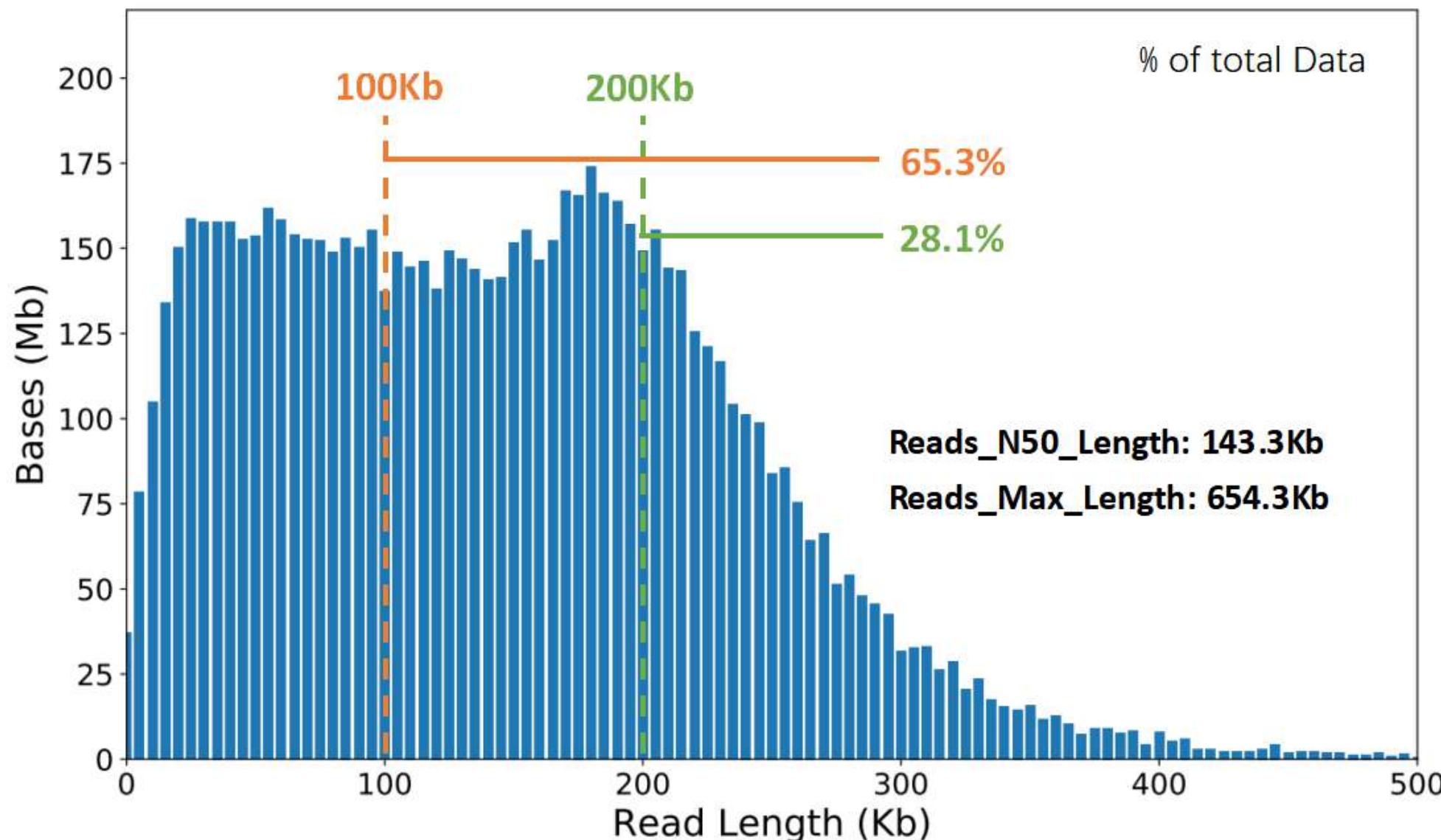
Alexander Wittenberg @AW_NGS · Mar 12

...

Just obtained amazing results on Fusarium spp genome using R10.3 @nanopore PromethION data, Bonito basecalling and Medaka consensus calling. Achieved chromosome-level assembly with QV52. That is >99.999% consensus accuracy! #RNNGS21



Read length and capacity go beyond

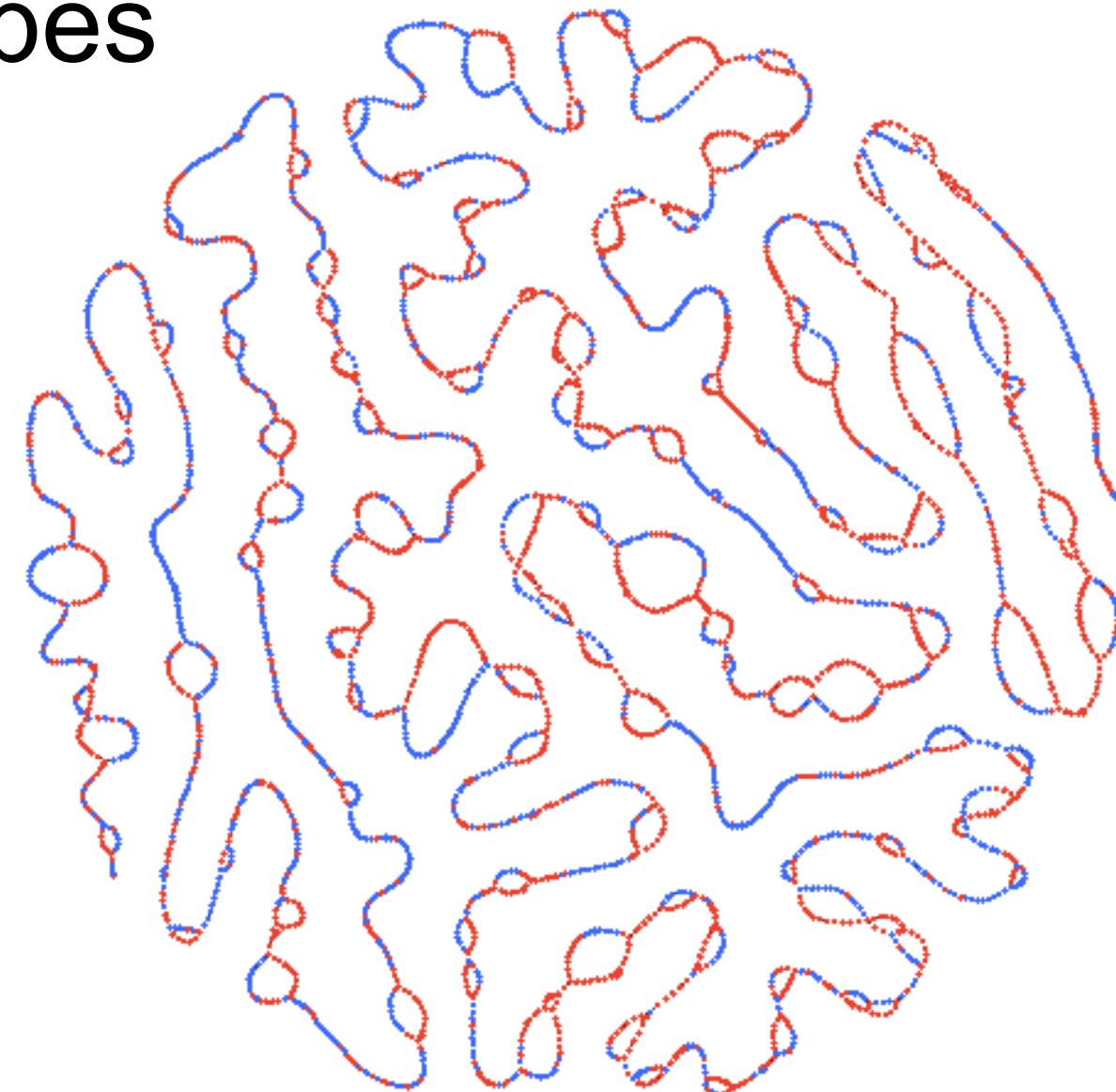


What you can do with long reads: Resolving haplotypes

Credit: Jason Chin

Two genomes. One
assembly. Two colors.
Many bubbles. Game
against entropy.

<http://t.co/uCPmxCRiZ6>

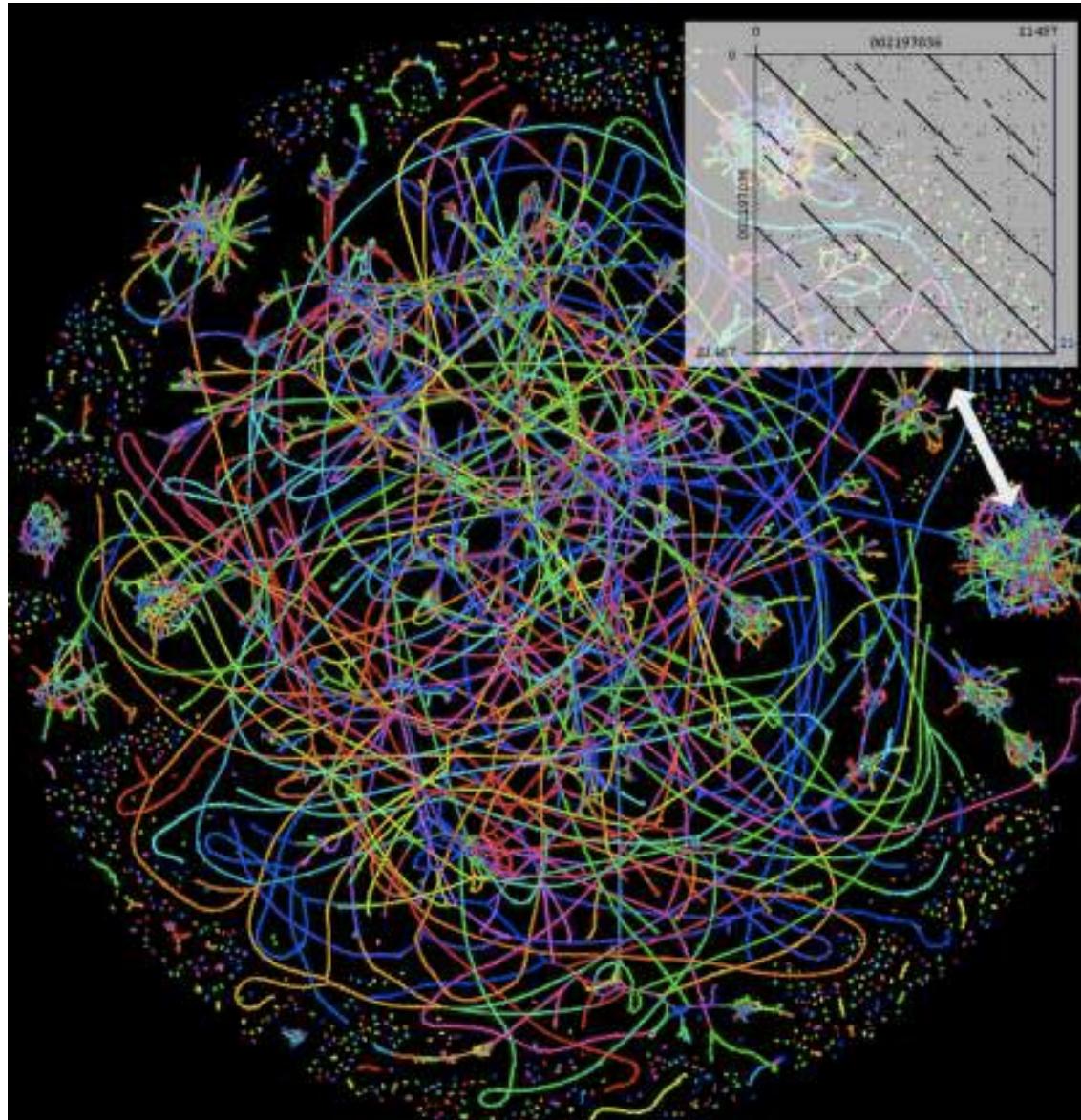


Current limitation of long reads..

Credit: Jason Chin

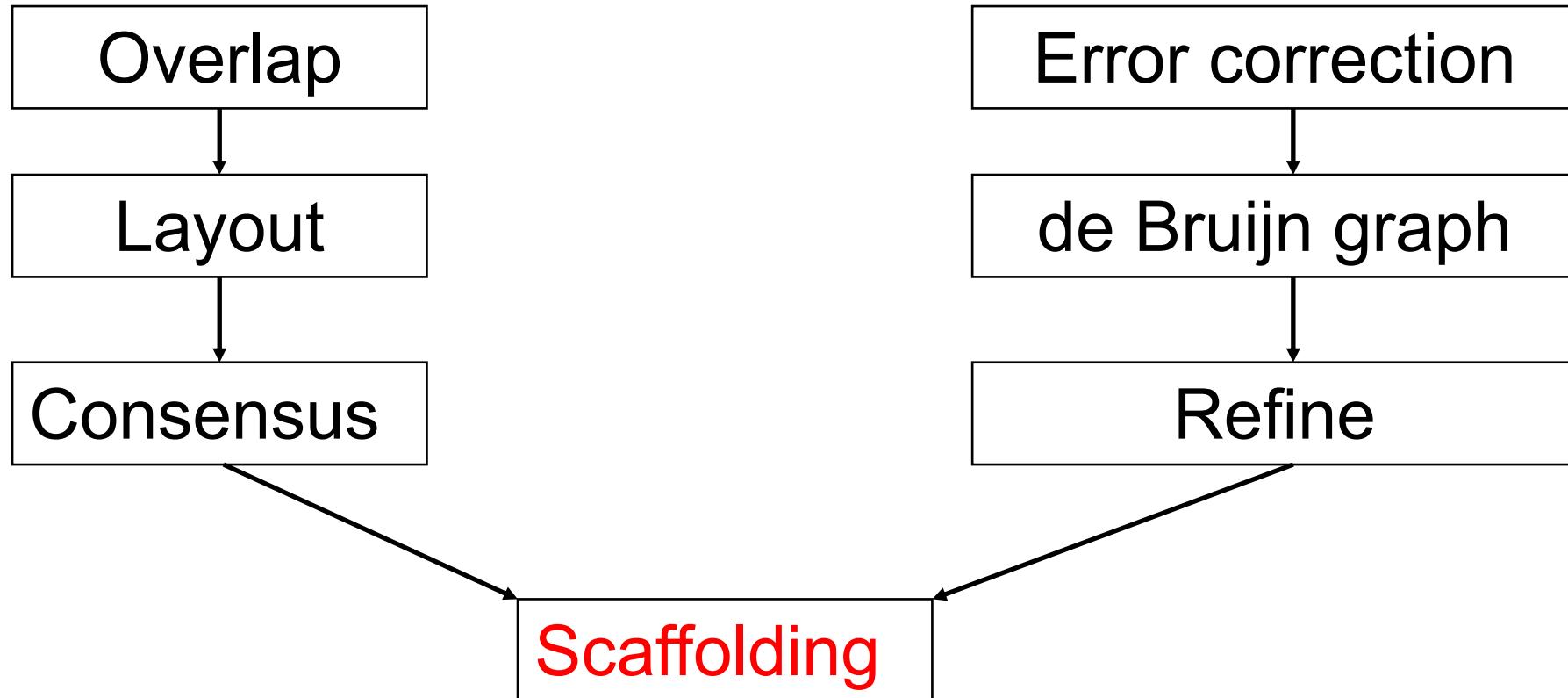
What are those blobs in the genome assembly graph?
Intriguing repeats that have no NCBI blast hit.

<http://t.co/2y7stBGs4W>



Scaffolding

OLC and DBG assemblers



Scaffolding

OLC and DBG attempt to construct longest and most accurate **contigs** (contiguous stretch of assembled bases)

Scaffolding is to order and orient contigs with respect to each other

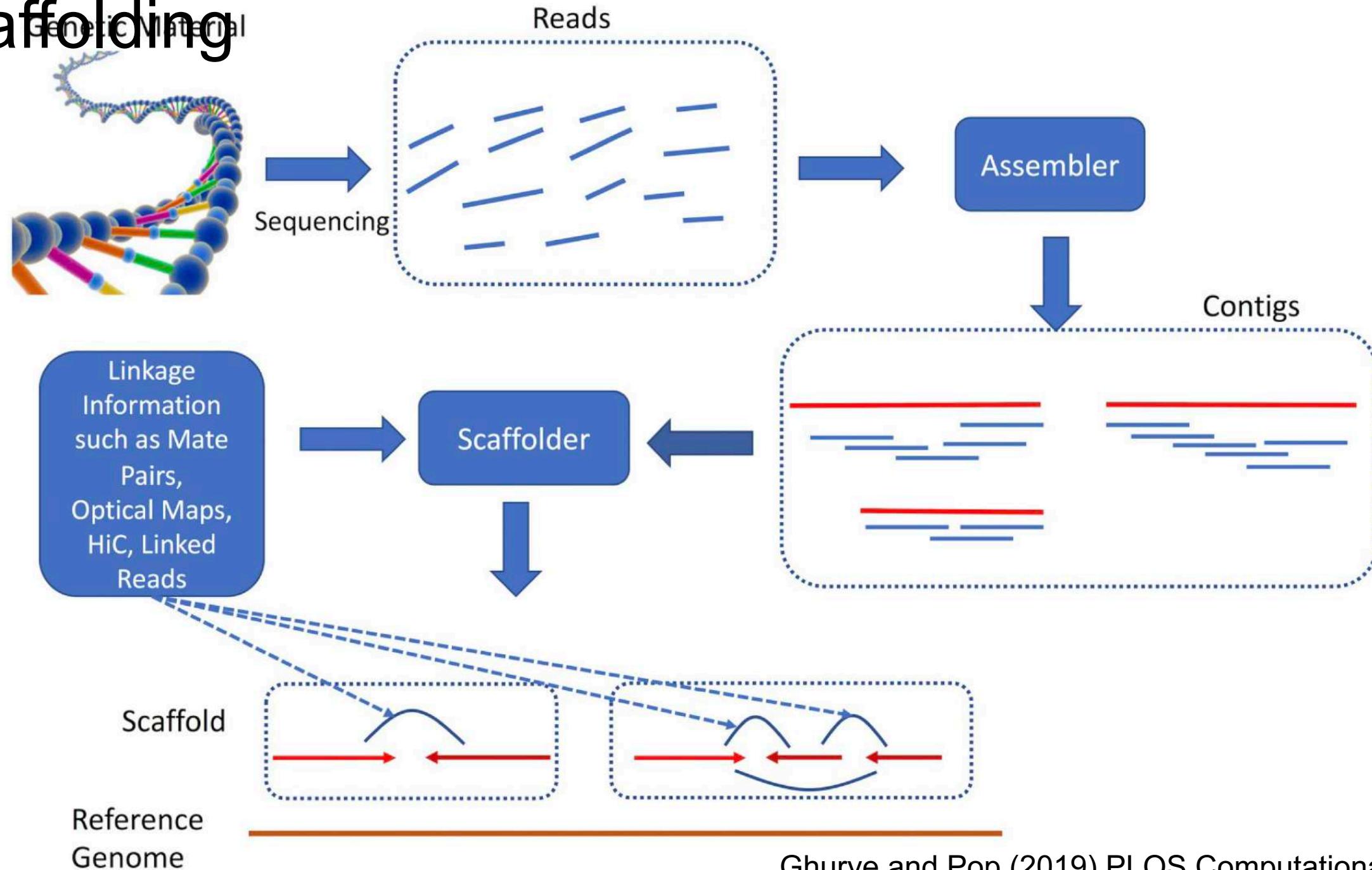
Various data types:

Paired ends / Mate pairs

Genetic map

Additional long range information

Scaffolding



Scaffolding: Paired end sequencing



Because of technology limitation (usually ~150bp at each end), whole fragment is not sequenced. But the distance between two mates equals to length of fragment (**insert size**)

Scaffolding: Paired end sequencing

- DNA fragment (200-800 bp)



- Single end



- Paired end (up to 800 bp span)



- Mate pair (up to 40 kbp span)

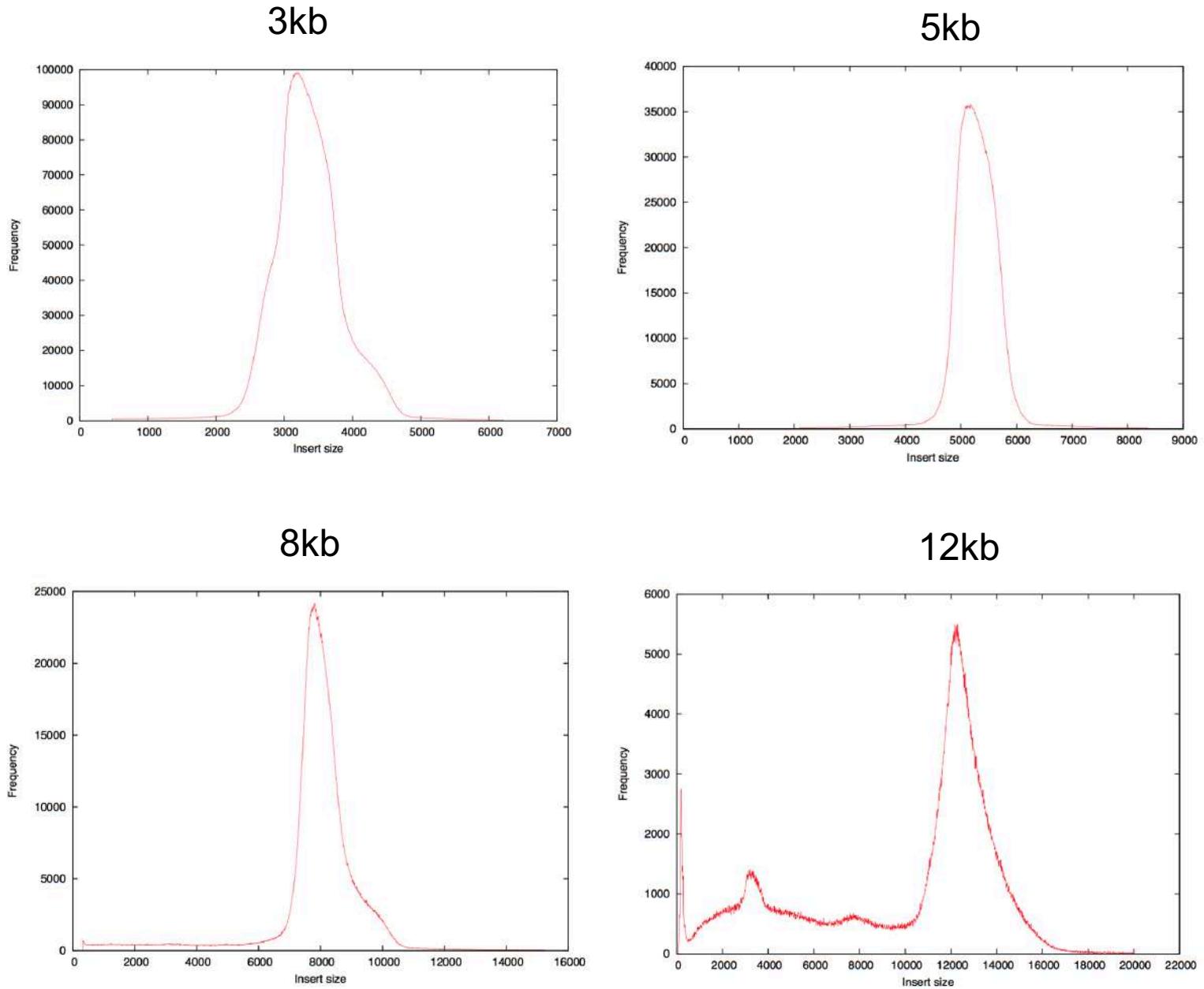


Examples

How to check insert size?

Remap the data back to the assembly

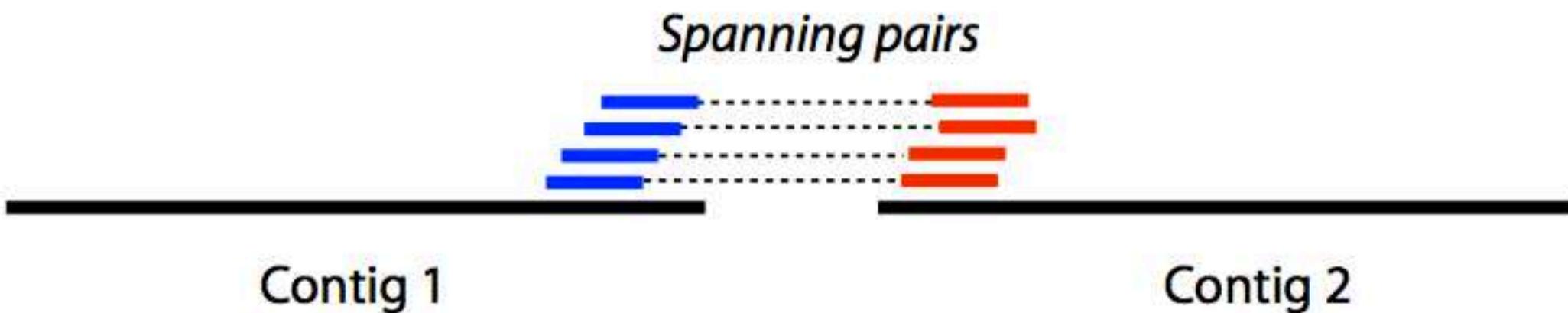
Problem can arise in larger insert sizes



Scaffolding (Illumina; obsoleted)

Say we have a collection of pairs and we assemble them as usual

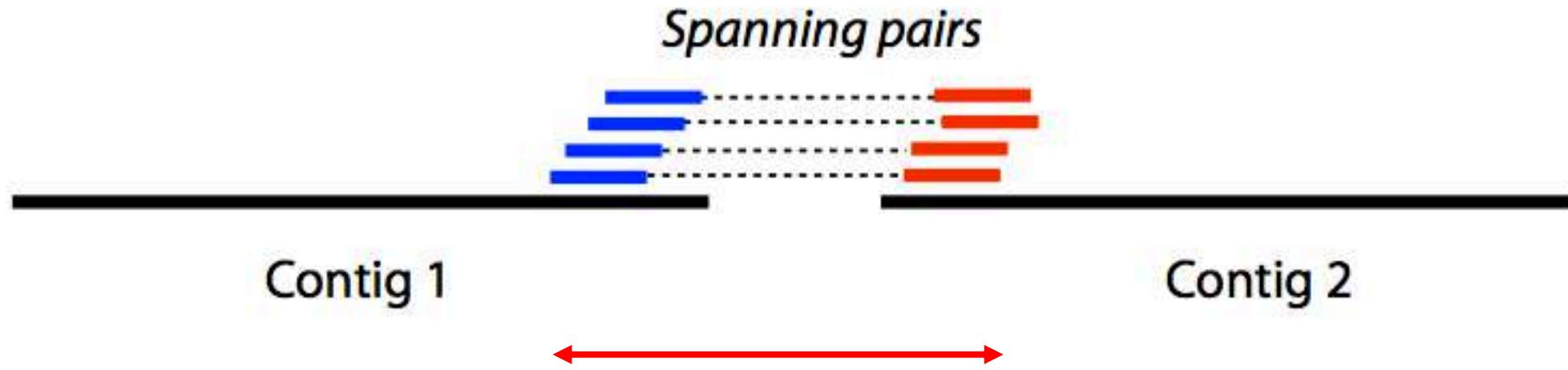
Assembly yields two contigs:



...and we discover that some of the mates at one edge of contig 1 are paired with mates in contig 2

Call these *spanning pairs*

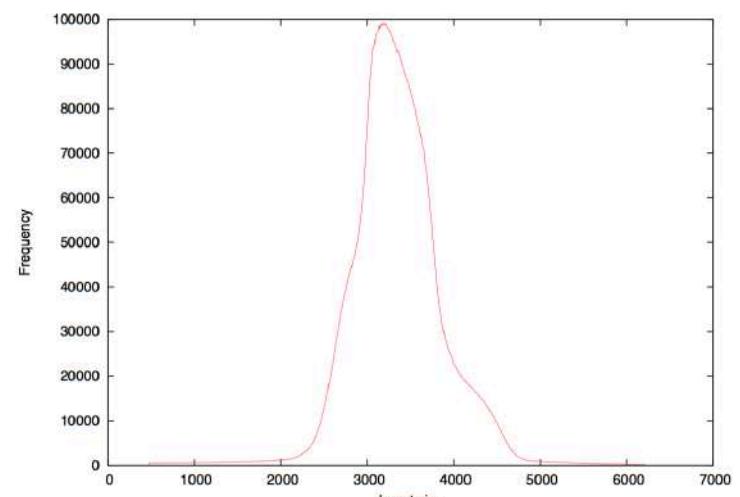
Scaffolding (Illumina; obsoleted)



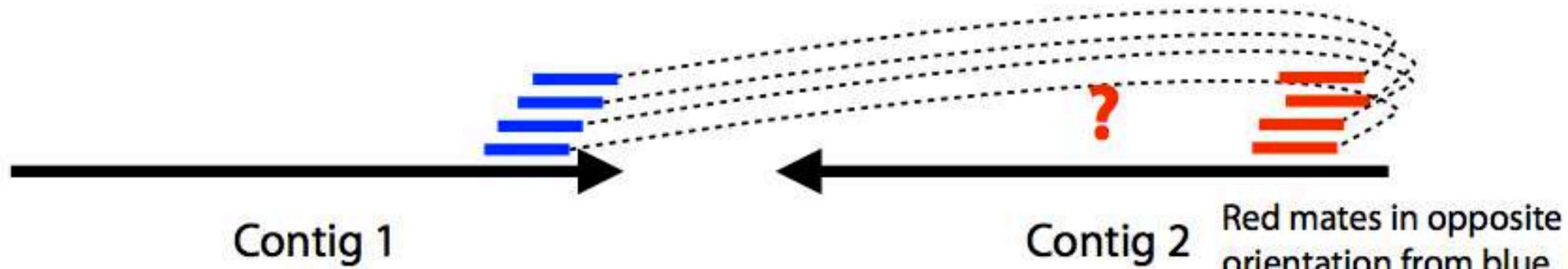
Does the distance equal to the insert size distribution mapped to the rest the genome?

Yes = Accept and Contig1NNNNContig2

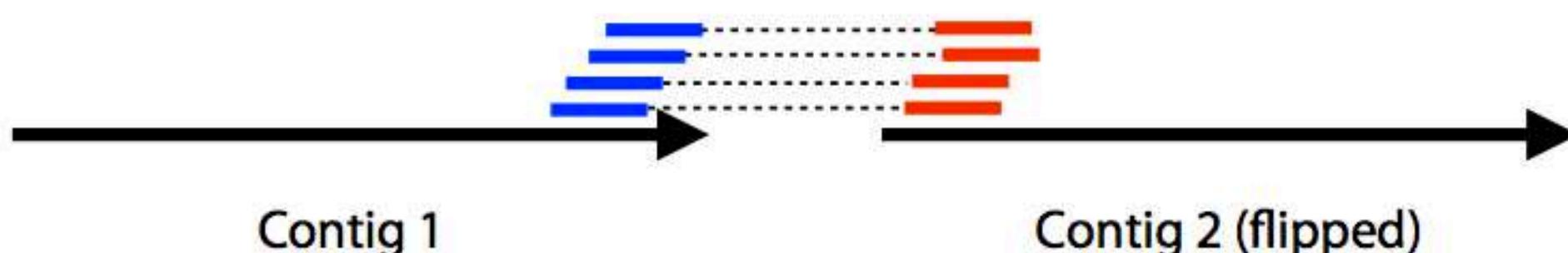
No = Reject



Scaffolding (Illumina; obsoleted)



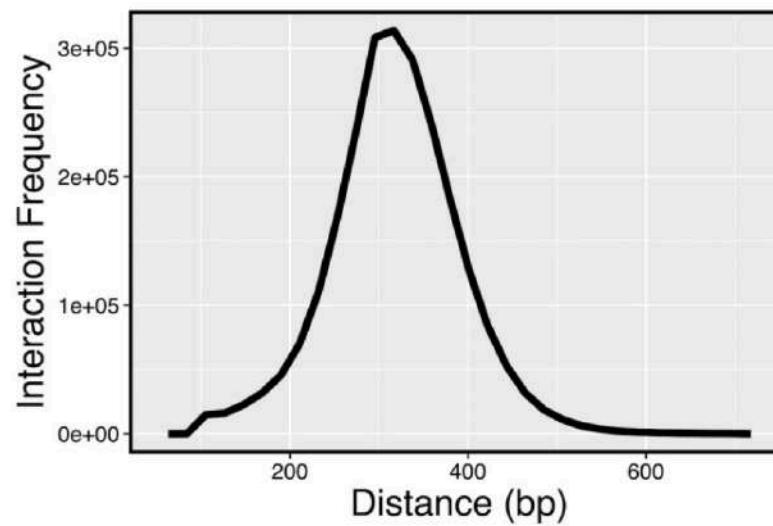
What does the picture look like if contigs 1 and 2 are close, but we assembled contig 2 “backwards” (i.e. reverse complemented)



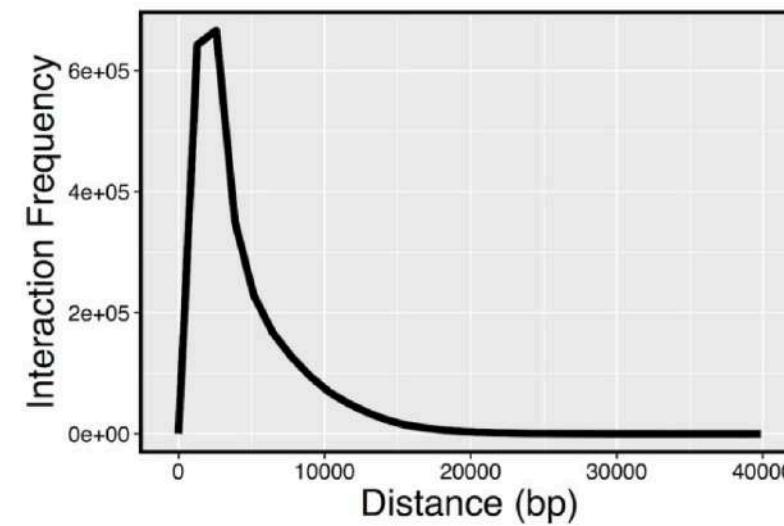
Pairs also tell us about contigs' relative *orientation*

The genomic span covered by different technologies

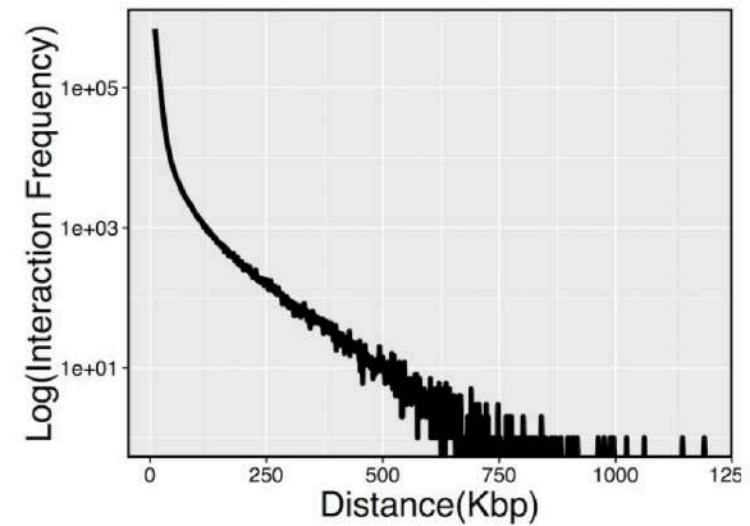
Illumina



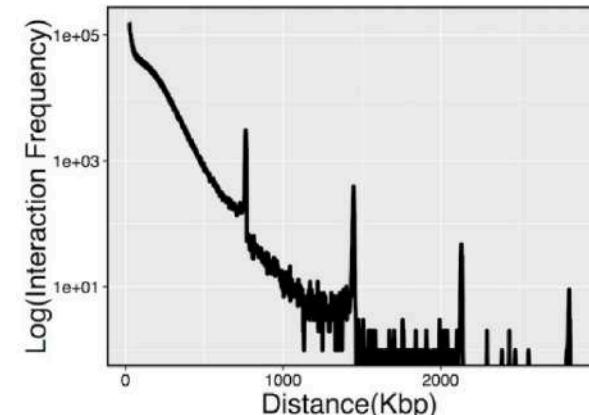
Pacbio



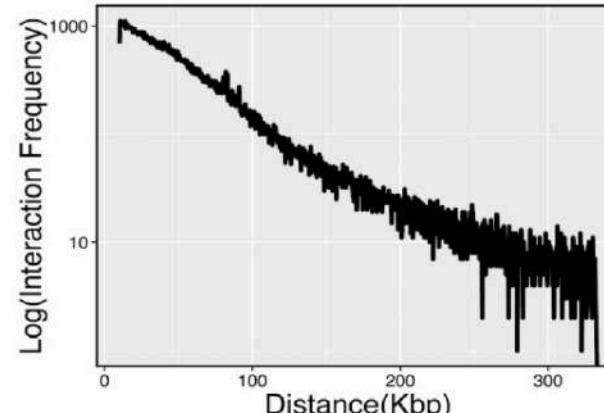
Oxford Nanopore



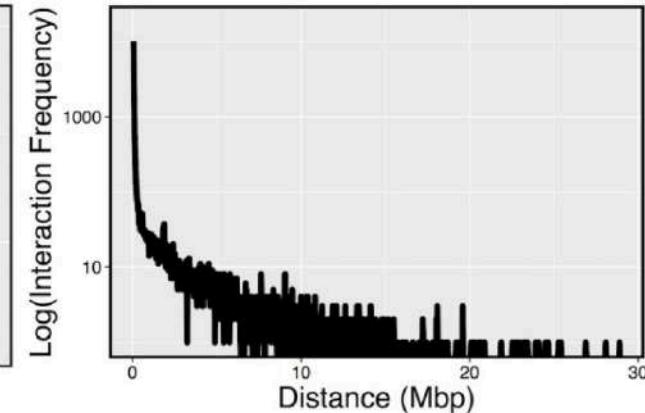
Optical Maps



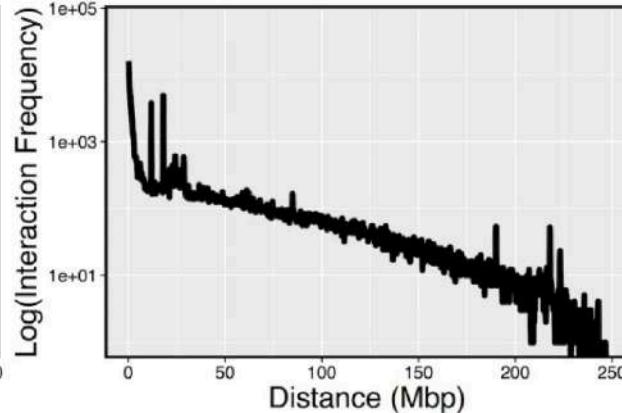
Linked Reads



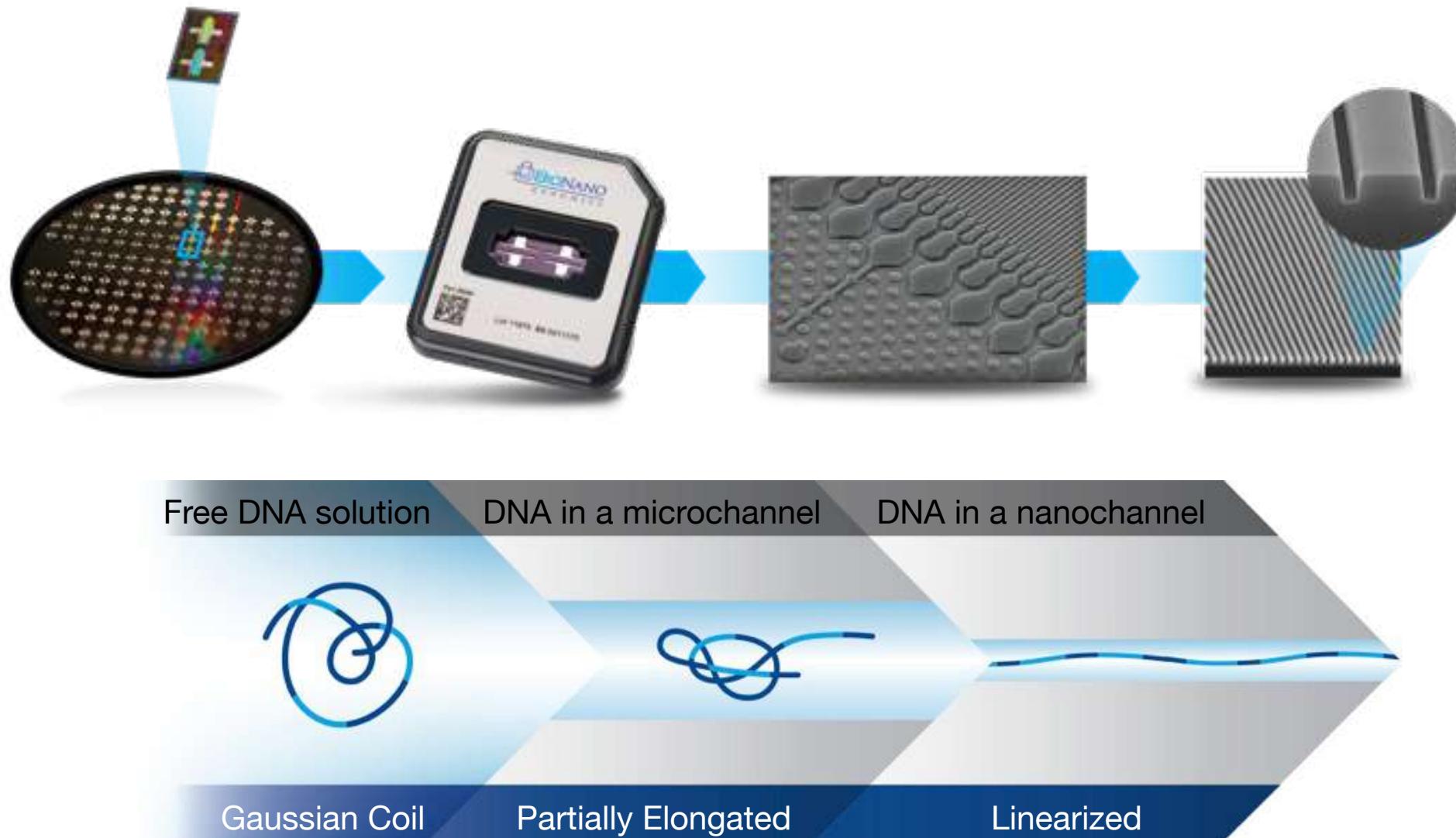
Chicago



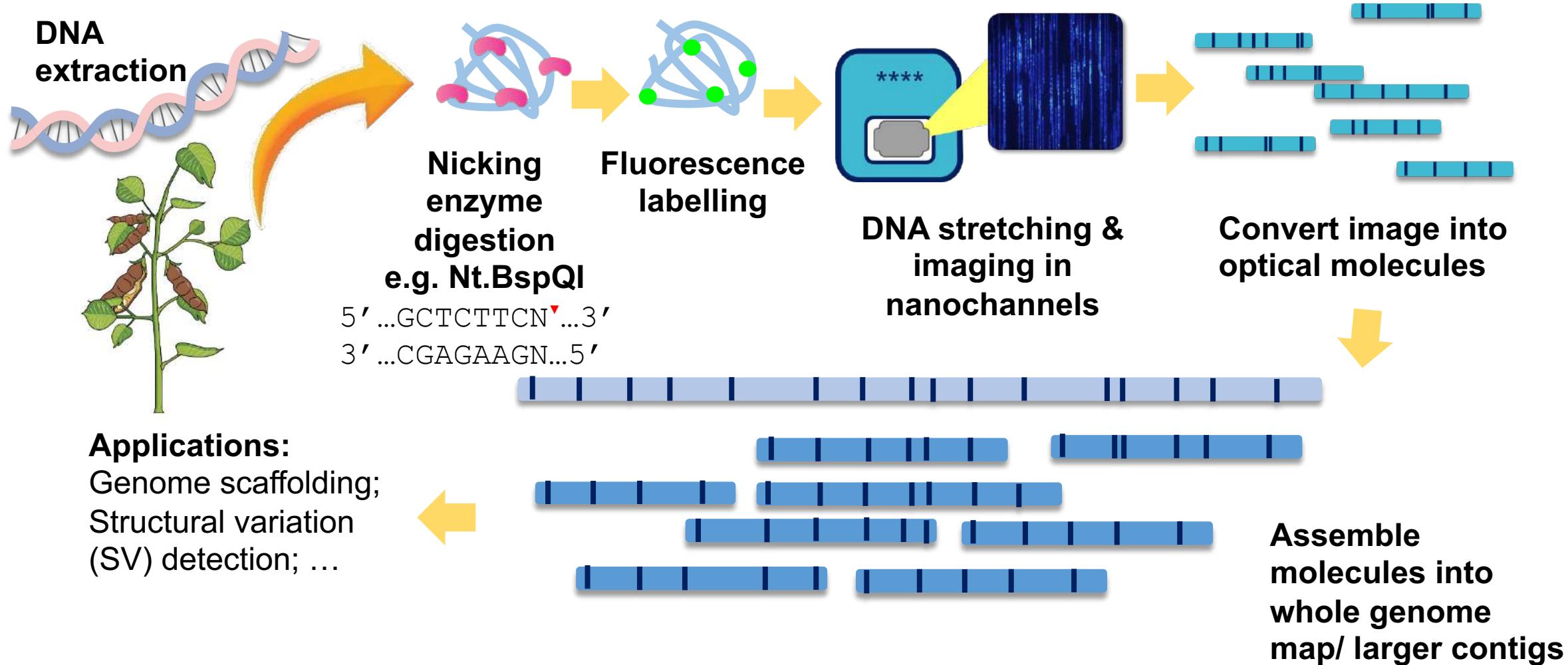
HiC



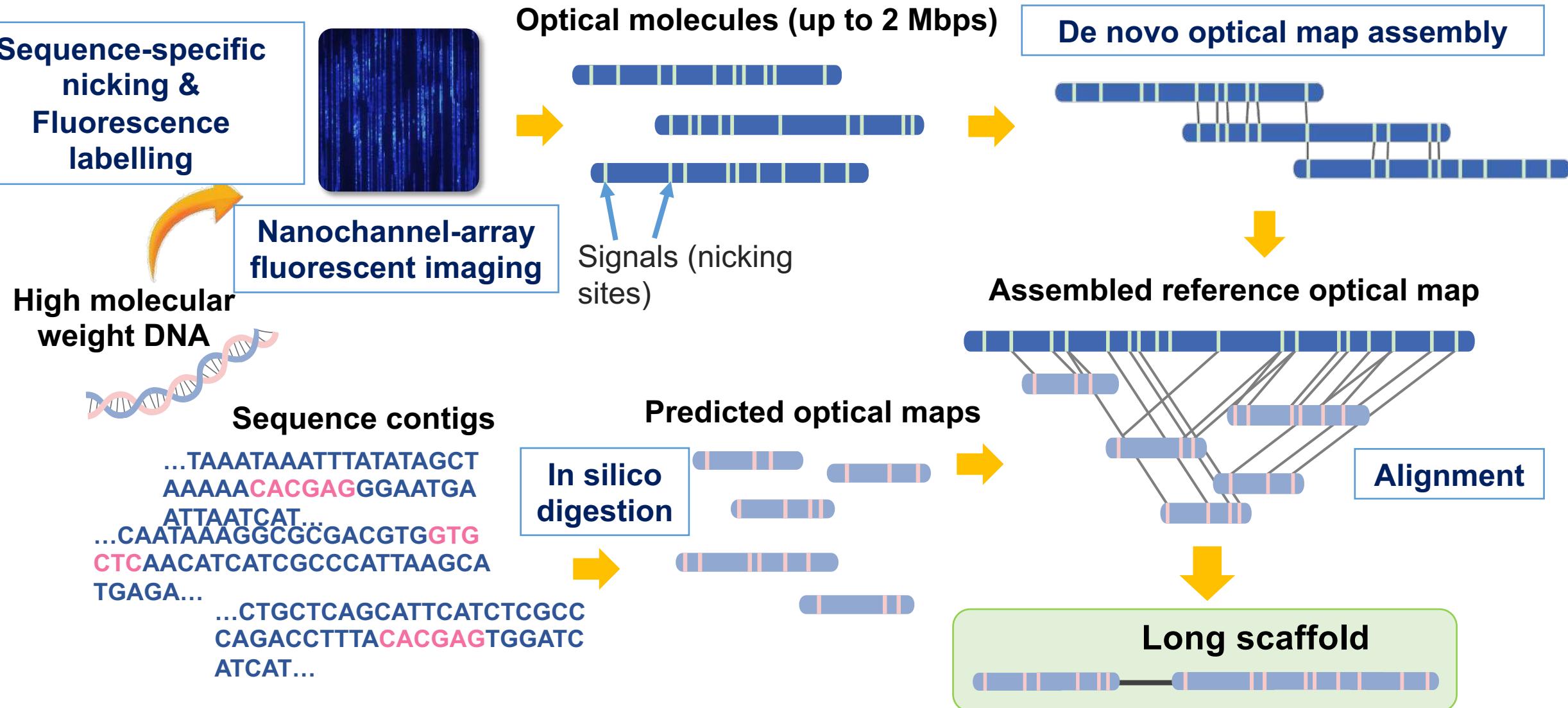
Optical map: DNA linearized in nanochannel array



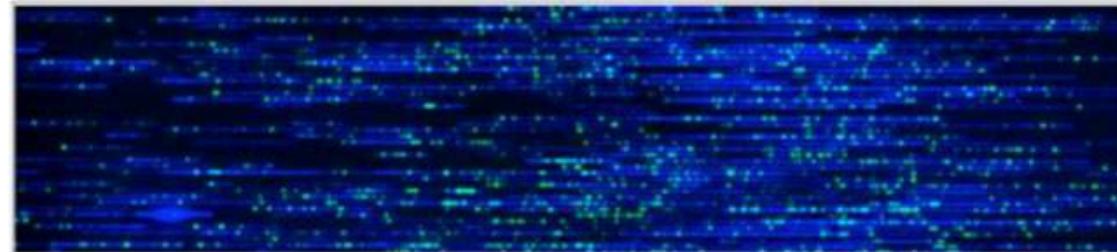
Workflow of an optical mapping procedure



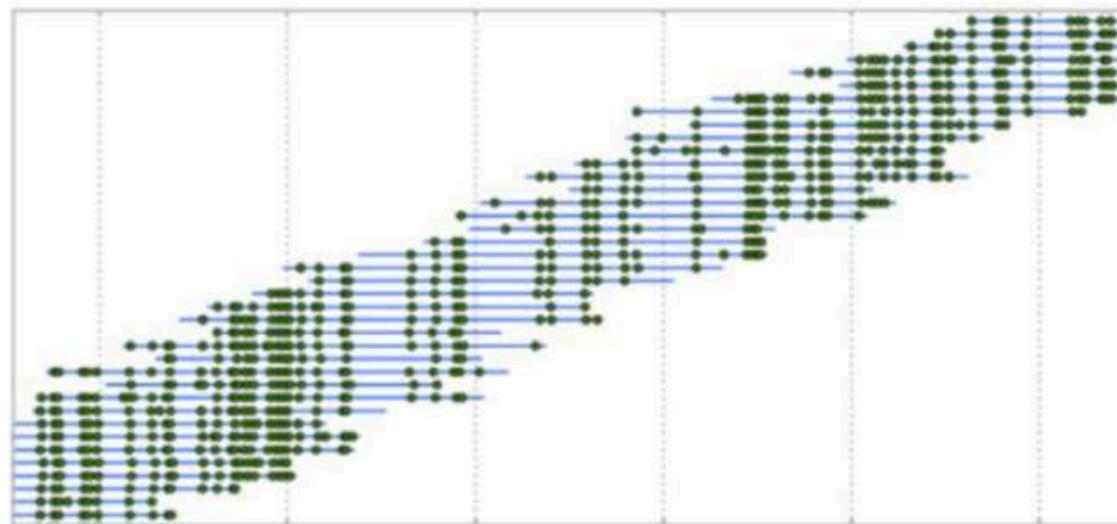
Optical mapping-assisted scaffolding principles



Raw Image Data

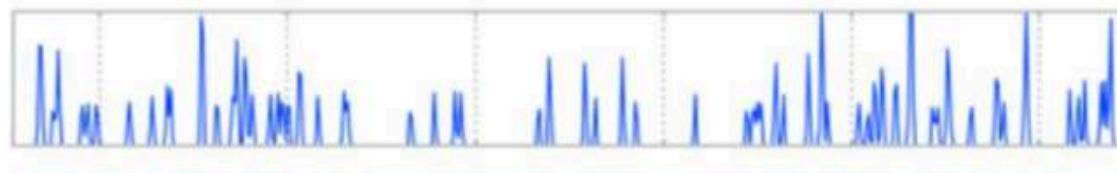


Conversion to
Molecules



Population of Molecules

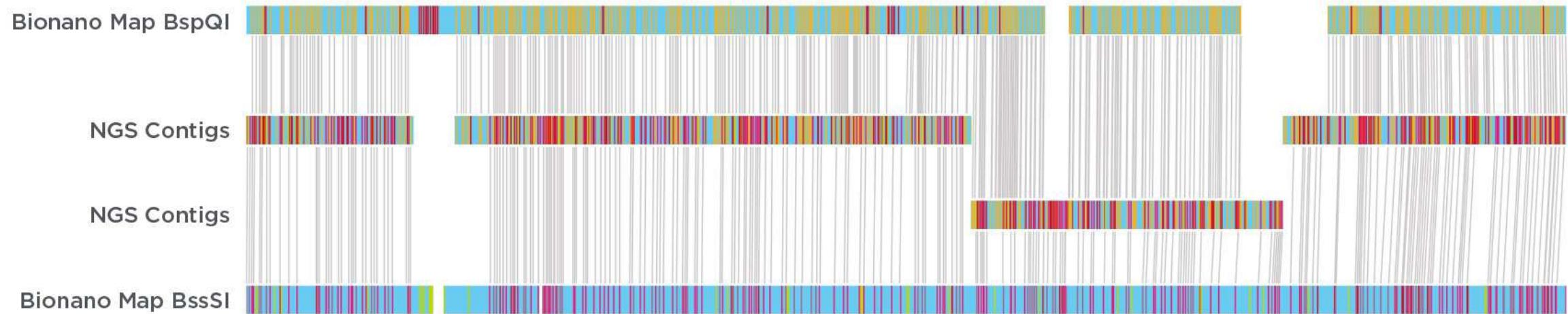
Aggregation &
Assembly



Consensus Genome Map

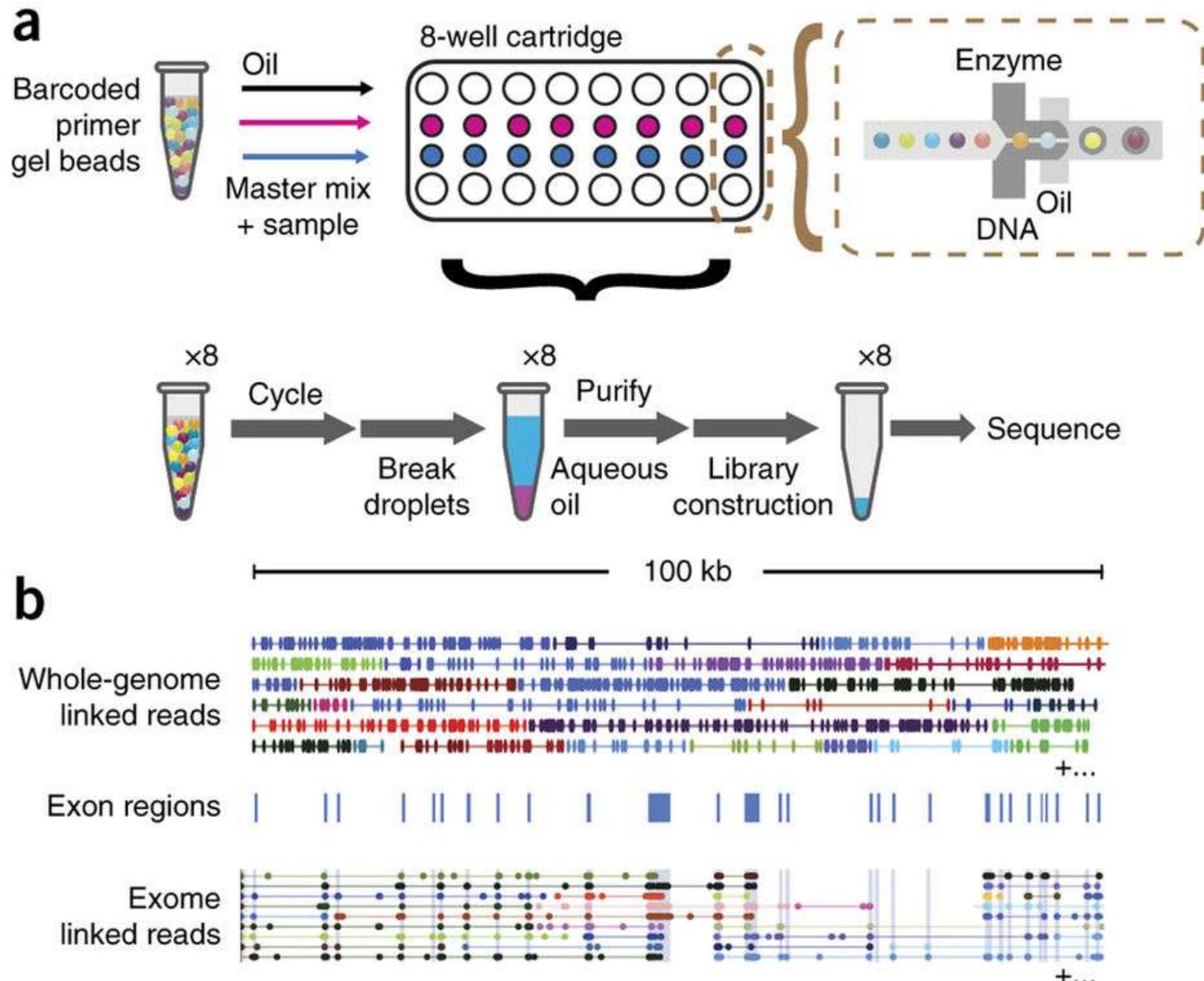


TWO ENZYME HYBRID SCAFFOLDING



Haplotyping germline and cancer genomes with high-throughput linked-read sequencing

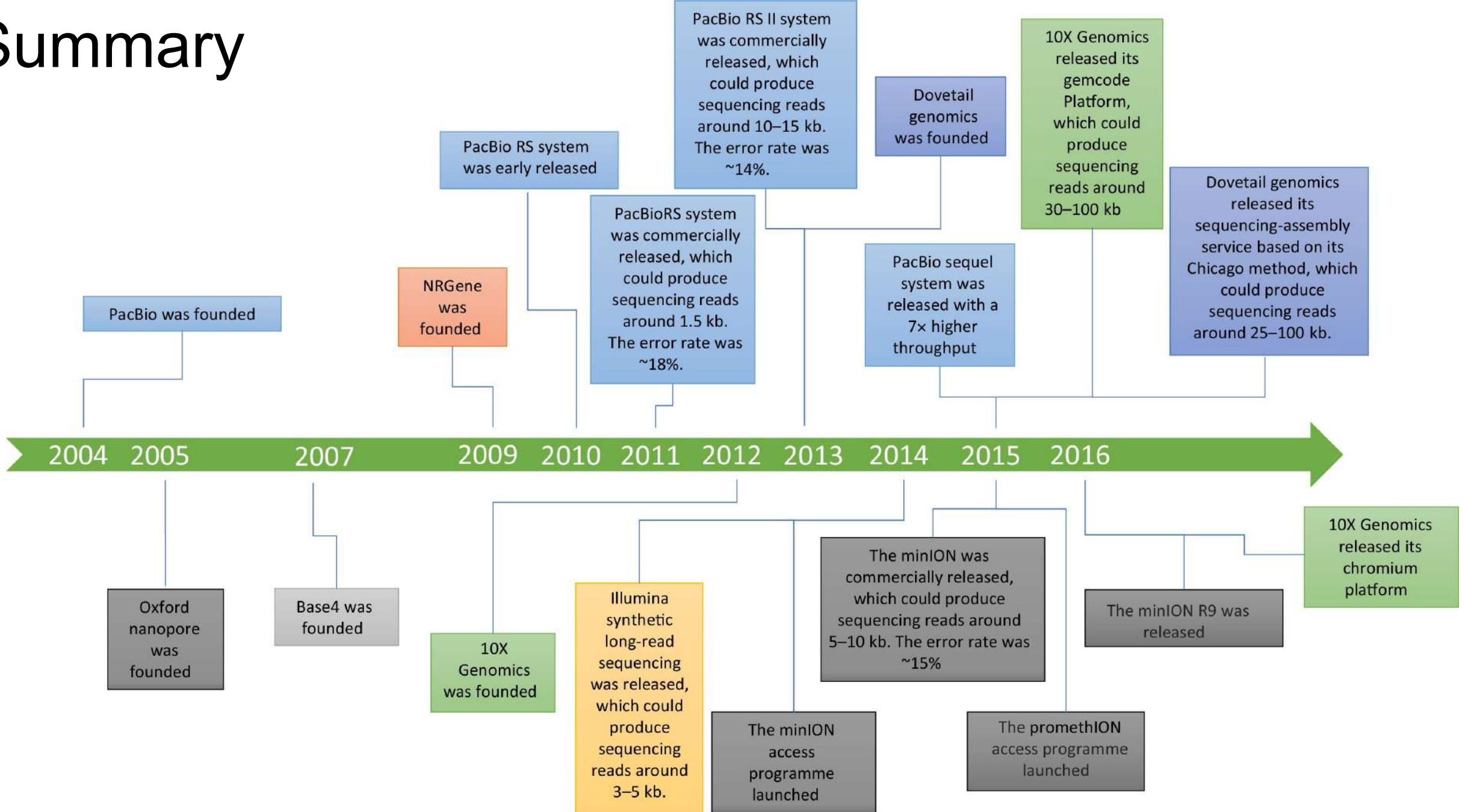
- Long range information from short reads using 14bp barcodes
- Very low input DNA (ng) and 20 mins preparation time
- 1ng of DNA is split across 100,000 Gel coated beads
- Single-cell available



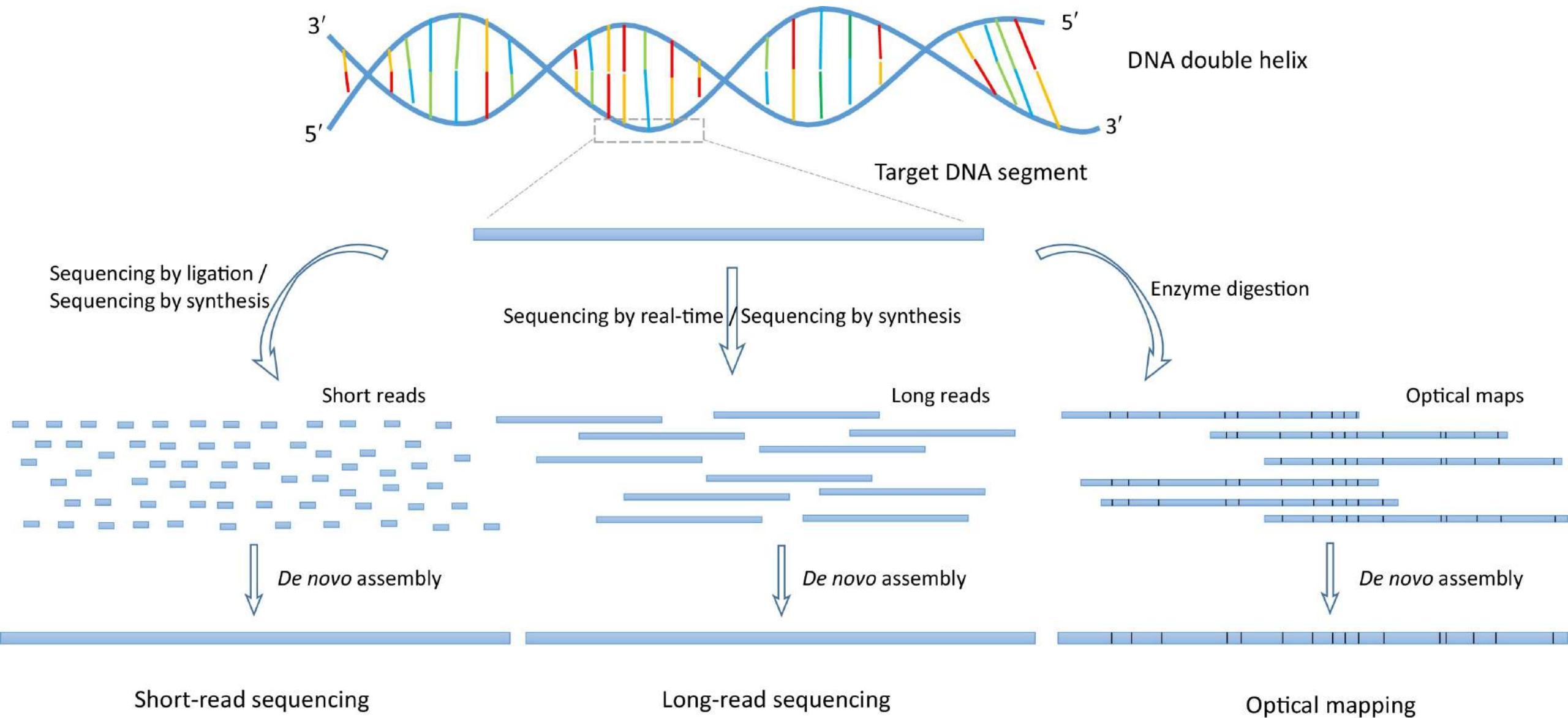
10X Genomics

<https://www.youtube.com/watch?v=aUyFzwRFWJQ>

Summary

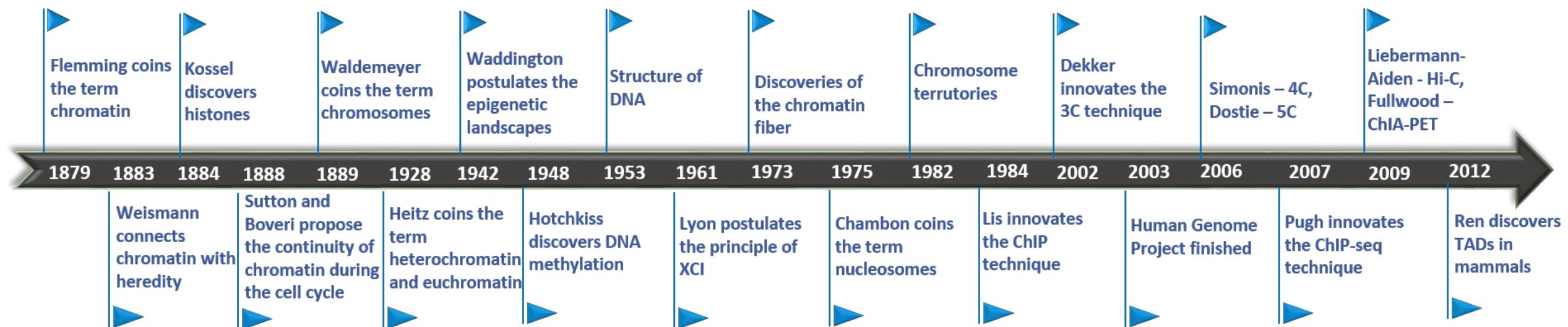


Summary

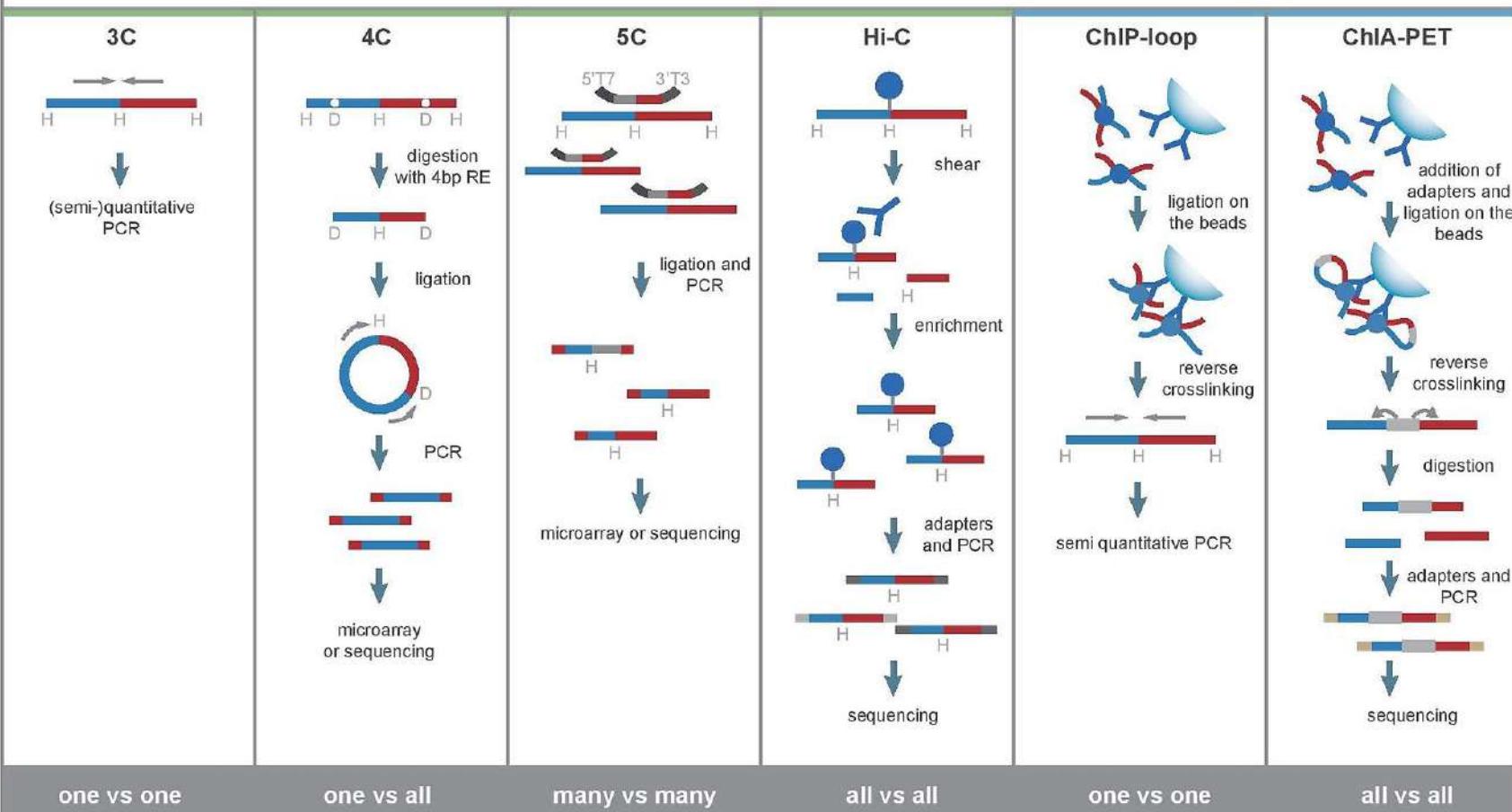
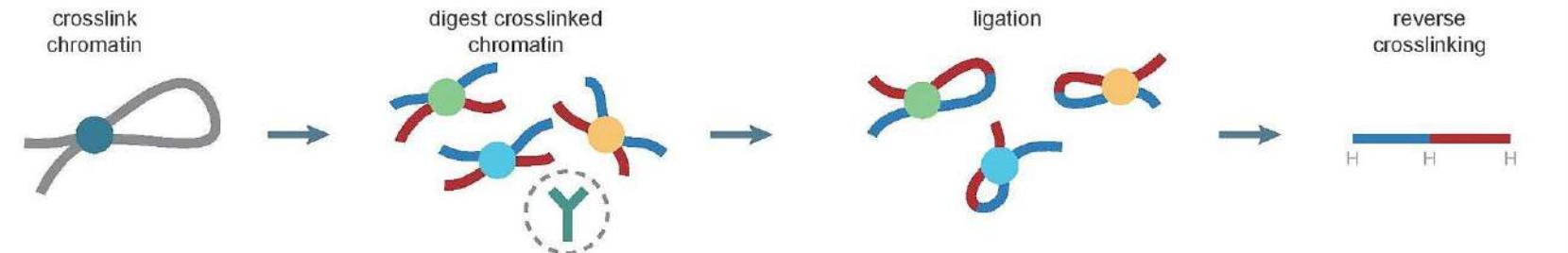


Scaffolding using Chromosome conformation capture

Chromosome conformation capture techniques (often abbreviated to 3C technologies or 3C-based methods) are a set of molecular biology methods used to analyze the spatial organization of chromatin in a cell. These methods quantify the **number of interactions between genomic loci that are nearby in 3-D space**, but may be **separated by many nucleotides** in the linear genome



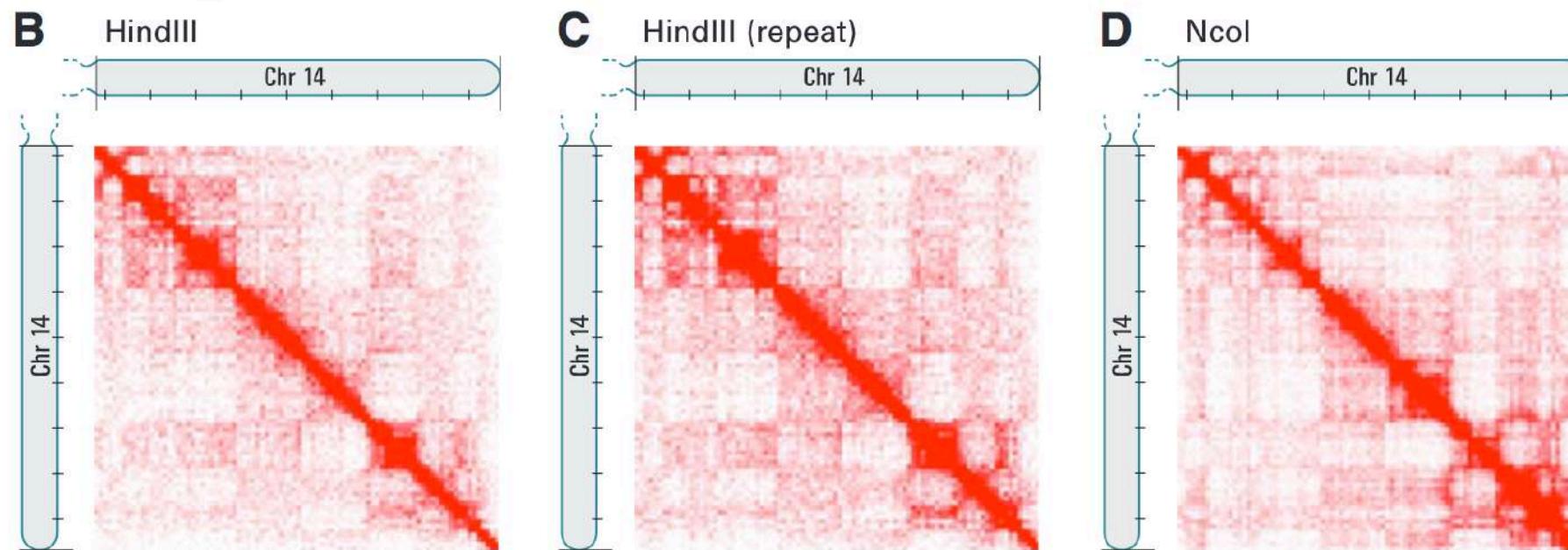
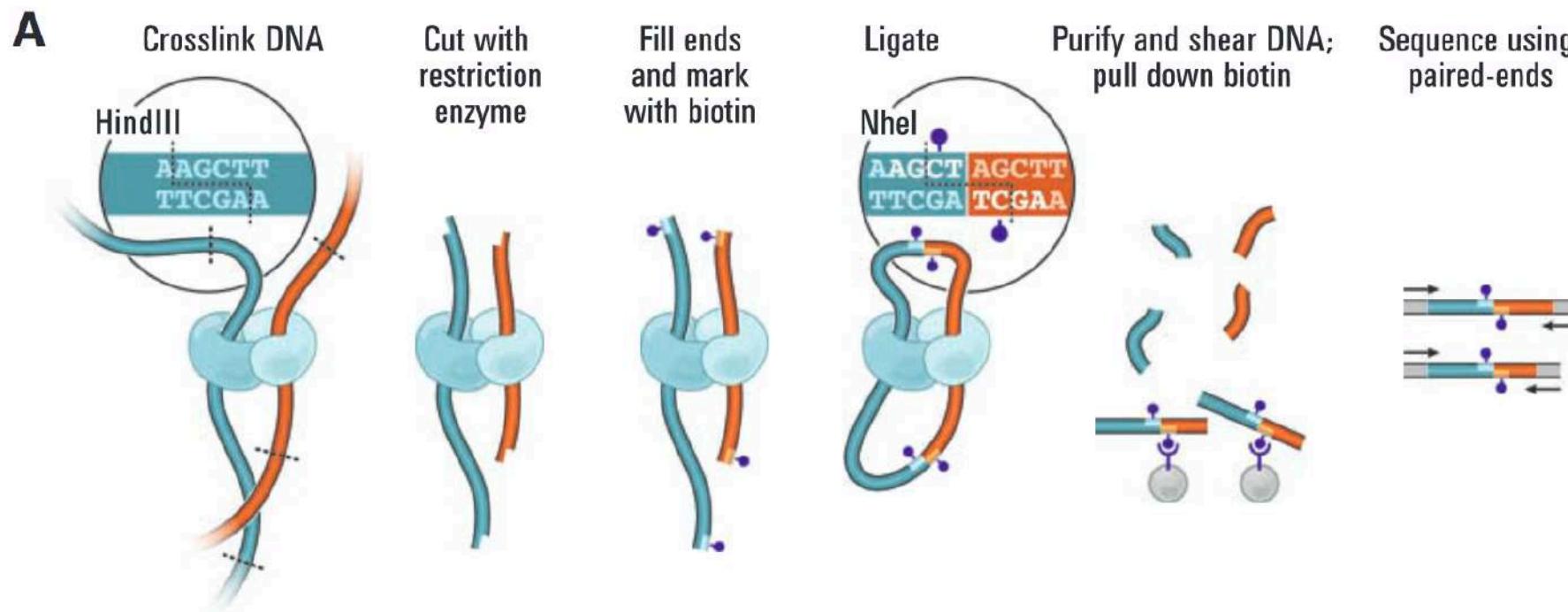
Chromosome Conformation Technologies

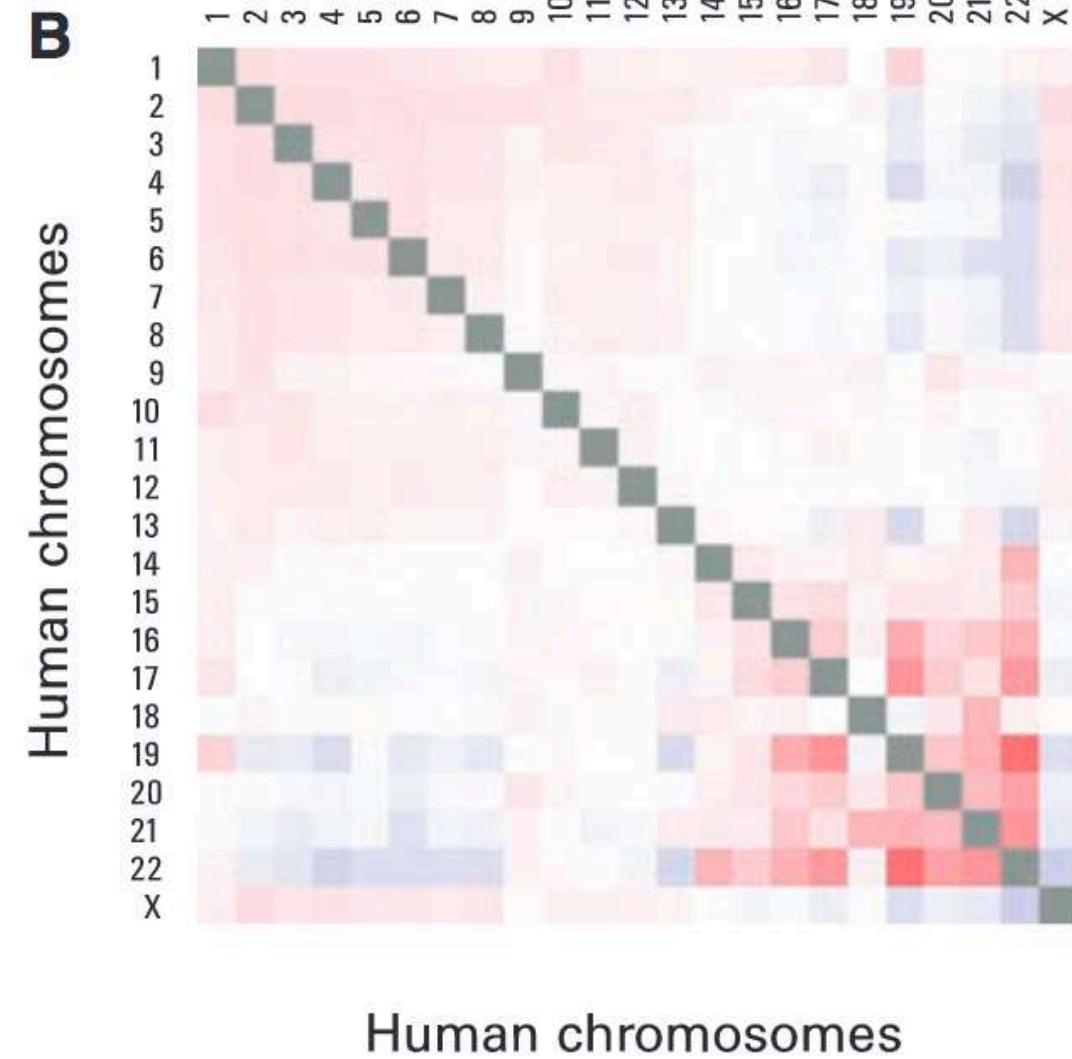
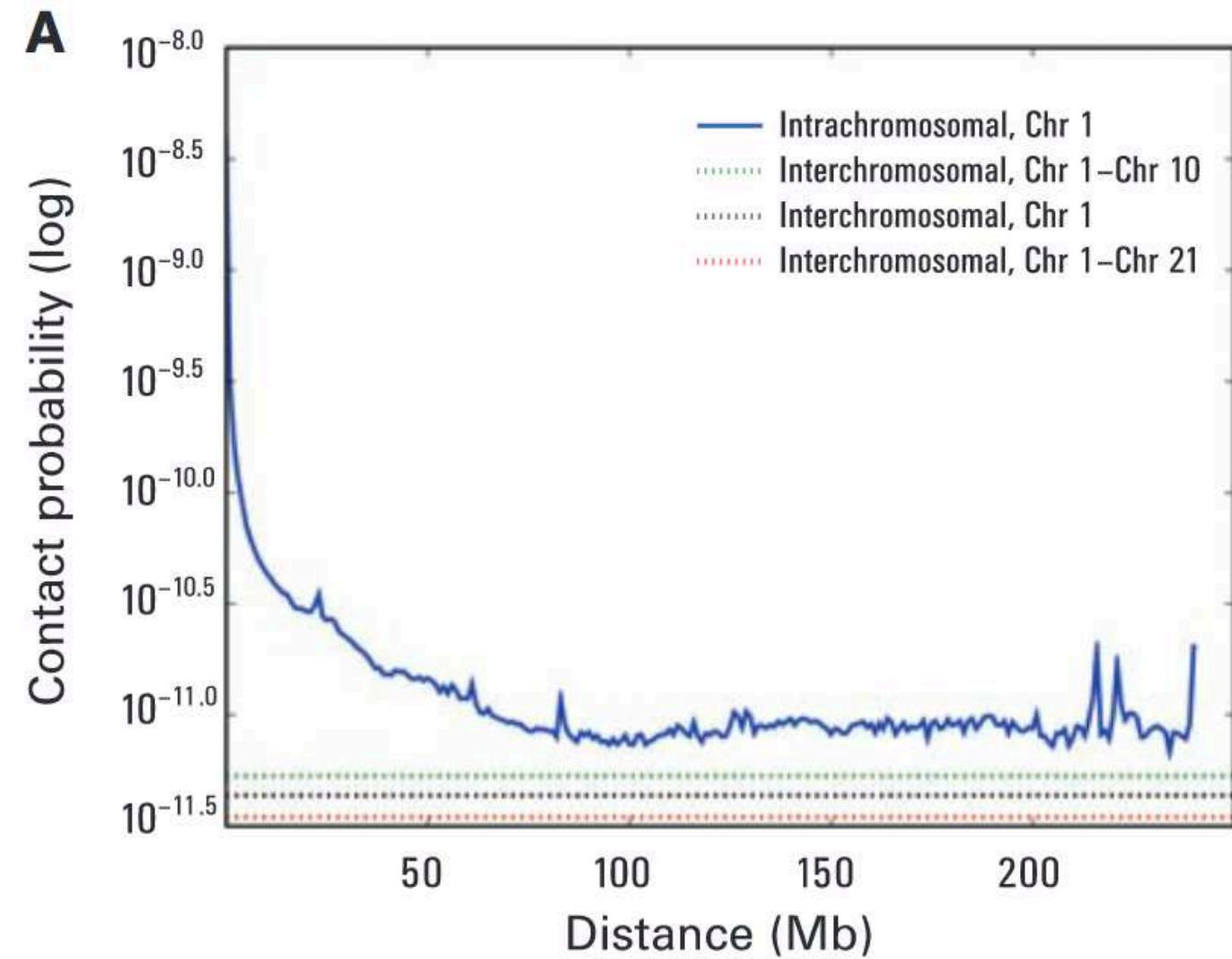


Comprehensive Mapping of Long-Range Interactions Reveals Folding Principles of the Human Genome

Erez Lieberman-Aiden,^{1,2,3,4*} Nynke L. van Berkum,^{5*} Louise Williams,¹ Maxim Imakaev,² Tobias Ragoczy,^{6,7} Agnes Telling,^{6,7} Ido Amit,¹ Bryan R. Lajoie,⁵ Peter J. Sabo,⁸ Michael O. Dorschner,⁸ Richard Sandstrom,⁸ Bradley Bernstein,^{1,9} M. A. Bender,¹⁰ Mark Groudine,^{6,7} Andreas Gnirke,¹ John Stamatoyannopoulos,⁸ Leonid A. Mirny,^{2,11} Eric S. Lander,^{1,12,13†} Job Dekker^{5†}

We describe Hi-C, a method that probes the three-dimensional architecture of whole genomes by coupling proximity-based ligation with massively parallel sequencing. We constructed spatial proximity maps of the human genome with Hi-C at a resolution of 1 megabase. These maps confirm the presence of chromosome territories and the spatial proximity of small, gene-rich chromosomes. We identified an additional level of genome organization that is characterized by the spatial segregation of open and closed chromatin to form two genome-wide compartments.





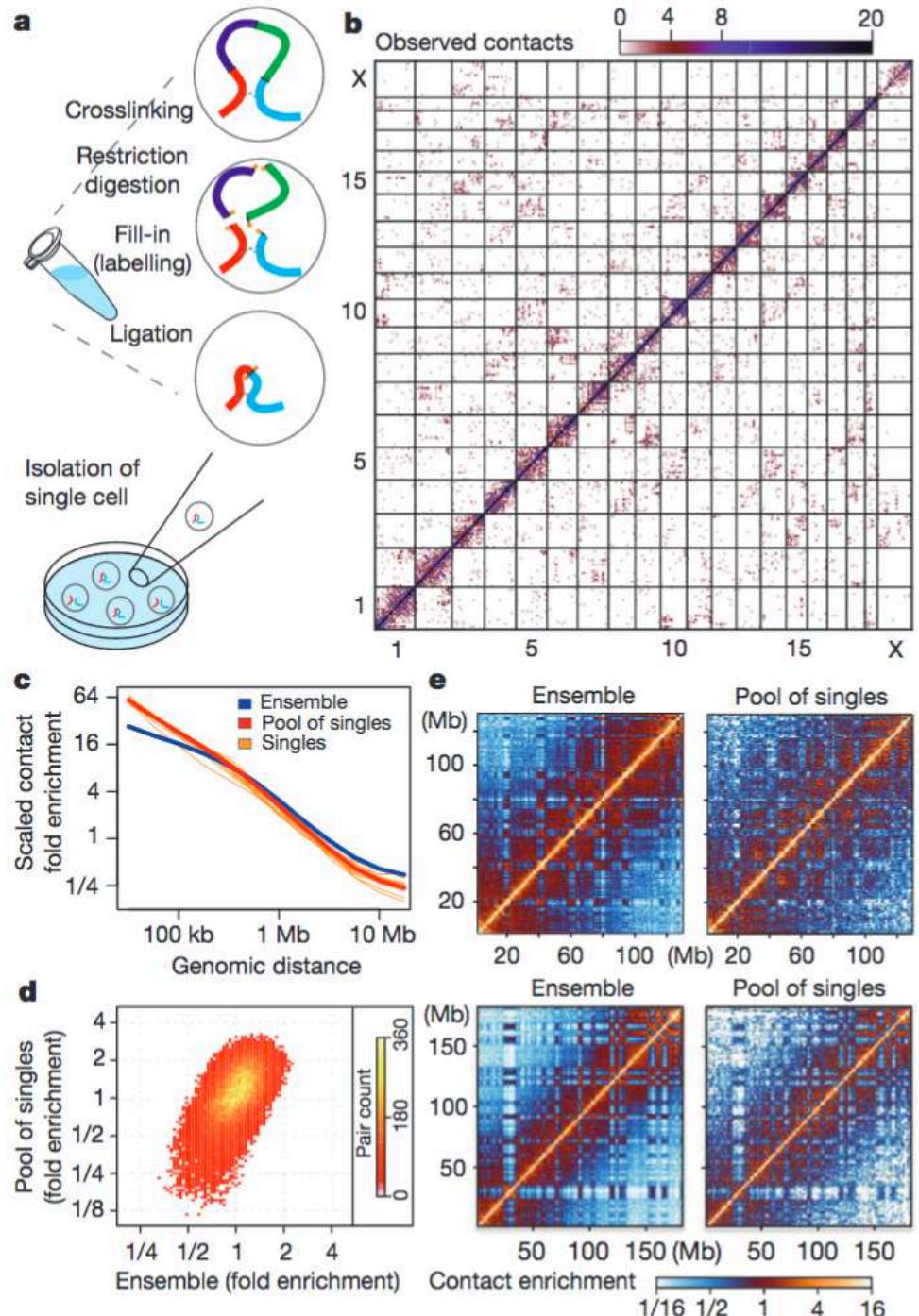
Hi-C at single cell level

ARTICLE

doi:10.1038/nature12593

Single-cell Hi-C reveals cell-to-cell variability in chromosome structure

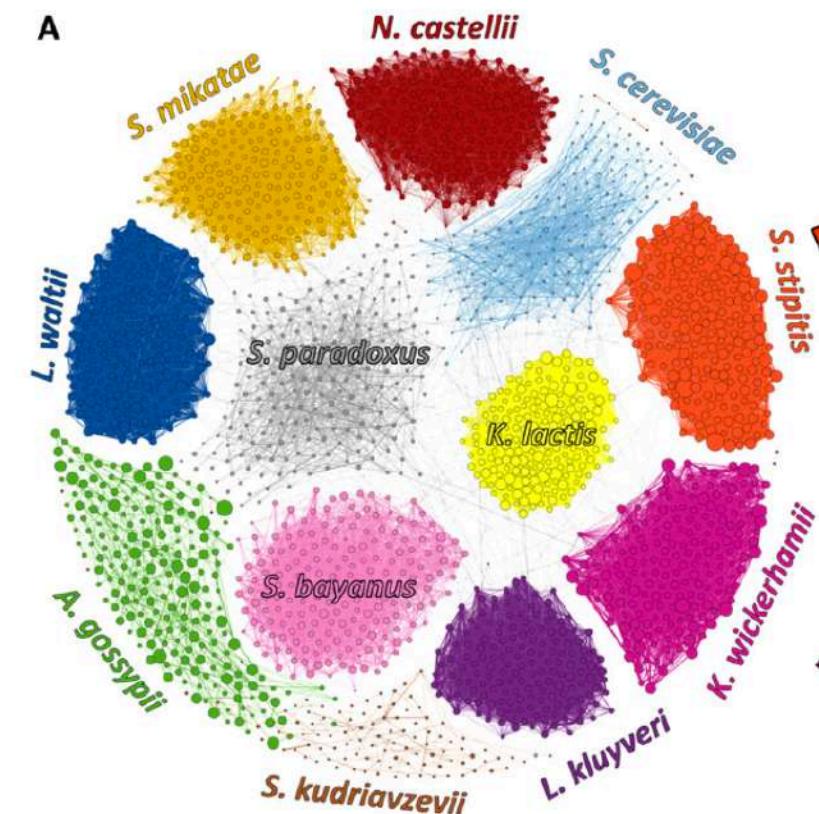
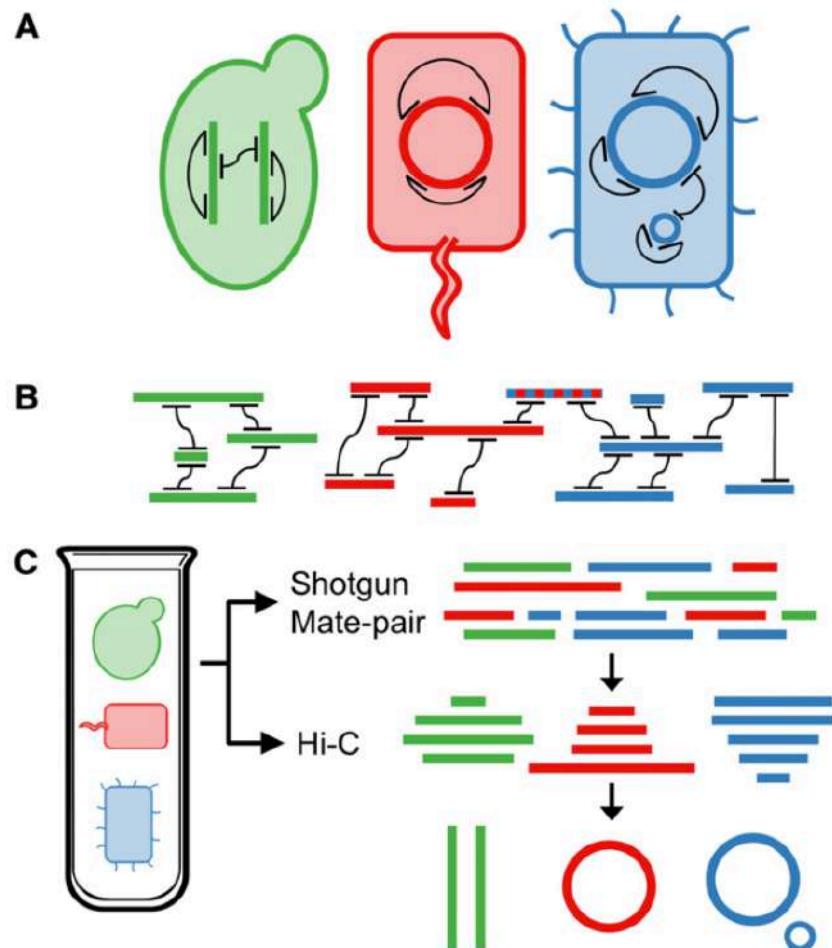
Takashi Nagano^{1*}, Yaniv Lubling^{2*}, Tim J. Stevens^{3*}, Stefan Schoenfelder¹, Eitan Yaffe², Wendy Dean⁴, Ernest D. Laue³, Amos Tanay² & Peter Fraser¹



Species-Level Deconvolution of Metagenome Assemblies with Hi-C-Based Contact Probability Maps

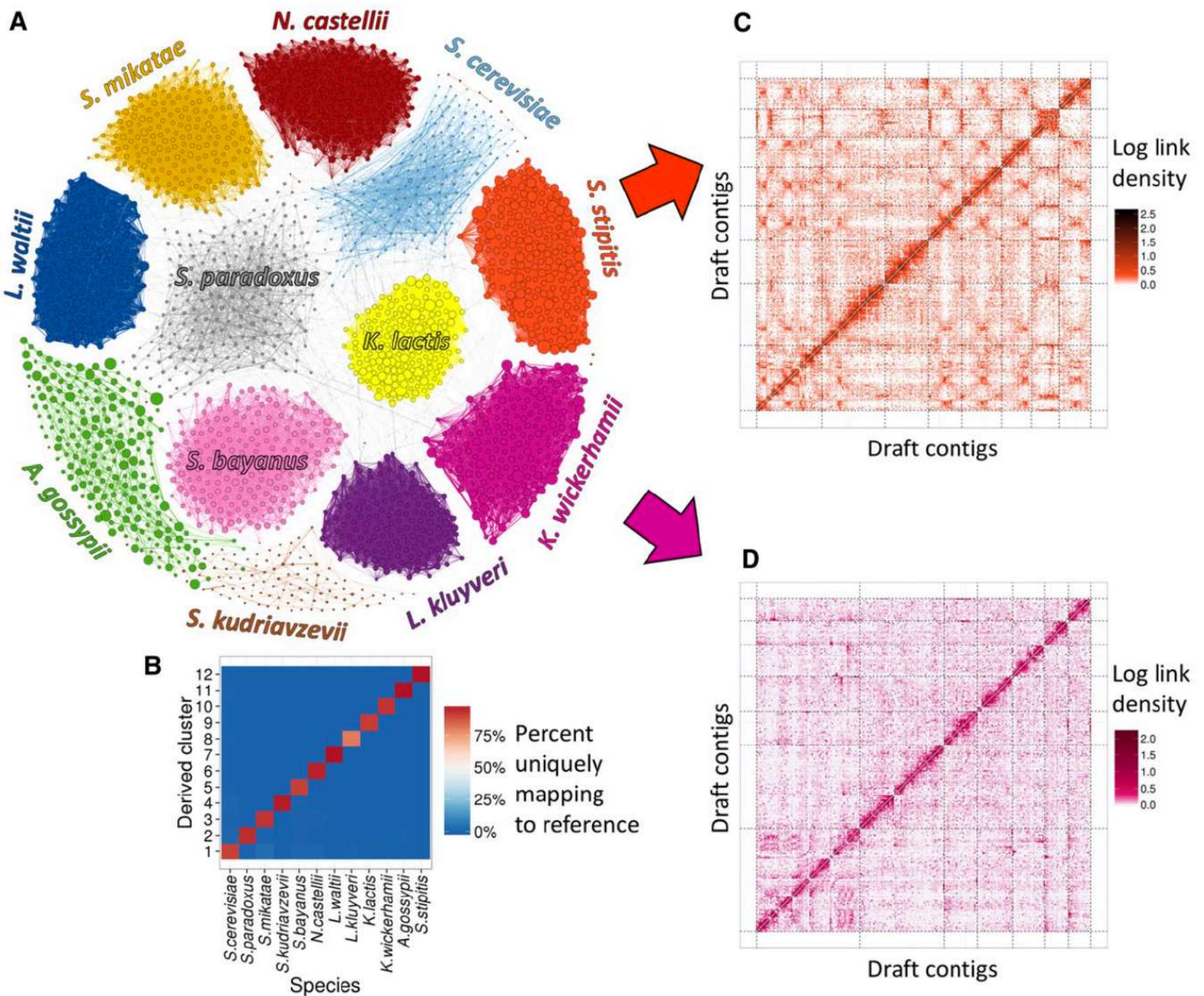
Joshua N. Burton,¹ Ivan Liachko,¹ Maitreya J. Dunham,² and Jay Shendure²

Department of Genome Sciences, University of Washington, Seattle, Washington 98195-5065



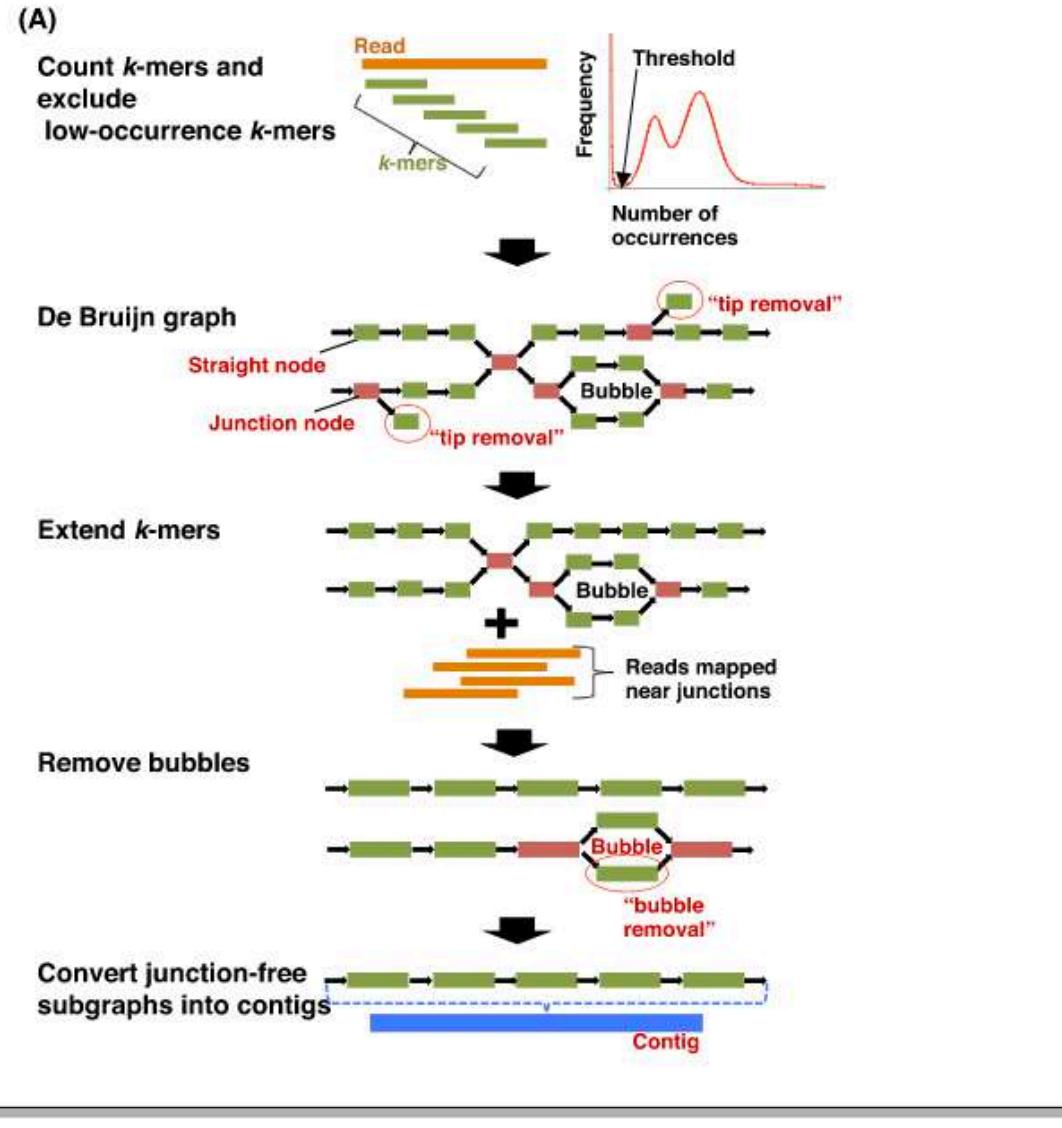
■ Table 2 Sequencing libraries used in MetaPhase analyses

Sample	Library Type	Read Length, bp	Read Pairs, millions
M-Y	Shotgun	101	85.7
	Mate-pair	100	9.2
	Hi-C	100	81.0

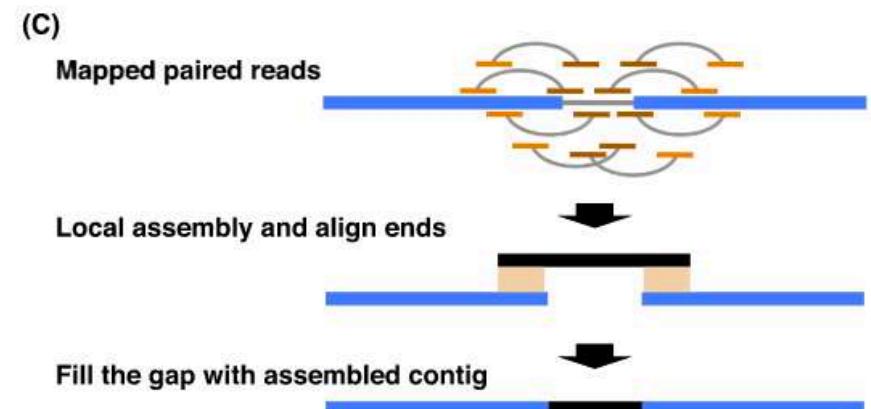
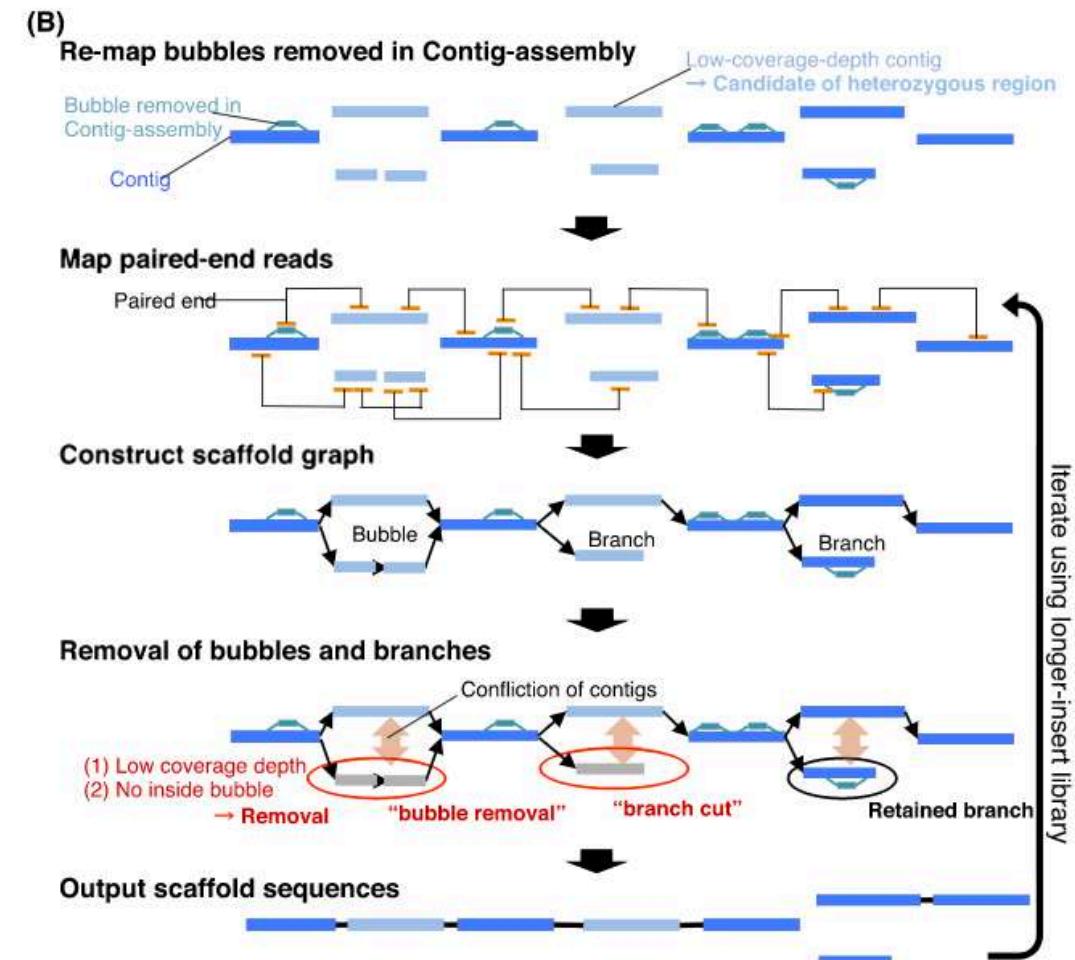


Case studies

Would you understand everything in this paper?



Efficient de novo assembly of highly heterozygous genomes from whole-genome shotgun short reads



Why sequence a genome? (2021 version)

- **Genomics advance our understanding of organisms across tree of life**
 - All previous published genomes that were fragmented are being redone again
 - To reveal greater insights and ease of use for community
 - New genomes are expected to be of good quality
- **Reveal more variations within species**
 - Population genomics is not just **remapping** anymore
 - More accurate inference of structure variation
 - Gene level
- Better analysis power in a genomics world

Lower quality genomes are getting improved

LETTER

OPEN

doi:10.1038/nature22971

Improved maize reference genome with single-molecule technologies

Yinping Jiao¹, Paul Peluso², Jinghua Shi³, Tiffany Liang³, Michelle C. Stitzer⁴, Bo Wang¹, Michael S. Campbell¹, Joshua C. Stein¹, Xuehong Wei¹, Chen-Shan Chin², Katherine Guill⁵, Michael Regulski¹, Sunita Kumari¹, Andrew Olson¹, Jonathan Gent⁶, Kevin L. Schneider⁷, Thomas K. Wolfgruber⁷, Michael R. May⁸, Nathan M. Springer⁹, Eric Antoniou¹, W. Richard McCombie¹, Gernot G. Presting⁷, Michael McMullen⁵, Jeffrey Ross-Ibarra¹⁰, R. Kelly Dawe⁶, Alex Hastie³, David R. Rank² & Doreen Ware^{1,11}

RESEARCH ARTICLE

Open Access



CrossMark

An improved genome assembly uncovers prolific tandem repeats in Atlantic cod

Ole K. Tørresen^{1*}, Bastiaan Star¹, Sissel Jentoft^{1,2}, William B. Reinar¹, Harald Grove³, Jason R. Miller⁴, Brian P. Walenz⁵, James Knight⁶, Jenny M. Ekholm⁷, Paul Peluso⁷, Rolf B. Edvardsen⁸, Ave Tooming-Klunderud¹, Morten Skage¹, Sigbjørn Lien³, Kjetill S. Jakobsen¹ and Alexander J. Nederbragt^{1,9*}

An improved assembly of the loblolly pine mega-genome using long-read single-molecule sequencing

Aleksey V. Zimin^{1,2}, Kristian A. Stevens³, Marc W. Crepeau³, Daniela Puiu², Jill L. Wegrzyn⁴, James A. Yorke¹, Charles H. Langley³, David B. Neale⁵ and Steven L. Salzberg^{2,6,*}

Research

Improved genome assembly of American alligator genome reveals conserved architecture of estrogen signaling

Edward S. Rice,¹ Satomi Kohno,² John St. John,³ Son Pham,⁴ Jonathan Howard,⁵ Liana F. Lareau,⁶ Brendan L. O'Connell,^{1,7} Glenn Hickey,¹ Joel Armstrong,¹ Alden Deran,¹ Ian Fiddes,¹ Roy N. Platt II,⁸ Cathy Gresham,⁹ Fiona McCarthy,¹⁰ Colin Kern,¹¹ David Haan,¹ Tan Phan,¹² Carl Schmidt,¹³ Jeremy R. Sanford,¹⁴ David A. Ray,⁸ Benedict Paten,¹⁵ Louis J. Guillette Jr.,^{16,†} and Richard E. Green^{1,6,7}

Single-molecule sequencing and optical mapping yields an improved genome of woodland strawberry (*Fragaria vesca*) with chromosome-scale contiguity

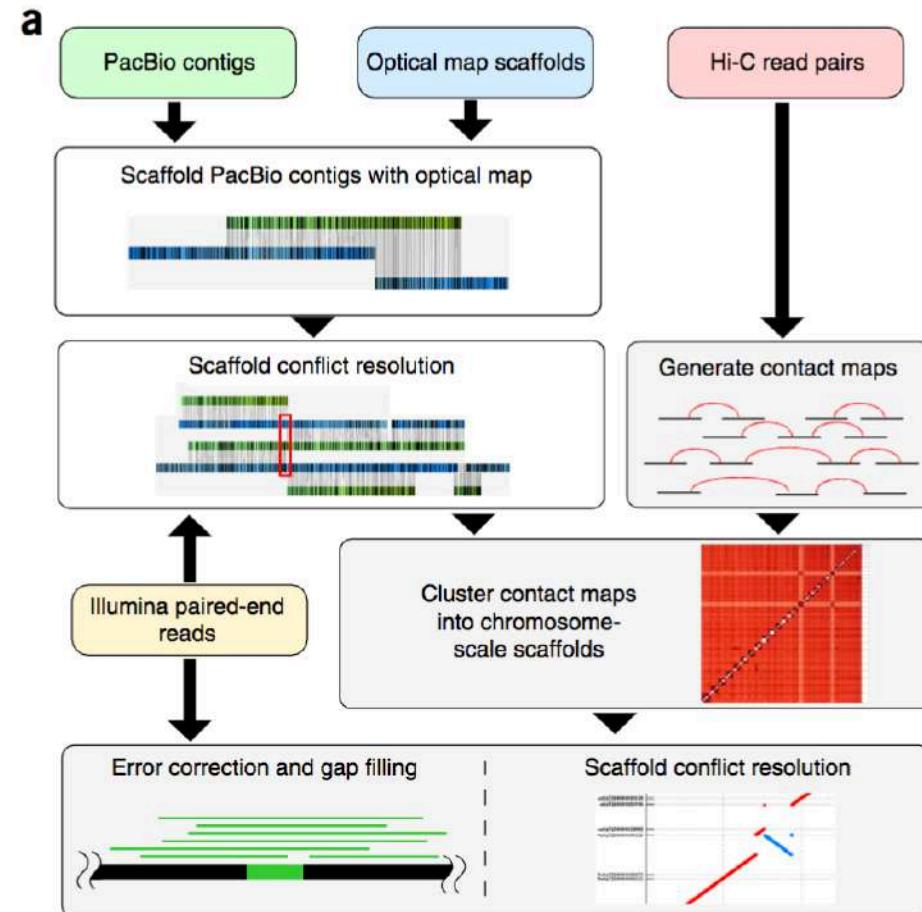
Patrick P. Edger^{1,2,*†}, Robert VanBuren^{1,‡}, Marivi Colle¹, Thomas J. Poorten³, Ching Man Wai¹, Chad E. Niederhuth⁴, Elizabeth I. Alger¹, Shujun Ou^{1,2}, Charlotte B. Acharya³, Jie Wang⁵, Pete Callow¹, Michael R. McKain⁶, Jinghua Shi⁷, Chad Collier⁷, Zhiyong Xiong⁸, Jeffrey P. Mower⁹, Janet P. Slovin¹⁰, Timo Hytönen¹¹, Ning Jiang^{1,2}, Kevin L. Childs^{5,12} and Steven J. Knapp^{3,*}

An improved assembly and annotation of the allohexaploid wheat genome identifies complete families of agronomic genes and provides genomic evidence for chromosomal translocations

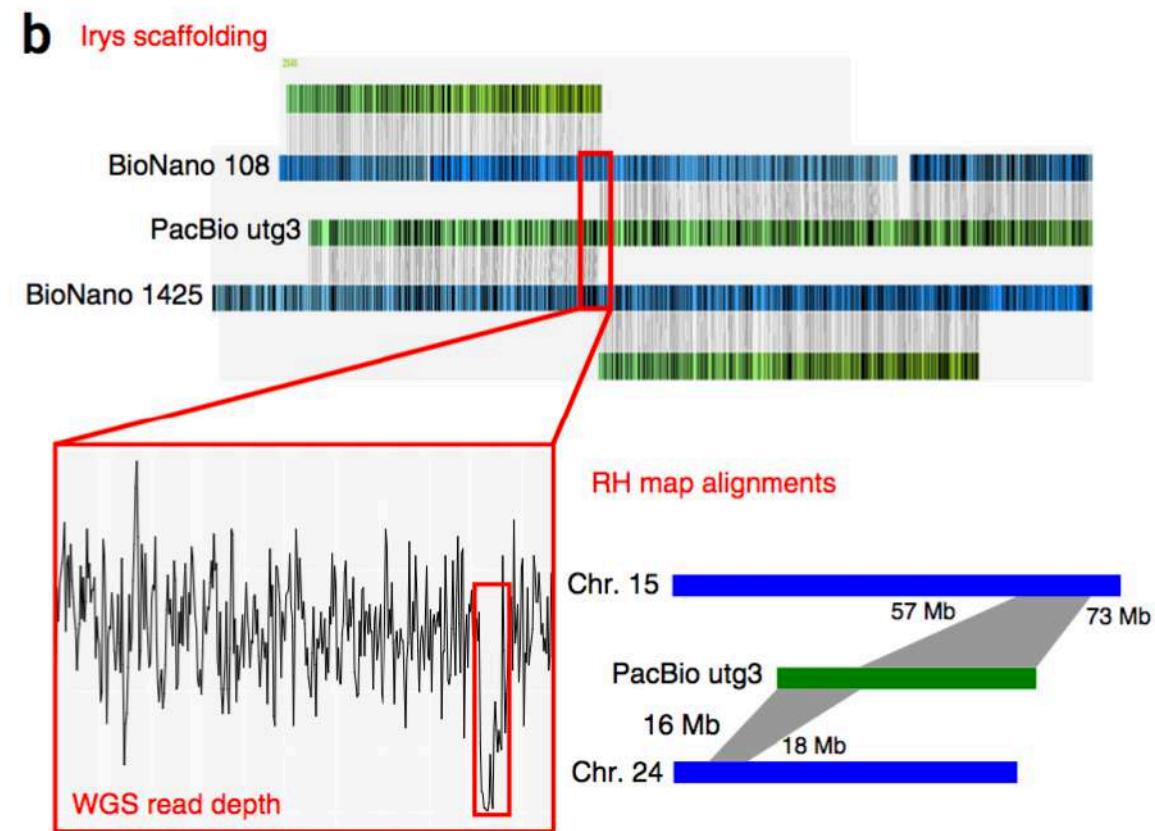
Bernardo J. Clavijo,^{1,9} Luca Venturini,^{1,9} Christian Schudoma,¹ Gonzalo Garcia Accinelli,¹ Gemy Kaithakottil,¹ Jonathan Wright,¹ Philippa Borrill,² George Kettleborough,¹ Darren Heavens,¹ Helen Chapman,¹ James Lipscombe,¹ Tom Barker,¹ Fu-Hao Lu,² Neil McKenzie,² Dina Raats,¹ Ricardo H. Ramirez-Gonzalez,^{1,2} Aurore Coince,¹ Ned Peel,¹ Lawrence Percival-Alwyn,¹ Owen Duncan,³ Josua Trösch,³ Guotai Yu,² Dan M. Bolser,⁴ Guy Namaati,⁴ Arnaud Kerhornou,⁴ Manuel Spannagl,⁵ Heidrun Gundlach,⁵ Georg Haberer,⁵ Robert P. Davey,^{1,6} Christine Fosker,¹ Federica Di Palma,^{1,6} Andrew L. Phillips,⁷ A. Harvey Millar,³ Paul J. Kersey,⁴ Cristobal Uauy,² Ksenia V. Krasileva,^{1,6,8} David Swarbreck,^{1,6} Michael W. Bevan,² and Matthew D. Clark^{1,6}

Single-molecule sequencing and chromatin conformation capture enable *de novo* reference assembly of the domestic goat genome

Derek M Bickhart^{1,18}, Benjamin D Rosen^{2,18}, Sergey Koren^{3,18}, Brian L Sayre⁴, Alex R Hastie⁵, Saki Chan⁵, Joyce Lee⁵, Ernest T Lam⁵, Ivan Liachko⁶, Shawn T Sullivan⁷, Joshua N Burton⁶, Heather J Huson⁸, John C Nystrom⁸, Christy M Kelley⁹, Jana L Hutchison², Yang Zhou^{2,10}, Jiajie Sun¹¹, Alessandra Crisà¹², F Abel Ponce de León¹³, John C Schwartz¹⁴, John A Hammond¹⁴, Geoffrey C Waldbieser¹⁵, Steven G Schroeder², George E Liu², Maitreya J Dunham⁶, Jay Shendure^{6,16}, Tad S Sonstegard¹⁷, Adam M Phillippy³, Curtis P Van Tassel² & Timothy P L Smith⁹



New genomes are expected to have high quality



Correcting misassemblies

... ARS1 comprises just 31 scaffolds and 649 gaps covering 30 of the 31 haploid, acrocentric goat chromosomes (excluding only the Y chromosome),

Table 1 Assembly statistics

Assembly ^a	Contigs ^b	Scaffolds	Unplaced contigs ^c	Degenerate contigs ^d	Contig NG50 (Mb) ^e	Scaffold NG50 (Mb) ^{e,f}	Assembly size (Gb)	Assembly in scaffolds (%)
PacBio	3,074	–	–	30,693	3.795	–	2.914	N/A
Optical Map	–	2,944	–	–	–	1.487	2.748	N/A
PacBio + Optical Map	1,109	333	1,242	30,693	10.197	20.623	2.910	90.89
PacBio + Hi-C	2,115	31	959	30,693	3.795	88.799	2.910	87.97
PacBio + Optical Map + Hi-C	1,780	31	571	30,693	10.197	87.347	2.910	89.05
ARS1	680	31	654	29,315	18.702	87.277	2.924	88.32

^aAssemblies are listed in order of inclusion of scaffolding technologies toward the final assembly (ARS1), with the original contigs (PacBio) scaffolded using different technologies (Optical Map and Hi-C). Because the optical map program (Irys Scaffold) generates an assembly from the consensus of labeled DNA molecules, we have included scaffold statistics from these data (optical map) for comparison. ^bThe number of continuous stretches of sequence within the scaffold without gaps >3 bases in length of at least 10 bases. ^cUnplaced contigs are defined as input contigs or scaffolds that were not placed by the optical map or Hi-C in a scaffold were excluded from the scaffold counts. ^dDegenerate contigs were assembled unitigs that had less than 50 PacBio reads supporting their assembly (**Supplementary Note**). Differences in degenerate contig counts in the final ARS1 assembly are due to PBJelly merging of degenerate contigs (538 contigs) or removal due to no supporting PacBio read alignments (840). ^eAll NG50 values are based on the ARS1 assembly size (2.924 Gb). ^fNo scaffolds were generated for the PacBio entry.

A golden goat genome

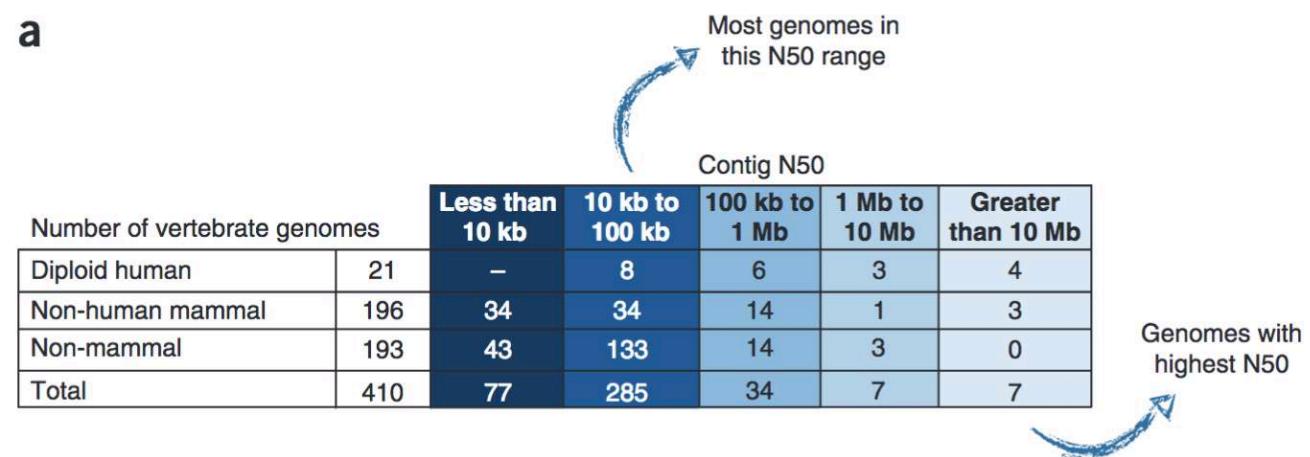
Kim C Worley

The newly described *de novo* goat genome sequence is the most contiguous diploid vertebrate assembly generated thus far using whole-genome assembly and scaffolding methods. The contiguity of this assembly is approaching that of the finished human and mouse genomes and suggests an affordable roadmap to high-quality references for thousands of species.

.... This report generates sighs of relief from researchers frustrated with the highly fragmented genome sequences available for most species....

... The lower costs and greater accessibility of these methods bring potential for wider impact....

a



b

	Goat CHIR_1.0	Goat ARS1	Human GRCh38
Total sequence length	2.6 Gb	2.9 Gb	3.2 Gb
Total assembly gap length	140 Mb	38 Mb	160 Mb
Gaps between scaffolds	411	0	349
Number of scaffolds	77,431	29,907	735
Scaffold N50	14 Mb	87 Mb	67 Mb
Number of contigs	337,494	30,399	1,385
Contig N50	18.9 kb	26.2 Mb	56.4 Mb
Number of chromosomes and plasmids	30	31	25

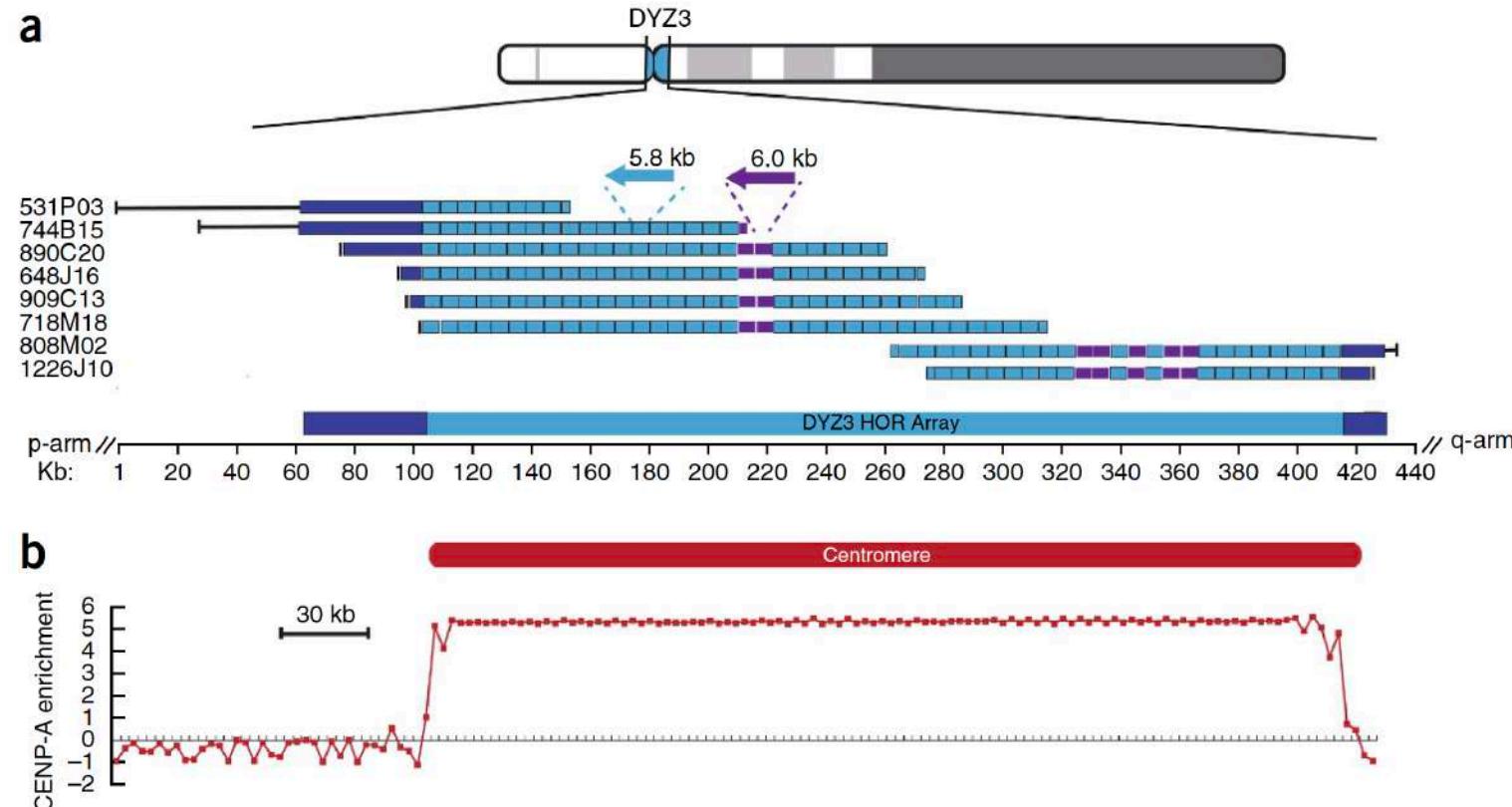
c



Linear assembly of a human centromere on the Y chromosome

Miten Jain^{1,5} , Hugh E Olsen^{1,5}, Daniel J Turner², David Stoddart², Kira V Bulazel³, Benedict Paten¹, David Haussler¹, Huntington F Willard^{3,4}, Mark Akeson¹ & Karen H Miga^{1,3}

The human genome reference sequence remains incomplete owing to the challenge of assembling long tracts of near-identical tandem repeats in centromeres. We implemented a nanopore sequencing strategy to generate high-quality reads that span hundreds of kilobases of highly repetitive DNA in a human Y chromosome centromere. Combining these data with short-read variant validation, we assembled and characterized the centromeric region of a human Y chromosome.

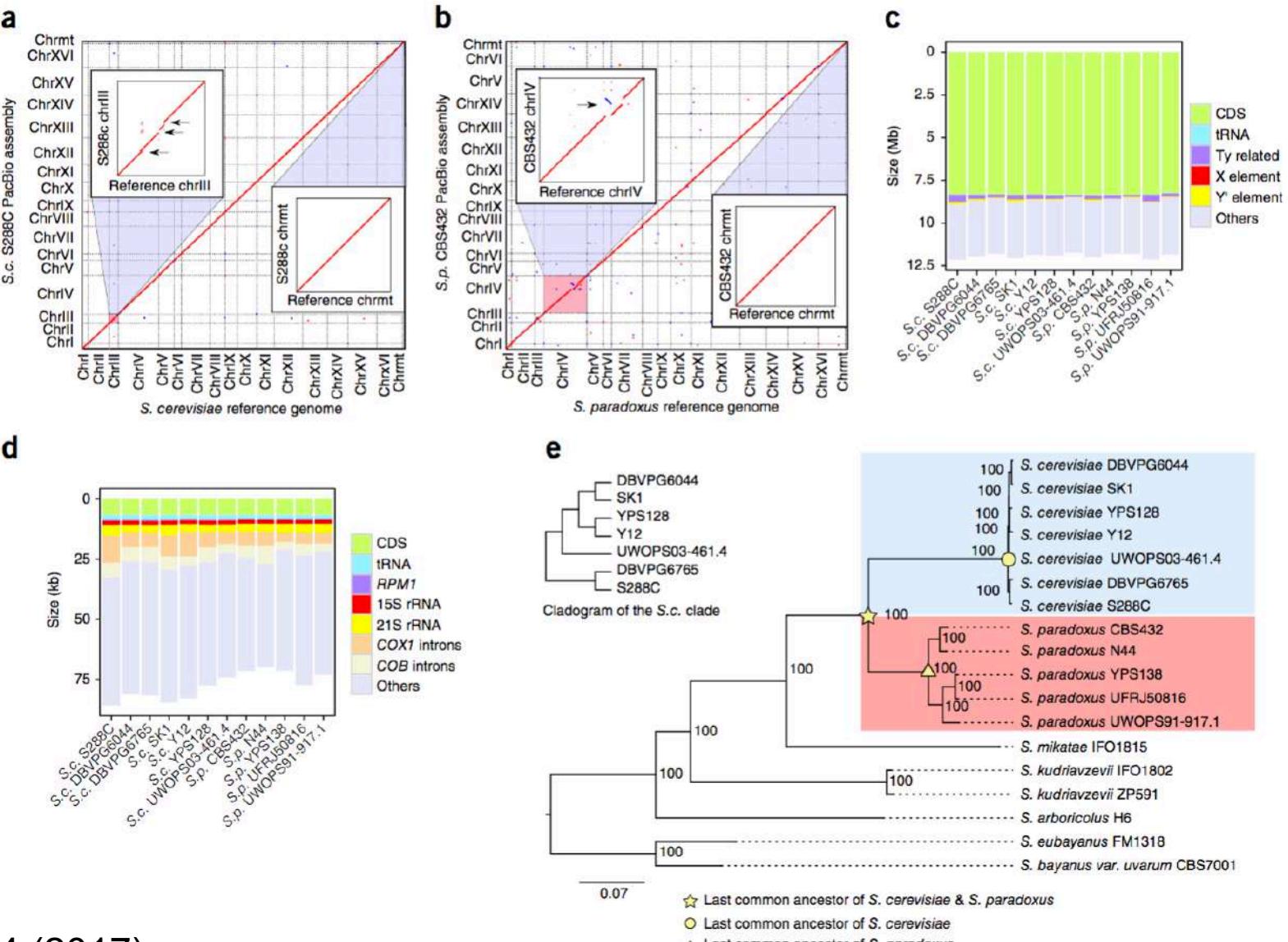


Contrasting evolutionary genome dynamics between domesticated and wild yeasts

Population genomics

Jia-Xing Yue¹ , Jing Li¹, Louise Aigrain², Johan Hallin¹ , Karl Persson³ , Karen Oliver², Anders Bergström², Paul Coupland^{2,5}, Jonas Warringer³ , Marco Cosentino Lagomarsino⁴, Gilles Fischer⁴, Richard Durbin² & Gianni Liti¹

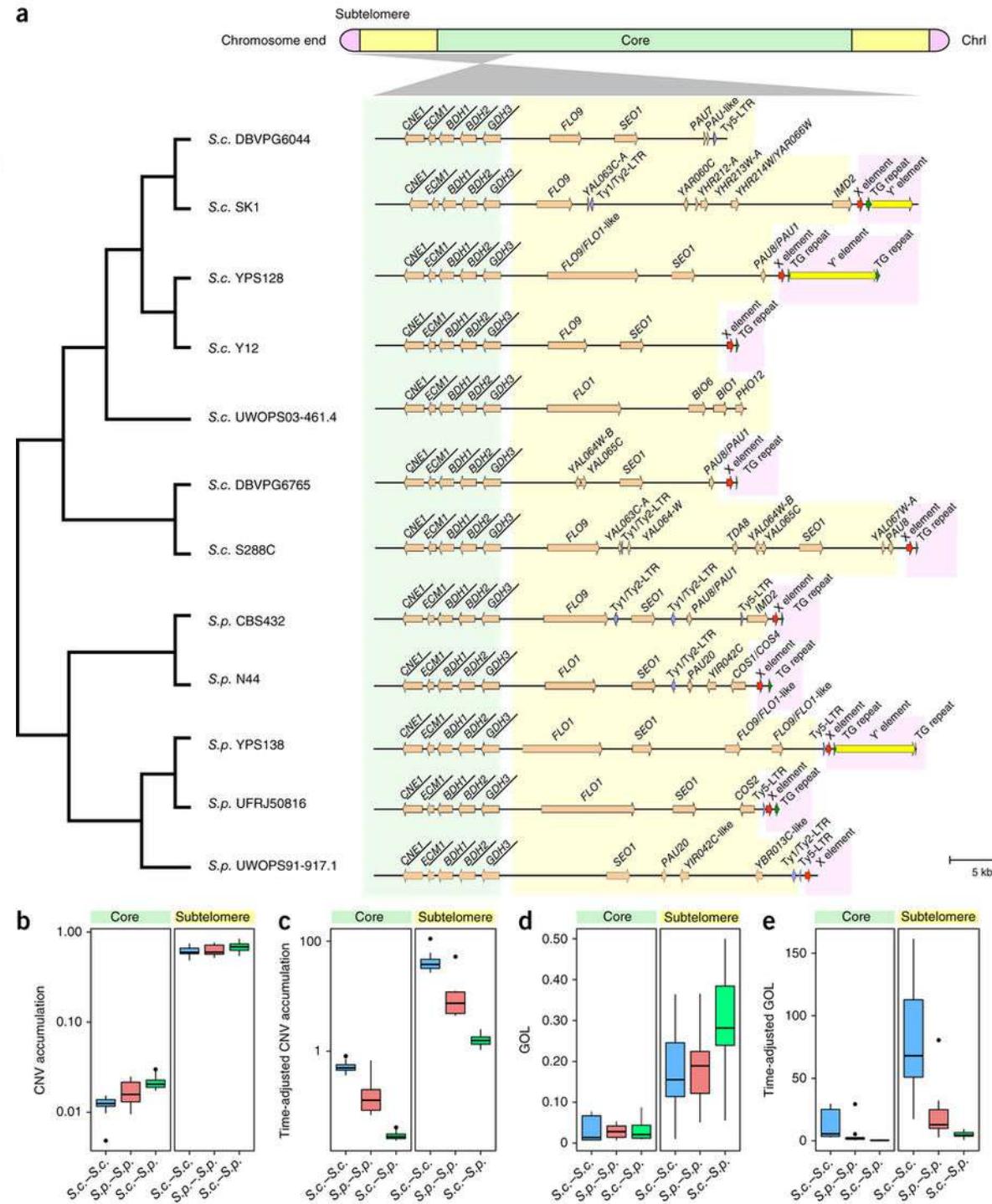
- long-read sequencing to generate **end-to-end genome assemblies** for **12 strains** representing major subpopulations of the partially domesticated yeast *Saccharomyces cerevisiae* and its wild relative *S. paradoxus*.



Contrasting evolutionary genome dynamics between domesticated and wild yeasts

Jia-Xing Yue¹ , Jing Li¹, Louise Aigrain², Johan Hallin¹ , Karl Persson³ , Karen Oliver², Anders Bergström², Paul Coupland^{2,5}, Jonas Warringer³ , Marco Cosentino Lagomarsino⁴, Gilles Fischer⁴, Richard Durbin² & Gianni Liti¹

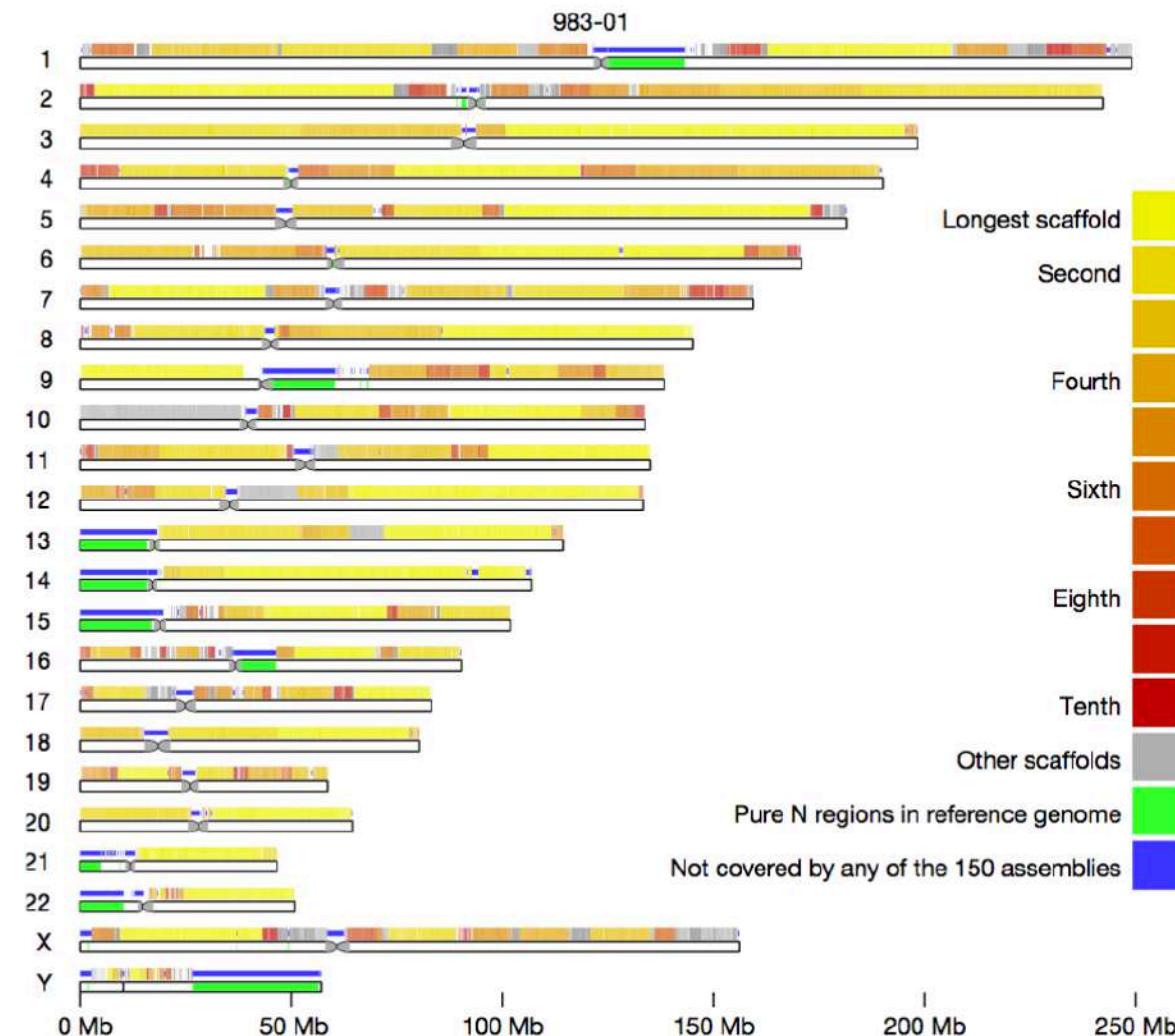
- enable precise definition of chromosomal boundaries between cores and subtelomeres
- S. paradoxus* shows faster accumulation of balanced rearrangements (inversions, reciprocal translocations and transpositions), *S. cerevisiae* accumulates unbalanced rearrangements (novel insertions, deletions and duplications) more rapidly.
- Such striking contrasts between wild and domesticated yeasts are likely to reflect the influence of human activities on structural genome evolution.



Sequencing and *de novo* assembly of 150 genomes from Denmark as a population reference

Lasse Maretty^{1,*}, Jacob Malte Jensen^{2,3,*}, Bent Petersen^{4*}, Jonas Andreas Sibbesen^{1*}, Siyang Liu^{1,5*}, Palle Villesen^{2,3,6*}, Laurits Skov^{2,3*}, Kirstine Belling^{2*}, Christian Theil Have⁷, Jose M. G. Izarzugaza⁴, Marie Grosjean⁴, Jette Bork-Jensen⁷, Jakob Grove^{3,8,9}, Thomas D. Als^{3,8,9}, Shujia Huang^{10,11}, Yuqi Chang¹⁰, Ruiqi Xu⁵, Weijian Ye⁵, Junhua Rao⁵, Xiaosen Guo^{10,12}, Jihua Sun^{5,7}, Hongzhi Cao¹⁰, Chen Ye¹⁰, Johan van Beusekom⁴, Thomas Espeseth^{13,14}, Esben Flindt¹², Rune M. Friberg^{2,3}, Anders E. Halager^{2,3}, Stephanie Le Hellard^{14,15}, Christina M. Hultman¹⁶, Francesco Lescat^{3,8,9}, Shengting Li^{3,8,9}, Ole Lund⁴, Peter Løngren⁴, Thomas Mailund^{2,3}, Maria Luisa Matey-Hernandez⁴, Ole Mors^{3,6,9}, Christian N. S. Pedersen^{2,3}, Thomas Sicheritz-Pontén⁴, Patrick Sullivan^{16,17}, Ali Syed⁴, David Westergaard⁴, Rachita Yadav⁴, Ning Li⁵, Xun Xu¹⁰, Torben Hansen⁷, Anders Krogh¹, Lars Bolund^{8,10}, Thorkild I. A. Sørensen^{7,18,19}, Oluf Pedersen⁷, Ramneek Gupta⁴, Simon Rasmussen⁴§, Søren Besenbacher^{2,6}§, Anders D. Børglum^{3,8,9}§, Jun Wang^{3,10,12}§, Hans Eiberg²⁰§, Karsten Kristiansen^{10,12}§, Søren Brunak^{4,21}§ & Mikkel Heide Schierup^{2,3,22}§

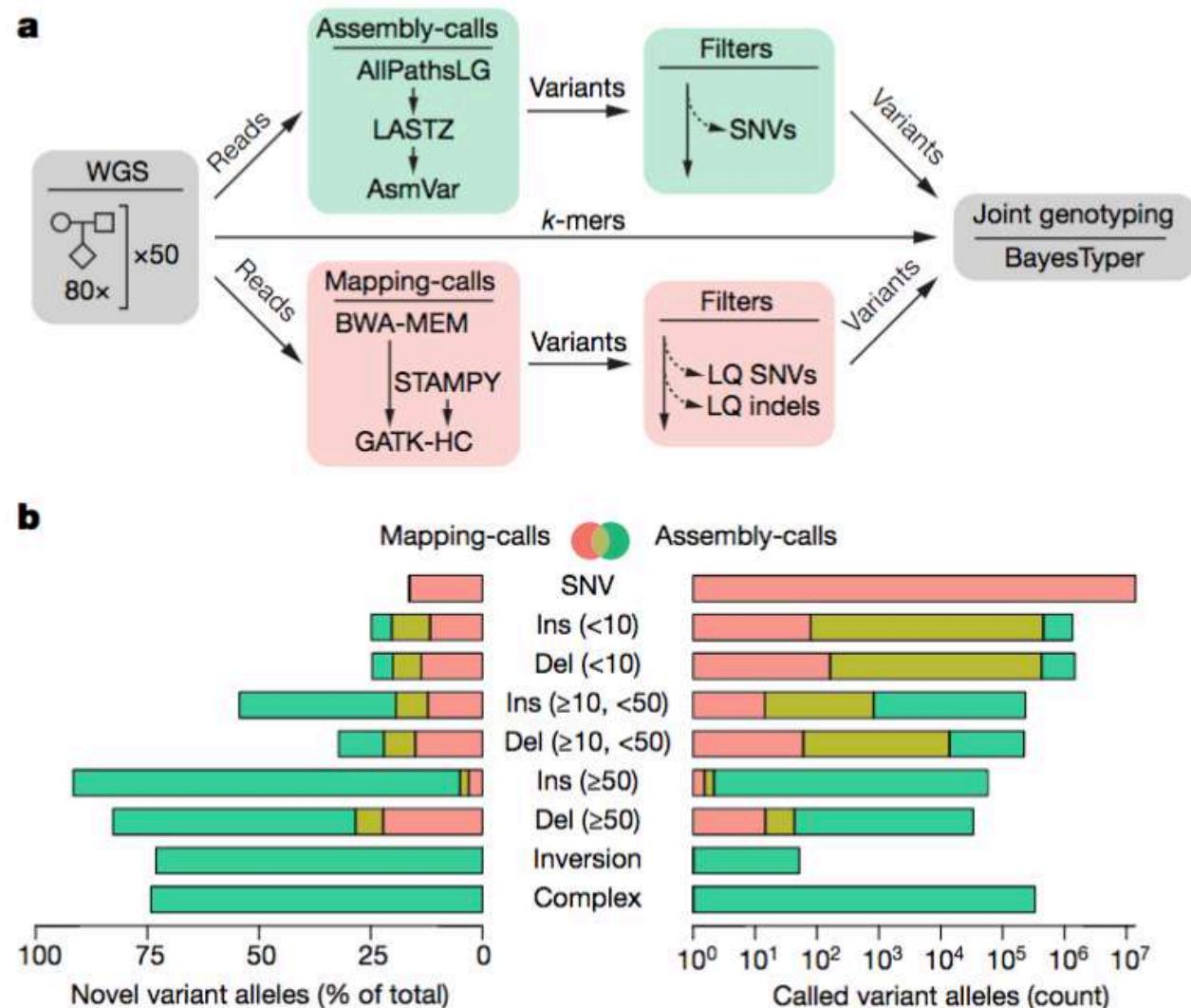
- Hundreds of thousands of human genomes are now being sequenced to characterize genetic variation and use this information to augment association mapping studies of complex disorders and other phenotypic traits.
- Genetic variation is identified mainly by mapping short reads to the reference genome. However, these approaches are biased against discovery of structural variants and variation in the more complex parts of the genome.
- report *de novo* assemblies of 150 individuals (50 trios) from the GenomeDenmark project.



We found that 16.4% of the called SNVs were novel (not in the Single Nucleotide Polymorphism database 142 (dbSNP142) or 1000 Genomes Project phase 3 structural variant call-set), **whereas as many as 91.6% of insertions ≥50 bp were novel** ([Fig. 2b](#)).

The fraction of novel variants increased rapidly with variant length, especially for insertions ([Fig. 2d](#)), with most longer variants contributed by the assembly-based approach...

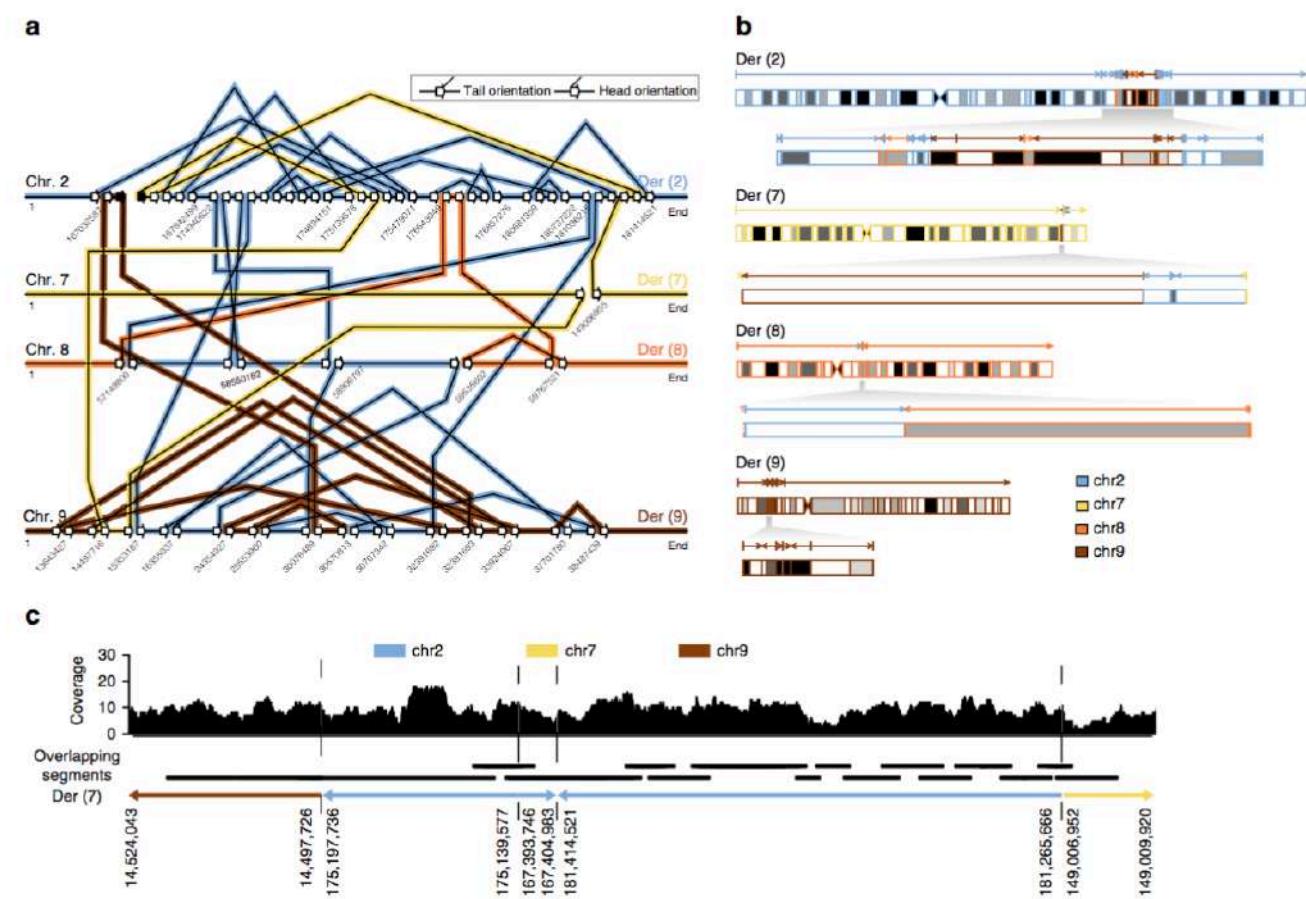
For instance, ...we **called 33,653 deletions ≥50 bp**, whereas the **1000 Genomes Project identified 42,279 such variants in 25 times more individuals who were more diverse than our study population**.



Mapping and phasing of structural variation in patient genomes using nanopore sequencing

Mircea Cretu Stancu¹, Markus J. van Roosmalen¹, Ivo Renkens¹, Marleen M. Nieboer¹, Sjors Middelkamp¹, Joep de Ligt¹, Giulia Pregno², Daniela Giachino², Giorgia Mandrile², Jose Espejo Valle-Inclan¹, Jerome Korzelius¹, Ewart de Brujin¹, Edwin Cuppen³, Michael E. Talkowski^{4,5,6}, Tobias Marschall¹, Jeroen de Ridder¹ & Wigard P. Kloosterman¹

- long reads are superior to short reads with regard to detection of de novo chromothripsis rearrangements.
- long reads also enable efficient phasing of genetic variations, which we leveraged to determine the parental origin of all de novo chromothripsis breakpoints and to resolve the structure of these complex rearrangements.



Example of metagenomics

Metagenomic Discovery of Biomass-Degrading Genes and Genomes from Cow Rumen

Matthias Hess,^{1,2*} Alexander Sczyrba,^{1,2*} Rob Egan,^{1,2} Tae-Wan Kim,³ Harshal Chokhawala,³ Gary Schroth,⁴ Shujun Luo,⁴ Douglas S. Clark,^{3,5} Feng Chen,^{1,2} Tao Zhang,^{1,2} Roderick I. Mackie,⁶ Len A. Pennacchio,^{1,2} Susannah G. Tringe,^{1,2} Axel Visel,^{1,2} Tanja Woyke,^{1,2} Zhong Wang,^{1,2} Edward M. Rubin^{1,2†}

- 268Gb of metagenomics data
- Identified 27,755 putative carbohydrate-active genes from a cow rumen metagenome
- Expressed 90 candidates of which 57% had enzymatic activity against cellulosic substrates
- Assembled 15 uncultured microbial genomes

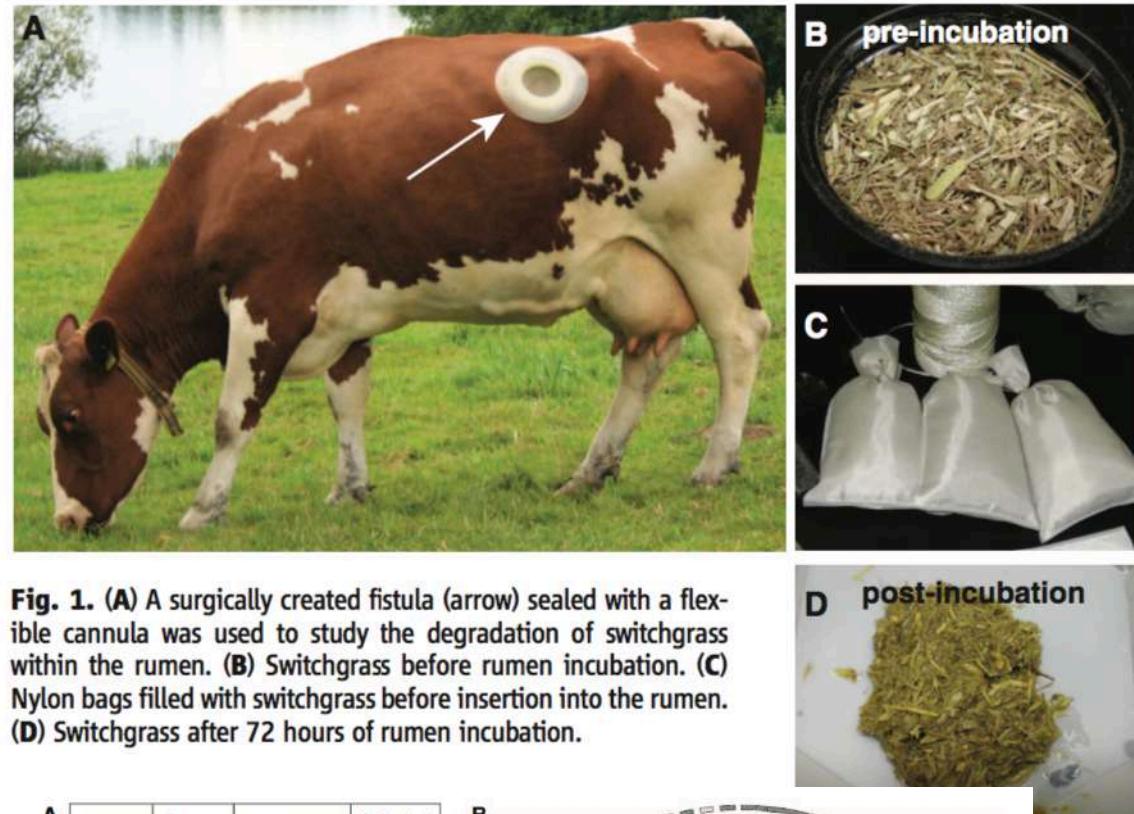
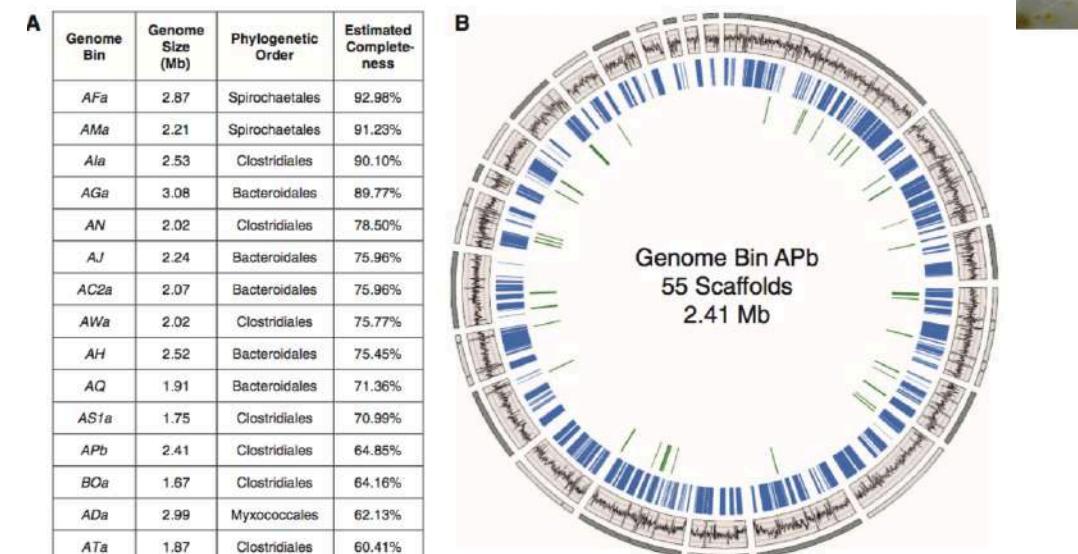


Fig. 1. (A) A surgically created fistula (arrow) sealed with a flexible cannula was used to study the degradation of switchgrass within the rumen. (B) Switchgrass before rumen incubation. (C) Nylon bags filled with switchgrass before insertion into the rumen. (D) Switchgrass after 72 hours of rumen incubation.

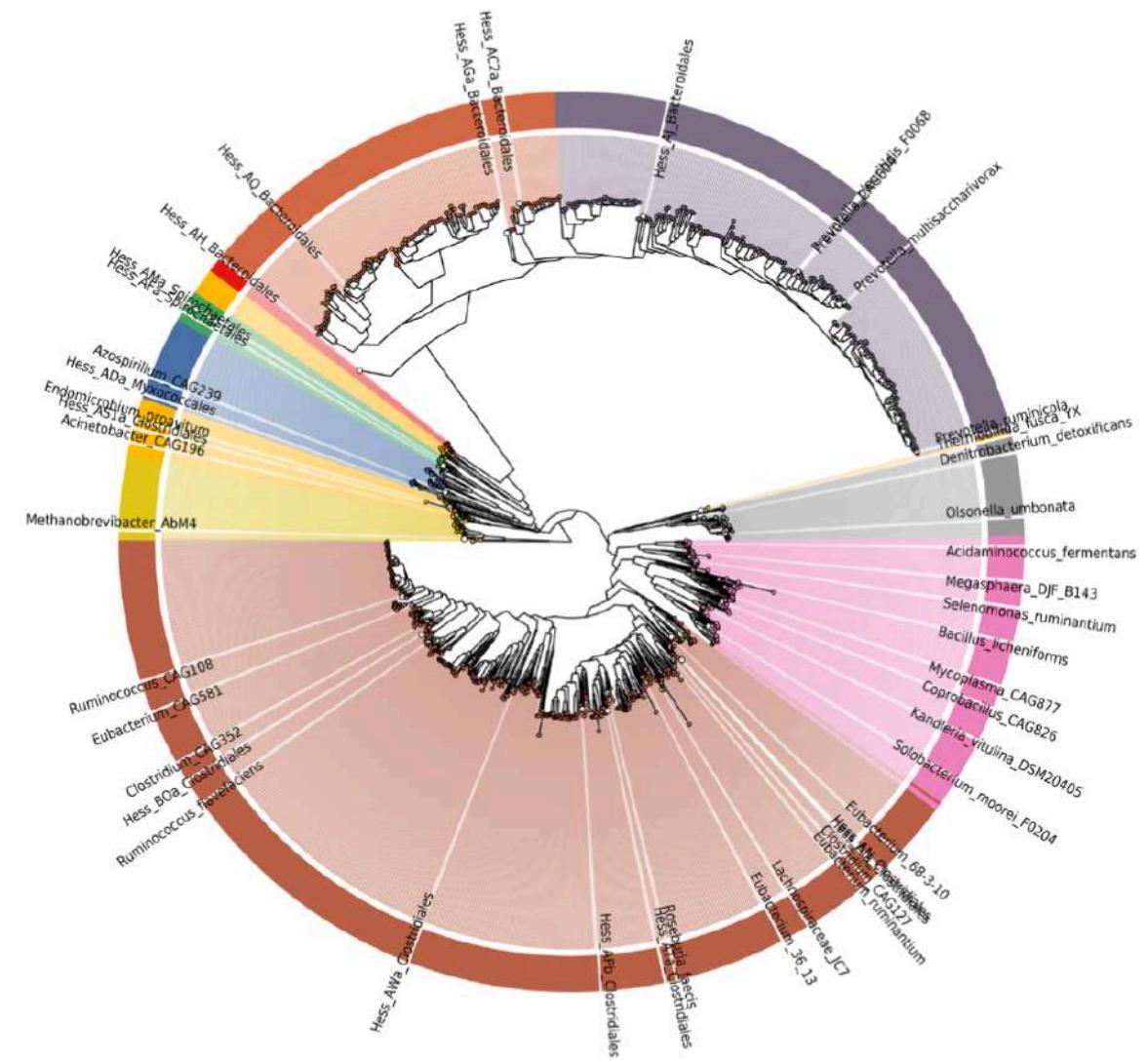


genome; innermost circle (green tick marks), location of glycoside hydrolase genes on draft genome.

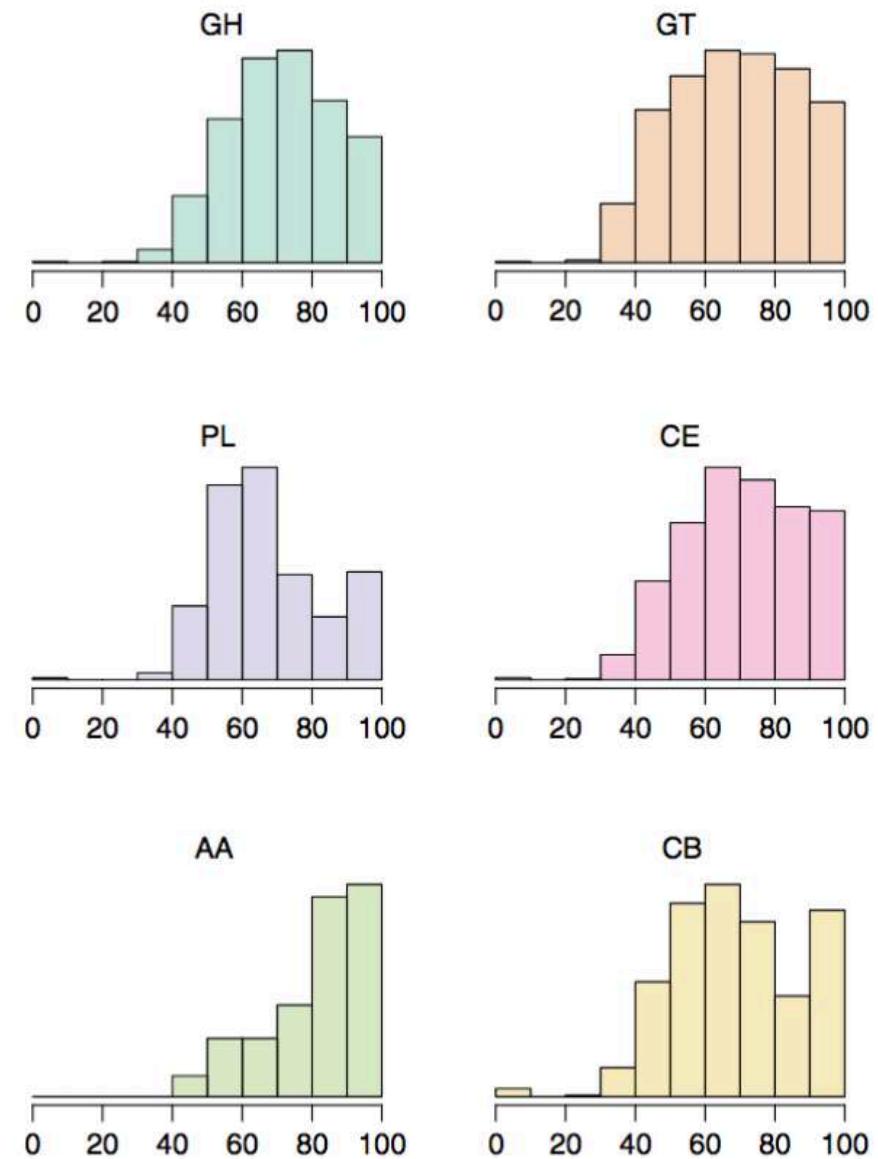
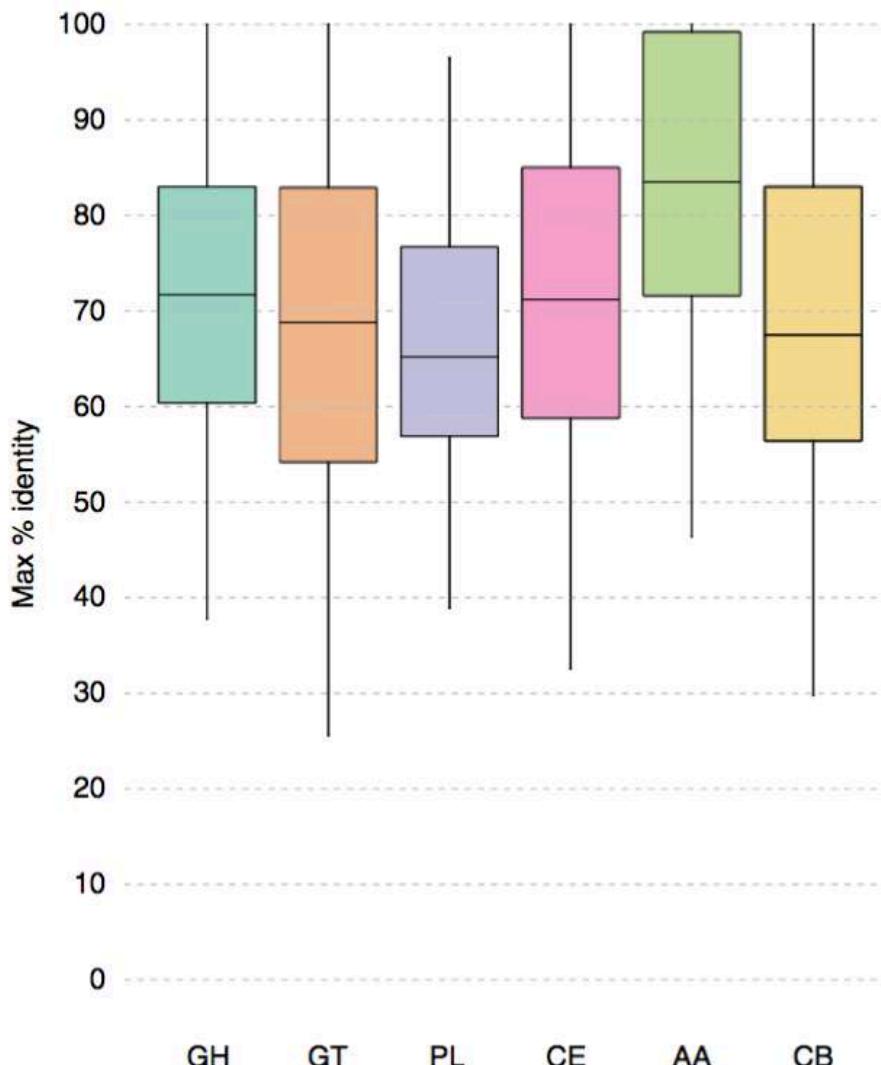
Assembly of 913 microbial genomes from metagenomic sequencing of the cow rumen

Robert D. Stewart¹, Marc D. Auffret², Amanda Warr¹, Andrew H. Wiser³, Maximilian O. Press¹,
Kyle W. Langford³, Ivan Liachko³, Timothy J. Snelling⁴, Richard J. Dewhurst¹, Alan W. Walker¹,
Rainer Roehe² & Mick Watson¹

- 800 Gb of sequence data derived from 43 Scottish cattle
- Using metagenomic binning and Hi-C techniques
- Assembly of 913 draft bacterial and archaeal genomes
- Most of these genomes represent previously unsequenced strains and species.
- The draft genomes contain over 69,000 proteins predicted to be involved in carbohydrate metabolism, over 90% of which do not have a good match in public databases.



- The draft genomes contain over 69,000 proteins predicted to be involved in carbohydrate metabolism, over 90% of which do not have a good match in public databases.



- Inclusion of the 913 genomes presented here improves metagenomic read classification by sevenfold against the study's own data, and by fivefold against other publicly available rumen datasets.
- dataset substantially improves the coverage of rumen microbial genomes in the public databases and represents a valuable resource for biomass-degrading enzyme discovery and studies of the rumen microbiome

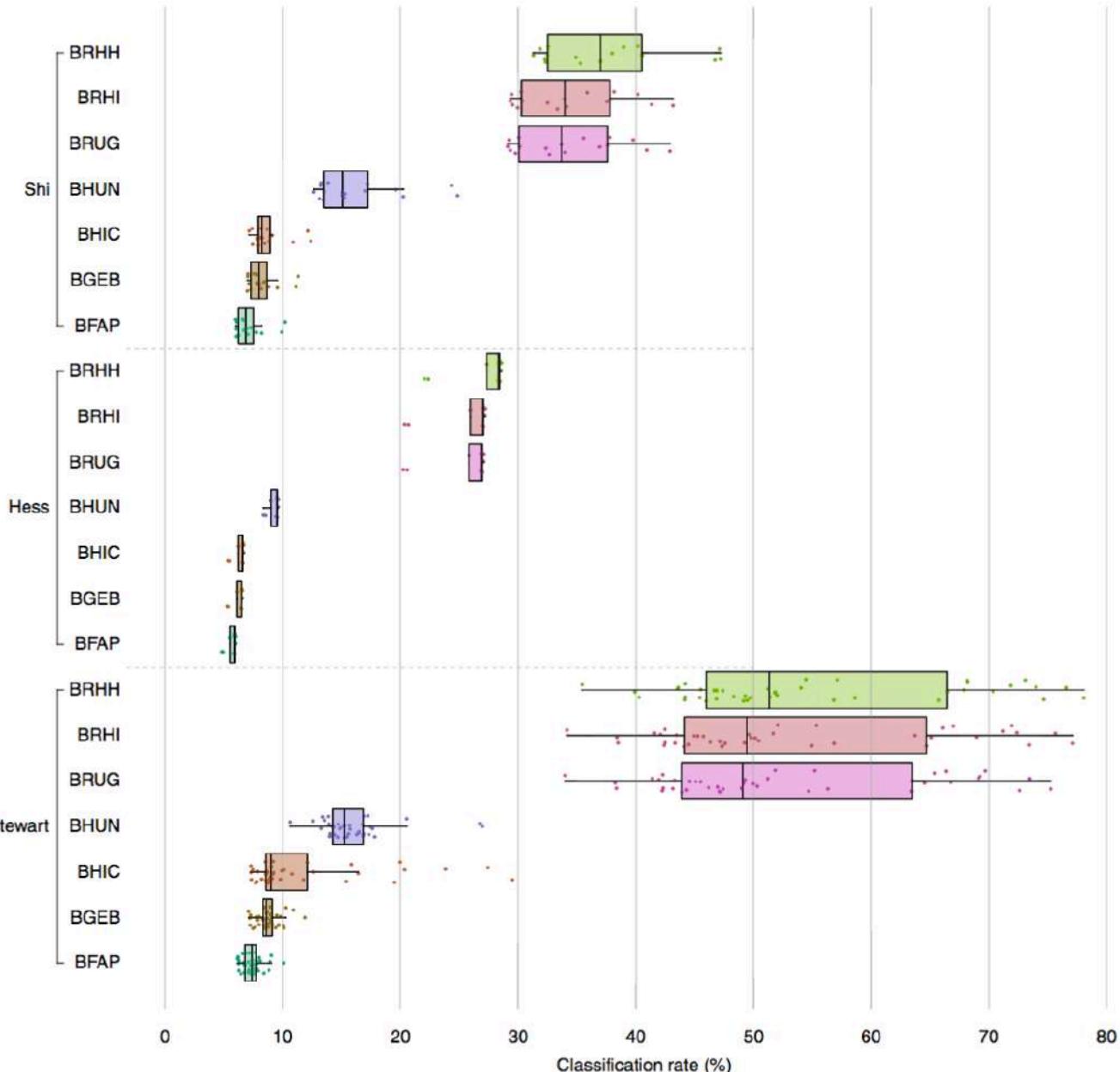
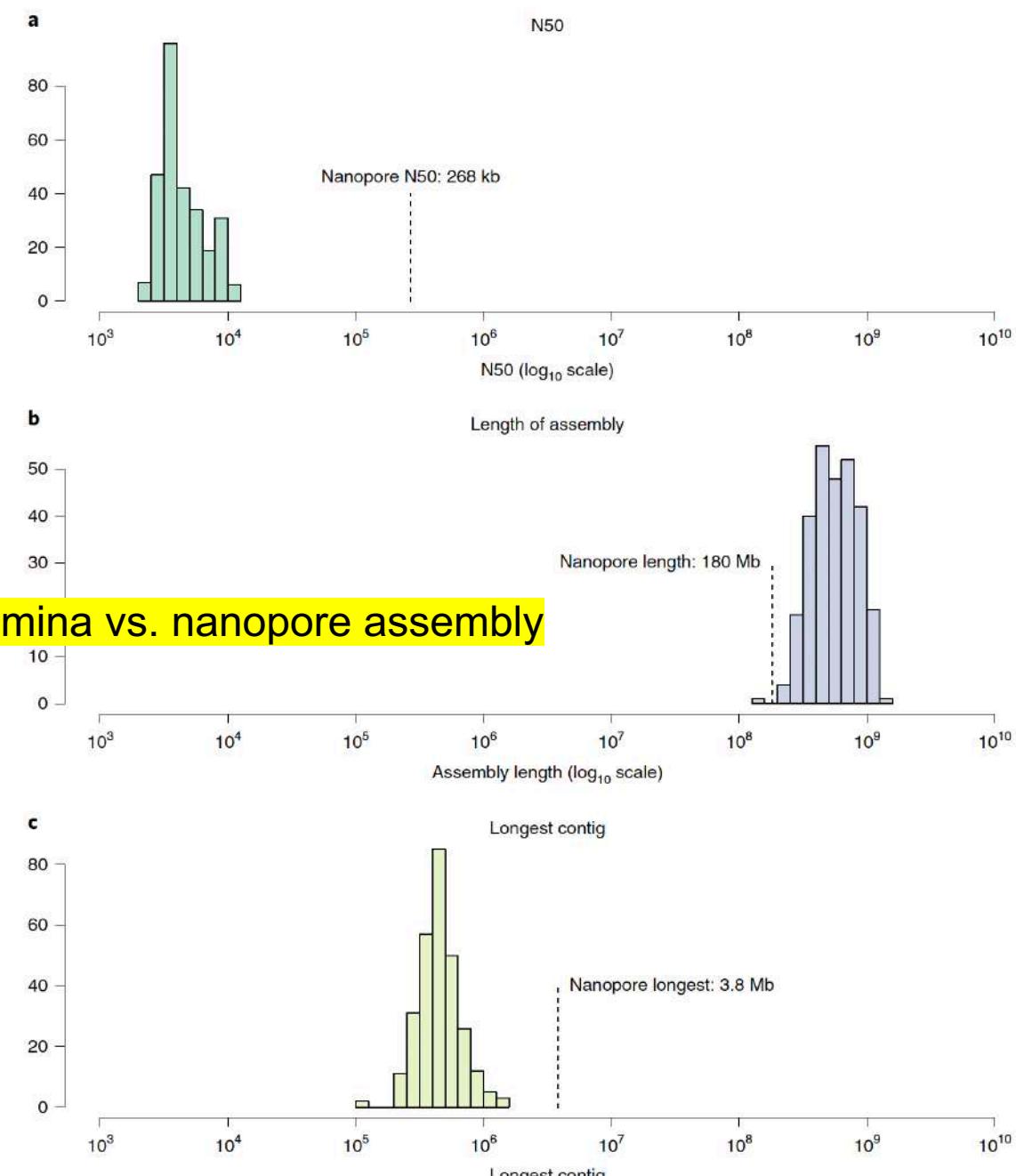


Fig. 4 Classification rate for three datasets against various Kraken databases. BFAP bacterial, archaeal, fungal and protozoan genomes from RefSeq, BGEB BFAP + 1003 GEBA genomes, BHIC BFAP + 63 hRUG genomes, BHUN BFAP + 410 genomes from the Hungate 1000 project, BRUG BFAP + 850 RUG MAGs, BRHI BFAP + all 913 genomes from this study, BRHH BFAP + 913 RUGs + 410 Hungate 1000 genomes. Addition of rumen-specific RUGs or Hungate 1000 genomes has the most dramatic effect

Compendium of 4,941 rumen metagenome-assembled genomes for rumen microbiome biology and enzyme discovery

Robert D. Stewart¹, Marc D. Auffret^{ID 2}, Amanda Warr¹, Alan W. Walker^{ID 3}, Rainer Roehe^{ID 2} and Mick Watson^{ID 1*}

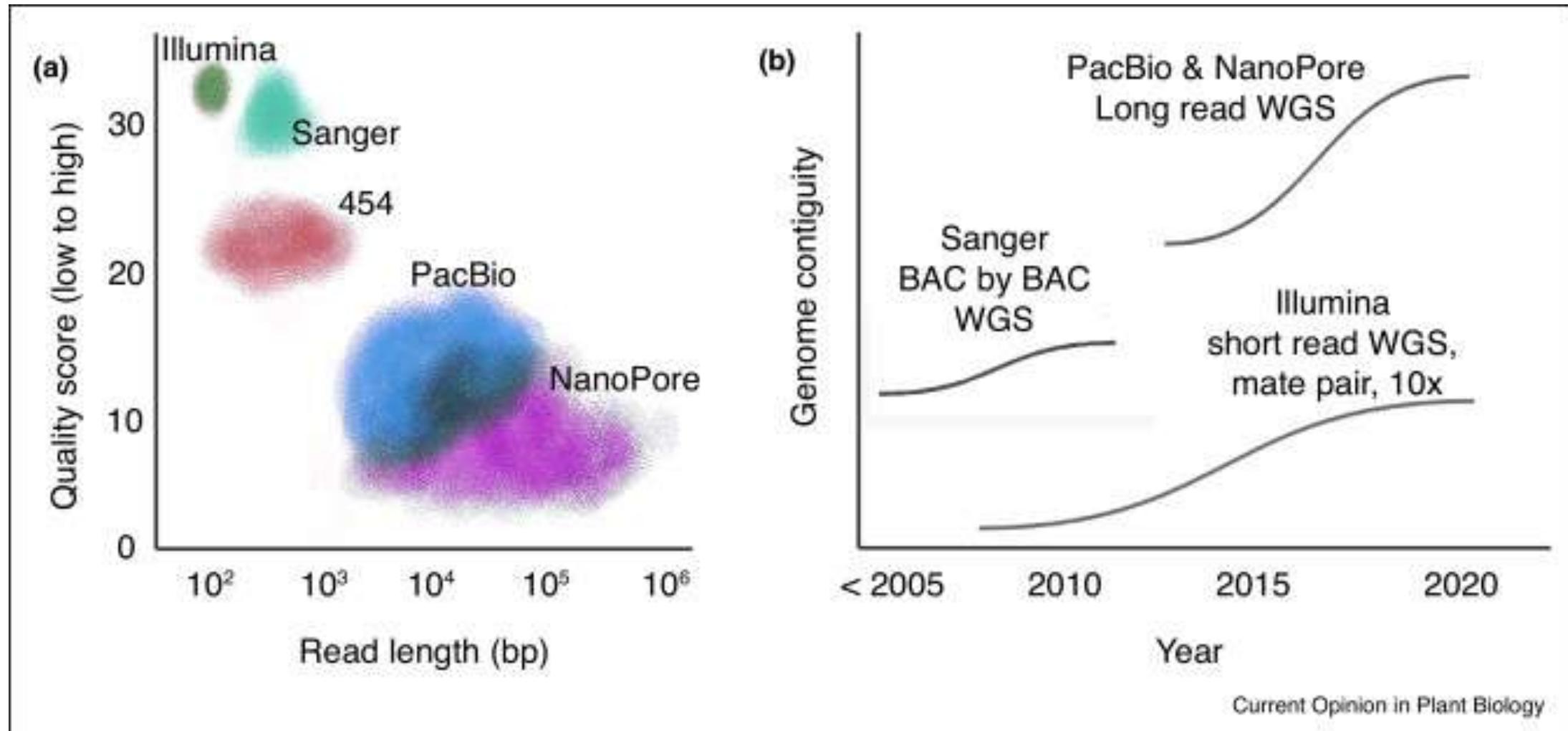
- 6.5 Tb of sequence data derived from 283 ruminant cattles
- Using metagenomic binning and Hi-C techniques
- Assembly of 4,941 draft bacterial and archaeal genomes
- Long read is being used: “We also present a metagenomic assembly of nanopore (MinION) sequencing data (from one rumen sample) that contains at least three whole bacterial chromosomes as single contigs”



Summary and opinions

Summary and opinions

Advances in sequencing technology have dramatically improved genome contiguity over the last two decades

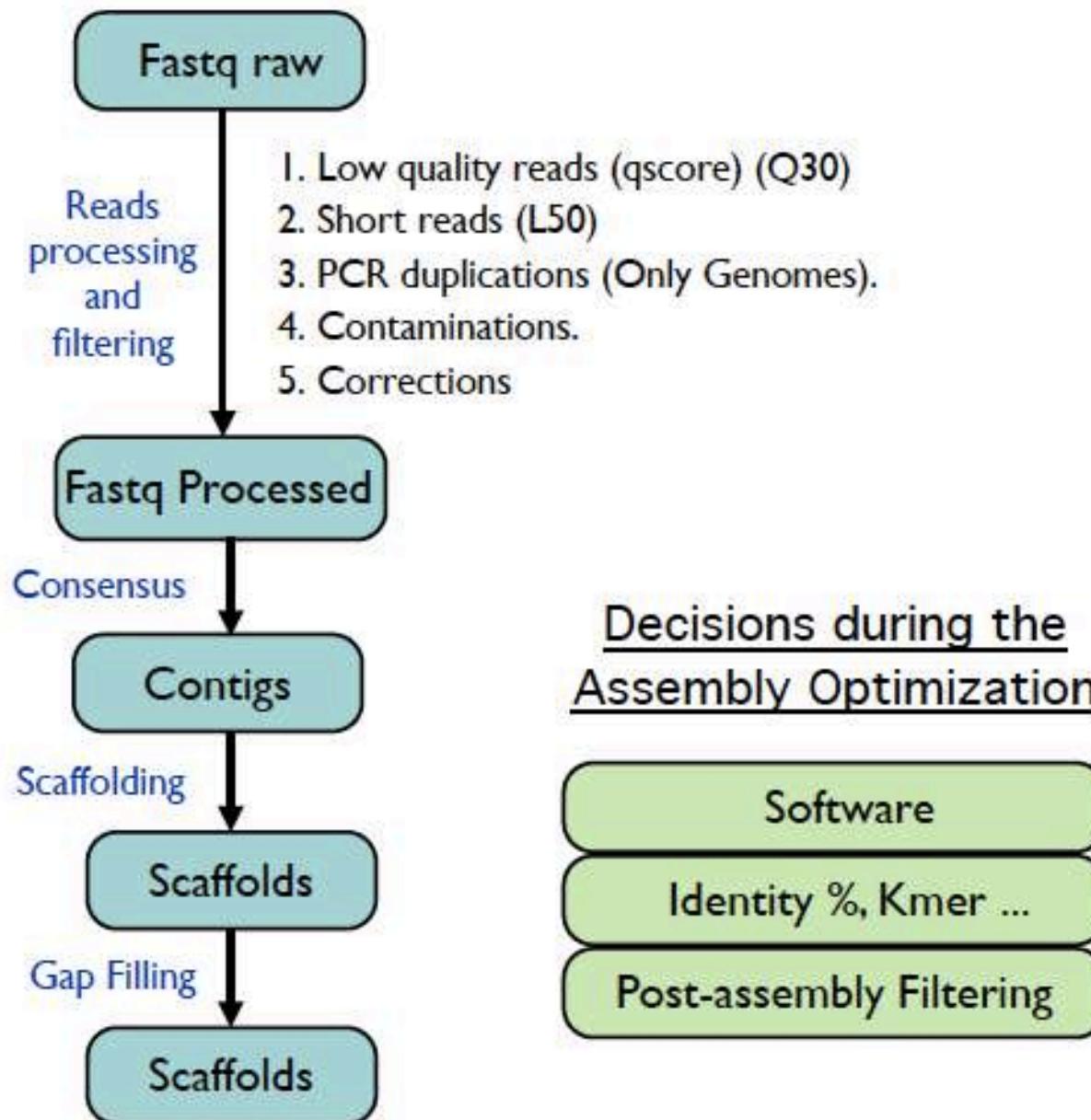
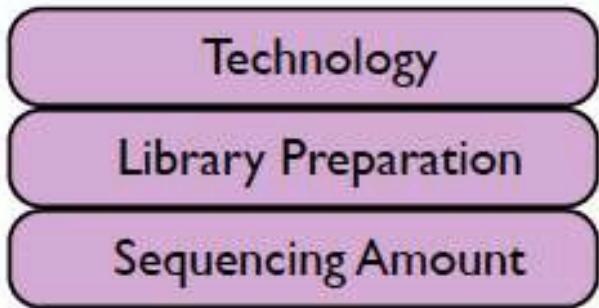


Summary

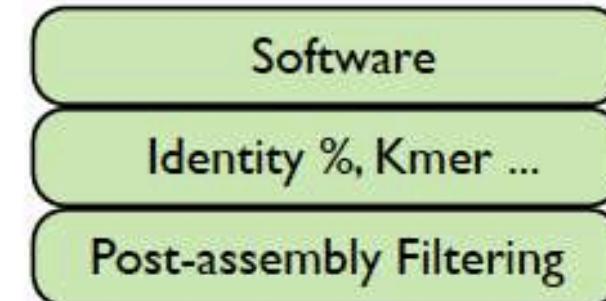
- Expectation is higher in assembly of a genome
- Population genomics is moving from a mapping (resequencing) to assembly approach
- Long read technologies are improving rapidly fast so every standard lab can generate a high quality assembly
- Assembly processes need to scale up to accommodate the advancing technologies and changing biological questions

Overview of a sequencing project

Decisions during the Experimental Design



Decisions during the Assembly Optimization



Things to consider

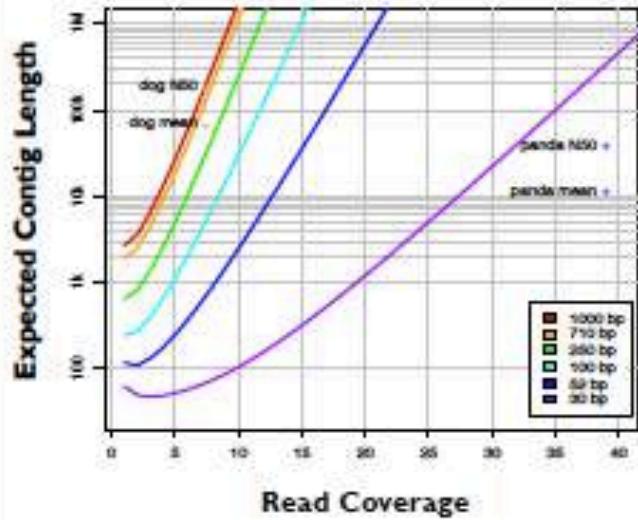
- \$\$\$\$\$\$\$\$\$
- **Project type**
 - virus, bacteria, eukaryote, meta-genome
- **Goals**
 - Just an assembly to showcase the world?
 - Sequence pandemic species = conservation? (No right or wrong answer)
 - Any biological question?
 - Why *de novo* sequence a species?
- **Hardware**
 - You need CPUs, but RAM is more important
 - Imagine storing all the hashes or kmers
 - This may change depending on nature of data (all long reads within n years?)

Consider technologies and experiments

- Use multiple techniques to answer your questions
 - Long read only
 - Long read + Hi-C
 - Long read + optical maps + Hi-C
 - 10X linked reads
 - 10X + Hi-C
 - Single cell?
 - Experimental advancement?
- Sometimes limitations becomes experiment preparation rather than the technological one

Ingredients for a good assembly

Coverage



High coverage is required

- Oversample the genome to ensure every base is sequenced with long overlaps between reads
- Biased coverage will also fragment assembly

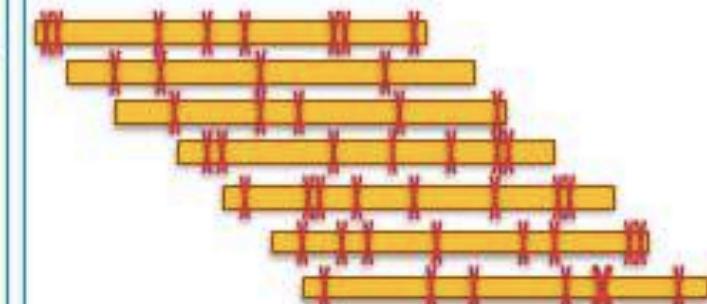
Read Length



Reads & mates must be longer than the repeats

- Short reads will have *false overlaps* forming hairball assembly graphs
- With long enough reads, assemble entire chromosomes into contigs

Quality



Errors obscure overlaps

- Reads are assembled by finding kmers shared in pair of reads
- High error rate requires very short seeds, increasing complexity and forming assembly hairballs

FUTURE ISSUES

1. High-error reads: Third-generation DNA sequencing technologies (e.g., from Pacific Biosciences and Oxford Nanopore) generate much longer reads than previously possible (tens of thousands of base pairs), but with the cost of much higher error rates.
2. Metagenomics/mixtures of organisms: Increasingly, scientists are sequencing the genomes within mixtures of organisms, whether in the context of metagenomics or within clinical samples (e.g., mixtures of tumor cells). Most of the theoretical framework for sequence assembly was developed for isolated genomes. New methods will need to be developed that can both cope with and characterize heterogeneity within closely related genomes.
3. Dealing with big data: As DNA sequencing costs drop, scientists are increasingly able to focus on larger genomes (such as those of plants) and mixtures (such as soil metagenomes). New approaches will be needed that allow genome sequence assemblers to scale with the amount of data being generated.

Not covered but should be

Alignment method in overlap graph

String graph (reduced overlap graph)

Shortest Superstring Problem (SSP)

Hamiltonian path

Choice of kmers in DBG

Bloom filter

References

shorturl.at/xBC06