

# Week 2: Genome assembly & annotation

- Genome assembly
  - Overlap layout consensus
  - de Bruijn graphs
- Genome annotation
  - Hidden Markov Models

# Day 06: Genome assembly

- Genome assembly
  - Overlap layout consensus
  - de Bruijn graphs

# Why sequence the genome?

- Determine the "complete" sequence of a haploid genome.
  - Previously "snippets" of the genome were available.
- Identify the sequence and location of every gene.
- Use as a "map" to then track the location and frequency of genetic variation.
- Unravel the genetic architecture of inherited and somatic traits/diseases.
- To understand genome and species evolution.

# Sequencing of the human genome

"All the News  
That's Fit to Print"

# The New York Times

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\$1 beyond the greater New York metropolitan area.

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## Late Edition

New York: Today, afternoon thunderstorms, high 88. Tonight, showers end, low 67. Tomorrow, partly cloudy with showers late, high 81. Yesterday, high 88, low 74. Weather map, Page D8.

## Genetic Code of Human Life Is Cracked by Scientists

### JUSTICES REAFFIRM MIRANDA RULE, 7-2; A PART OF 'CULTURE'

By LINDA GREENHOUSE

WASHINGTON, June 26 — The Supreme Court reaffirmed the Miranda decision today by a 7-to-2 vote that erased a shadow over one of the most famous rulings of modern times and acknowledged that the Miranda warnings "have become part of our national culture."

The court said in an opinion by Chief Justice William H. Rehnquist that because the 1966 Miranda decision "announced a constitutional rule," a statute by which Congress had sought to overrule the decision was itself unconstitutional.

Miranda had appeared to be in jeopardy, both because of that long-ignored but recently rediscovered law, by which Congress has tried to overrule Miranda 32 years ago, and because of the court's perceived hostility to the original decision.

The chief justice said, though, that the 1968 law, which replaced the Miranda warning with a case-by-case test of whether a confession was voluntary, could be upheld only if the Supreme Court decided to overturn Miranda. But with Miranda having

Judges Antonin Scalia and Clarence Thomas cast the dissenting votes.

The decision overturned a ruling last year by the federal appeals court in Richmond, Va., which held that Congress was entitled to the last word because Miranda's presumption that a confession was not voluntary unless preceded by the warnings was not required by the Constitution.

The decision today — only 14 pages long, in Chief Justice Rehnquist's typically spare style — brought an abrupt and to one of the odder episodes in the court's recent history, an intense and strangely delayed re-fighting of a previous generation's battle over the rights of criminal suspects. Miranda v. Arizona was a hallmark of the Warren Court, and Chief Justice Rehnquist, despite his record as an early and tenacious critic of that decision, evidently did not want its repudiation to be an imprint of his own tenure.

There was considerable drama in the courtroom today as the chief justices announced that he would de-

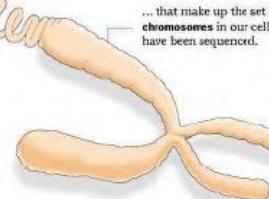
### The Book of Life

The three billion base pairs ...

BASE PAIRS  
Rungs between  
the strands of  
the double helix



... of the intertwining  
double helix of DNA ...  
... make up the set of  
chromosomes in our cells,  
have been sequenced.



By ordering the base units, scientists hope to  
locate the genes and determine their functions.

The New York Times

### Science Times

A special issue

- Putting the genome to work.
- Some information has already paid research dividends.
- Two research methods, two results.
- From Mendel to genome.
- More articles, charts and photos of the genome effort.

Section F



Paul Hester/The New York Times

### A SHARED SUCCESS

#### 2 Rivals' Announcement Marks New Medical Era, Risks and All

By NICHOLAS WADE

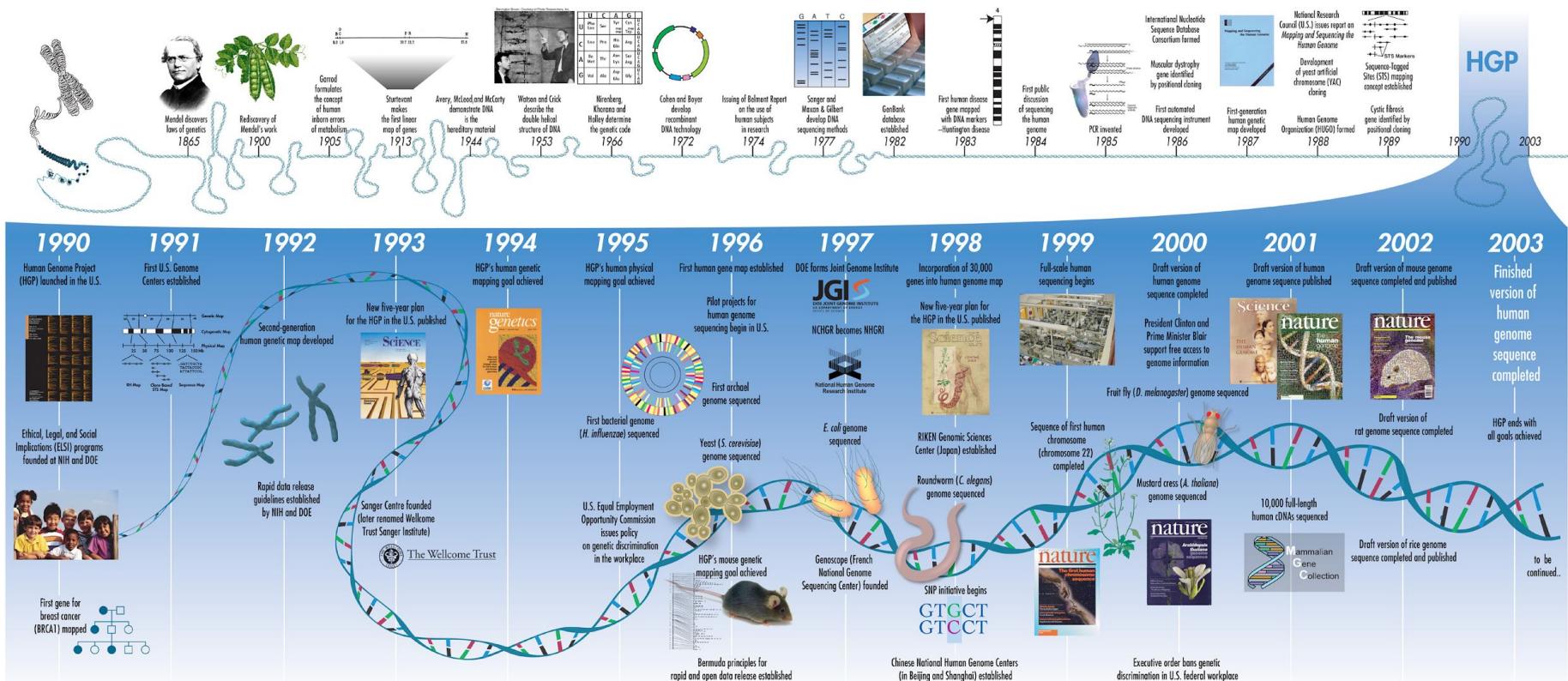
WASHINGTON, June 26 — In an achievement that represents a pinnacle of human self-knowledge, two rival groups of scientists said today that they had deciphered the hereditary script, the set of instructions that defines the human organism.

"Today we are learning the language in which God created life," President Clinton said at a White House ceremony attended by members of the two teams, Dr. James D. Watson, co-discoverer of the structure of DNA, and, via satellite, Prime Minister Tony Blair of Britain. [Excerpts, Page D8.]

The teams' leaders, Dr. J. Craig Venter, president of Celera Genomics, and Dr. Francis S. Collins, director of the National Human Genome Research Institute, praised each other's contributions and signaled a spirit of cooperation from now on, even though the two efforts will remain firmly independent.

The human genome, the ancient script that has now been deciphered, consists of two sets of 23 giant DNA

# Genome sequencing has a long history



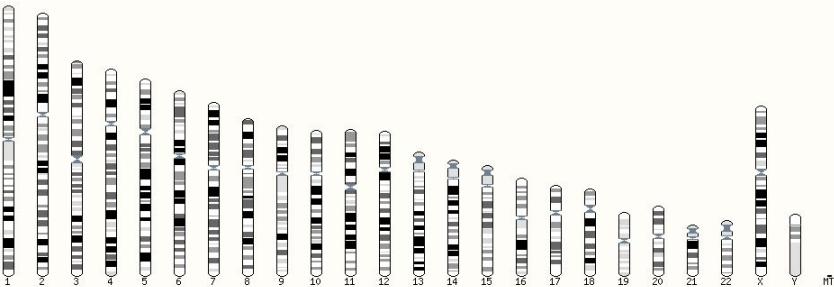
# Genome sequencing technologies

Technology	Read length (bp)	Error rate	Native paired-end read support
ABI/Solid	75	Low (~2%)	Yes
Illumina/Solexa	100–150	Low (<2%)	Yes
IonTorrent	~200	Medium (~4%)*	No
Roche/454	400–600	Medium (~4%)*	No
Sanger	Up to ~2,000 bp	Low (~2%)	Yes
Pacific Biosciences	Up to ~15,000‡	High (~18%)	Yes (in strobe read mode)
Oxford nanopore	Up to ~20,000	High (~12%)	



# Genome sequence build

## The Human Genome – Summary

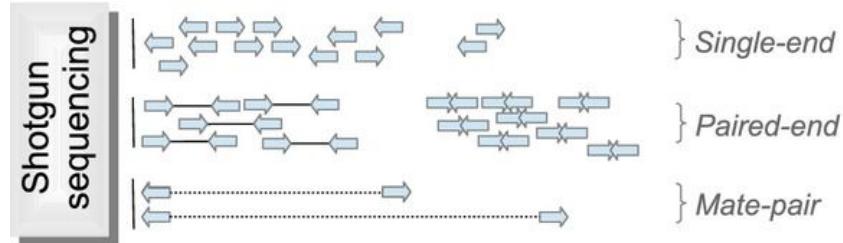
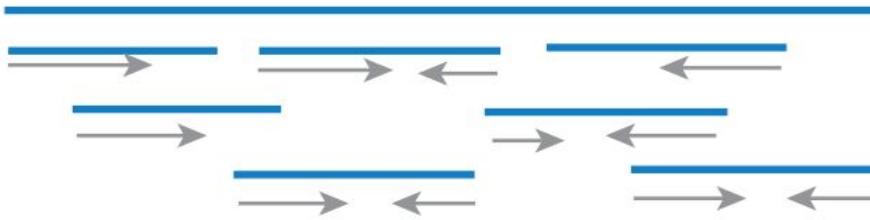


<b>Assembly</b>	GRCh38.p13 (Genome Reference Consortium Human Build 38), INSDC Assembly <a href="#">GCA_000001405.28</a> , Dec 2013
<b>Base Pairs</b>	4,537,931,177
<b>Golden Path Length</b>	3,096,649,726
<b>Annotation provider</b>	Ensembl
<b>Annotation method</b>	Full genebuild
<b>Genebuild started</b>	Jan 2014
<b>Genebuild released</b>	Jul 2014
<b>Genebuild last updated/patched</b>	Jun 2019
<b>Database version</b>	98.38
<b>Gencode version</b>	GENCODE 32

### Gene counts (Primary assembly)

<b>Coding genes</b>	20,444 (incl 667 readthrough)
<b>Non coding genes</b>	23,949
Small non coding genes	4,871
Long non coding genes	16,857 (incl 304 readthrough)
Misc non coding genes	2,221
<b>Pseudogenes</b>	15,214 (incl 8 readthrough)
<b>Gene transcripts</b>	227,530

# Genome assembly & annotation – Overview



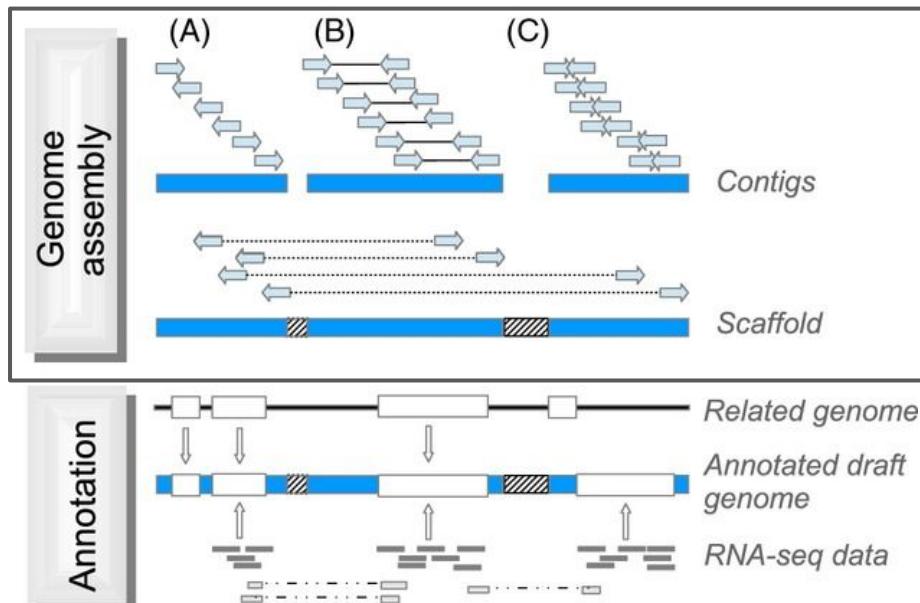
**read:** a short/long word that comes out of sequencer

**mate pair:** a pair of reads from two ends of the same insert fragment

**contig:** a contiguous sequence formed by several overlapping reads with no gaps

**scaffold:** an ordered and oriented set of contigs, usually by mate pairs

**consensus sequence:** derived from the sequence multiple alignment of reads in a contig



# Genome assembly - the problem

Input: GGC GTCTATATCTGGCTCTAGGCCCTCATTTTT

Copy: GGC GTCTATATCTGGCTCTAGGCCCTCATTTTT  
GGC GTCTATATCTGGCTCTAGGCCCTCATTTTT  
GGC GTCTATATCTGGCTCTAGGCCCTCATTTTT  
GGC GTCTATATCTGGCTCTAGGCCCTCATTTTT

Fragment: GGC GTCTA TATCTCGG CTCTAGGCCCTC ATTTTTT  
GGC GTCTATAT CTCGGCTCTAGGCCCTCA TTTTTT  
GGCGTC TATATCT CGGCTCTAGGCCCT CATTTTTT  
GGCGTCTAT ATCTCGGCTCTAG GCCCTCA TTTTTT

# Genome assembly - the problem

Reconstruct  
this

CTAGGCCCTCAATTTT  
CTCTAGGCCCTCAATTTT  
GGCTCTAGGCCCTCATTTTT  
CTCGGCTCTAGGCCCTCATTTT  
TATCTCGACTCTAGGCCCTCA  
TATCTCGACTCTAGGCC  
TCTATATCTCGGCTCTAGG  
GGCGTCTATATCTCG  
GGCGTCGATATCT  
GGCGTCTATATCT

→ GGCGTCTATATCTCGGCTCTAGGCCCTCATTTTT

From these

# Genome assembly - the problem

Reconstruct  
this

CTAGGCCCTCAATTTT  
GGCGTCTATATCT  
CTCTAGGCCCTCAATTTT  
TCTATATCTCGGCTCTAGG  
GGCTCTAGGCCCTCATTTTT  
CTCGGCTCTAGCCCCTCATTTT  
TATCTCGACTCTAGGCCCTCA  
GGCGTCGATATCT  
TATCTCGACTCTAGGCC  
GGCGTCTATATCTCG

From these

→ GGCGTCTATATCTCGGCTCTAGGCCCTCATTTTT

# Genome assembly - the problem

CTAGGCCCTCAATTTT  
CTCTAGGCCCTCAATTTT  
GGCTCTAGGCCCTCATTTTT  
CTCGGCTCTAGCCCTCATTTT  
TATCTCGACTCTAGGCCCTCA  
TATCTCGACTCTAGGCC  
TCTATATCTCGGCTCTAGG  
GGCGTCTATATCTCG  
GGCGTCGATATCT  
GGCGTCTATATCT  
GGCGTCTATATCTCGGCTCTAGGCCCTCATTTTT

Coverage at this position = 6

177 nucleotides in total  
Genome is 35 nucleotides  
**Average coverage =  $177 / 35 \sim 7x$**

# Genome assembly - the problem

Say two reads truly originate from overlapping stretches of the genome.  
Why might there be differences?

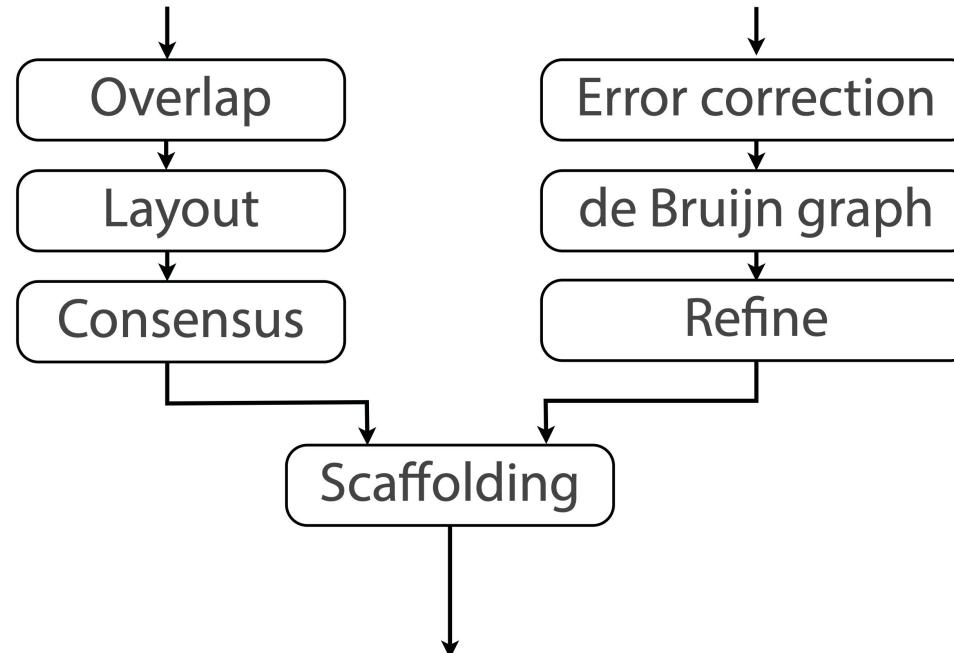
The diagram illustrates two DNA sequence reads. The top read is TATCTCGACTCTAGGCC, and the bottom read is TCTATATCTCGGCTCTAGG. Vertical lines above the reads indicate where they overlap. A red arrow points to the second base pair of the bottom read, specifically the 'T' in 'CT'.

TATCTCGACTCTAGGCC  
| | | | | | | | | |  
TCTATATCTCGGCTCTAGG  
↑

1. Sequencing error
2. Ploidy

# Genome assembly - two major approaches

1. Overlap-Layout-Consensus (OLC) assembly
2. de Bruijn graph (DBG) assembly



# Introduction to graph theory

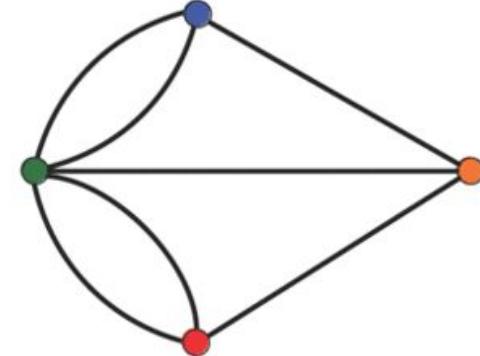


[1736] Seven Bridges of Königsberg

Can one walk through the city so that they cross each of those bridges once and only once?



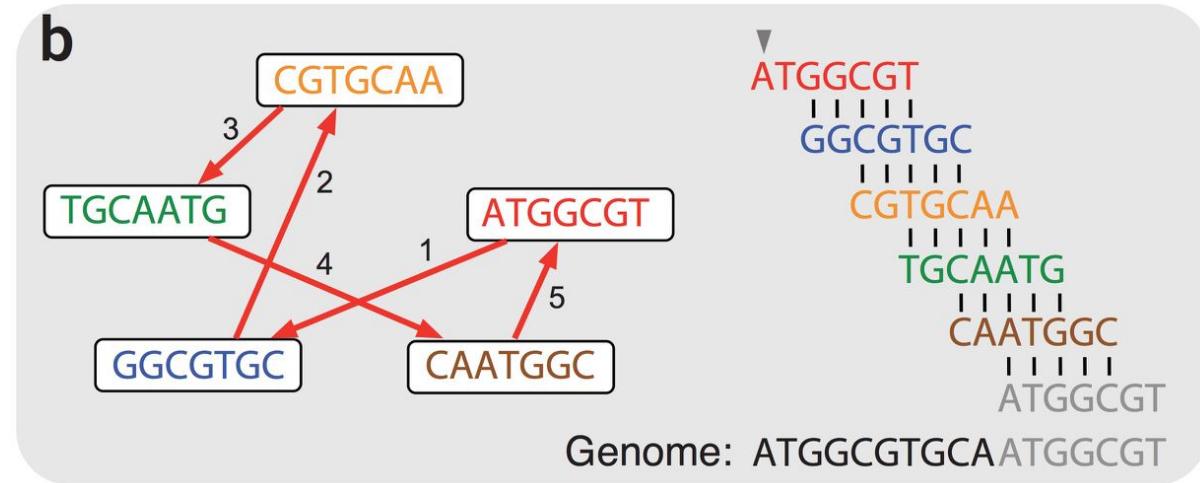
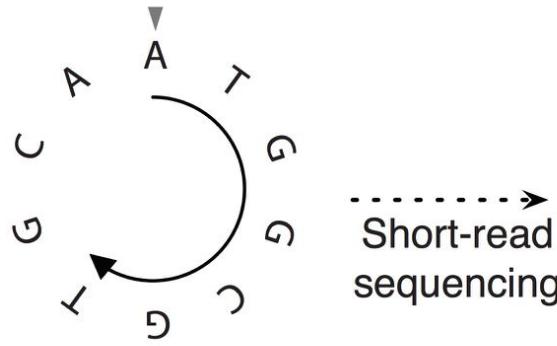
Students choose an option



Graph: (Nodes, Edges, Weights)

(Eulerian) Path exists if the graph contains zero or two vertices that have an odd degree.

# Overlap graphs for sequence assembly



**Nodes:** Reads

**Edges:** Alignments between reads ( $\geq 5$  bases)

**Genome:** Walk along a Hamiltonian cycle (visit each vertex exactly once) to combine alignments between successive reads and reconstruct the full circular genome.

# Overlap graphs for sequence assembly

Break reads into shorter k-mers!

Resulting k-mers often represent nearly all k-mers from the genome for sufficiently small k.

**Nodes:** k-mers

**Edges:** Overlap between k-mers

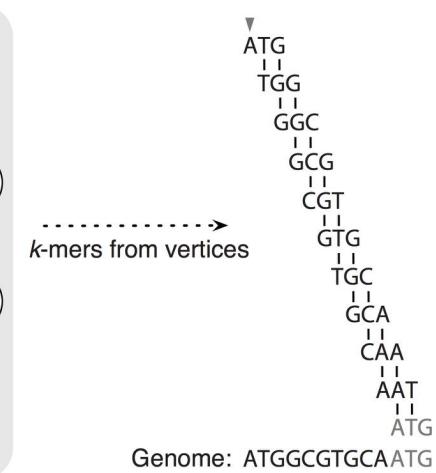
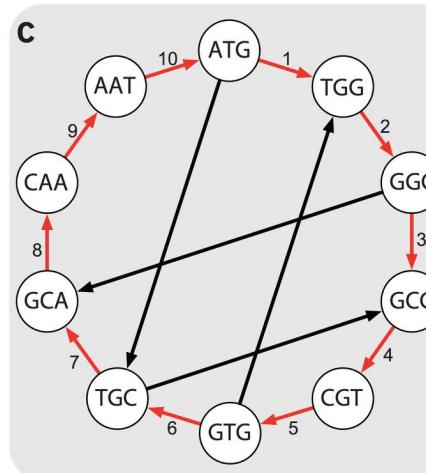
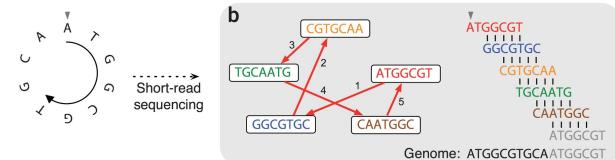
**Genome:** Walk the Hamiltonian cycle

Large genomes result in too many reads:

- $10^6$  reads  $\rightarrow 10^{12}$  pairwise alignments.
- $10^9$  reads  $\rightarrow 10^{18}$  alignments.

There is no known efficient algorithm for finding a Hamiltonian cycle in a large graph with millions (let alone billions) of nodes.

Find a path that visits all *nodes* of a graph exactly once!



# Building a consensus

TAGATTACACAGATTACTGA TTGATGGCGTAA CTA  
TAGATTACACAGATTACTGACTTGATGGCGTAAACTA  
TAG TTACACAGATTATTGACTTCATGGCGTAA CTA  
TAGATTACACAGATTACTGACTTGATGGCGTAA CTA  
TAGATTACACAGATTACTGACTTGATGGCGTAA CTA

↓      ↓      ↓      ↓      ↓  
TAGATTACACAGATTACTGACTTGATGGCGTAA CTA



Take reads that make up a contig and line them up

Take *consensus*, i.e. majority vote

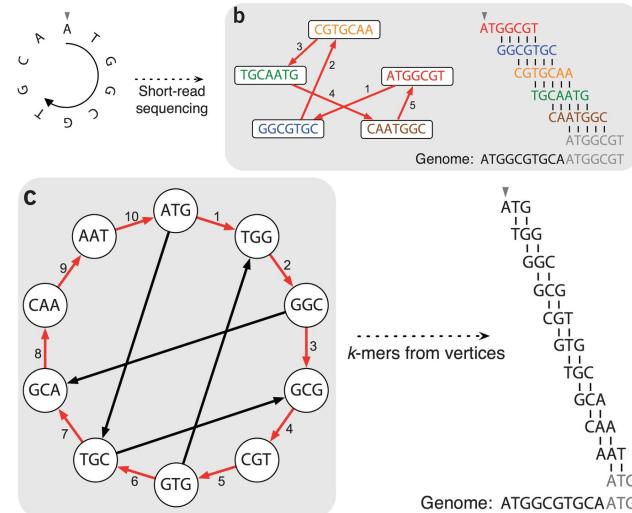
# Issues

Four hidden assumptions that do not hold for real sequencing:

1. We can generate all k-mers present in the genome.
2. All k-mers are error free.
3. Each k-mer appears at most once in the genome.
4. The genome consists of a single circular chromosome.

E.g., a technology that generates 100-nucleotide long reads:

- may miss some 100-mers present in the genome (even if the read coverage is high)
- the 100-mers that it does generate typically have errors.

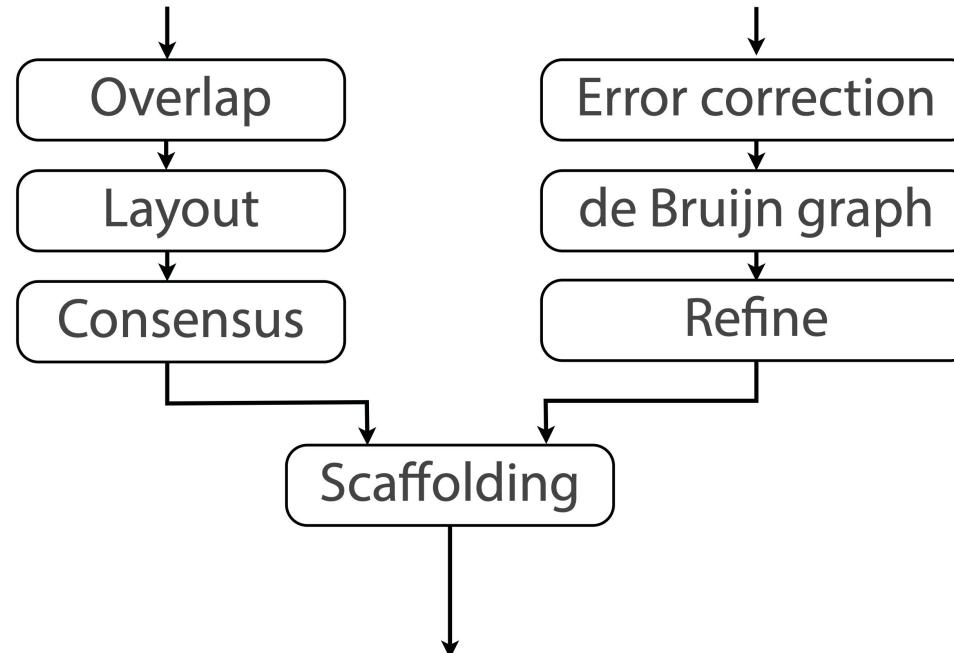


The main drawback of OLC is that building the overlap graph can be very slow.

E.g., 2nd-gen sequencing datasets contain ~100s of millions or billions of reads, 100s of billions of nucleotides total.

# Genome assembly - two major approaches

1. Overlap-Layout-Consensus (OLC) assembly
2. de Bruijn graph (DBG) assembly



# The shortest common superstring problem

Find a shortest circular 'superstring' that contains all possible 'substrings' of length k (k-mers) over a given alphabet.

Consider:

- alphabet: 0 & 1
- all 3-mers: 000, 001, 010, 011, 100, 101, 110, 111.

(There exist  $n^k$  k-mers in an alphabet containing n symbols.)

A concatenation contains all 3-mers:

000001010011100101110111

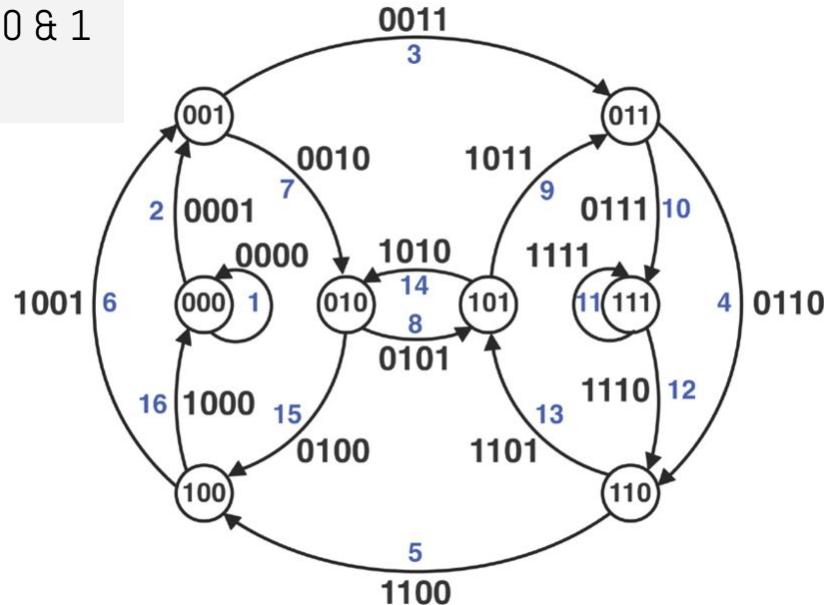
The circular superstring **0001110100** contains all 3-mers & each 3-mer exactly once.

How can we construct a superstring for all k-mers in the case of an arbitrary value of k and an arbitrary alphabet?

# de Bruijn graphs: the 'superstring problem'

alphabet: 0 & 1

$k = 4$



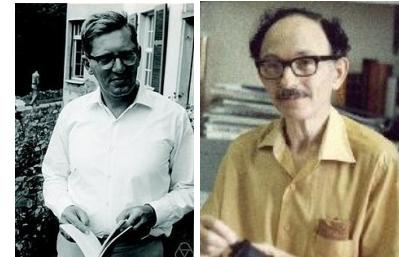
Does this graph have an Eulerian cycle? [Balanced?]

Following the blue numbered edges in order from 1 to 16 traces the cyclic superstring 0000110010111101.

Camille Flye  
Sainte-Marie  
(1894)



Nicolaas Govert De Bruijn &  
Irving John Good  
(1946)



How can we construct a superstring for all  $k$ -mers in the case of an arbitrary value of  $k$  and an arbitrary alphabet?

Construct a **directed graph**:

- Nodes: all prefixes & suffixes –  $(k-1)$ -mers
- Edges: all  $k$ -mers as edges.

# de Bruijn graphs for sequence assembly

Break reads into shorter k-mers!

Resulting k-mers often represent nearly all k-mers from the genome for sufficiently small k.

**Nodes:** (k-1)-mers [in- & out-degrees?]

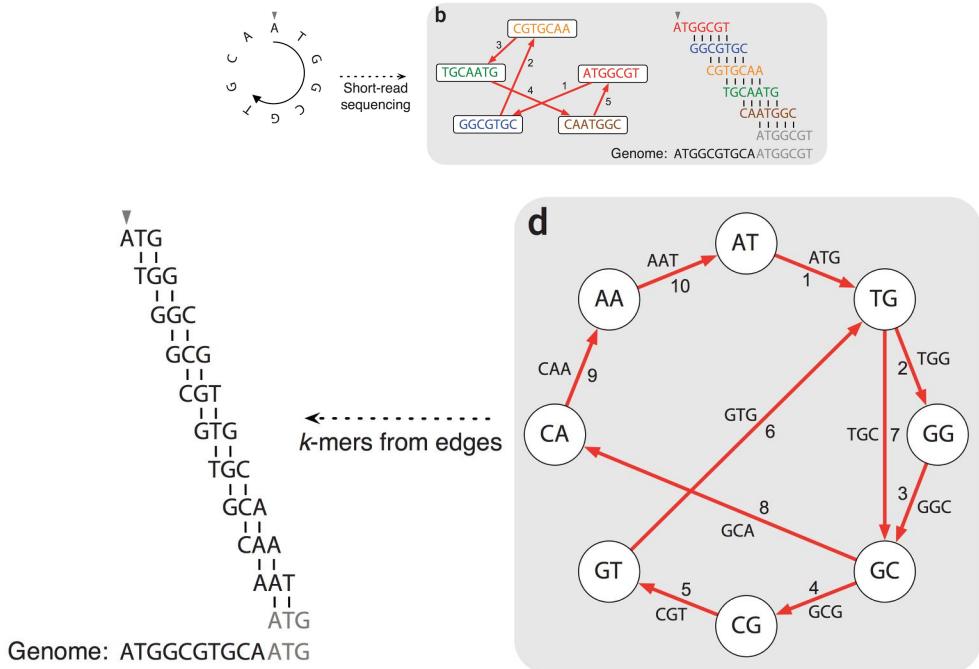
**Edges:** k-mers

**Genome:** Walking the Eulerian cycle

Send out an ant, find a cycle; Note edges traversed, send out another ant, ... until all of the graph's edges have been explored. Combine all cycles to form an Eulerian cycle!

Computationally tractable; time roughly proportional to the number of edges.

Finding a path that visits all *edges* of a graph exactly once is much easier!

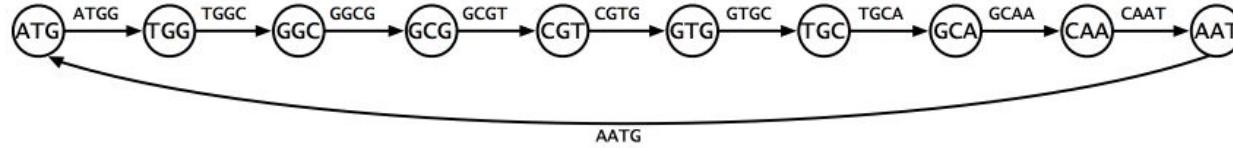


# de Bruijn graphs for sequence assembly – not so easy w/ real data

- Not all k-mers in the genome
  - Read breaking
- Errors in reads
  - Error correcting reads
  - Removing bulges in de Bruijn graphs
- DNA repeats [E.g., ATGCATGC → four 3-mers: ATG, TGC, GCA & CAT]
  - Incorporating k-mer multiplicity
- Multiple and linear chromosomes
  - Cycles to paths
- Unsequenced regions
  - Scaffolds

# de Bruijn graphs from reads with sequencing errors

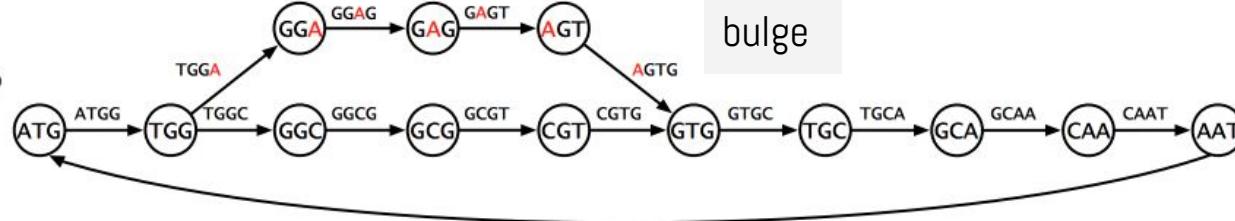
a



AATG

bulge

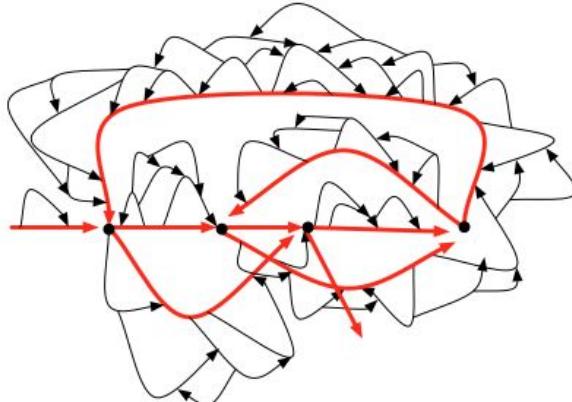
b



TGGAGTG (incorrect)

TGGCGTG (correct)

c

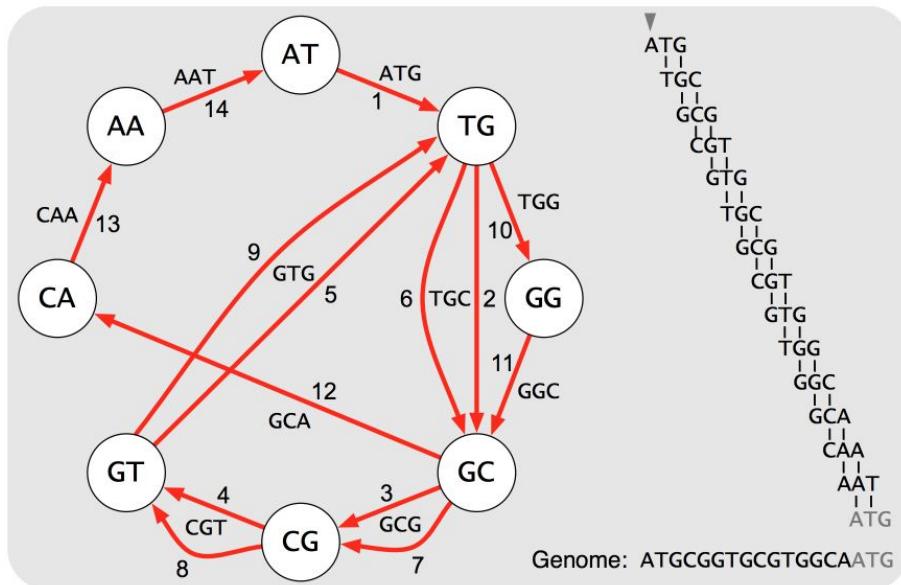


The process of bulge removal should leave only the red edges remaining, yielding an Eulerian path in the resulting graph.

# de Bruijn graphs for sequence assembly – not so easy w/ real data

- Not all k-mers in the genome
  - Read breaking
- Errors in reads
  - Error correcting reads
  - Removing bulges in de Bruijn graphs
- DNA repeats [E.g., ATGCATGC → four 3-mers: ATG, TGC, GCA & CAT]
  - Incorporating k-mer multiplicity
- Multiple and linear chromosomes
  - Cycles to paths
- Unsequenced regions
  - Scaffolds

# de Bruijn graphs for dealing with repeats



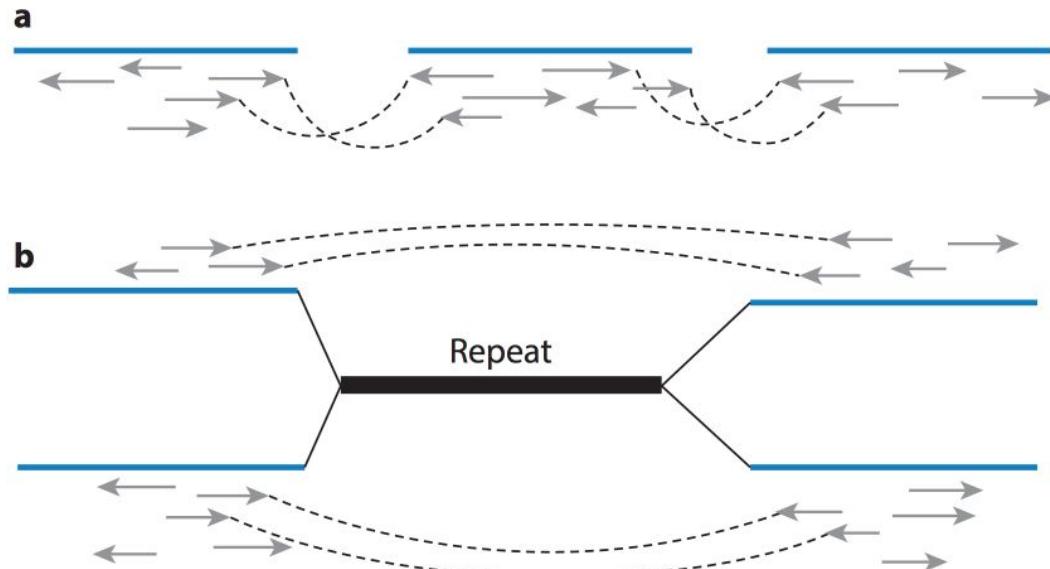
Genome: ATGCGTGCCTGGCA

Incorporate k-mer multiplicity:

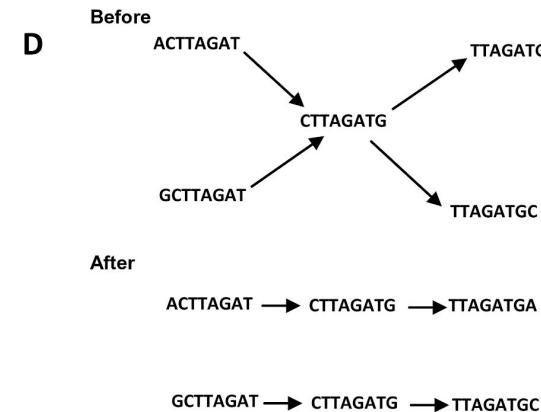
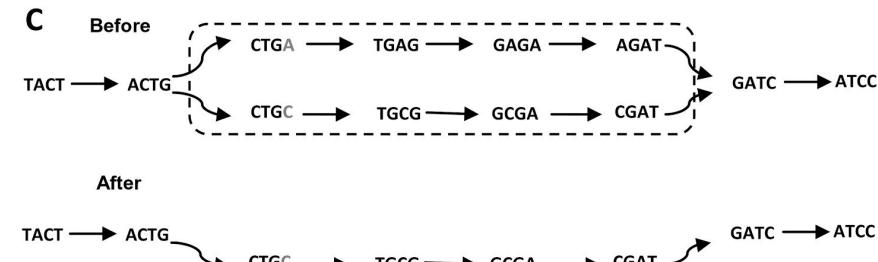
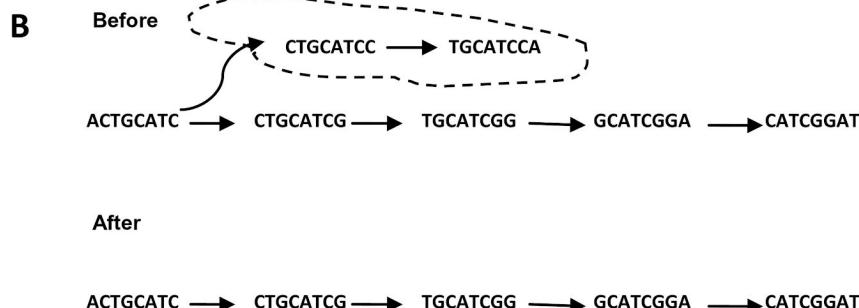
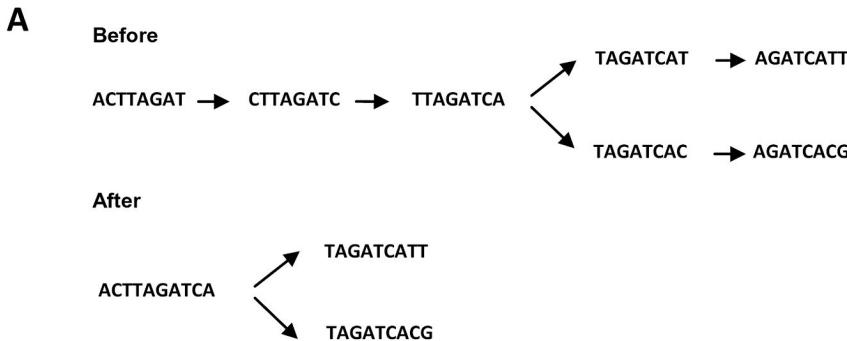
- Four 3-mers TGC, GCG, CGT, and GTG: multiplicity 2
- Six 3-mers ATG, TGG, GGC, GCA, CAA, and AAT: multiplicity 1

# de Bruijn graphs for sequence assembly – not so easy w/ real data

- Not all k-mers in the genome
  - Read breaking
- Errors in reads
  - Error correcting reads
  - Removing bulges in de Bruijn graphs
- DNA repeats
  - Incorporating k-mer multiplicity
- Multiple and linear chromosomes
  - Cycles to paths
- Unsequenced regions
  - Scaffolds



# Simplifying de Bruijn graphs



# Genome assembly - quality & contiguity

The diagram illustrates a genome assembly with several contigs represented by blue text. A red vertical bar highlights a specific position where the sequence 'CTAGGCCCTCAATTTT' appears twice. An arrow points to this position with the text 'Coverage at this position = 6'. The contigs are:

- CTAGGCCCTCAATTTT
- CTCTAGGCCCTCAATTTT
- GGCTCTAGGCCCTCATTNTT
- CTCGGCTCTAGCCCCTCATTNTT
- TATCTCGACTCTAGGCCCTCA
- TATCTCGACTCTAGGCC
- TCTATATCTCGGCTCTAGG
- GGCGTCTATATCTCG
- GGCGTCGATATCT
- GGCGTCTATATCT
- GGCGTCTATATCTCGGCTCTAGGCCCTCATTNTT

177 nucleotides in total

Genome is 35 nucleotides

$$\text{Average coverage} = 177 / 35 \sim 7x$$

**N50**: A statistic used for assessing the contiguity of a genome assembly.

- The contigs in an assembly are sorted by size and added, starting with the largest.
- N50 is the size of the contig that makes the total greater than or equal to 50% of the genome size.

# Algorithms for genome assembly

- Error detection and correction based on sequence composition of the reads.
- Graph construction to represent reads/k-mers and their shared sequence.
- Graph adjustments:
  - Reduction of simple non-intersecting paths to single nodes.
  - Removal of error-induced paths (recognized as spurs or bubbles).
  - Collapse of polymorphism-induced complexity (bubbles).
  - Simplification of tangles (using information outside the graph: individual, paired-end, or mate-pair reads to constraints on path distance & outcome).
- Conversion of reduced paths to contigs and scaffolds.
- Reduction of alignments to a consensus sequence.

# Genome sequencing technologies

Technology	Read length (bp)	Error rate	Native paired-end read support
ABI/Solid	75	Low (~2%)	Yes
Illumina/Solexa	100–150	Low (<2%)	Yes
IonTorrent	~200	Medium (~4%)*	No
Roche/454	400–600	Medium (~4%)*	No
Sanger	Up to ~2,000 bp	Low (~2%)	Yes
Pacific Biosciences	Up to ~15,000‡	High (~18%)	Yes (in strobe read mode)
Oxford nanopore	Up to ~20,000	High (~12%)	

# Genome assemblers

Assemblers	Technology	Availability	Notes
ALLPATHS-LG	Illumina, Pacific Biosciences	<a href="ftp://ftp.broadinstitute.org/pub/crd/ALLPATHS/Release-LG">ftp://ftp.broadinstitute.org/pub/crd/ALLPATHS/Release-LG</a>	Requires a specific sequencing recipe (BOX 3)
SOAPdenovo	Illumina	<a href="http://soap.genomics.org.cn/soapdenovo.html">http://soap.genomics.org.cn/soapdenovo.html</a>	Also used for transcriptome and metagenome assembly
Velvet	Illumina, SOLiD, 454, Sanger	<a href="http://www.ebi.ac.uk/~zerbino/velvet">http://www.ebi.ac.uk/~zerbino/velvet</a>	May have substantial memory requirements for large genomes
ABySS	Illumina, SOLiD, 454, Sanger	<a href="http://www.bcgsc.ca/platform/bioinfo/software/abyss">http://www.bcgsc.ca/platform/bioinfo/software/abyss</a>	Also used for transcriptome assembly

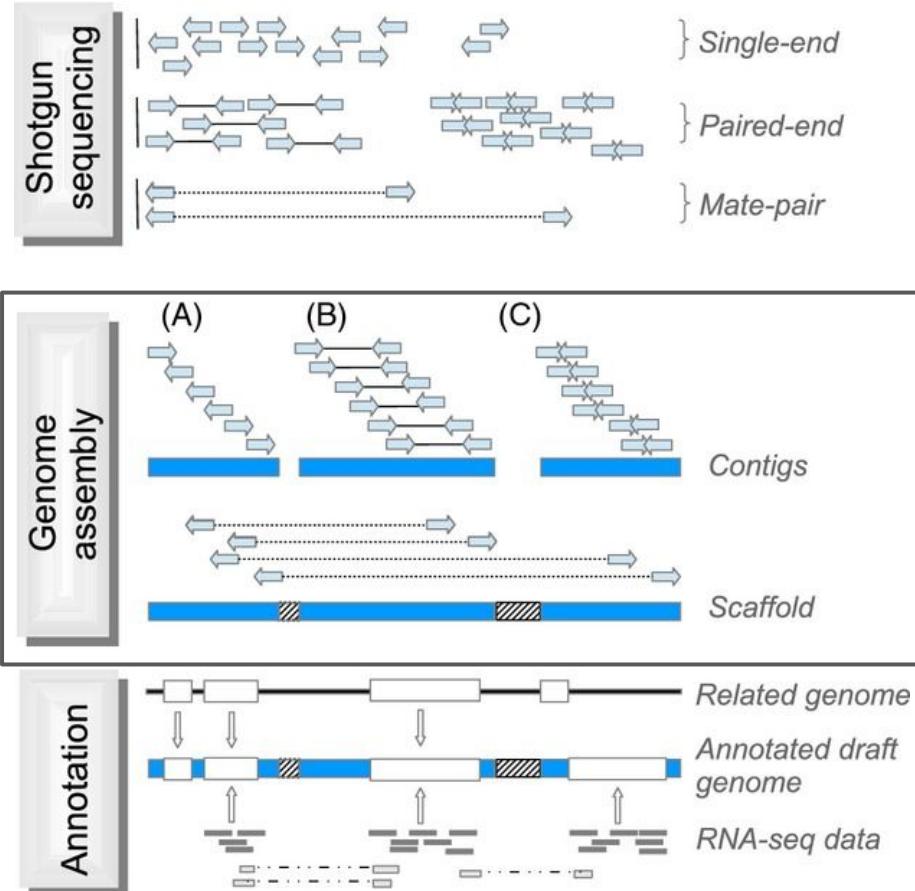
# Metagenome, Transcriptome, Single-cell assemblers

Assemblers	Technology	Availability	Notes
<b>Metagenome assemblers</b>			
Genovo	454	<a href="http://cs.stanford.edu/group/genovo">http://cs.stanford.edu/group/genovo</a>	Uses a probabilistic model for assembly
MetaVelvet	Illumina, SOLiD, 454, Sanger	<a href="http://metavelvet.dna.bio.keio.ac.jp">http://metavelvet.dna.bio.keio.ac.jp</a>	Based on Velvet
Meta-IDBA	Illumina	<a href="http://i.cs.hku.hk/~alse/hkubrg/projects/metaidba">http://i.cs.hku.hk/~alse/hkubrg/projects/metaidba</a>	Based on IDBA
<b>Transcriptome assemblers</b>			
Trinity	Illumina, 454	<a href="http://trinityrnaseq.sourceforge.net">http://trinityrnaseq.sourceforge.net</a>	Tailored to reconstruct full-length transcripts; may require substantial computational time
Oases	Illumina, SOLiD, 454, Sanger	<a href="http://www.ebi.ac.uk/~zerbino/oases">http://www.ebi.ac.uk/~zerbino/oases</a>	Based on Velvet
<b>Single-cell assemblers</b>			
SPAdes	Illumina	<a href="http://bioinf.spbau.ru/en/spades">http://bioinf.spbau.ru/en/spades</a>	
IDBA-UD	Illumina	<a href="http://i.cs.hku.hk/~alse/hkubrg/projects/idba_ud">http://i.cs.hku.hk/~alse/hkubrg/projects/idba_ud</a>	Based on IDBA

# Algorithms for genome assembly

- New sequencing technologies → a different best computational strategy.
- Factors that influence the choice of algorithms:
  - Quantity of data (read length and coverage)
  - Quality of data (including error rates)
  - Genome structure (e.g., GC content and the number and size of repeated regions).
- de Bruijn graphs are best suited for current short-read sequencing technologies
  - Produce very large numbers of reads
  - Can represent genomes with repeats  
[Overlap methods need to mask repeats > read length]
- Long-read technology growing at a rapid pace.

# Genome assembly & annotation – Overview



# Genome assembly - the problem

Reconstruct  
this

CTAGGCCCTCAATTTT  
GGCGTCTATATCT  
CTCTAGGCCCTCAATTTT  
TCTATATCTCGGCTCTAGG  
GGCTCTAGGCCCTCATTTTT  
CTCGGCTCTAGCCCCTCATTTT  
TATCTCGACTCTAGGCCCTCA  
GGCGTCGATATCT  
TATCTCGACTCTAGGCC  
GGCGTCTATATCTCG

From these

→ GGCGTCTATATCTCGGCTCTAGGCCCTCATTTTT

# Genome assembly - two major approaches

