Lecture 14: DNA Sequencing

Study Chapter 8.9

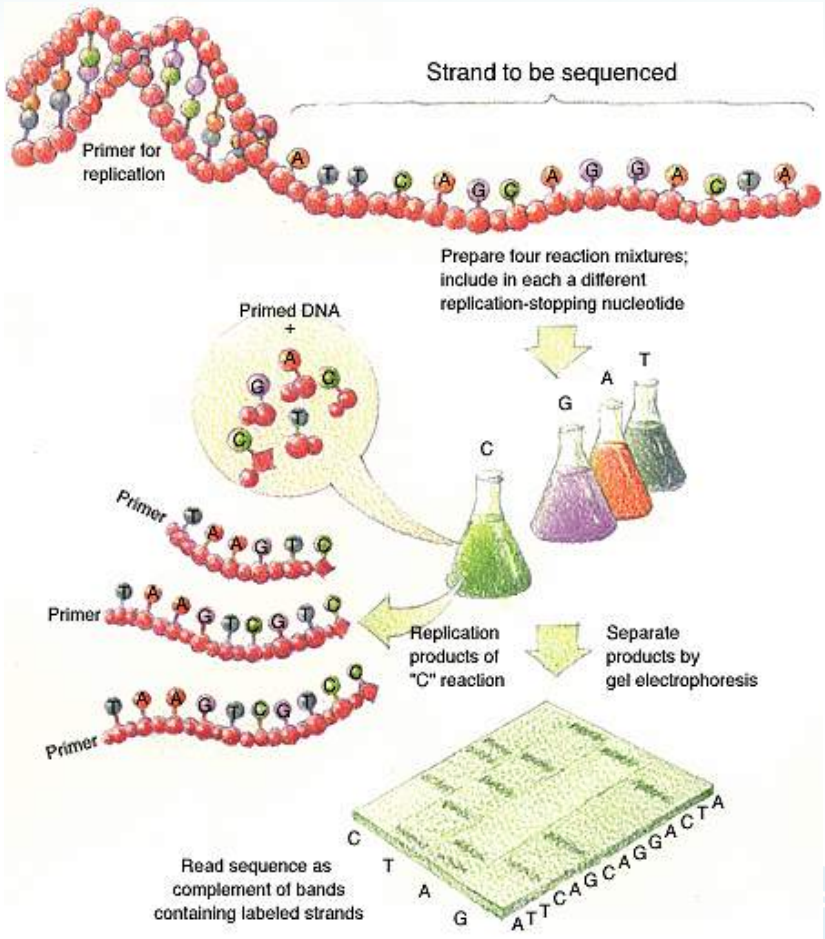
Midterm on Tuesday 10/15

Open book, open notes, no computer

Study Session on 10/14 in FB008 from 5pm-7pm

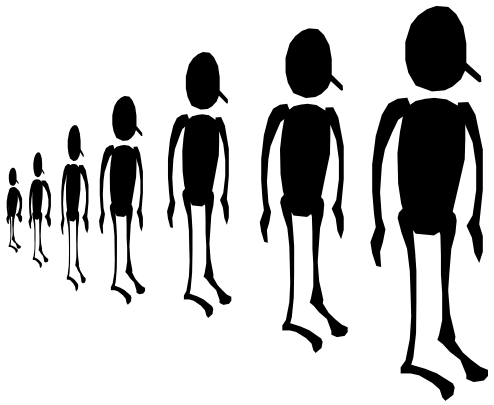
DNA Sequencing

- Shear DNA into millions of small fragments
- Read 500 – 700 nucleotides at a time from the small fragments (Sanger method)



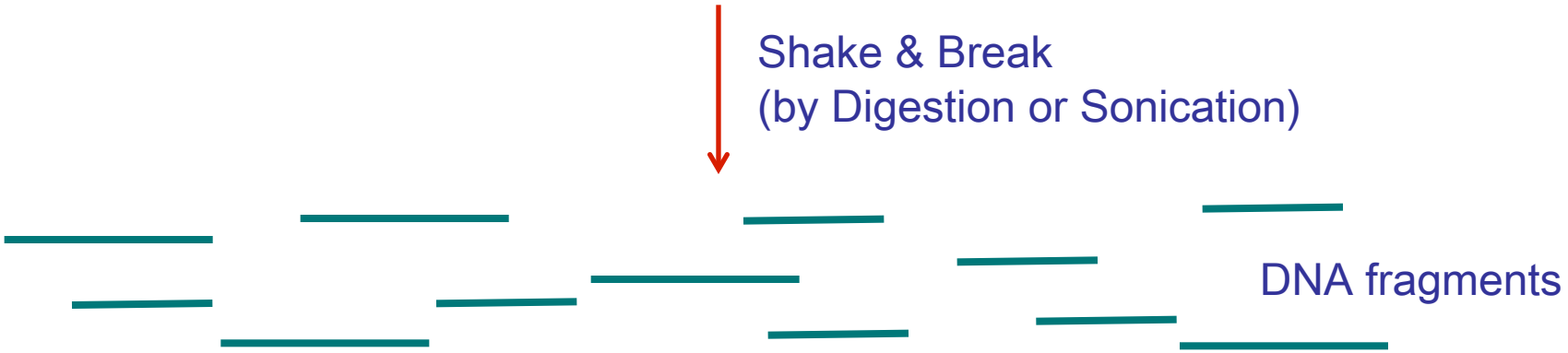
Fragment Assembly

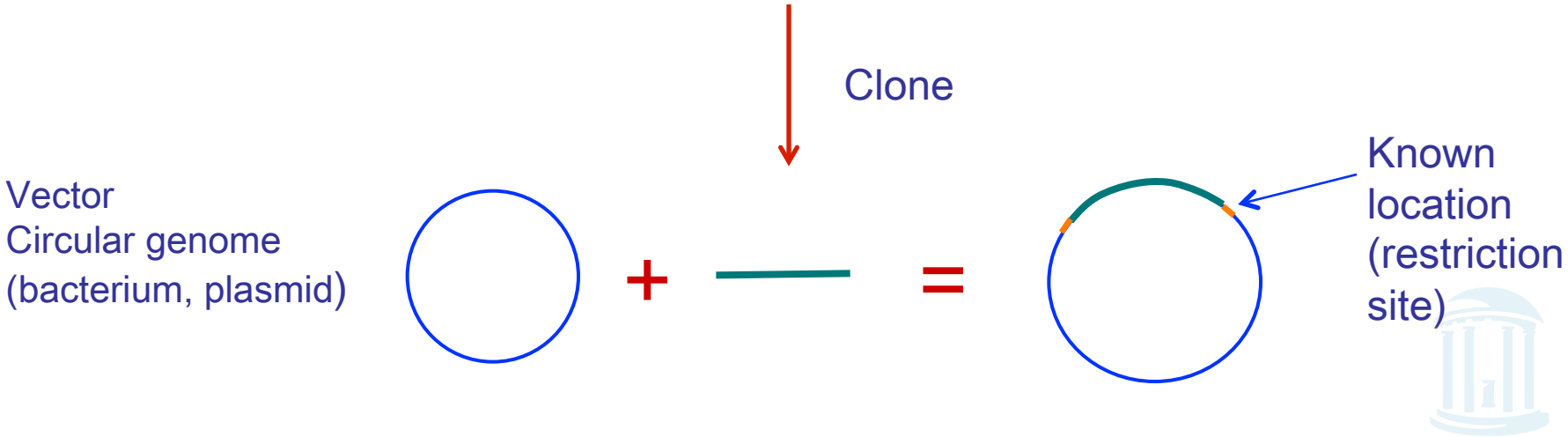
- Assembles the individual overlapping short fragments (reads) into a genomic sequence
- Shortest Superstring problem from last time is an overly simplified abstraction
- Problems:
  - DNA read error rate of 1% to 3%
  - Can't separate strands
  - DNA is **full** of repeats
- Let's take a closer look



Traditional DNA Sequencing

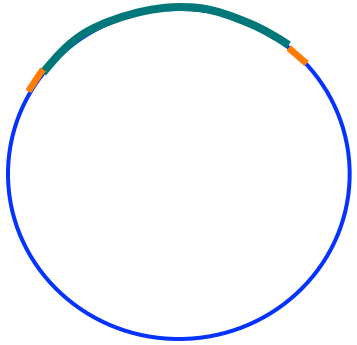
DNA





Different Types of Vectors

VECTOR	Size of insert (bp)
Plasmid	2,000 - 10,000
Cosmid	40,000
BAC (Bacterial Artificial Chromosome)	70,000 - 300,000
YAC (Yeast Artificial Chromosome)	> 300,000 Not used much recently



Dideoxy (Sanger) Sequencing

Template strand - g t a a g a c t g t

Coding strand - c a t t c t g a c a

ddT Reaction -

c a t

c a t t

c a t t c t

ddC Reaction -

c

c a t t c

c a t t c t g a c

ddG Reaction -

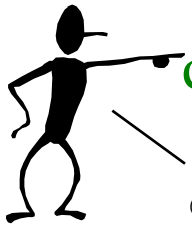
c a t t c t g

ddA Reaction -

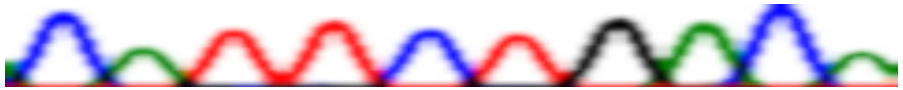
c a

c a t t c t g a

c a t t c t g a c a

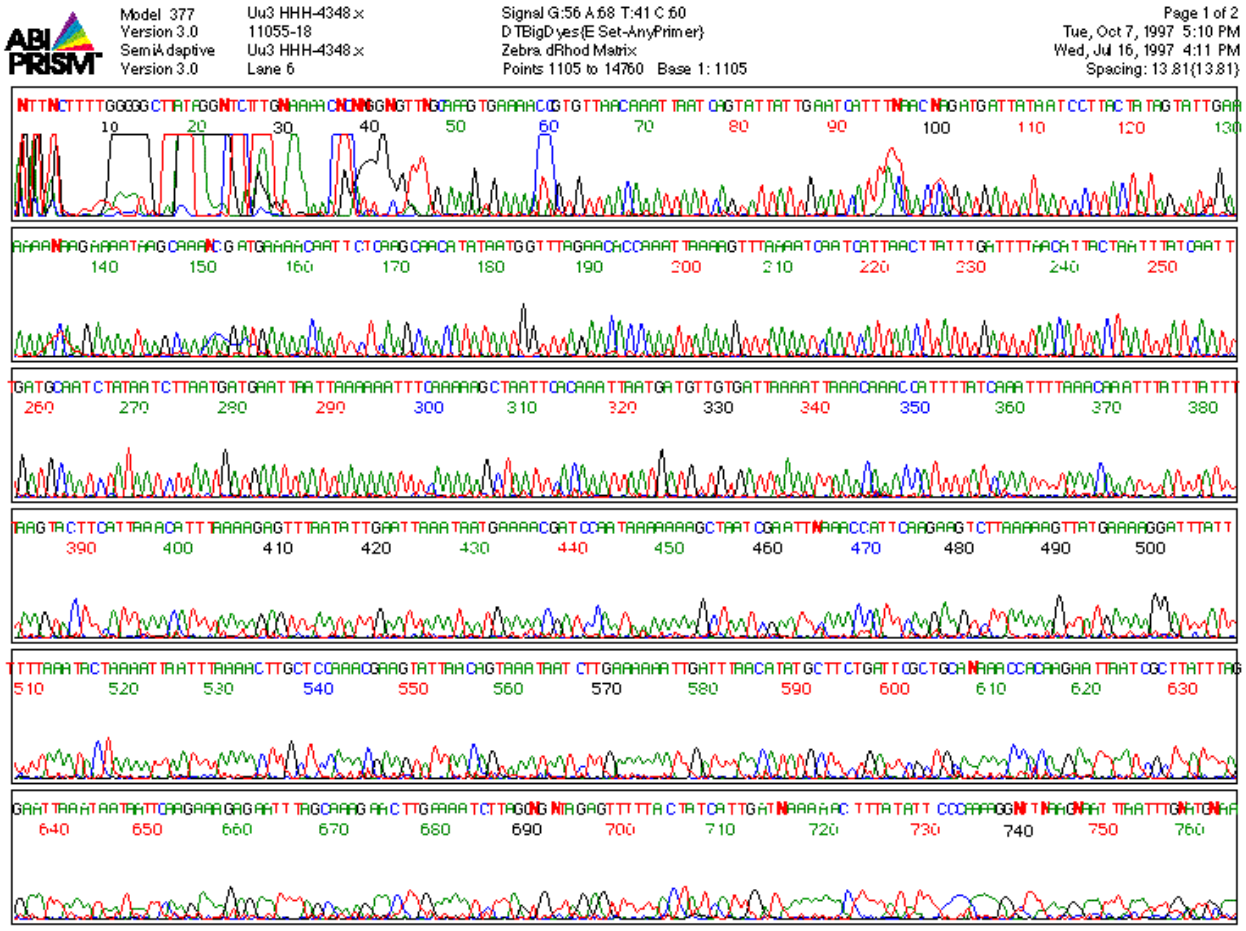


Good for up to
1000 base pairs



Challenging to Read Answers

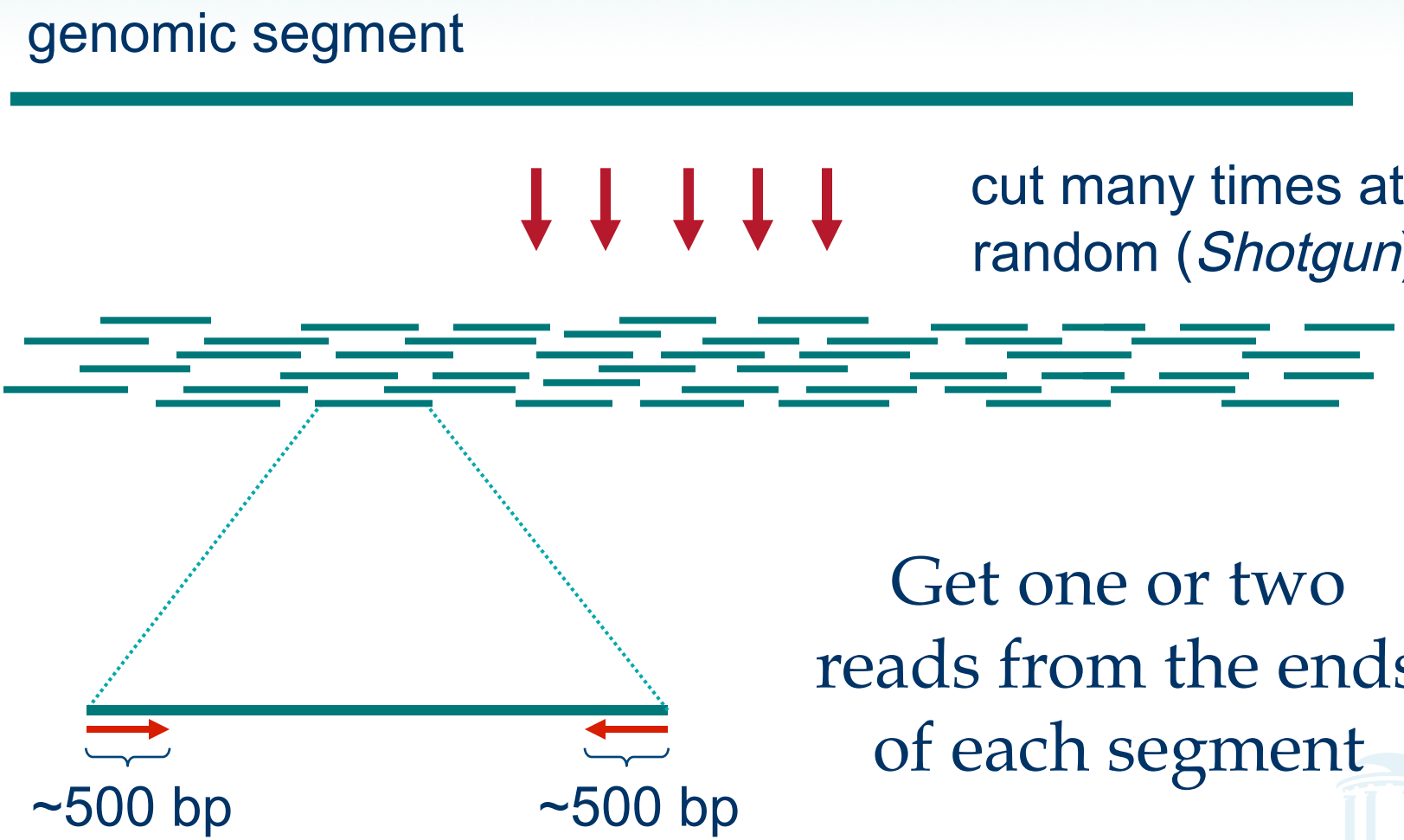
Electropherogram



Reading an Electropherogram

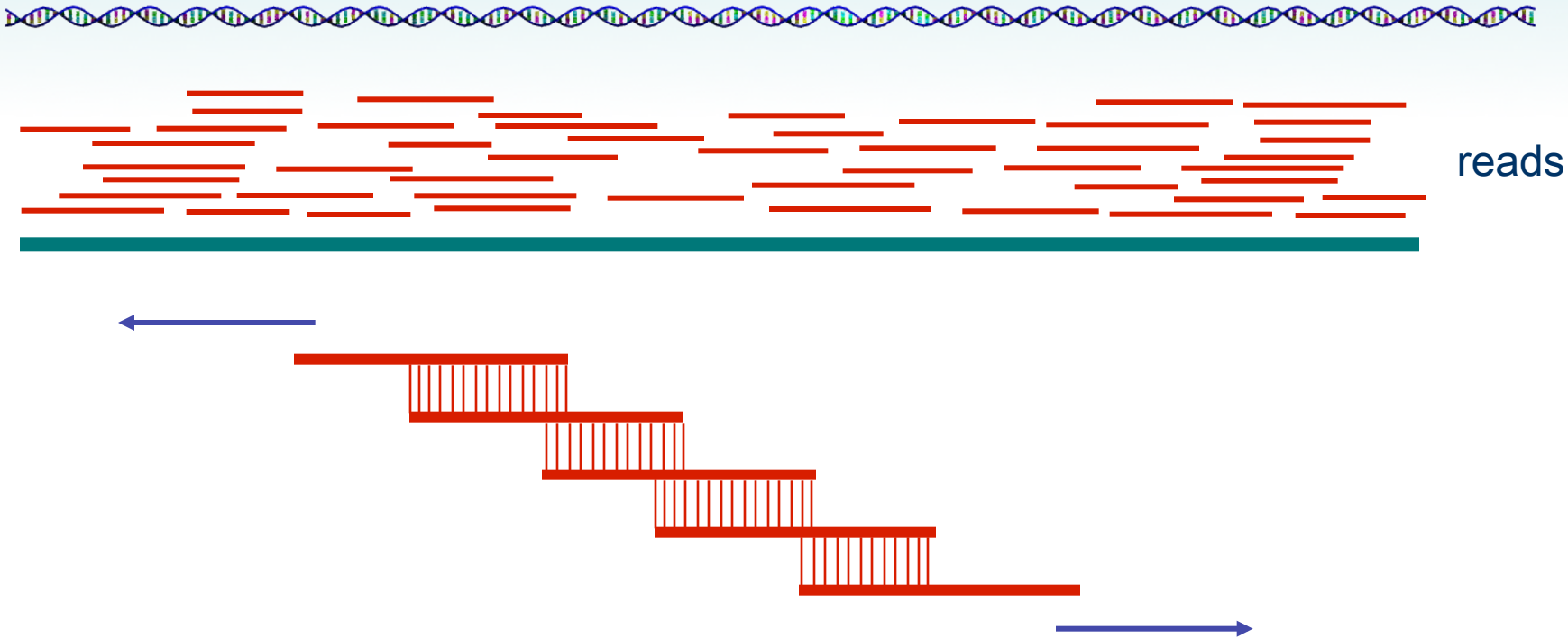
- Issues
  - Noisy start up due to anomalous migration of short fragments that carry bulky dyes
  - Traces become less uniform as run proceeds
  - Large dye responses can overwhelm succeeding lower amplitude responses
  - Occasional mismatches of reaction with template
- Methods for calling the nucleotides: **PHRED**
  - Base calls
  - Maintains quality scores
  - Monitors peak positions

Shotgun Sequencing



Get one or two reads from the ends of each segment

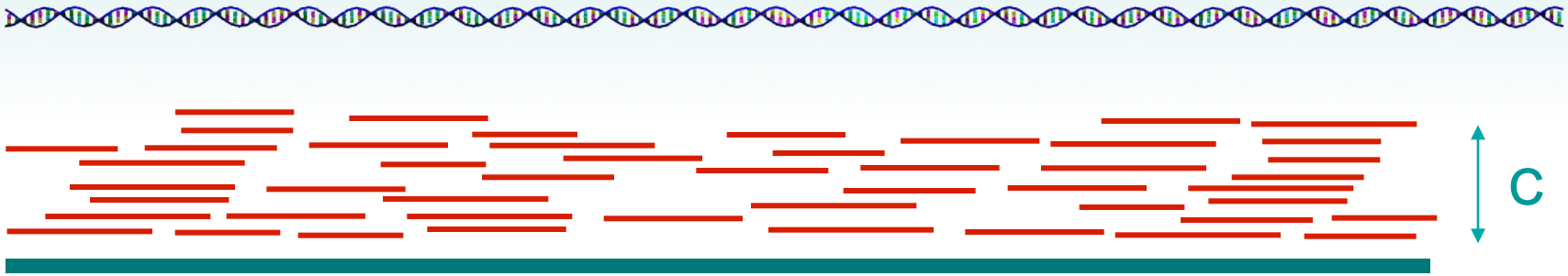
Fragment Assembly



Cover region with ~7-fold redundancy

Overlap reads and extend to reconstruct the original genomic region

Read Coverage



Length of genomic segment: L

Number of reads: n

Length of each read: l

Coverage $C = n\,l / L$

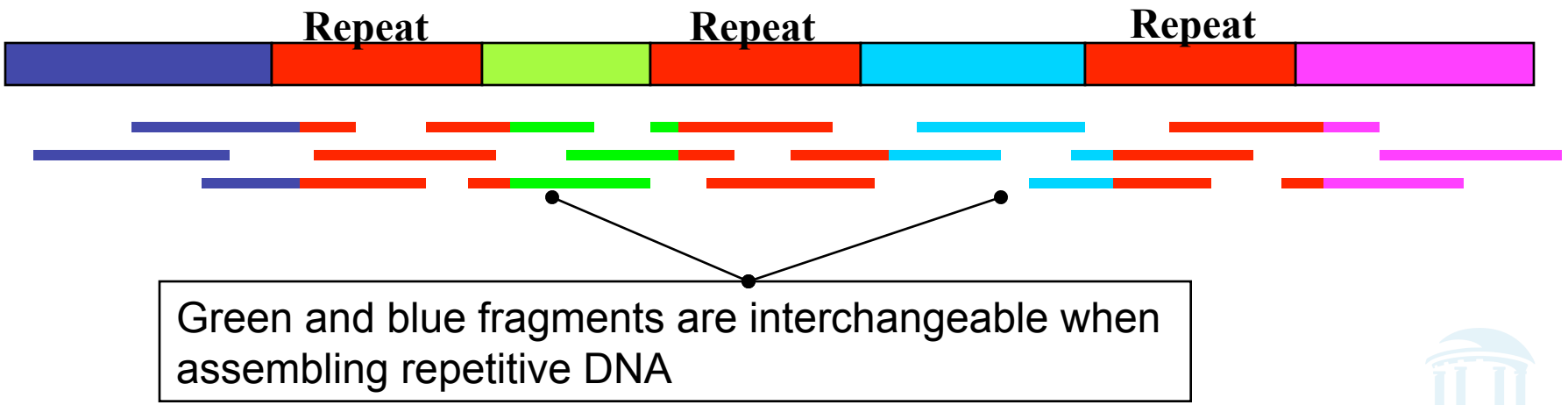
How much coverage is enough?

Lander-Waterman model:

Assuming uniform distribution of reads, C=10 results in 1 gapped region per 1,000,000 nucleotides

Challenges in Fragment Assembly

- **Repeats:** A **major** problem for fragment assembly
- > 50% of human genome is repeats:
  - over 1 million *Alu* repeats (about 300 bp)
  - about 200,000 LINE repeats (1000 bp and longer)



Types of Genome Assemblies

- De Novo –
  An assembly based entirely on self-consitency or self-similarity of short reads (contigs).

- Comparative –
  Refers an assembly of a genome using the sequence of a close relative as a scaffold or reference. Sometimes called a "template assembly" or ”a resequencing”

- Confounding problem for both types: Repeats

Repeat Types

- **Low-Complexity DNA** (e.g. ATATATATACATA…)
- **Microsatellite repeats** $(a_1 \ldots a_k)^N$ where k ~ 3-6
  (e.g. CAGCAGTAGCAGCACCAG)
- **Transposons/retrotransposons**
  - **SINE** Short Interspersed Nuclear Elements
    (e.g., *Alu*: ~300 bp long, $>10^6$ in human)
  - **LINE** Long Interspersed Nuclear Elements
    ~500 - 5,000 bp long, > 200,000 in human
  - **LTR retroposons** Long Terminal Repeats (~700 bp) at each end
- **Gene Families** genes duplicate & then diverge
- **Segmental duplications** ~very long, very similar copies

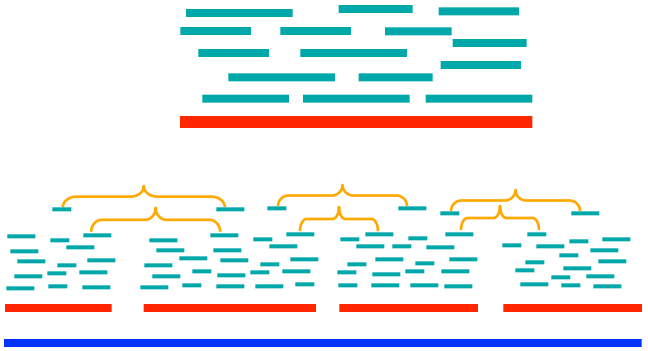
Overlap-Layout-Consensus

Assembler programs ARACHNE, PHRAP, CAP, TIGR, CELERA

Common Approach:

Overlap: find potentially overlapping reads

Layout: merge reads into **contigs** and then combine contigs into **supercontigs**



Consensus: requires many overlapping reads to derive the DNA sequence and to correct for read errors

..ACGATTACAATAGGTT..

Overlap

- Find the best match between the suffix of one read and the prefix of another (shortest superstring)
- Due to sequencing errors, most algorithms use dynamic programming to find the optimal *overlap alignment*
- Filter out fragment pairs that do not share a significantly long common substring

Overlapping Reads

- Make an index of all *k*-mers of all reads
  (*k* ~ 20-24)
- Find read-pairs sharing a k-mer
- Extend alignment –
  throw away if not >95% similar

Histogram Example

v = tagattacacagattattga

- Histogram of 3-mers (18 total)

	A_2	C_2	G_2	T_2
	A_3:C_3:G_3:T_3	A_3:C_3:G_3:T_3	A_3:C_3:G_3:T_3	A_3:C_3:G_3:T_3
A_1	0:0:0:0	2:0:0:0	2:0:0:0	0:0:0:3
C_1	0:1:1:0	0:0:0:0	0:0:0:0	0:0:0:0
G_1	0:0:0:2	0:0:0:0	0:0:0:0	0:0:0:0
T_1	0:1:1:1	0:0:0:0	1:0:0:0	2:0:1:0

Overlapping Reads and Repeats

- Does this really speed up the process?
- A *k*-mer that appears N times, initiates N^2 comparisons (you consider all pairs ofs reads that share the k-mer substring)
- For an *Alu* that appears 10^6 times → 10^{12} comparisons – too much
- **How to avoid repeats:**

  Discard all *k*-mers that appear more than

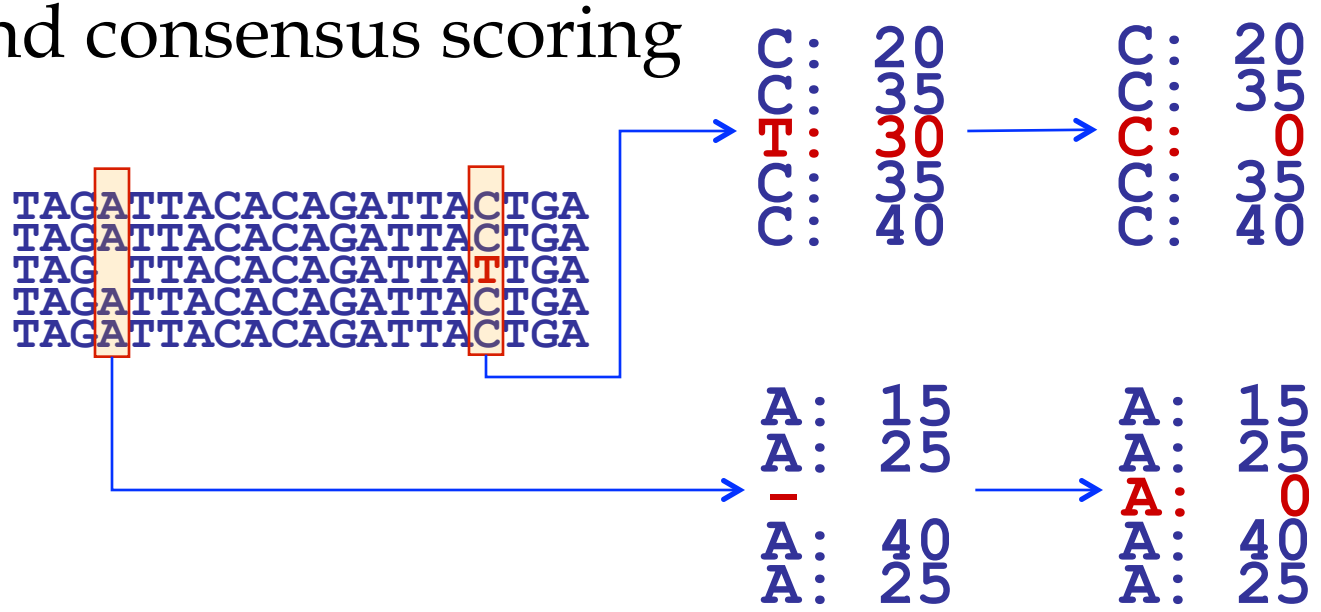
  $t \times$ Coverage, ($t \sim 10$)

Finding Overlapping Reads

k-mer table makes it easy to create local multiple alignments from the overlapping reads

Finding Overlapping Reads (cont'd)

- Correct errors using multiple alignment and consensus scoring



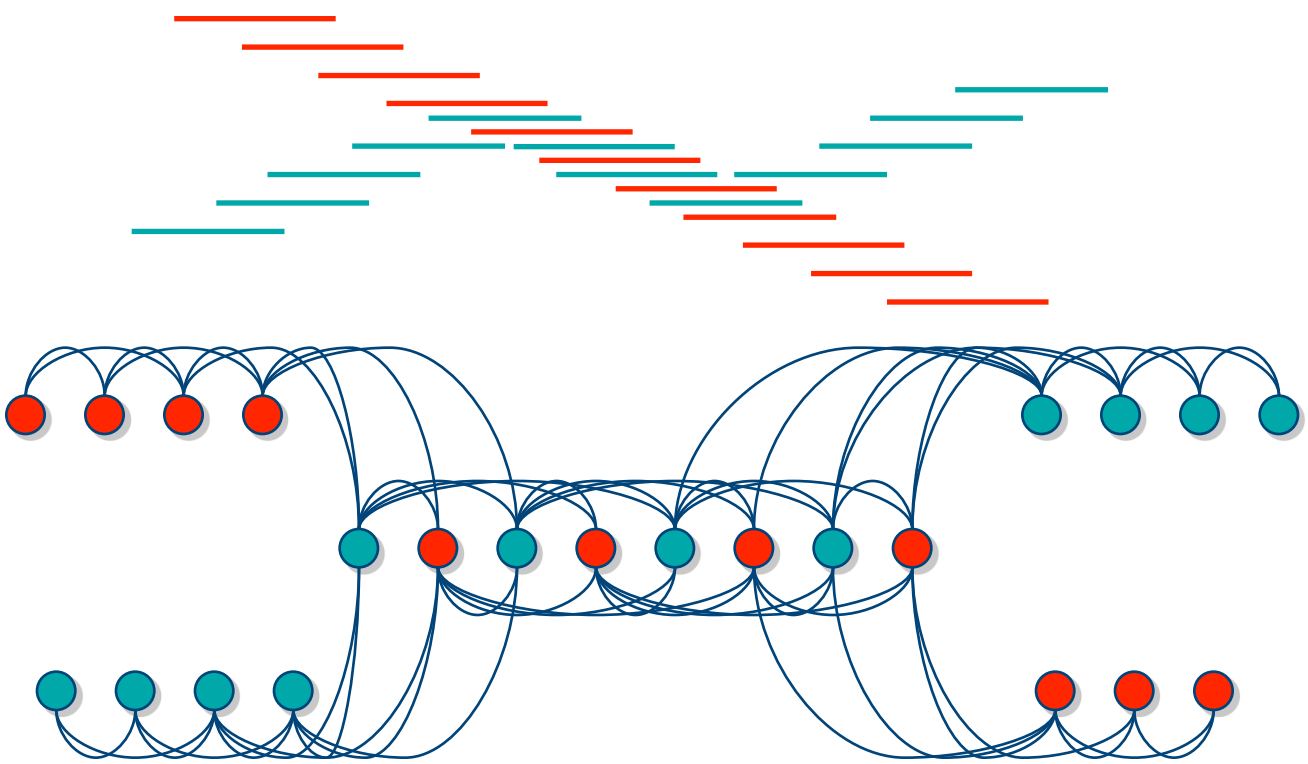
- Score alignments
- Accept alignments with good scores

Layout

- Repeats are still a major challenge
- Do two aligned fragments really overlap, or are they from two copies of a repeat?
- Solution: repeat masking – hide the repeats!!!
- Masking results in high rate of misassembly (up to 20%)
- Misassembly means alot more work at the finishing step

2. Merge Reads into Contigs

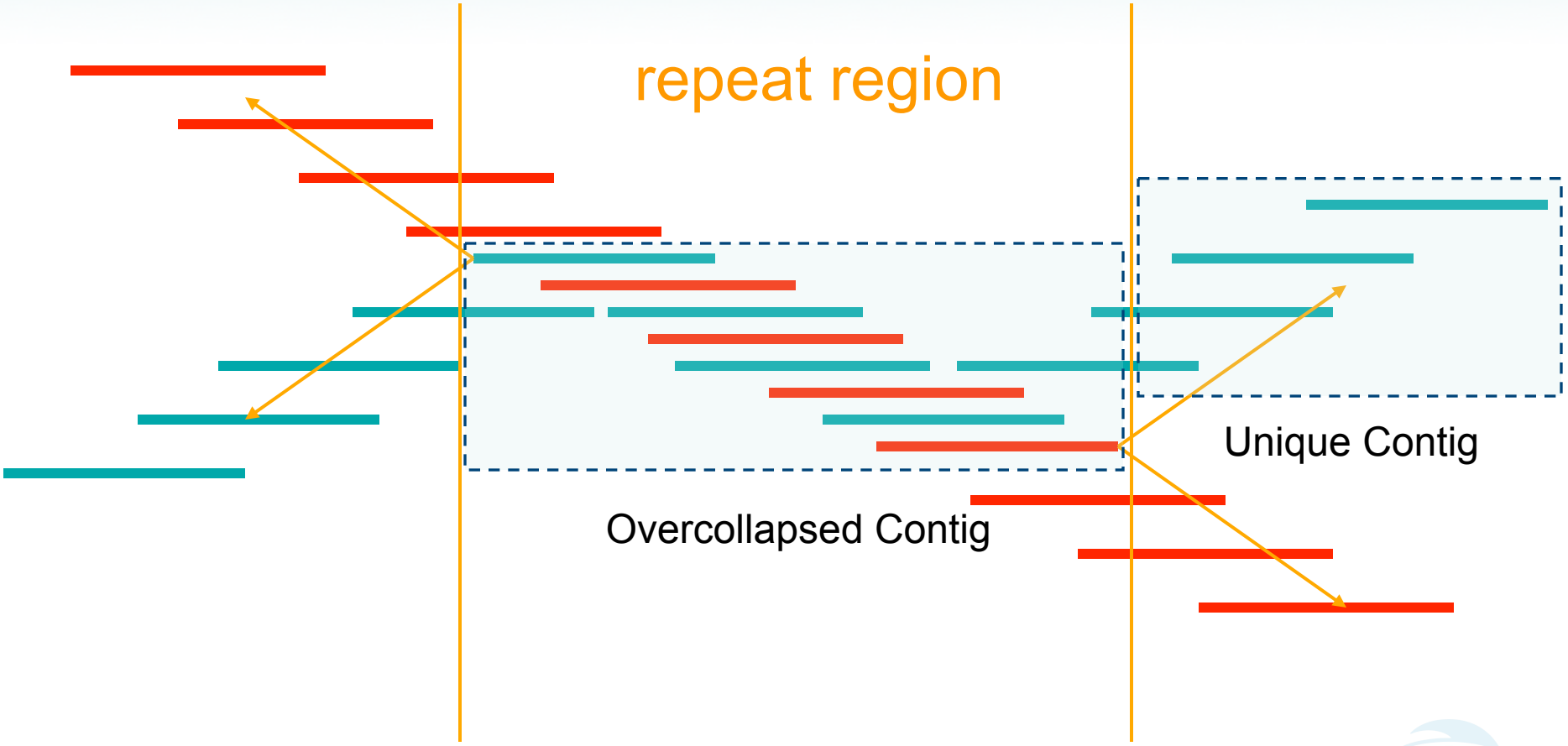
- Overlap graph:
  - Nodes: reads r_1…..r_n
  - Edges: overlaps (r_i, r_j, shift, orientation, score)



Reads that come from two regions of the genome (blue and red) that contain the same repeat

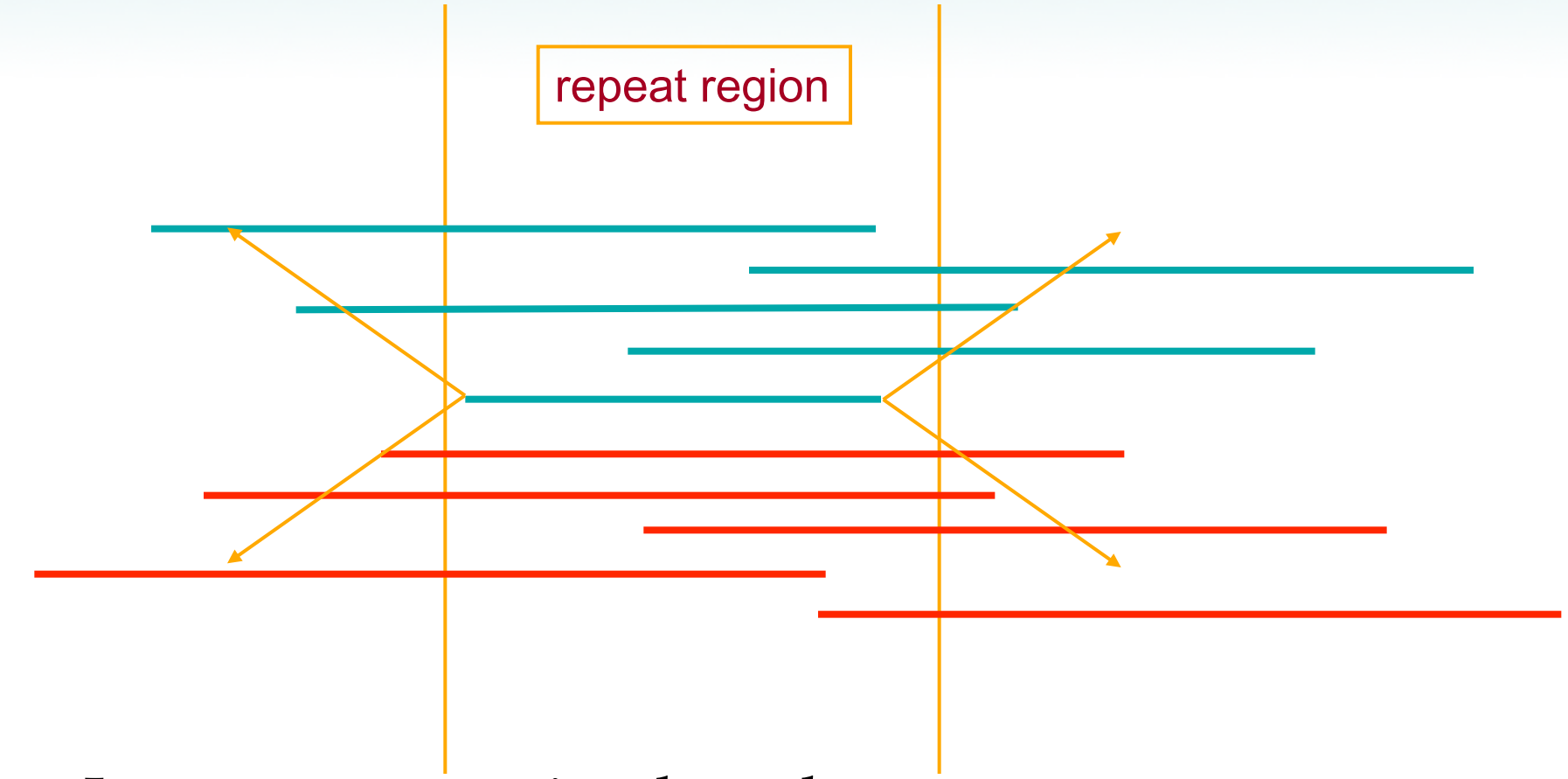
Note:
of course, we don't know the "color" of these nodes

2. Merge Reads into Contigs



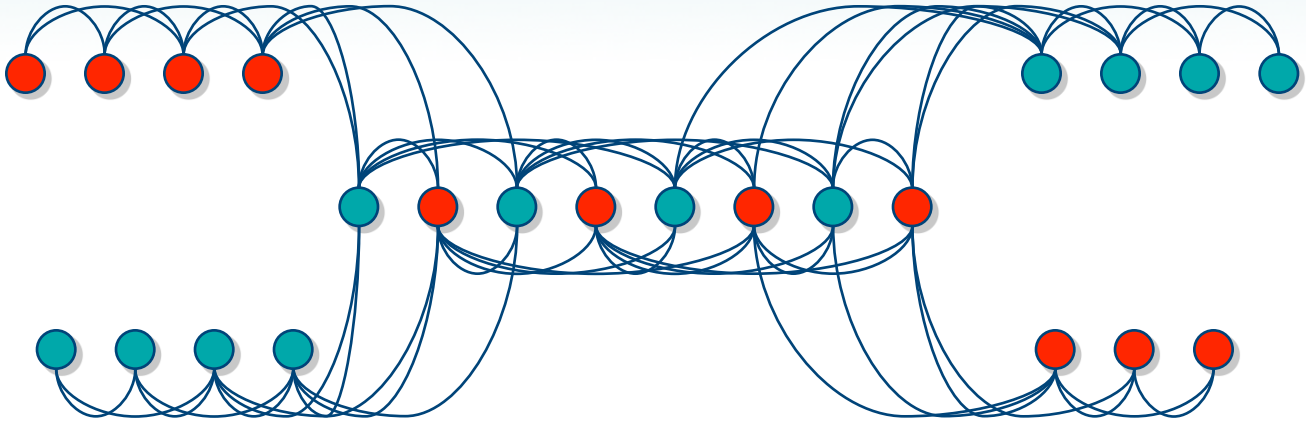
We want to merge reads up to potential repeat boundaries

2. Merge Reads into Contigs

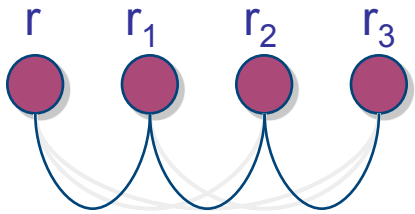


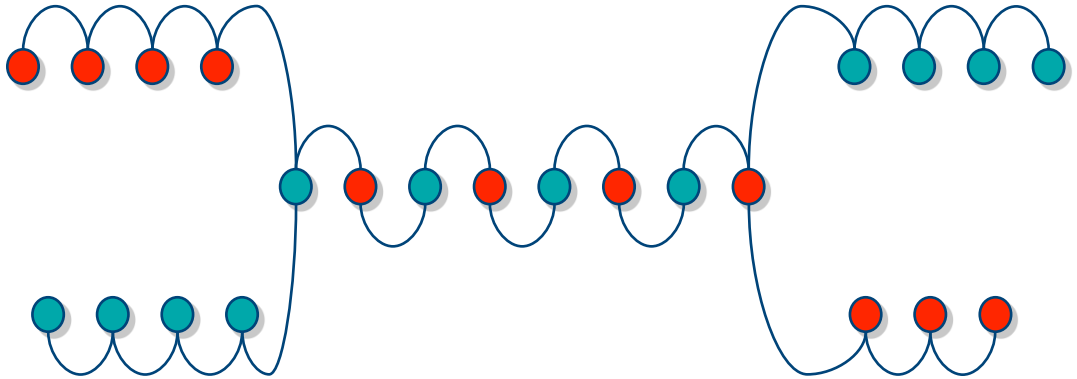
- Ignore non-maximal reads
- Merge only maximal reads into contigs

2. Merge Reads into Contigs



- Remove transitively inferable overlaps
  - If read r overlaps to the right reads r_1, r_2, and r_1 overlaps r_2, then (r, r_2) can be inferred by (r, r_1) and (r_1, r_2)





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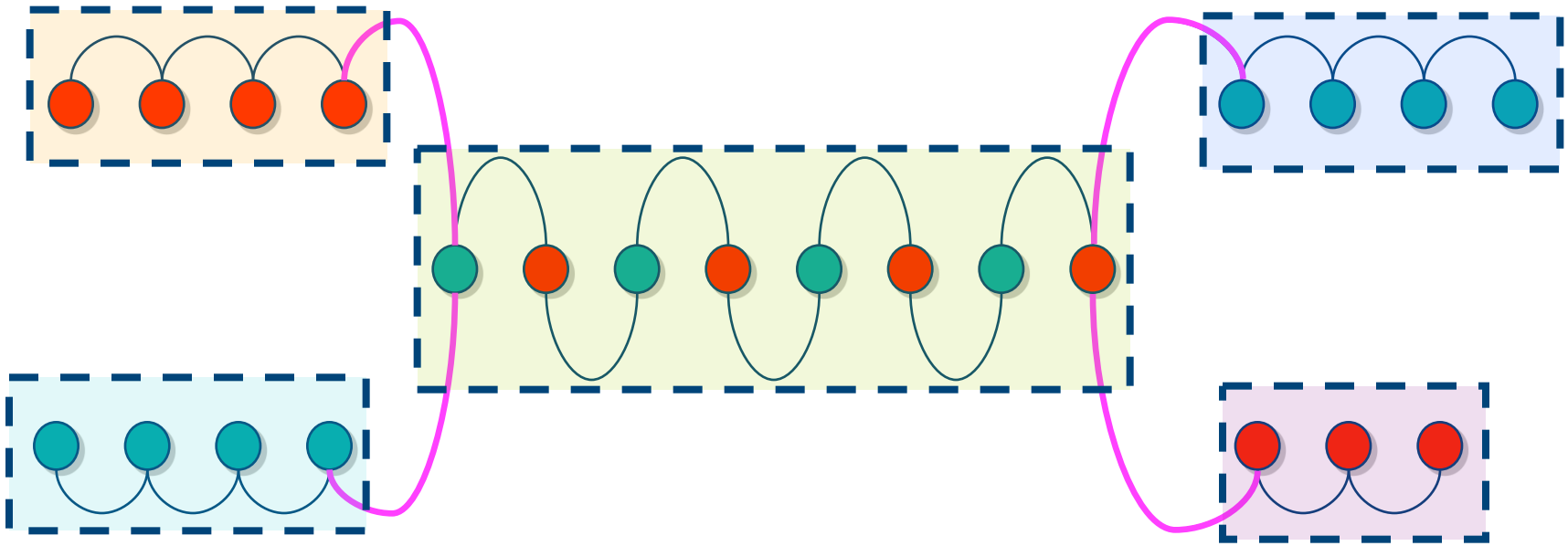

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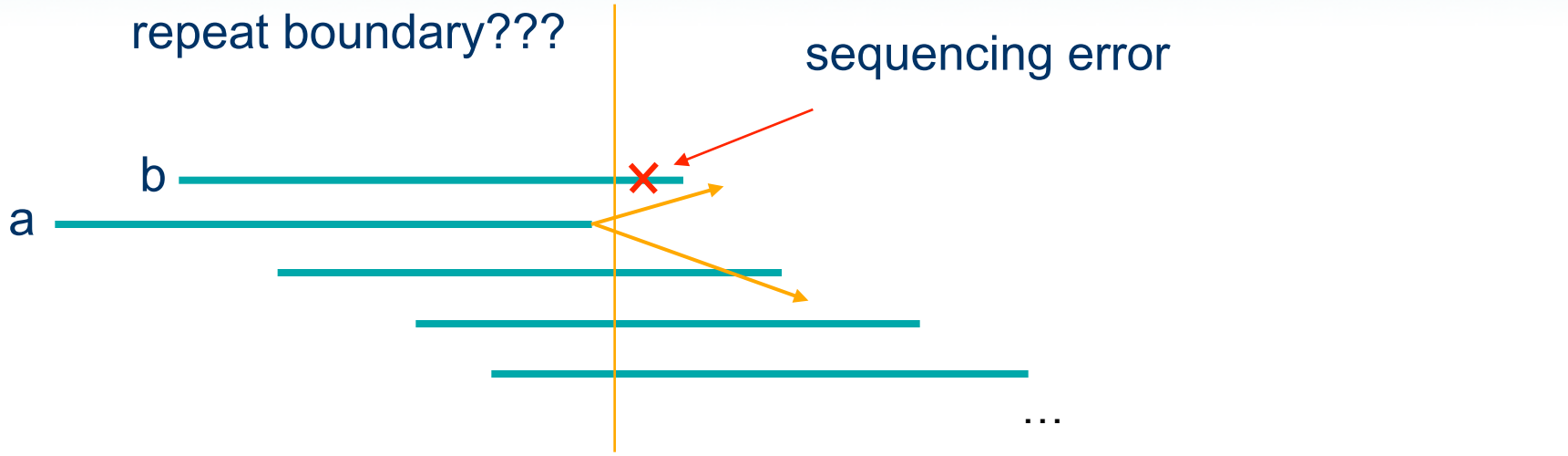
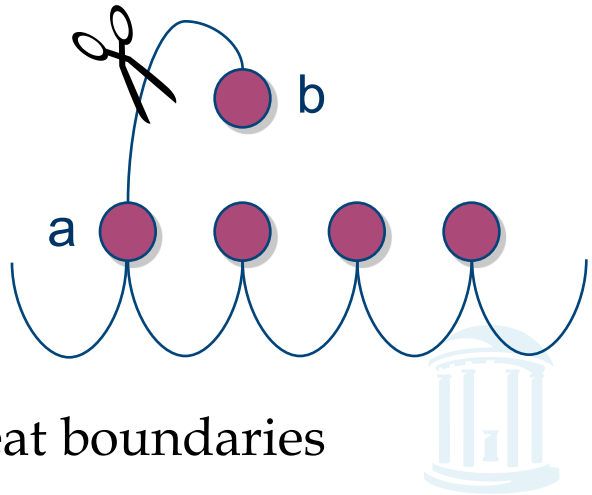
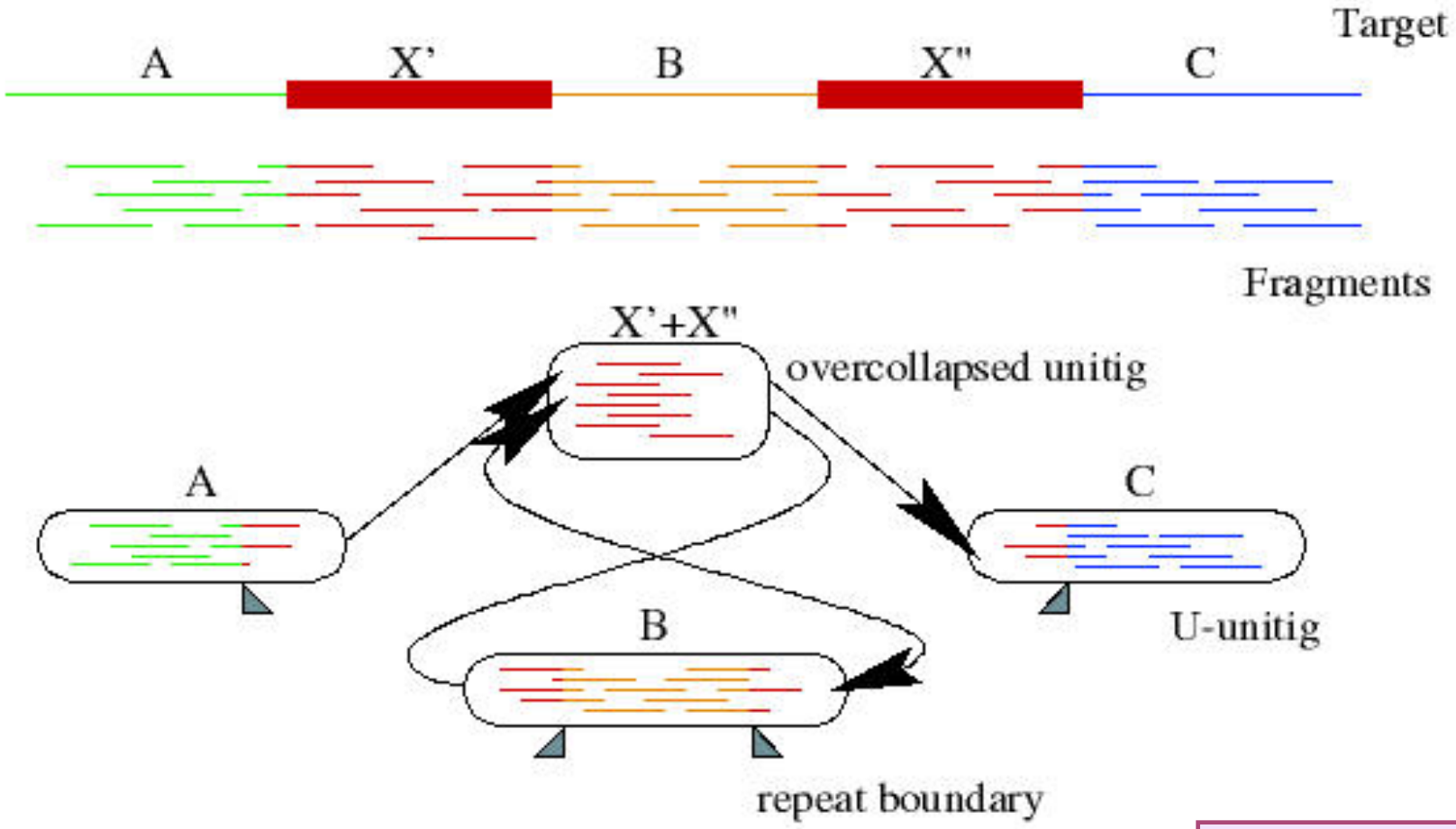




- Ignore "hanging" reads, when detecting repeat boundaries

Overlap graph after forming contigs



Unitigs:
Gene Myers, 95

Repeats, errors, and contig lengths

- Repeats shorter than read length are easily resolved
  - Read that spans across a repeat disambiguates order of flanking regions
- Repeats with more base pair diffs than sequencing error rate are OK
  - We throw overlaps between two reads in different copies of the repeat
- To make the genome **appear** less repetitive, try to:
  - Increase read length
  - Decrease sequencing error rate

Role of error correction:

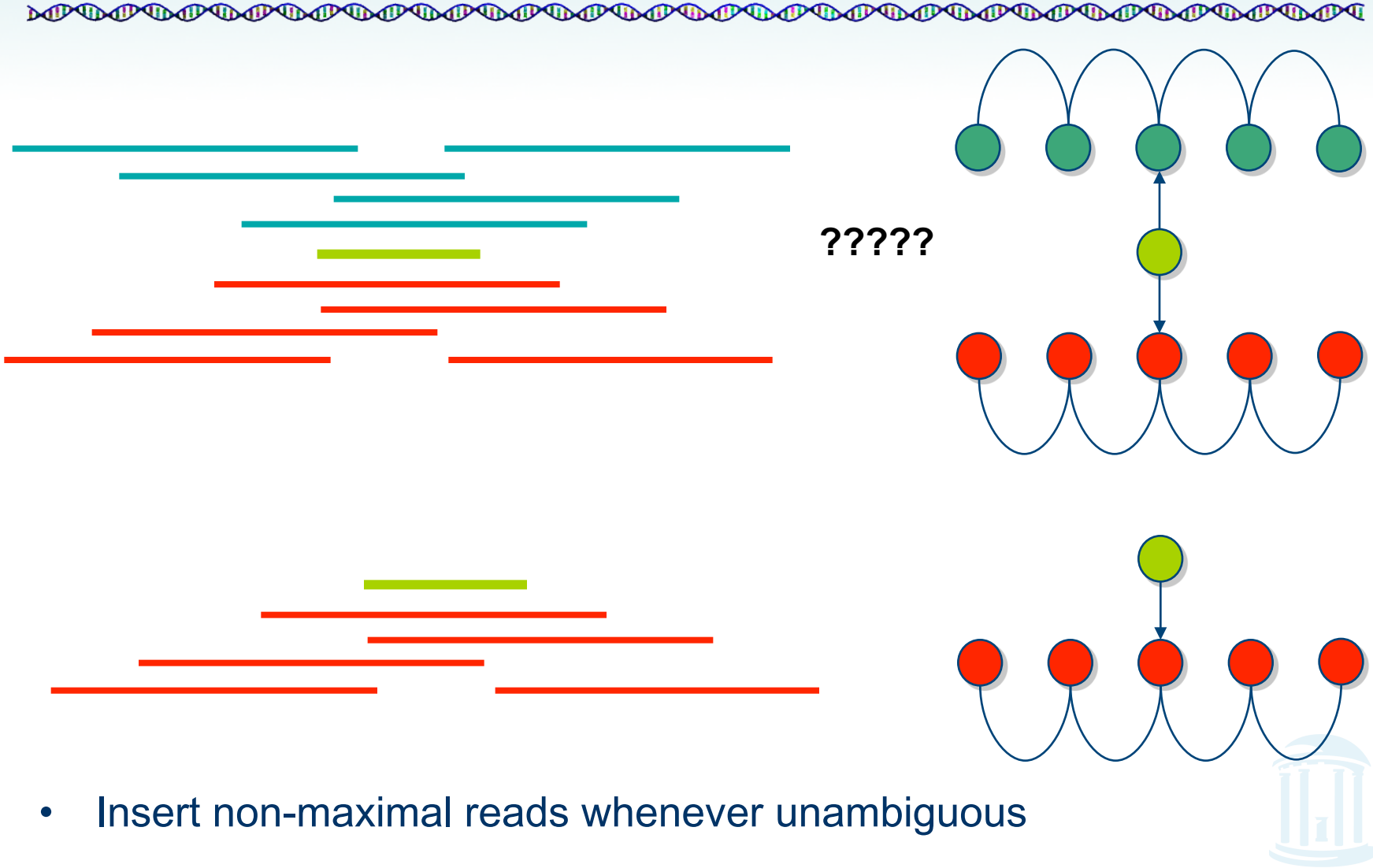
Discards up to 98% of single-letter sequencing errors

decreases error rate

⇒ decreases effective repeat content

⇒ increases contig length

2. Merge Reads into Contigs

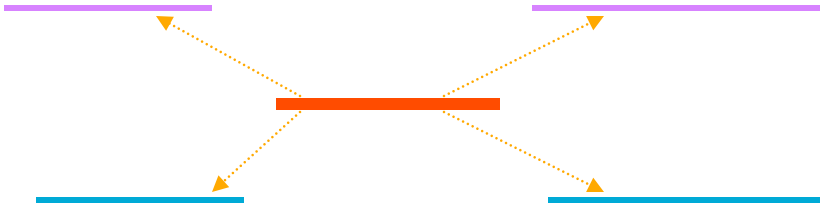


- Insert non-maximal reads whenever unambiguous

Link Contigs into Supercontigs

Normal density

Too dense:
Overcollapsed?

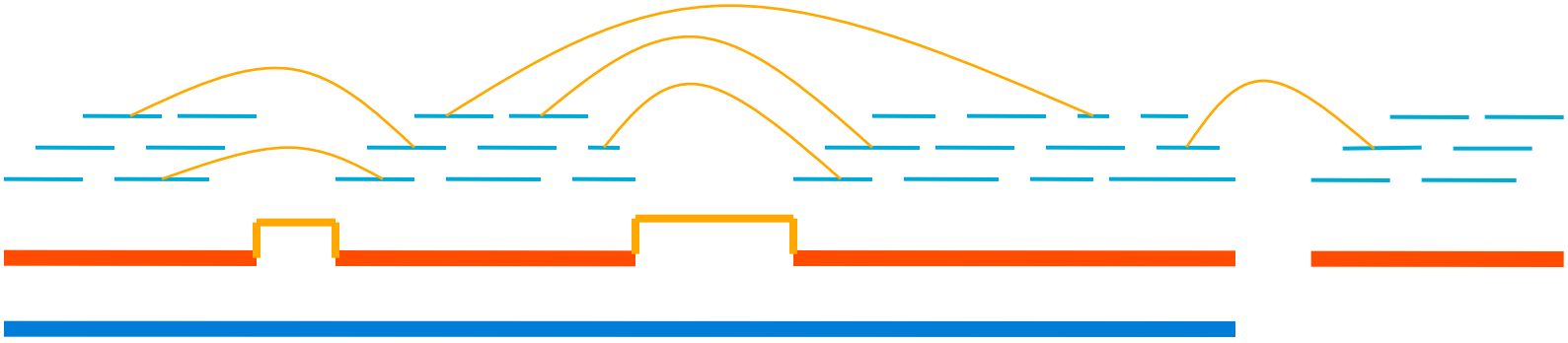


Inconsistent links:
Overcollapsed?

Link Contigs into Supercontigs (cont'd)

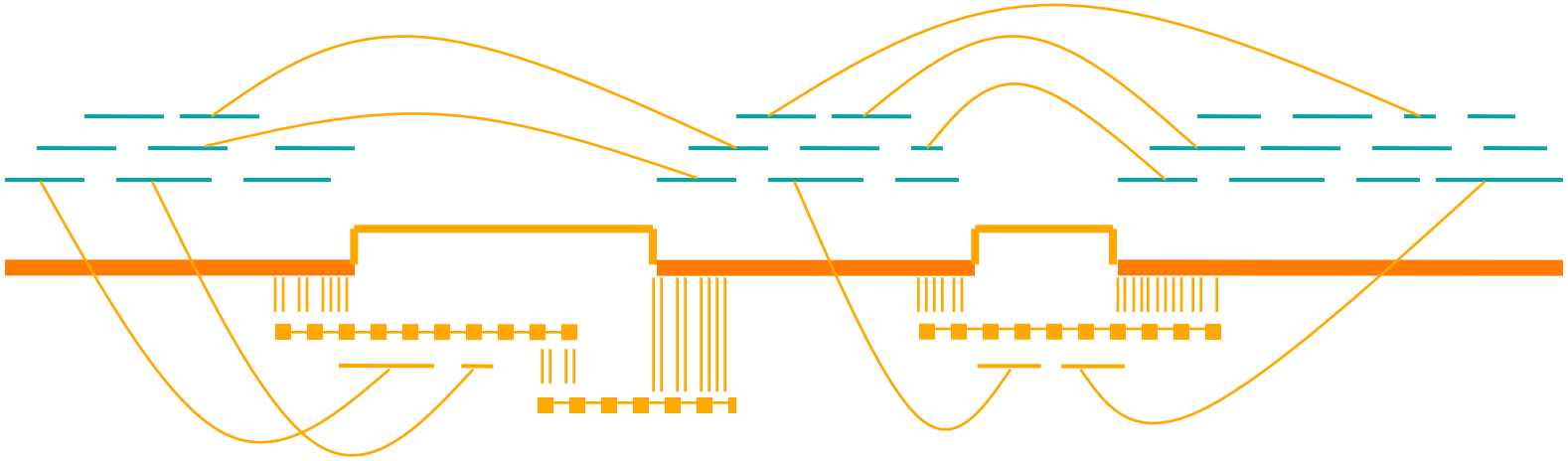
Find all links between unique contigs

Connect contigs incrementally, if ≥ 2 links

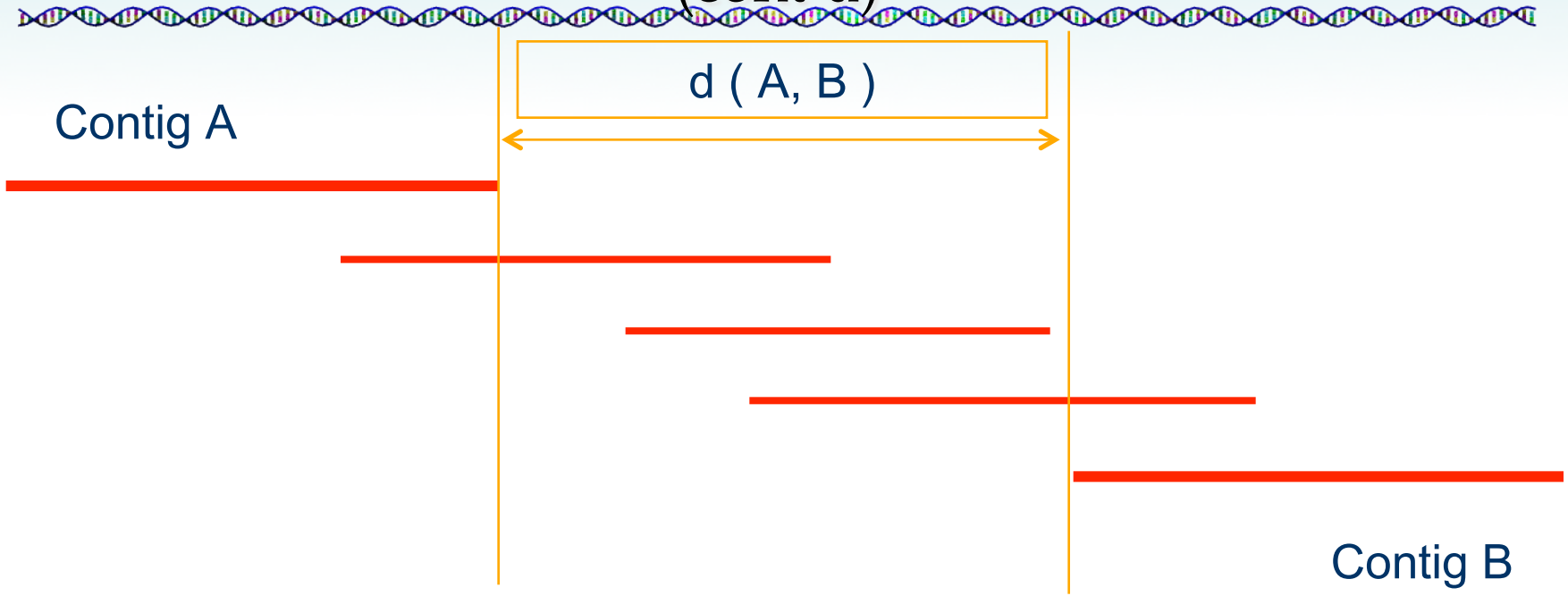


Link Contigs into Supercontigs (cont'd)

Fill gaps in supercontigs with paths of overcollapsed contigs



Link Contigs into Supercontigs (cont'd)



Define G = (V, E)

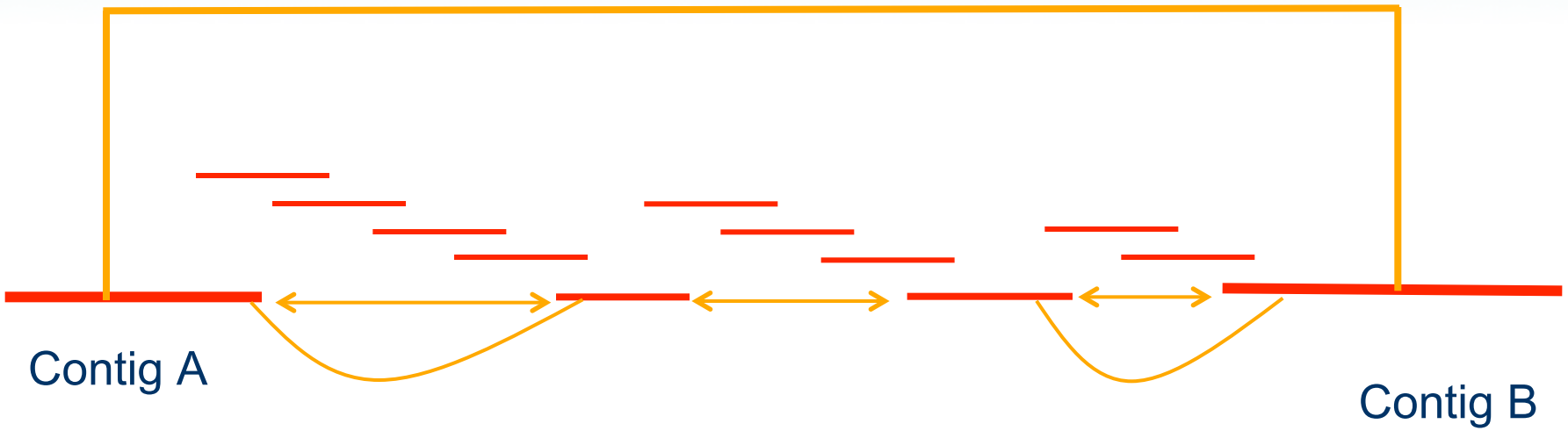
V := contigs

E := (A, B) such that d(A, B) < C

Reason to do so: Efficiency; full shortest paths cannot be computed

Link Contigs into Supercontigs

(cont'd)



Define T: contigs linked to either A or B

Fill gap between A and B if there is a path in G passing only from contigs in T

Consensus

- A consensus sequence is derived from a profile of the assembled fragments
- A sufficient number of reads is required to ensure a statistically significant consensus
- Reading errors are corrected

Derive Consensus Sequence

Derive multiple alignment from pairwise read alignments

Derive each consensus base by weighted voting

Some Assemblers

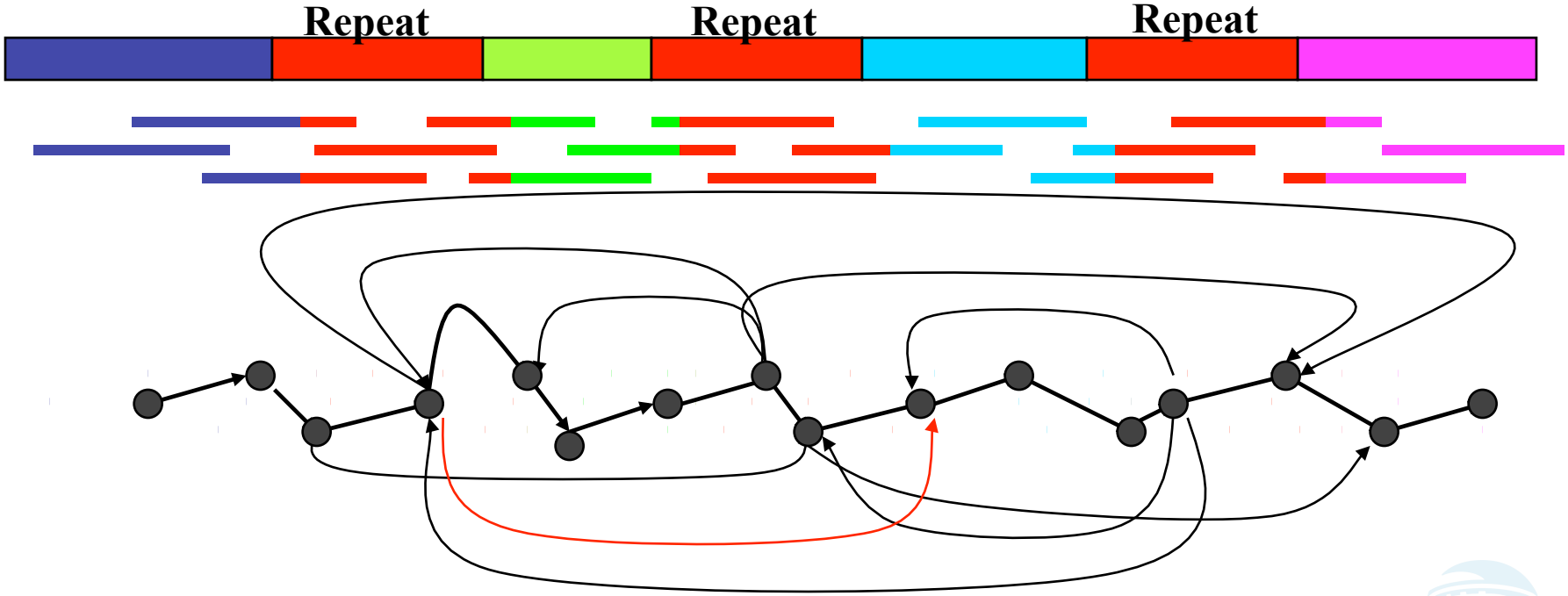
- PHRAP
  - Early assembler, widely used, good model of read errors
  - Overlap $O(n^2)$ → layout (no mate pairs) → consensus
- Celera
  - First assembler to handle large genomes (fly, human, mouse)
  - Overlap → layout → consensus
- Arachne
  - Public assembler (mouse, several fungi)
  - Overlap → layout → consensus
- Phusion
  - Overlap → clustering → PHRAP → assemblage → consensus
- Euler
  - Indexing → Euler graph → layout by picking paths → consensus

EULER Fragment Assembly

- Traditional "overlap-layout-consensus" technique has a high rate of mis-assembly
- EULER uses the Eulerian Path approach borrowed from the SBH problem
- Fragment assembly without repeat masking can be done in linear time with greater accuracy

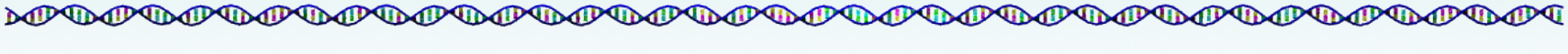
Overlap Graph: Hamiltonian Approach

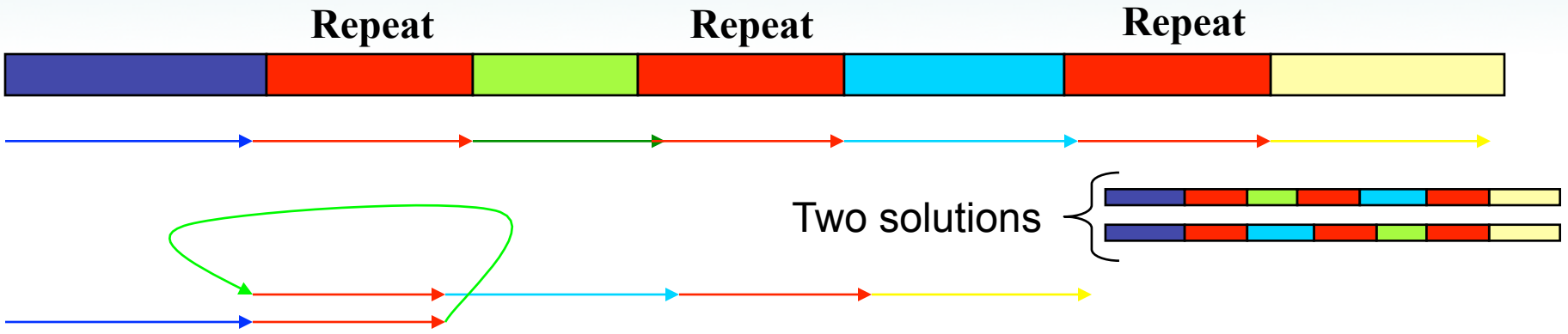
Each vertex represents a read from the original sequence.
Vertices from repeats are connected to many others.

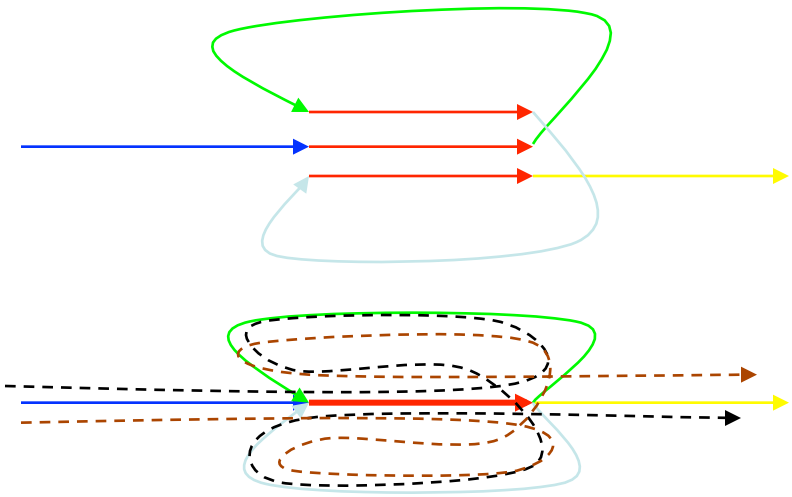


Find a path visiting every VERTEX exactly once: Hamiltonian path problem

Overlap Graph: Eulerian Approach





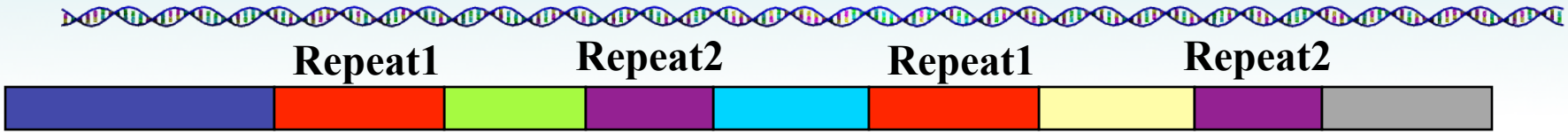


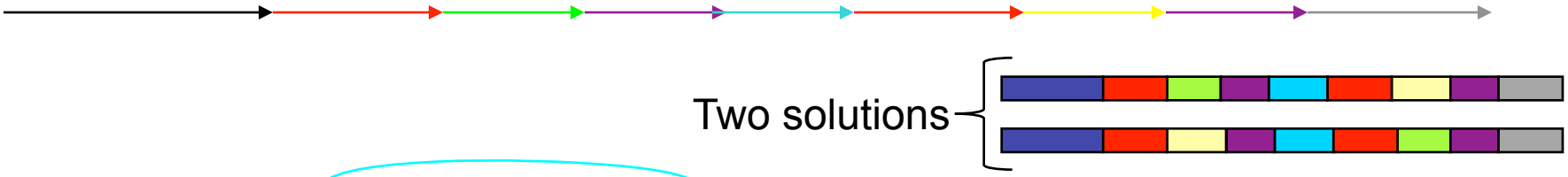
Placing each repeat edge together gives a clear progression of the path through the entire sequence.

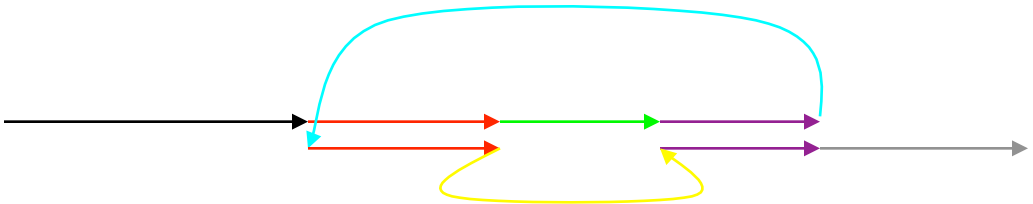
Find a path visiting every EDGE exactly once:

Eulerian path problem

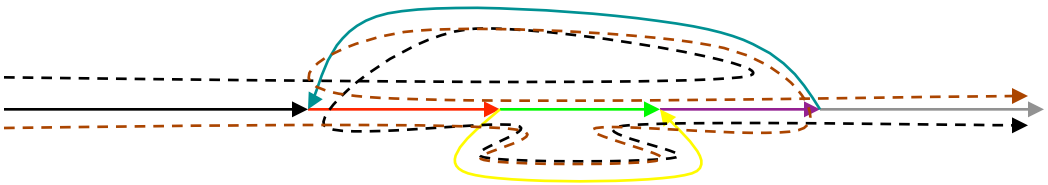
Multiple Repeats







Can be easily constructed with any number of repeats



Construction of Repeat Graph

- Construction of repeat graph from *k* – mers: emulates an SBH experiment with a huge (virtual) DNA chip.

- Breaking reads into *k* – mers: Transform sequencing data into virtual DNA chip data.

Construction of Repeat Graph (cont'd)

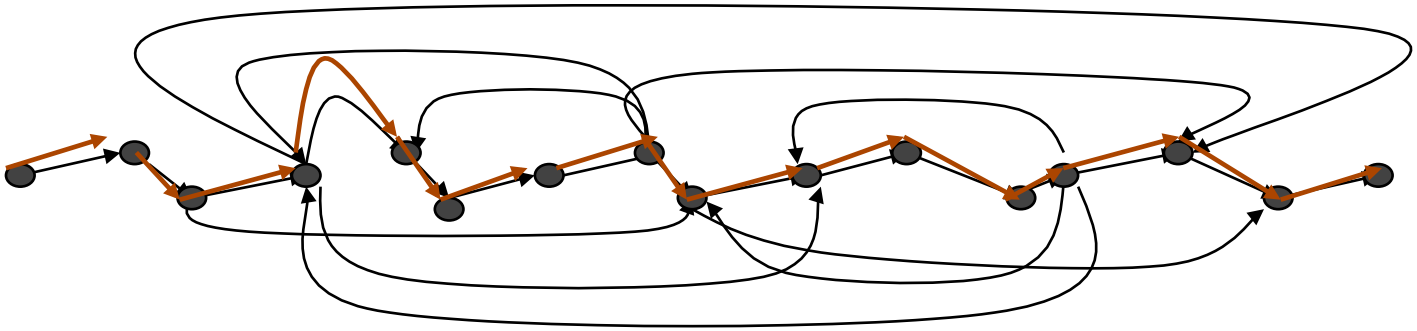
- Error correction in reads: "consensus first" approach to fragment assembly. Makes reads (almost) error-free BEFORE the assembly even starts.

- Using reads and mate-pairs to simplify the repeat graph (Eulerian Superpath Problem).

Approaches to Fragment Assembly

Find a path visiting every VERTEX exactly once in the OVERLAP graph:

Hamiltonian path problem

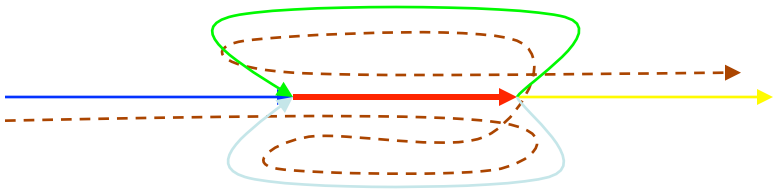


NP-complete: algorithms unknown

Approaches to Fragment Assembly (cont'd)

Find a path visiting every EDGE exactly once in the REPEAT graph:

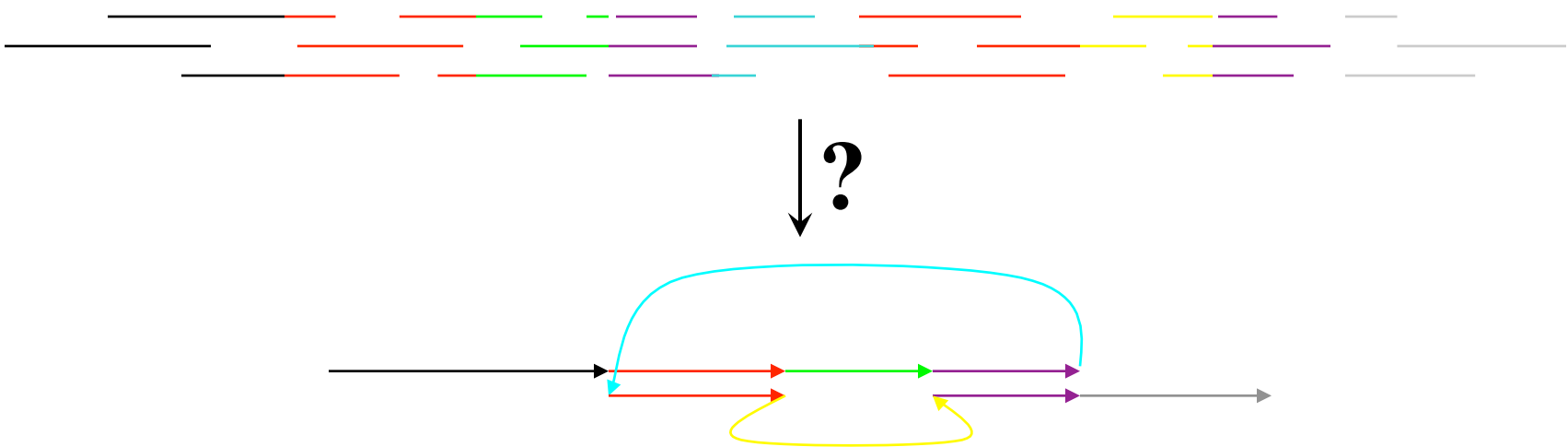
Eulerian path problem



Linear time algorithms are known

Making Repeat Graph Without DNA

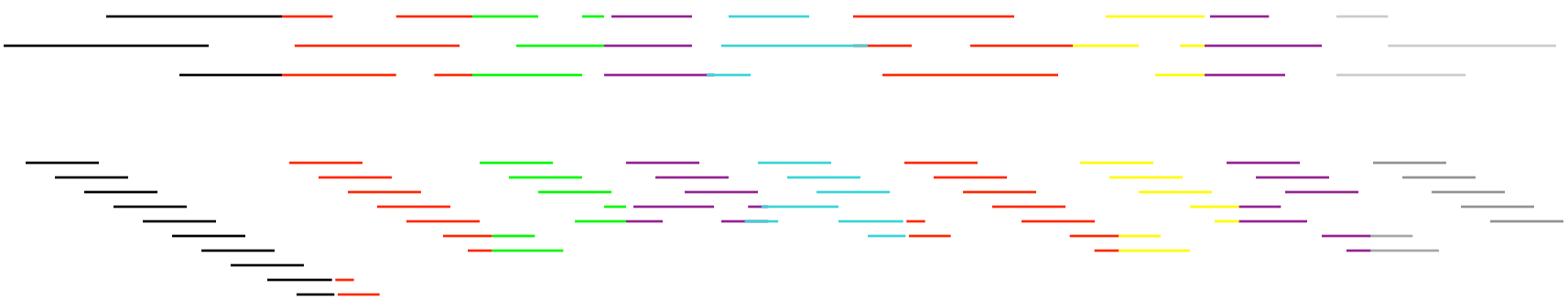
- Problem: Construct the repeat graph from a collection of reads.



- Solution: Break the reads into smaller pieces.

Repeat Sequences: Emulating a DNA Chip

- Virtual DNA chip allows the biological problem to be solved within the technological constraints.



Repeat Sequences: Emulating a DNA Chip (cont'd)

- Reads are constructed from an original sequence in lengths that allow biologists a high level of certainty.

- They are then broken again to allow the technology to sequence each within a reasonable array.

Minimizing Errors

- If an error exists in one of the 20-mer reads, the error will be perpetuated among all of the smaller pieces broken from that read.

Minimizing Errors (cont'd)

- However, that error will not be present in the other instances of the 20-mer read.

- So it is possible to eliminate most point mutation errors before reconstructing the original sequence.

Conclusions

- Graph theory is a vital tool for solving biological problems

- Wide range of applications, including sequencing, motif finding, protein networks, and many more

References

- Simons, Robert W. *Advanced Molecular Genetics Course*, UCLA (2002). http://www.mimg.ucla.edu/bobs/C159/Presentations/Benzer.pdf

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