

Module 4: RNASeq

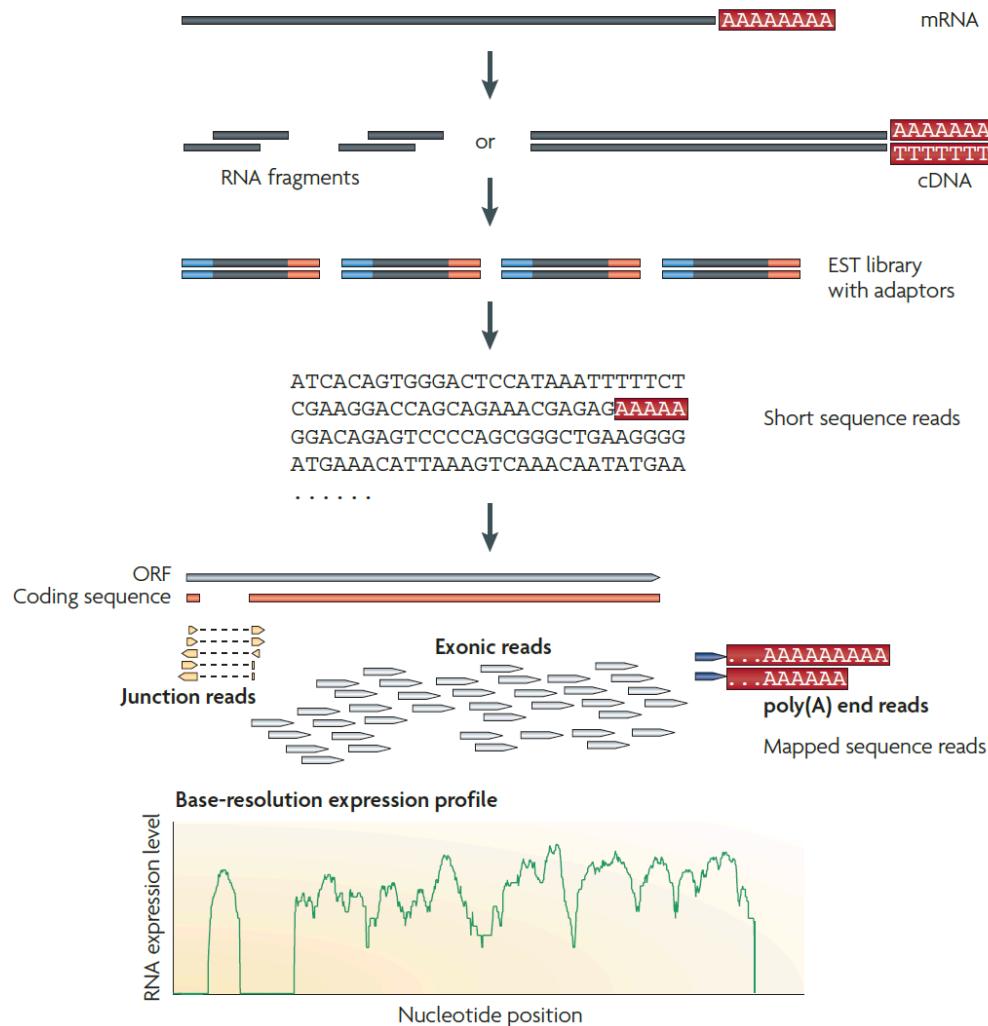
Class Poll: Lab 1

- Did you feel like you had enough time to complete Lab 1a and Lab 1b during the lab hours?

Other Updates

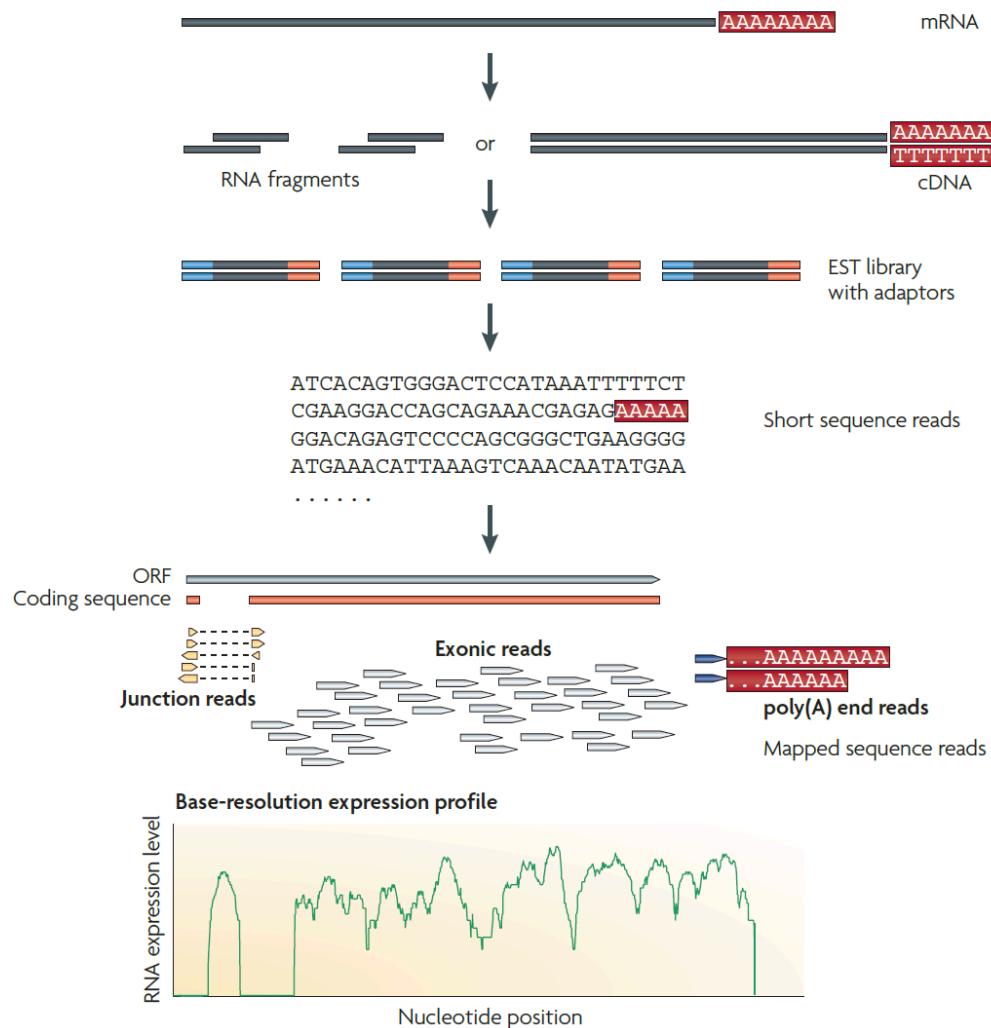
- Lab 1 and Group Assignment #1 marks
- Error troubleshooting

Typical RNA Experiment



1. Long RNAs are converted into a library of cDNA fragments through either RNA fragmentation or DNA fragmentation.
2. Sequencing adaptors (blue) are subsequently added to each cDNA fragment.
3. A short sequence is obtained from each cDNA using high-throughput sequencing technology.

Typical RNA Experiment

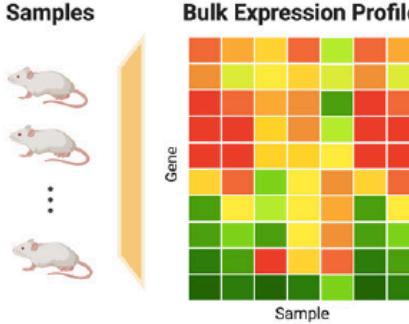
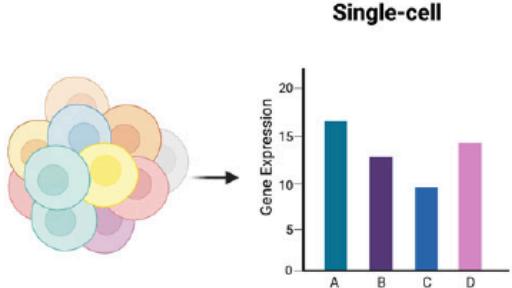
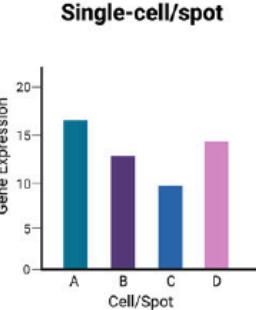
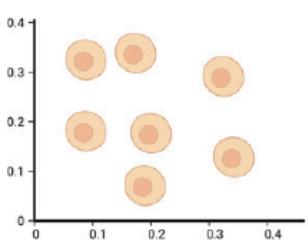


4. The resulting sequence reads are aligned with the reference genome or transcriptome, and classified as three types: exonic reads, junction reads and poly(A) end-reads.
5. These three types are used to generate a base-resolution expression profile for each gene.

Types of RNA Experiments ²

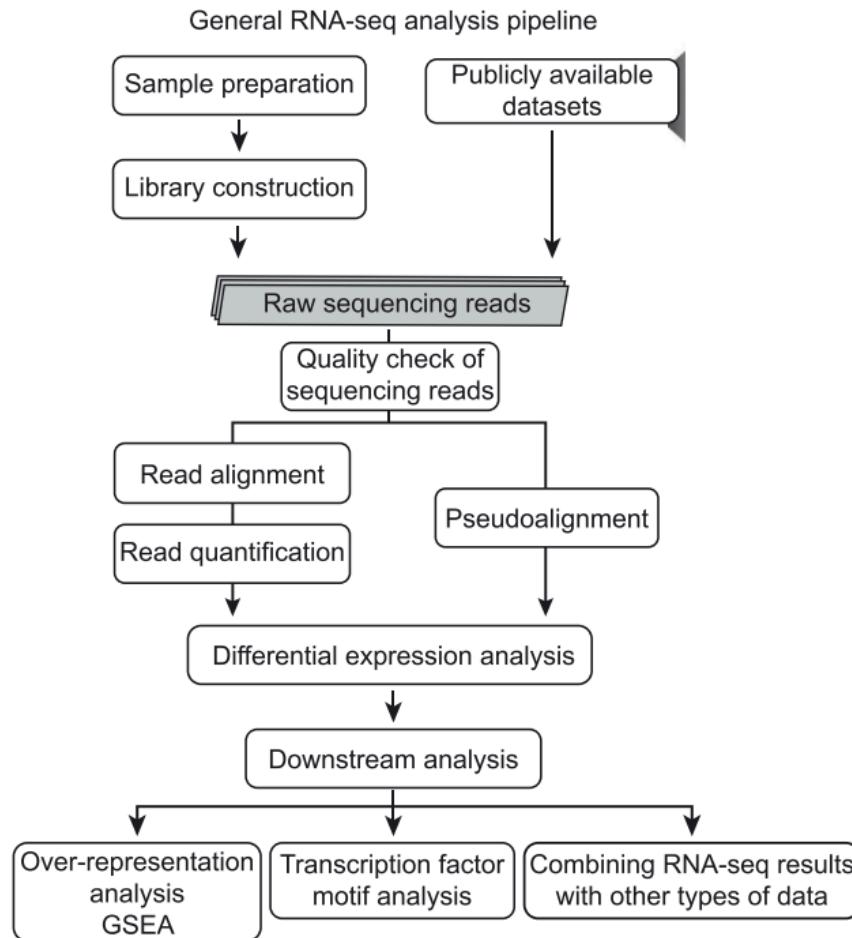
1. **Bulk RNA sequencing:** allows genome-wide analysis across the whole transcriptome within a cell population using NGS technology
 - highly reproducible among technical replicates
2. **Single-cell RNA sequencing (scRNA-seq):** enables the comparison of the transcriptomes of individual cells and the analysis of heterogeneity within a cell population
 - has a greater proportion of zeros, more variability, and a more complex distribution than bulk RNA-seq data
3. **High-throughput spatial transcriptomics (HST):** provides gene expression profiles at the cell or close-to-cell level while also preserving spatial tissue context information

Types of RNA Experiments ²

	Bulk RNA-Seq	Single-cell RNA-seq	High-throughput Spatial Transcriptomics																				
Level	 <p>Samples Gene Sample</p>	 <p>Single-cell Gene Expression Cell</p> <table border="1"><thead><tr><th>Cell</th><th>Gene Expression</th></tr></thead><tbody><tr><td>A</td><td>~17</td></tr><tr><td>B</td><td>~13</td></tr><tr><td>C</td><td>~10</td></tr><tr><td>D</td><td>~14</td></tr></tbody></table>	Cell	Gene Expression	A	~17	B	~13	C	~10	D	~14	 <p>Single-cell/spot Gene Expression Cell/Spot</p> <table border="1"><thead><tr><th>Cell/Spot</th><th>Gene Expression</th></tr></thead><tbody><tr><td>A</td><td>~17</td></tr><tr><td>B</td><td>~13</td></tr><tr><td>C</td><td>~10</td></tr><tr><td>D</td><td>~14</td></tr></tbody></table>  <p>Cell/Spot Coordinates Cell/Spot Coordinates</p>	Cell/Spot	Gene Expression	A	~17	B	~13	C	~10	D	~14
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Data Structure	Subject x Gene Expression Count Data	Cell x Gene Expression Count Data	Cell/Spot x Gene Expression Count Data Cell/Spot 2-dimensional Coordinates																				
Detection Target	Differentially Expressed Genes	Differentially Expressed Genes Cell Sub-populations	Spatially Variable Genes Tissue Architecture Cell-Cell Communication																				

A general pipeline for bulk RNA-seq analysis³

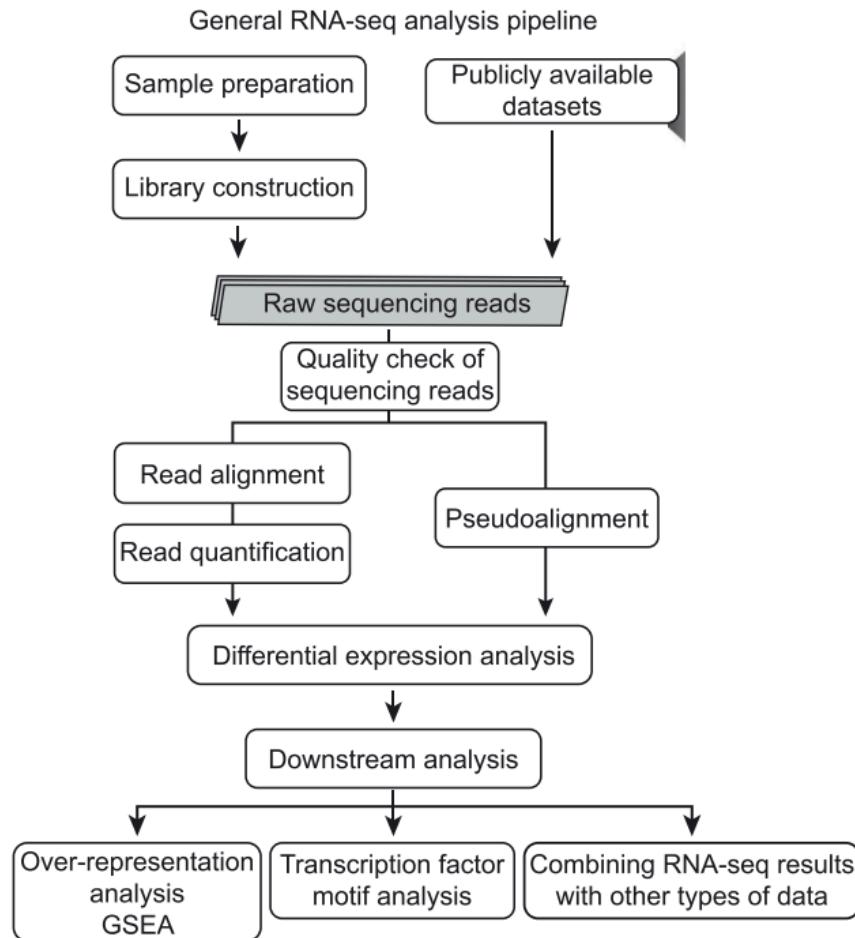
A



- Raw sequencing reads can be obtained by preparing library or by accessing publicly available datasets.
- Raw sequencing reads can be processed to measure transcript levels by using:
 - i. read alignment & quantification **or**
 - ii. pseudoalignment
- Quantified reads are then used to perform differential expression analysis

A general pipeline for bulk RNA-seq analysis³

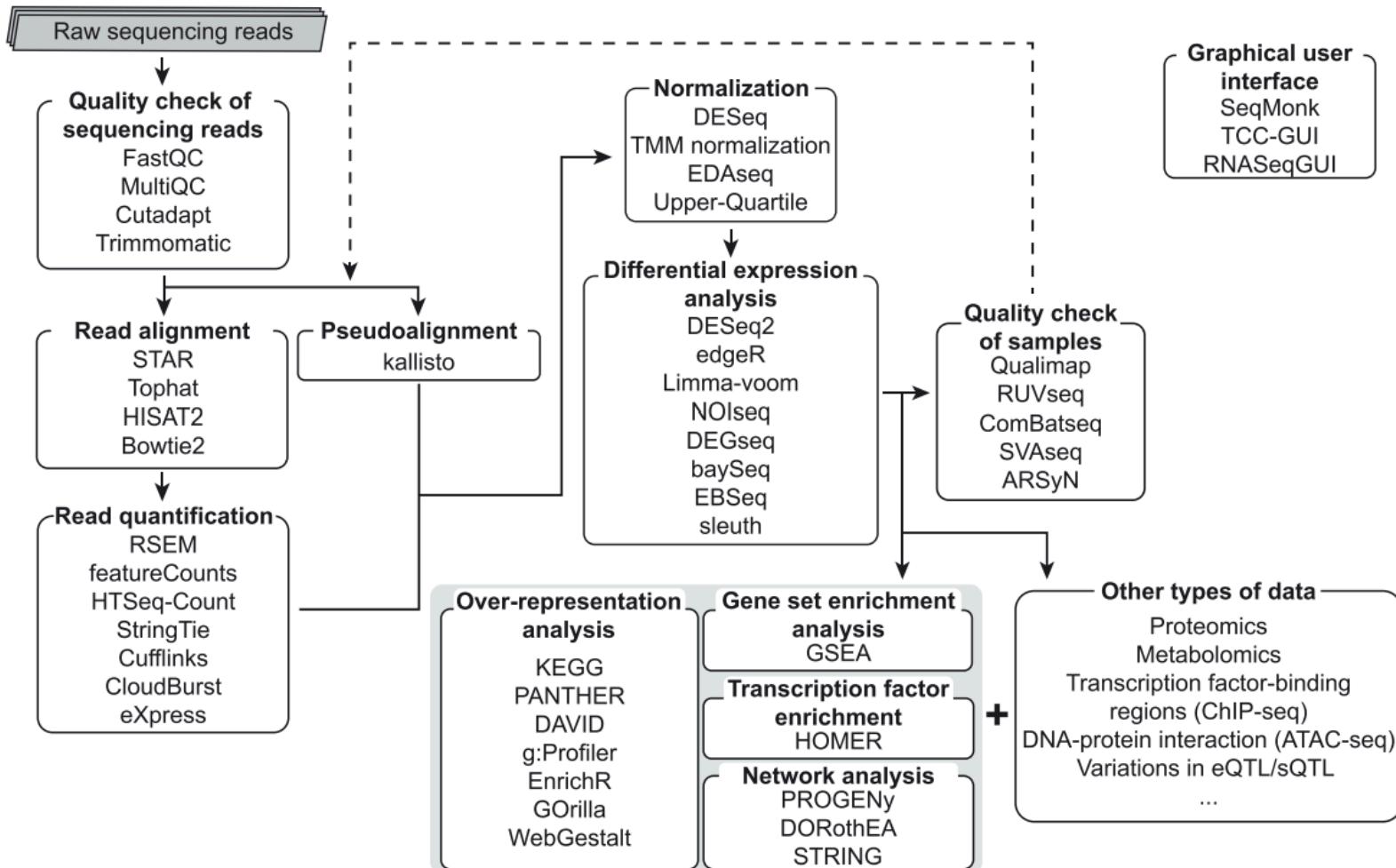
A



- Downstream signaling analysis includes:
 - Gene set enrichment analysis (GSEA)
 - Transcription factor motif analysis
 - Combinatorial analysis with other types of datasets.

Common tools in RNASeq Analysis Pipeline ³

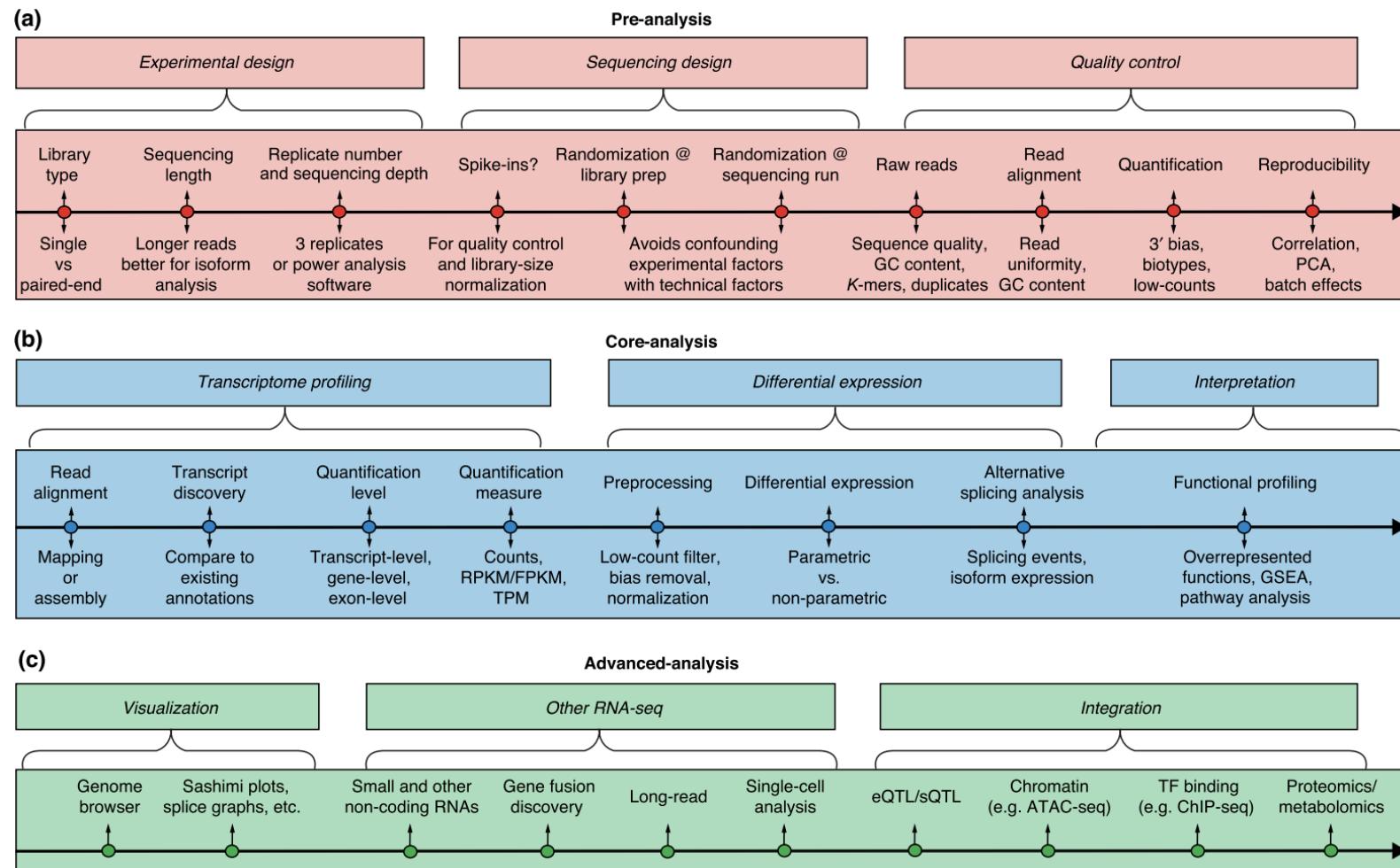
B



Roadmap of RNASeq Analyses ⁴

- Scientists plan experiments and adopt different analysis strategies depending on the organism being studied and their research goals.
- There is no optimal pipeline for the variety of different applications and analysis scenarios in which RNA-seq can be used.

Roadmap of RNASeq Analyses ⁴



Experimental Design

Library Type	Use Case
Single-end (SE) Reads	Sufficient for studies of gene expression levels in well-annotated organisms.
Paired-end (PE) Reads	Preferable for de novo transcript discovery or isoform expression analysis, especially in poorly annotated transcriptomes.

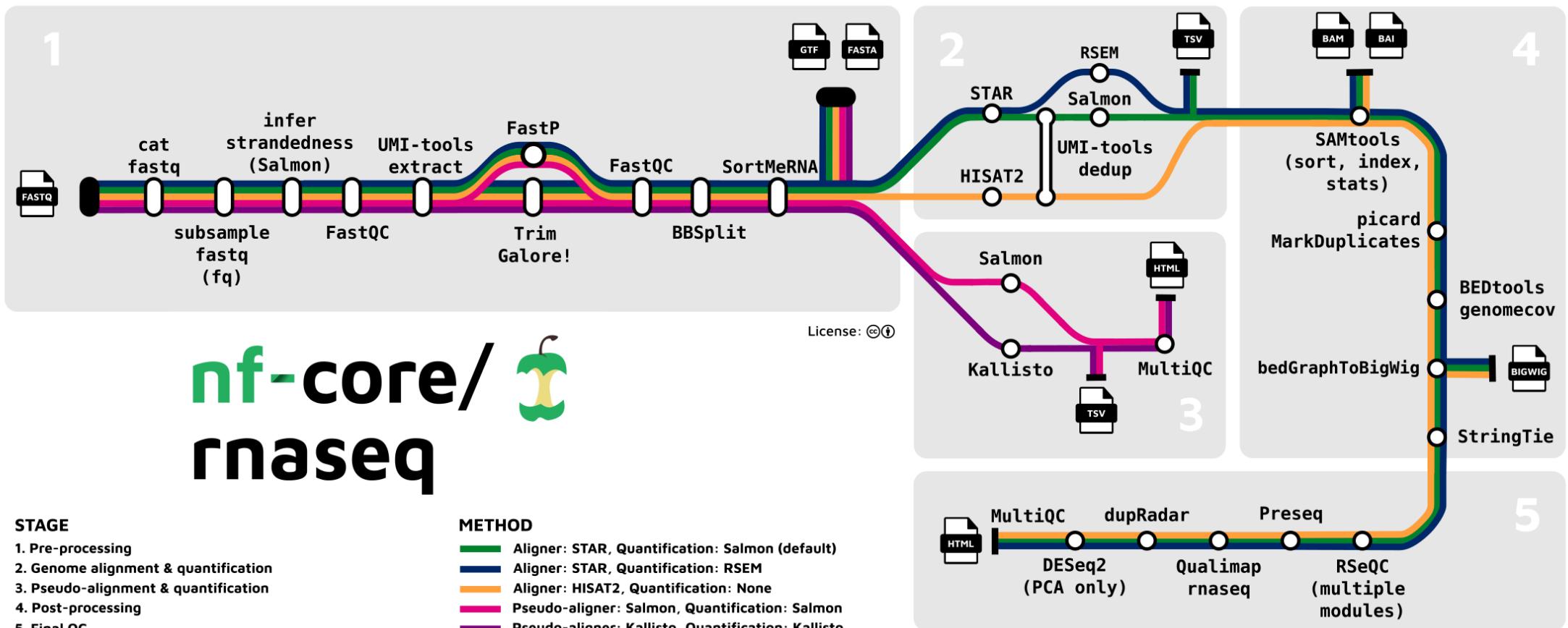
Read Length ⁵

Feature	Short Reads (50–600bp)	Long Reads (>5kbp)
Error Rate	Lower	Higher
Throughput	Higher	Lower
Alignment	Suffers from multi-mapping issues due to shorter lengths.	Easier to map accurately
de novo assembly	Not ideal; they do not span shared regions or exon junctions.	Preferred; eliminates ambiguity in the assembly step.
Expression Quantification	Preferred due to higher throughput, though requires advanced statistical methods.	Can cover entire transcripts, simplifying transcript determination for each read.

Sequencing Depth

- The number of sequenced reads for a given sample
- More transcripts detected and quantified as sequencing depth increases.

Use Case	Requirement
Medium to highly expressed genes	>5 million reads
Low-expression genes	Requires deeper sequencing (up to 100 million reads) for precise quantification.
Single-cell studies	Reliable quantification achievable with 1 million reads; highly expressed genes detectable with 50,000 reads (or as few as 20,000 for splenic tissues).



Quality Control - Read Trimming

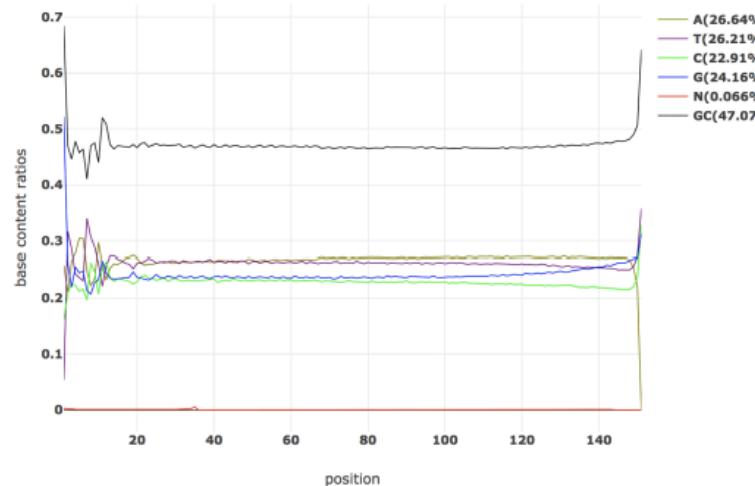
- Trim Galore: (default) a wrapper around Cutadapt and FastQC (quality control)
 - Cutadapt requires at least 3bp matching of the adapter sequence and the read for it to be recognized as an adapter
 - If the adapter is <3 bp, they won't be detected, and usually will be reported as a mismatch or soft clip

Quality Control - Read Trimming

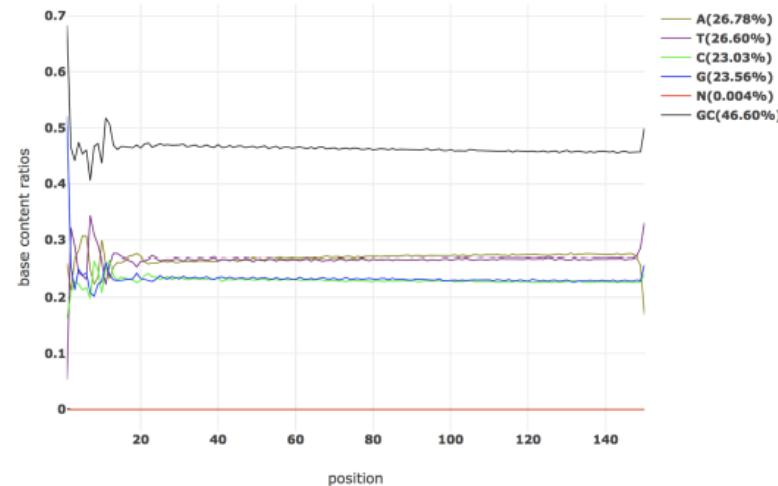
- fastp: ultra-fast all-in-one FASTQ preprocessor for quality profiling, read filtering, read pruning, adapter trimming, polyG/polyX tail trimming, UMI preprocessing
 - can trim adapters with even only one base in the tail.
 - Assumes:
 1. there is only one adapter in the data and
 2. the second one is that adapter sequences are only in the read tails
 - the assumptions are valid for major next-generation sequencers like Illumina HiSeq series, NextSeq series and NovaSeq series.
- ([link](#)) Performance comparison between: cutadapt vs fastp, fastqc vs fastp

Why do we care about PolyG trimming?

- PolyG is a common issue that can be observed from Illumina NextSeq and NovaSeq series (technical issue associated with sequencers).
- It can cause serious base content separation problem, which means A and T, or C and G have much different base content ratio.
- fastp also implements polyX tail trimming, where X means any base of A/T/C/G.



(a) before fastp preprocessing



(b) after fastp preprocessing

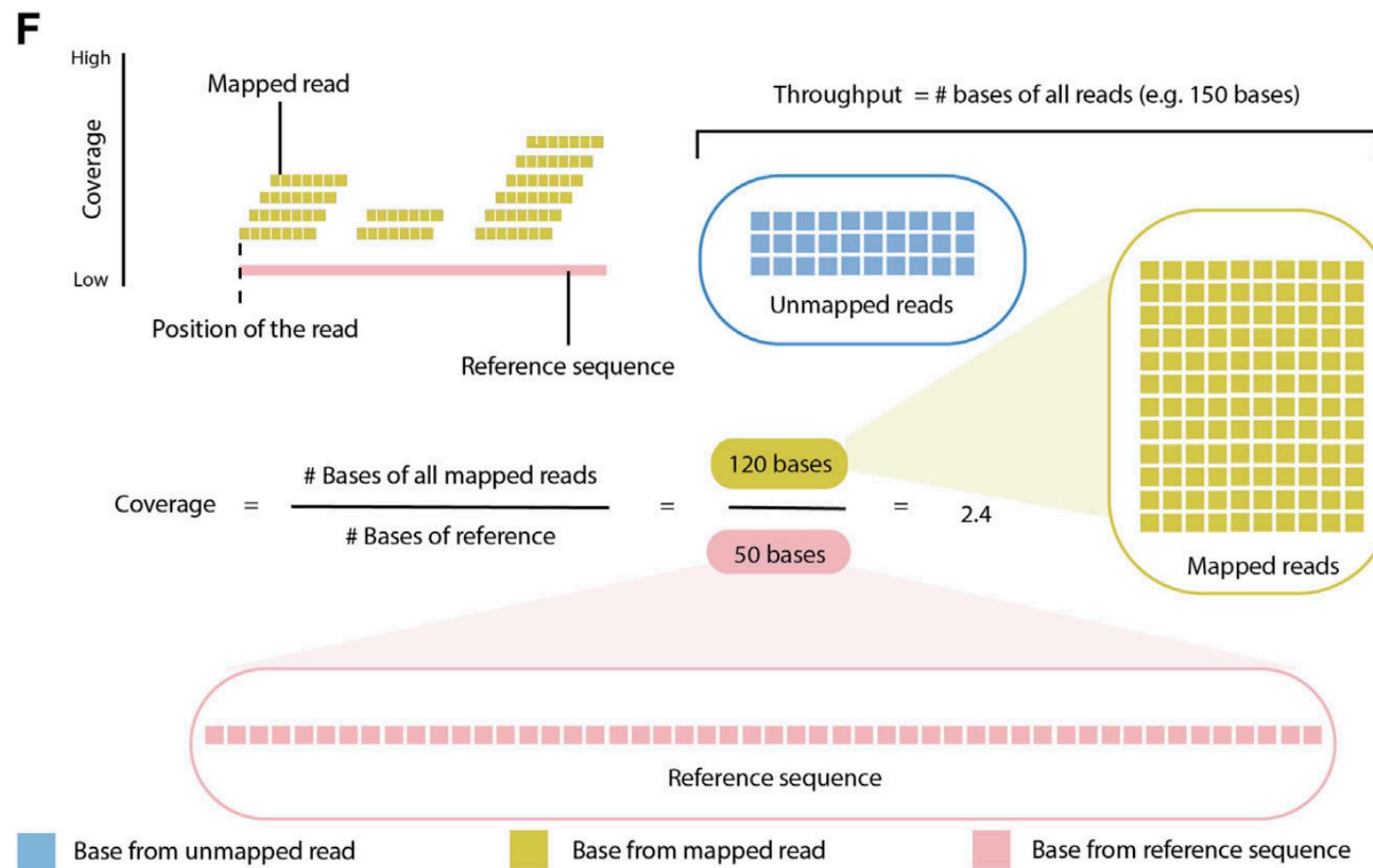
Other QC tools

- [UMI-tools](#): scRNASeq
 - removes Unique Molecular Identifiers (UMIs)/Random Molecular Tags (RMTs) and single cell RNA-Seq cell barcode
 - identify PCR duplicates using the UMIs and perform different levels of analysis
- [BBSplit](#): metagenomics
 - used for sorting reads based on their alignment to multiple reference genomes in metagenomics studies where samples may contain a mixture of organisms
 - Use case: separate host DNA from microbial DNA or differentiate between multiple microbial species.
- [SortMeRNA](#): filter rRNA fragments from metatranscriptomic data

Genome index - Why do we do this?

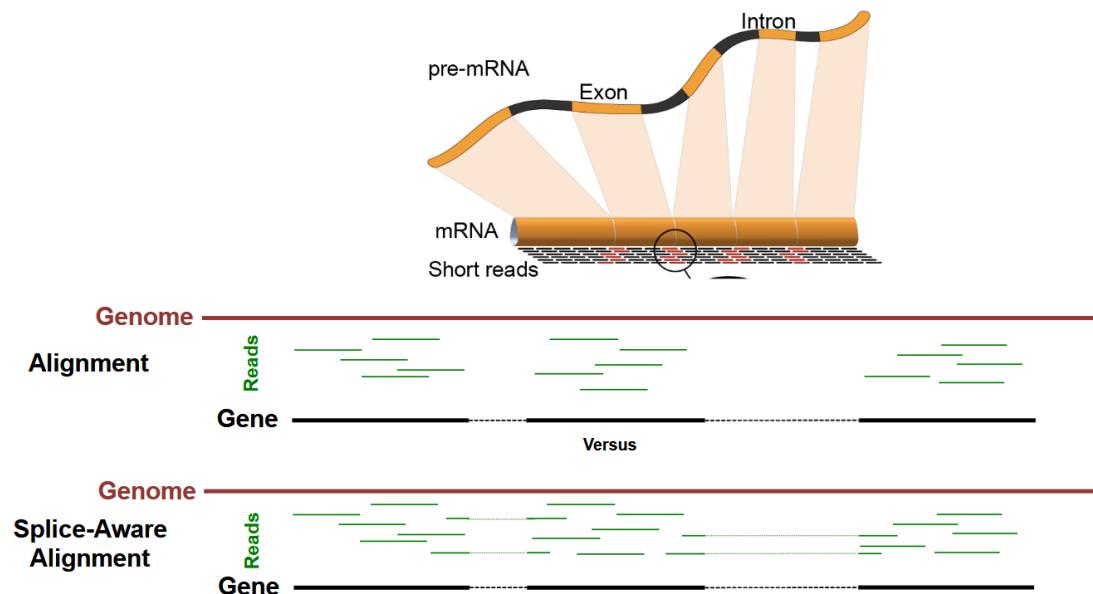
- Indexing the genome allows for more efficient mapping of the reads to the genome. Once index is built, it can be queried any number of times.
- When using `nf-core/rnaseq`, you should initialize genome indices for the alignmener(s)/pseudoaligner(s), especially if you plan to run the same dataset multiple times.
 - Hash-based (Salmon, Kallisto): Memory intensive and slower; simpler in design but more sensitive
 - Suffix arrays (Salmon, STAR): Requires large amount of memory to load the suffix array and genome sequence prior to alignment
 - Burrows-Wheeler transform (Bowtie2, BWA-MEM): non-splice aware; not recommended

Read alignment: Read Coverage



Read alignment: Tools

- The goal of the alignment is to find the locus in the reference sequence with the greatest match to each read.
- Generic aligners such as `BWA`, `bowtie2`, `BBMap`, etc., are not suitable for mapping RNAseq reads because they are not splice-aware.



Why do we need splice-aware alignment for RNASeq?

RNAseq reads are mRNA reads that only contain exonic regions, hence mapping them back to the genome requires splitting the individual reads that span an intron. It can be done only by splice-aware mappers.

Read alignment: Splice-Aware Aligner vs Pseudoaligner⁶

Splice-Aware Aligner: `star_salmon`, `star_rsem`, `hisat2`

- Ideal for detecting splicing events, fusion genes, and complex isoforms.
- Necessary if you want to do variant calling from RNA-seq data.
- Typically used when analyzing small RNAs or low-abundance transcripts.

Pseudoaligner: `salmon`, `kallisto`

- Best suited for rapid, large-scale gene/transcript quantification (e.g., in large cohorts).
- Offers fast, memory-efficient processing.
- Adequate for most standard mRNA-seq experiments where detailed isoform/splicing analysis is not the main goal.

Splice-Aware Aligners⁶

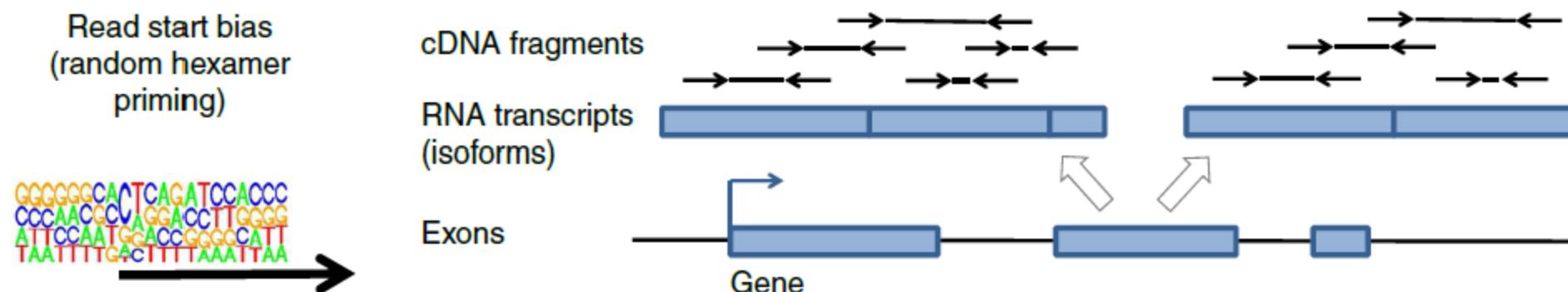
Pros	Cons
Can identify novel splicing events, alternative isoforms, and fusion events.	Typically more time- and memory-intensive due to the complexity of alignment.
Often more sensitive to RNAs such as microRNAs or transcripts expressed at low levels.	Reads that map equally well to multiple locations can be harder to resolve.
Offers base-by-base alignment necessary for variant calling (SNP, indel) or fusion gene detection.	

Pseudoaligners⁶

Pros	Cons
K-mer-based matching is faster and more memory-efficient.	Less effective at detecting novel splicing events or complex isoforms, as no explicit alignment across exon–intron boundaries is performed.
Ideal for large-scale projects focusing on gene-level or transcript-level abundance estimates.	Lacks base-by-base alignments, making it inappropriate for detecting SNPs, indels, or other variants.
Can achieve accuracy comparable to splice-aware aligners in standard RNA-seq for abundant transcripts.	May underperform in quantifying microRNAs or very low-abundance transcripts

Bias Correction: Sequence Bias ⁷

- Caused by the differential binding efficiency of random hexamer primers during RNA-Seq library preparation
- Represented by biased distribution of reads related to the sequence content
- Affects the accuracy of quantifying isoforms



Bias Correction: GC Bias ⁸

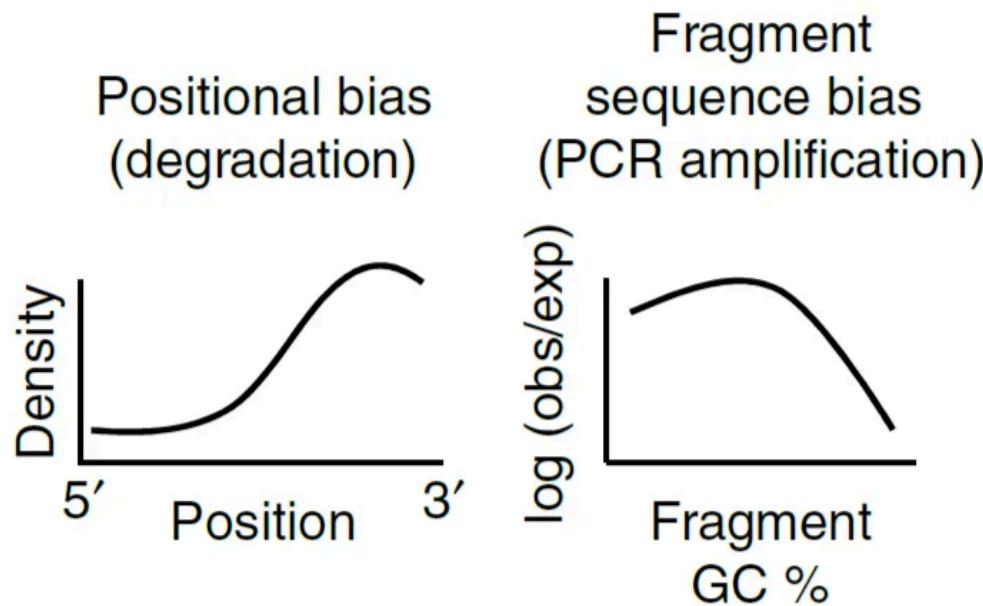
- Caused by the composition of the DNA molecule affecting many stages of the sequencing protocol such as the priming (9), size selection (10), PCR (11) and probability of sequencing errors (12,13).
- Represented by uneven counts of RNA-seq fragments (read coverage) along transcripts with increased coverage when the ends are AT rich
- Affects the accuracy of quantifying gene expression

Bias Correction: Positional Bias ¹⁴

Caused by:

1. RNA degradation: mRNA from different genes may degrade at different rates
 - RNA degradation can cause a 3' bias in read coverage along messenger RNA (mRNA) transcripts. Degraded samples may have an underrepresentation of long transcripts and an overrepresentation of short transcripts.
2. mRNA selection techniques: poly(A) selection in the sequencing protocol to mRNA enrichment

Bias Correction: Positional Bias¹⁴



- RNA degradation: Represented by the non-uniform distribution of reads over different positions of a transcript
- poly(A) selection skews sequenced mRNAs toward longer poly(A) tail lengths

Read Quantification

- **Salmon**: requires a set of target transcripts (either from a reference or de-novo assembly) in order to perform quantification
- **RSEM**: RSEM is one of the most accurate quantification tools for RNA-seq analysis
- **HISAT2**: uses Hierarchical Graph FM index (HGFM) combined with several alignment strategies, to enable rapid and accurate alignment of sequencing reads
 - good option if you have memory limitations
 - doesn't perform quantification in the `nf-core/rnaseq` pipeline

Lab 2: RNASeq using Nextflow

- Due on March 9 midnight
- Lab 2a and 2b will be released at the same time
 - **Lab 2a:** Run the Nextflow pipeline using a *Drosophila* dataset
 - **Lab 2b:** How to interpret pipeline output
- I will release a sample output report so that you may work on Lab 2b while the Nextflow pipeline is running
- You may work together as a group, but lab submissions are individual.