

# 系统生物学

天津医科大学  
生物医学工程与技术学院

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研究生

# 第三章 转录组学

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生物医学工程与技术学院

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# 教学提纲

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- 转录组学
- 研究方法

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- 技术简介
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- Methyl-Seq
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- 总结
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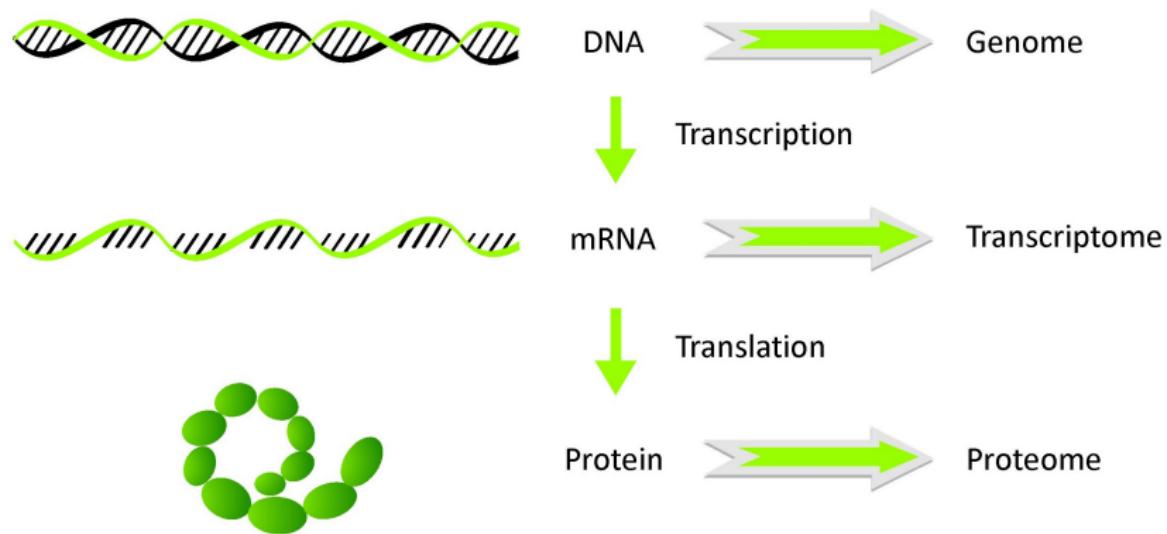
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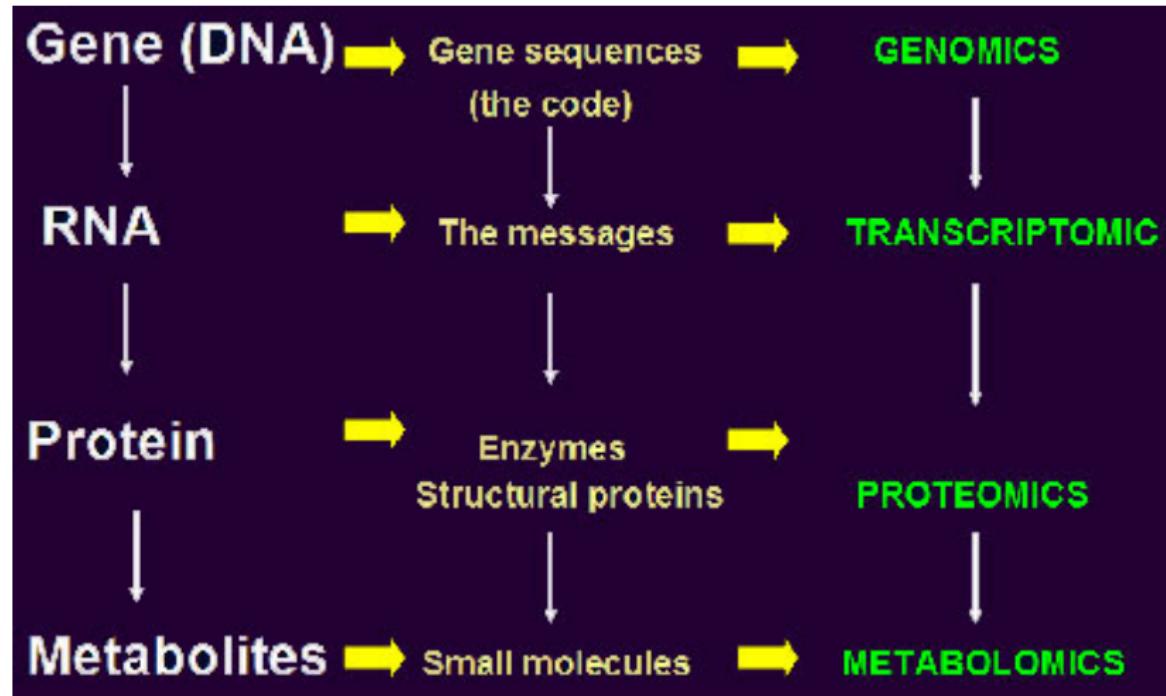
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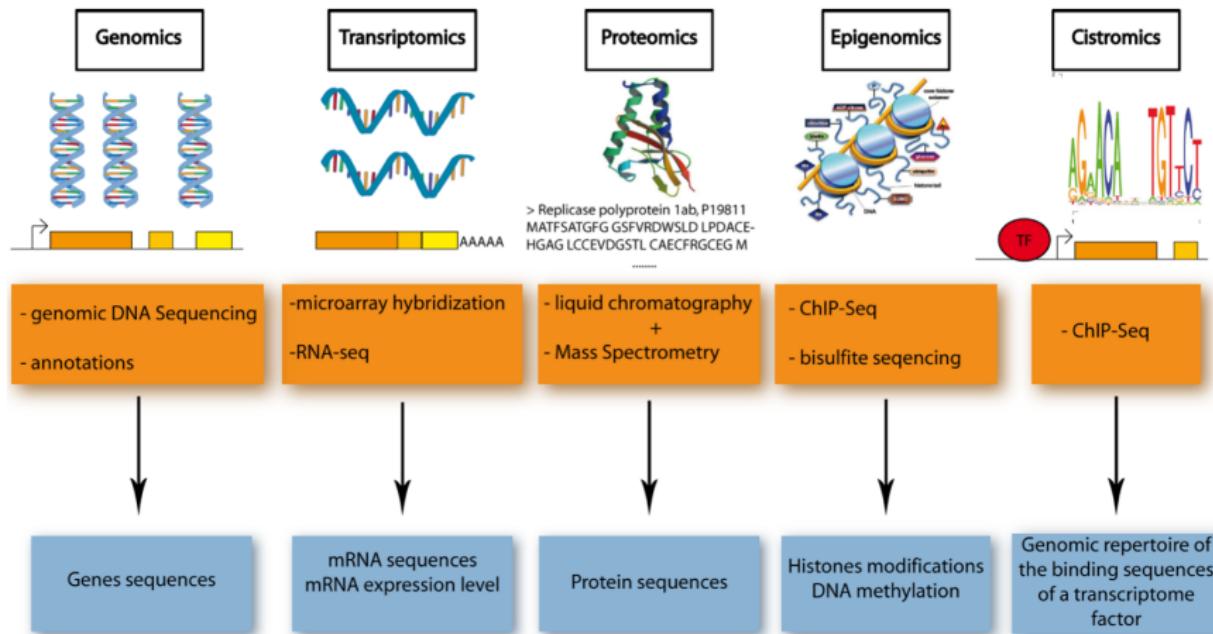
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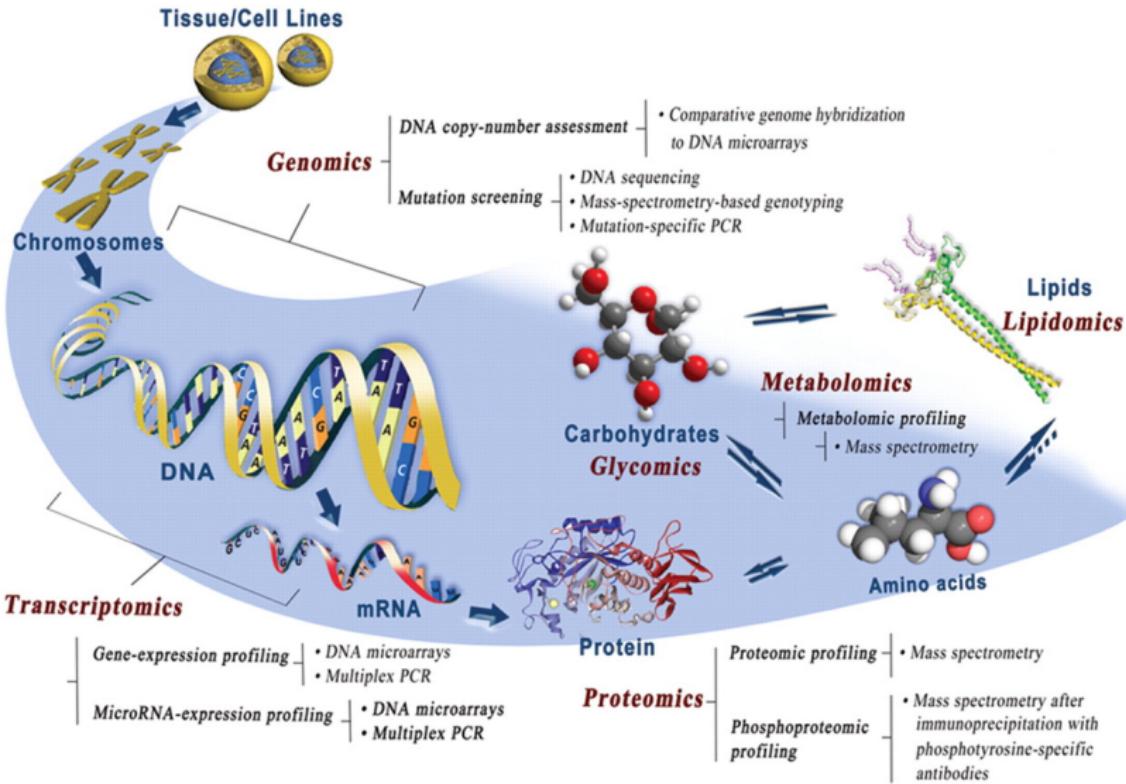








# 转录组学 | 组学



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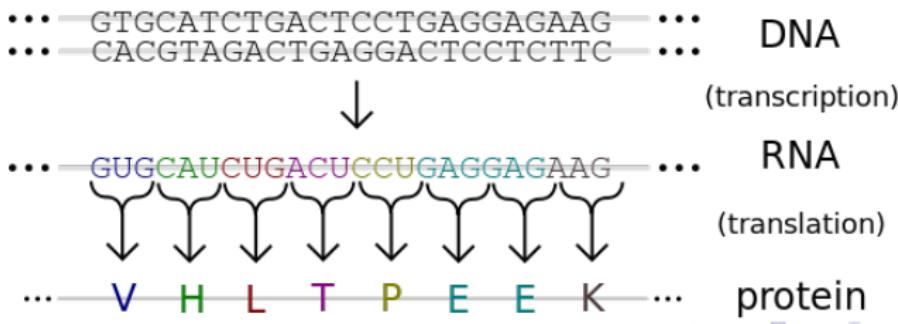
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## 基因表达

基因表达 (gene expression) 是用基因中的信息来合成基因产物的过程。产物通常是蛋白质，但对于非蛋白质编码基因，如转运 RNA (tRNA) 和小核 RNA (snRNA)，产物则是 RNA。

基因表达的过程可分为转录、RNA 剪接、翻译、蛋白质的翻译后修饰这几步。基因表达调控控制细胞的结构与功能，同时也是细胞分化、形态发生及生物体适应性的基础。不同的时间、不同的环境，以及不同部位的细胞，或是基因在细胞中的含量差异，皆可能使基因产生不同的表现。



## 基因表达谱

基因表达谱 (gene expression profile) 是一种在分子生物学领域，借助 cDNA、表达序列标签 (EST) 或寡核苷酸芯片来测定细胞基因表达情况 (包括特定基因是否表达、表达丰度、不同组织、不同发育阶段以及不同生理状态下的表达差异) 的方法。

通过一次性测定大量基因构建起细胞功能的总体态势图，可以从图谱中区分出正在分裂的细胞，以及细胞对于特征性治疗的反应。基因表达谱还有助于了解疾病的发病机制、药物的生理反应和治疗效果。

基因表达图谱从逻辑上说是基因测序的下一个步骤：基因序列包含细胞可能存在的功能的信息，而基因表达谱则包含细胞实际上正在完成的工作的信息。



## Technique

DNA microarray technology measures the relative activity of previously identified target genes.

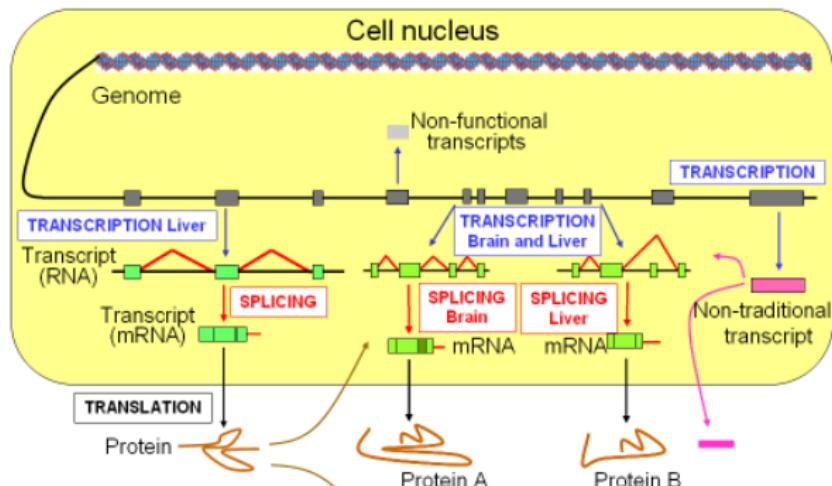
Sequence based techniques, like serial analysis of gene expression (**SAGE**, **SuperSAGE**) are also used for gene expression profiling. SuperSAGE is especially accurate and can measure **any active gene**, not just a predefined set.

The advent of next-generation sequencing has made sequence based expression analysis an increasingly popular, “digital” alternative to microarrays called **RNA-Seq**.



## 转录组

转录组 (transcriptome)，也称为“转录物组”，广义上指在相同环境 (或生理条件) 下的在一个细胞、或一群细胞中所能转录出的所有 RNA 的总和，包括信使 RNA (mRNA)、核糖体 RNA (rRNA)、转运 RNA (tRNA) 及非编码 RNA；狭义上则指细胞所能转录出的所有信使 RNA (mRNA)。



## 转录组

转录组这个术语可用于指代给定有机体中的转录本总集，或者是特定细胞类型中的特定转录本子集。

不考虑突变，固定给定细胞株的基因组数量基本上是不变的；与之不同，转录物组可以随外部环境条件而有所变化。由于转录物组包括了所有在细胞里的 mRNA 的转录，除却异常的 mRNA 降解现象（例如转录衰减）以外，转录组反映了在任何给定时间内活跃表达的基因。

转录物组学的研究，也被称为“基因表达谱”，检测了在一个特定的细胞群内的 mRNA 表达水平，通常采用基于 DNA 微阵列技术的高通量技术。使用新一代测序技术在核苷酸水平上来研究转录物组，被称为“RNA 测序 (RNA-Seq)”。



## Methods of construction

There are two general methods of inferring transcriptomes.

- One approach maps sequence reads onto a reference genome, either of the organism itself (whose transcriptome is being studied) or of a closely related species.
- The other approach, *de novo* transcriptome assembly, uses software to infer transcripts directly from short sequence reads.



## 转录组学

转录组学（或“转录物组学”，*transcriptomics*）是分子生物学的分支，负责研究在单个细胞或一个细胞群的特定细胞类型内所生产的 mRNA 分子。

转录组测定的是表达的基因数目。这个数目包括了在各种不同水平上表达的基因。



## 丰度

每个细胞里每一种 mRNA 分子的平均数称为该种 mRNA 的丰度。根据丰度可把 mRNA 群体分为两大类：

- 高丰度 mRNA 组分。通常由每个细胞里不到 100 种的 mRNA 而每种 mRNA 分子由 1000-10,000 份备份所组成，通常占总 mRNA 的 50% 左右。
- 除高丰度 mRNA 组分外，另一半 mRNA 由长约 10,000nt 的种类繁多的序列所组成，每种序列在 mRNA 中只有少量备份。称为“稀有 mRNA”或“复杂 mRNA”。



## 转录组学

大量表达的基因之间是有很大区别的。例如，卵清蛋白只在输卵管细胞里合成而不在肝脏内合成。它占输卵管内 mRNA 总量的一半。但是高丰度的 mRNA 只占表达基因数的很小一部分。根据生物体的基因数目以及不同类型细胞出现转录变化的基因数，人们需要了解不同表型细胞稀有 mRNA 基因相同的程度。

稀有 mRNA 是普遍共有的。一个细胞中的 mRNA 序列只有 10% 左右是该细胞独有的，大部分序列是许多（甚至是所有）类型的细胞所共有的。这提示哺乳动物中共有的基因数也许达 10,000 个，包括了各种类型细胞所需的功能。编码这种类型的功能的基因，有时被称为“**持家基因**”或“**组成型基因**”。这类功能不同于特定细胞表现型所需的特定功能（例如卵清蛋白或珠蛋白的功能）。编码特殊功能的基因称为“**奢侈基因**”。



## 问题

- 一个细胞、组织或生物体的全部 RNA 集合体中包括多少种 RNA，各种 RNA 的数量有多少？
- 在不同发育时期和不同外界环境作用下 RNA 集合体会出现怎样的变化？
- 在细胞中转录是怎样被调节的？
- .....

## 转录组学

转录组学 (transcriptomics) 是对转录水平上发生的事件及其相互关系和意义进行整体研究的一门学科。



## 问题

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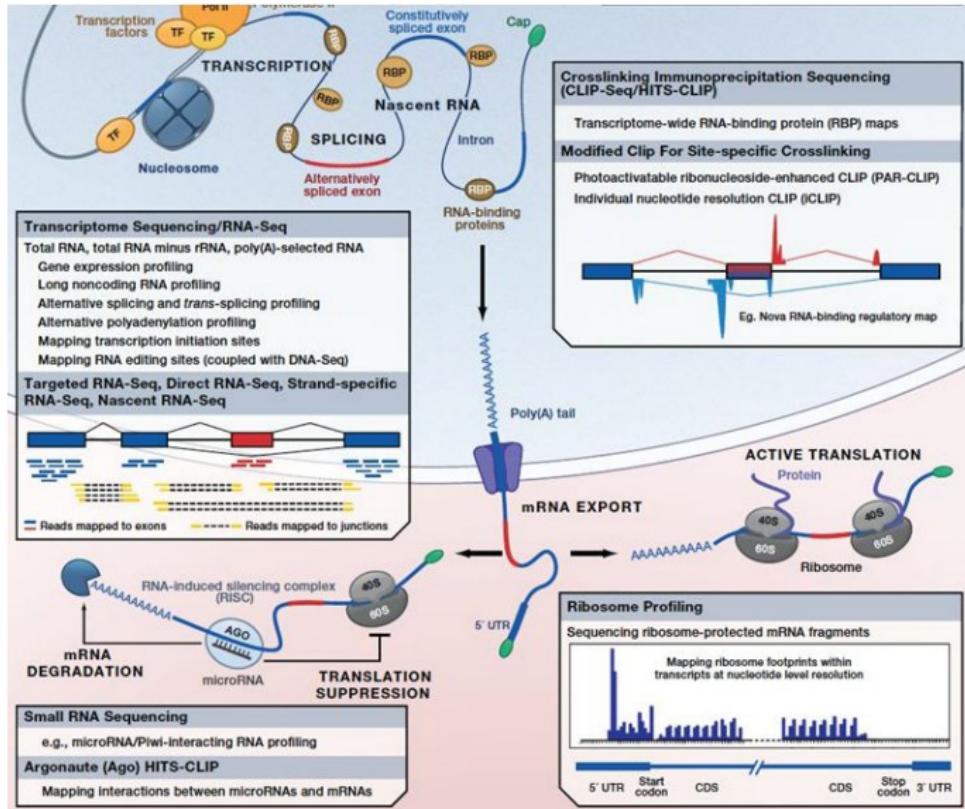


## 研究内容 (4 个水平)

- 对特定细胞的转录与加工机制进行研究
- 对转录物编制目录便于进一步归类研究
- 绘制动态的转录物图形
- 转录物调控网络



# 转录组学 | 概述 | 转录组学 | 研究内容



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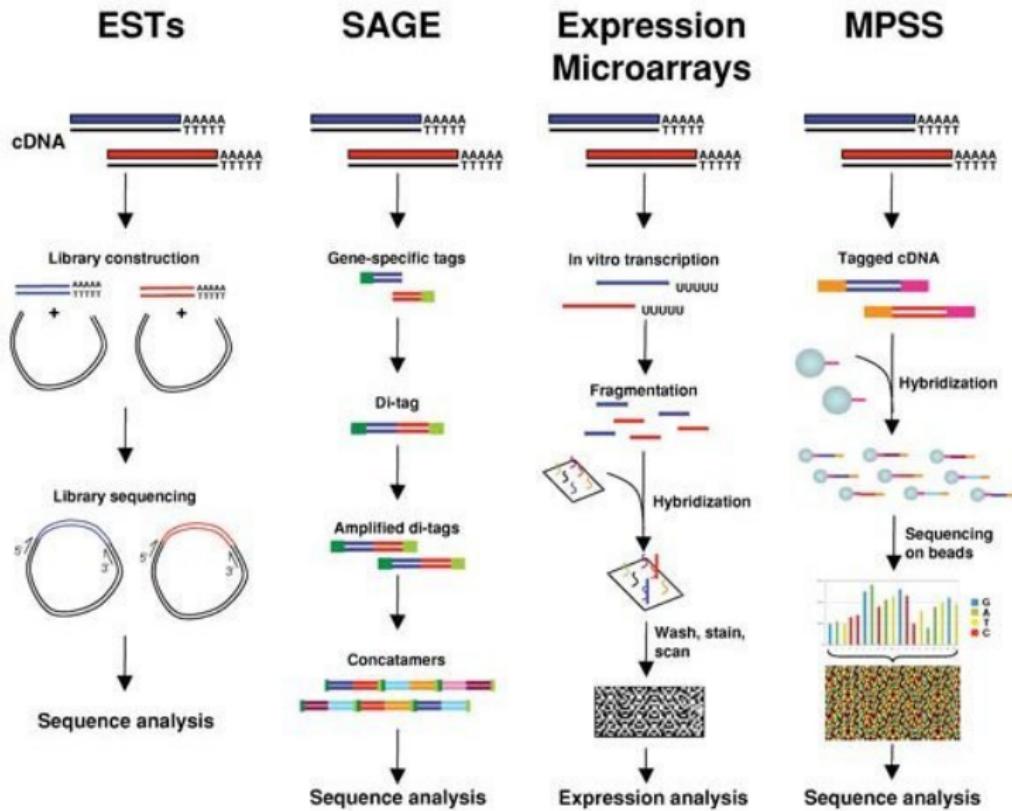
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# 转录组学 | 研究方法 | 概述



## ADVANTAGES:

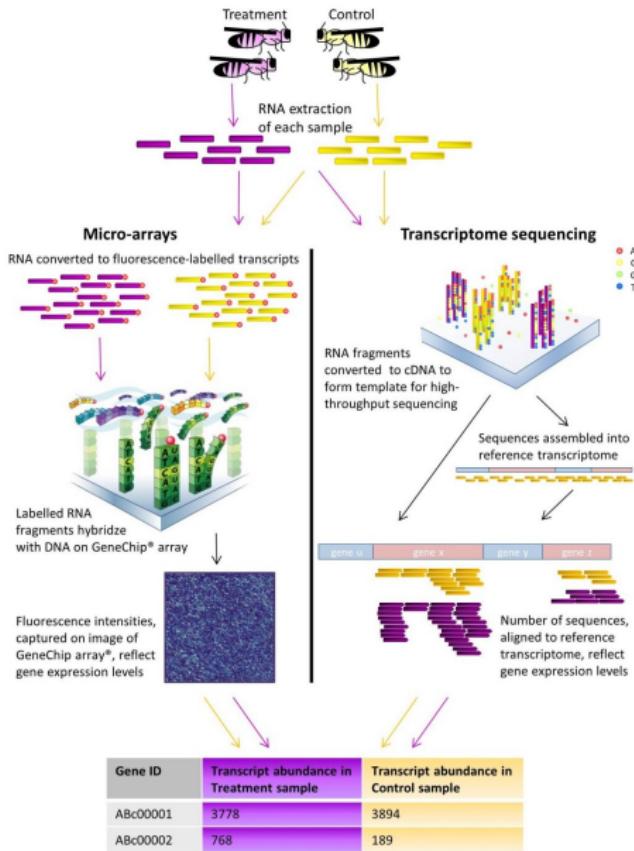
- |   |  |  |   |
|---|--|--|---|
| <ul style="list-style-type: none"><li>• Can detect novel genes and exons</li><li>• No hybridization required</li><li>• High specificity</li></ul> | <ul style="list-style-type: none"><li>• Can detect novel genes and exons</li><li>• No hybridization required</li></ul> | <ul style="list-style-type: none"><li>• Powerful method to find specific sequences</li><li>• Relatively fast and inexpensive</li></ul> | <ul style="list-style-type: none"><li>• Can detect novel genes and exons</li><li>• Tags are longer and more unique</li><li>• Identifies genes with lower expression levels</li><li>• Creates digital data that is easy to share and compare</li></ul> |
|---|--|--|---|

## DISADVANTAGES:

- |   |  |  |   |
|---|--|--|---|
| <ul style="list-style-type: none"><li>• Can not detect genes with low expression levels</li></ul> | <ul style="list-style-type: none"><li>• Costly and time-consuming</li><li>• Ambiguous tag assignment</li></ul> | <ul style="list-style-type: none"><li>• Can not detect novel genes</li><li>• Requires hybridization - false positives and negatives</li><li>• Difficult to compare data from different platforms</li></ul> | <ul style="list-style-type: none"><li>• Costly and time-consuming</li></ul> |
|---|--|--|---|



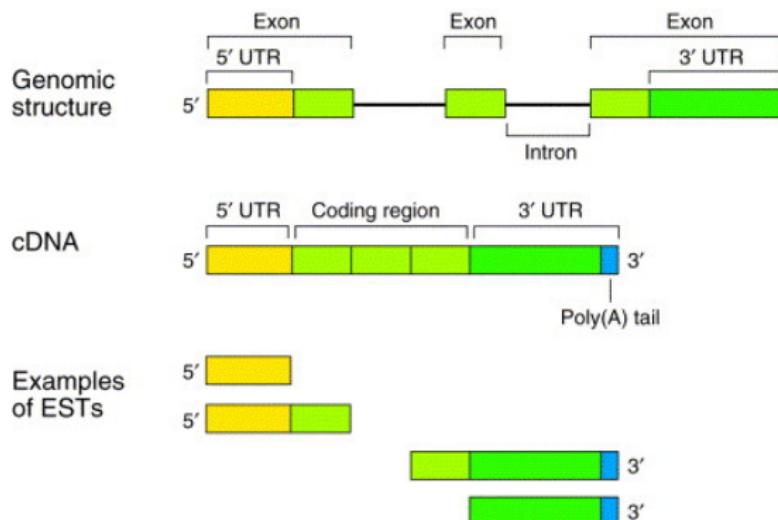
# 转录组学 | 研究方法 | 概述



## EST

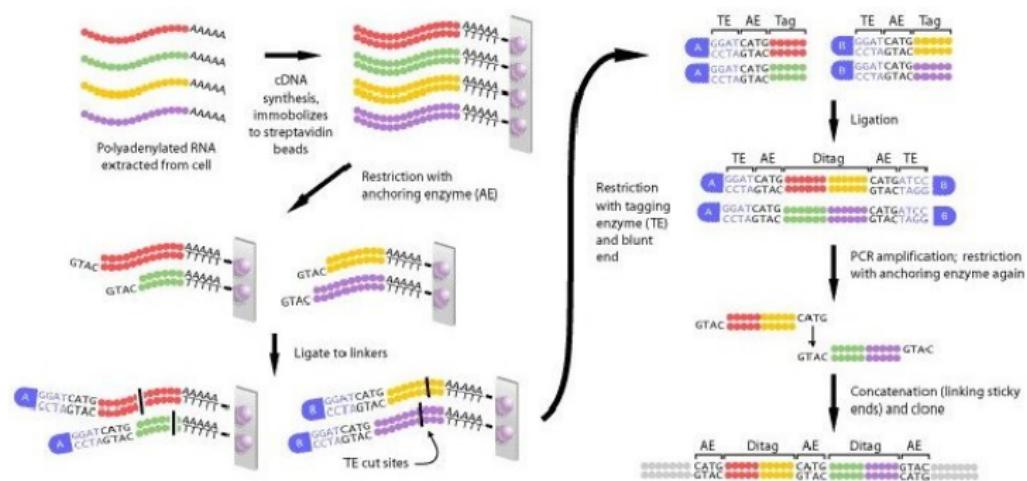
EST (expressed sequence tag, 表达序列标签) 是从 cDNA 文库中生成的一些很短的序列 (500~800bp)，代表在特定组织或发育阶段表达的基因。

In genetics, an expressed sequence tag or EST is a short sub-sequence of a cDNA sequence. ESTs may be used to identify gene transcripts, and are instrumental in gene discovery and in gene-sequence determination.



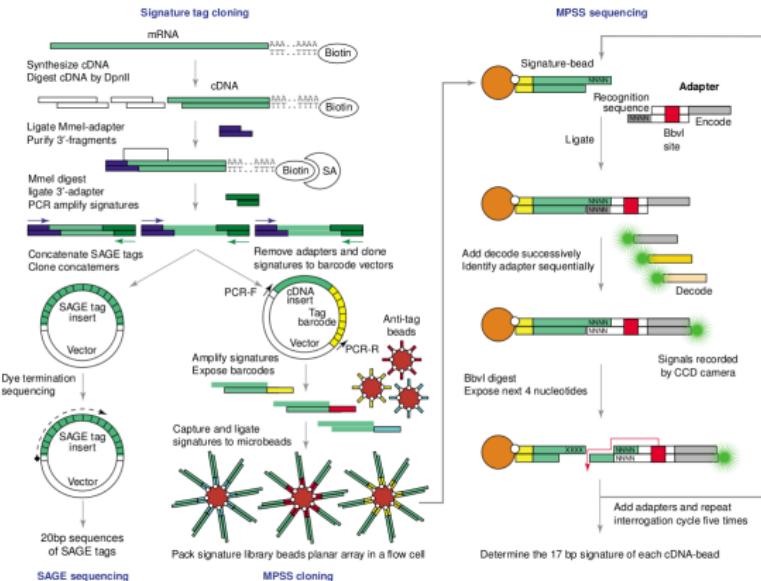
## SAGE

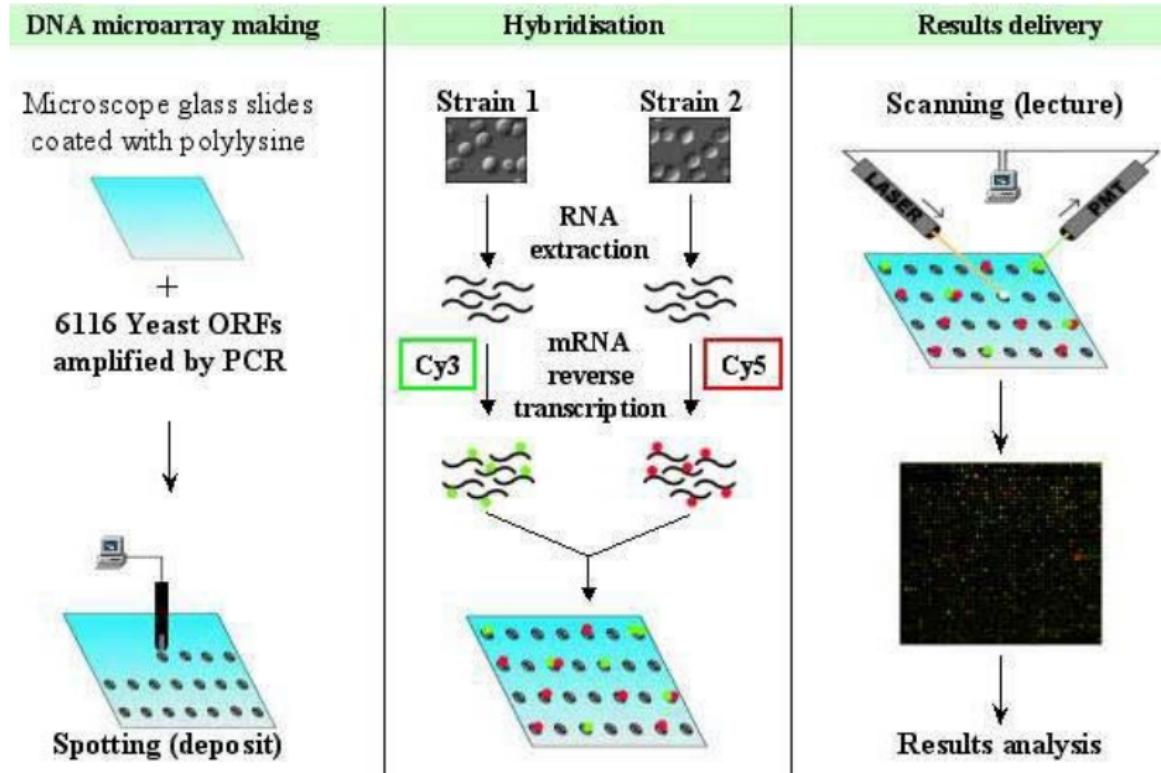
Serial analysis of gene expression (SAGE) is a technique used by molecular biologists to produce a snapshot of the messenger RNA population in a sample of interest in the form of small tags that correspond to fragments of those transcripts.



## MPSS

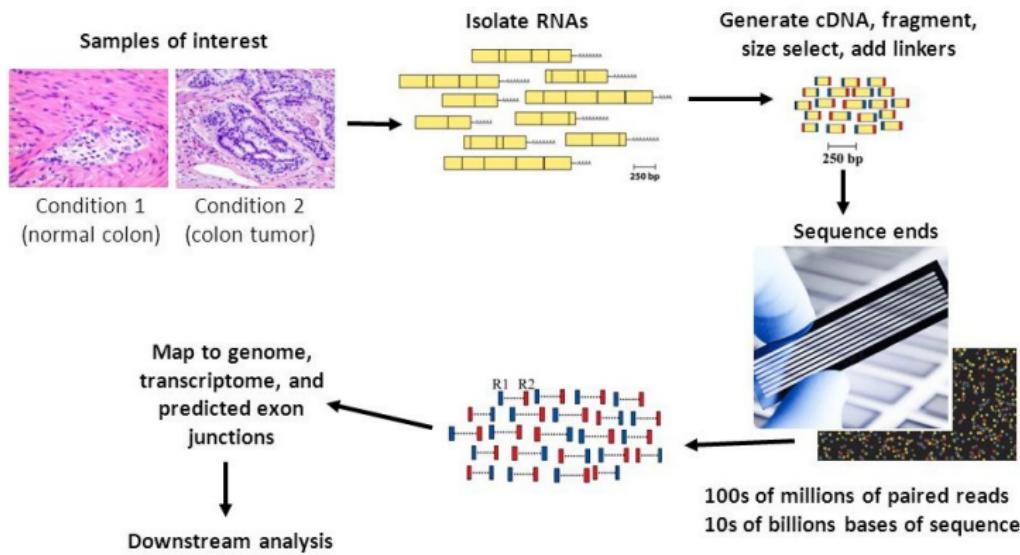
Massive parallel signature sequencing (MPSS) is a procedure that is used to identify and quantify mRNA transcripts, resulting in data similar to serial analysis of gene expression (SAGE), although it employs a series of biochemical and sequencing steps that are substantially different.





## RNA-Seq

RNA-seq (RNA sequencing), also called whole transcriptome shotgun sequencing (WTSS), uses next-generation sequencing (NGS) to reveal the presence and quantity of RNA in a biological sample at a given moment in time.



## Choose the right technology

RNA-seq	Microarray
Identification of novel genes, transcripts & exons	Well validated QC and analysis methods
Greater dynamic range	Well characterized biases
Less bias due to genetic variation	Quick turnaround from established core facilities
Repeatable	Currently less expensive (for model organisms)
No species-specific primer/probe design	
More accurate relative to qPCR	
Many more applications	



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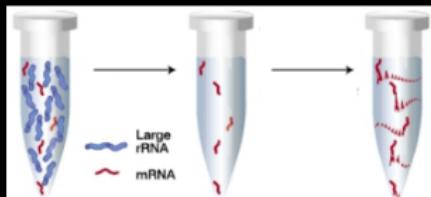
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## RNA

- RNA in cells consists of
  - 95% ribosomal rRNA and tRNA
  - other non-coding ncRNA
  - protein coding mRNA
- Sequence is transcribed from genome but
  - Introns spliced out
  - mRNA is polyadenylated ("A"s added to end)



## RNA-Seq

RNA 测序 (RNA sequencing, 简称 RNA-Seq, 也被称为全转录物组鸟枪法测序, Whole Transcriptome Shotgun Sequencing, 简称 WTSS) 是基于第二代测序技术的转录组学研究方法。RNA 测序是使用第二代测序的能力, 在给定时刻从一个基因组中, 揭示 RNA 的存在和数量的一个快照的技术。

RNA-seq (RNA sequencing), also called whole transcriptome shotgun sequencing (WTSS), uses next-generation sequencing (NGS) to reveal the presence and quantity of RNA in a biological sample at a given moment in time.



## RNA-Seq

首先提取生物样品的全部转录的 RNA，然后反转录为 cDNA 后进行二代高通量测序，在此基础上进行片段的重叠组装，从而可得到一个个的转录本。

进而可以形成对该生物样品当前发育状态的基因表达状况的全局了解。

进一步说，若和下一阶段的生物样品的 RNA-Seq 转录组进行比较，则可以得到全部的（在转录层面）基因表达的上调及下调——这就形成了表达谱，针对关键基因则可以形成你想要的通路 (pathway) 的构建。



## RNA-Seq

相较于一个静态的染色体而言，细胞内的转录物组是一个处于不断变化的动态过程。随着现在的下一代基因测序（NGS）技术的发展，使得可测得的 DNA 碱基覆盖面增加且样本输出的吞吐量增大。

有助于对细胞内 RNA 转录物进行测序，提供包括选择性剪接转录本、转录后修饰、基因融合、突变/SNPs 以及基因表达量改变等细节。

RNA 测序不仅能检测 mRNA 的转录，还能观测到包括总 RNA 和小 RNA（miRNA、tRNA 和核糖体 RNA）在内不同 RNA 群体的表达谱。RNA 测序还能用来确定外显子/内含子的边界，修正之前注释的 5' 和 3' 端基因边界。未来的 RNA 测序研究还包括观察感染时细胞传导路径的变化和癌症中不同基因表达程度。



## 技术

下一代基因测序之前，对转录物组学和基因表达的研究主要基于基因表达芯片（微阵列），后者包含数以千计用于探测靶向序列的 DNA 探针，可以得到所有表达出转录物的表达谱。基因表达芯片之后，基因表达的系列分析（SAGE）是主要的基因分析技术。

Prior to RNA-Seq, gene expression studies were done with hybridization-based microarrays. Issues with microarrays include cross-hybridization artifacts, poor quantification of lowly and highly expressed genes, and needing to know the sequence *a priori*. Because of these technical issues, transcriptomics transitioned to sequencing-based methods. These progressed from Sanger sequencing of Expressed Sequence Tag libraries, to chemical tag-based methods (e.g., serial analysis of gene expression), and finally to the current technology, NGS of cDNA (notably RNA-Seq).

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## poly(A)-poly(T)

Frequently, in mRNA analysis the 3' polyadenylated (poly(A)) tail is targeted in order to ensure that coding RNA is separated from noncoding RNA. This can be accomplished simply with poly (T) oligos covalently attached to a given substrate. Presently many studies utilize magnetic beads for this step.

## poly(T) & rRNA

Studies including portions of the transcriptome outside poly(A) RNAs have shown that when using poly(T) magnetic beads, the flow-through RNA (non-poly(A) RNA) can yield important noncoding RNA gene discovery which would have otherwise gone unnoticed.

Also, since ribosomal RNA represents over 90% of the RNA within a given cell, studies have shown that its removal via probe hybridization increases the capacity to retrieve data from the remaining portion of the transcriptome.

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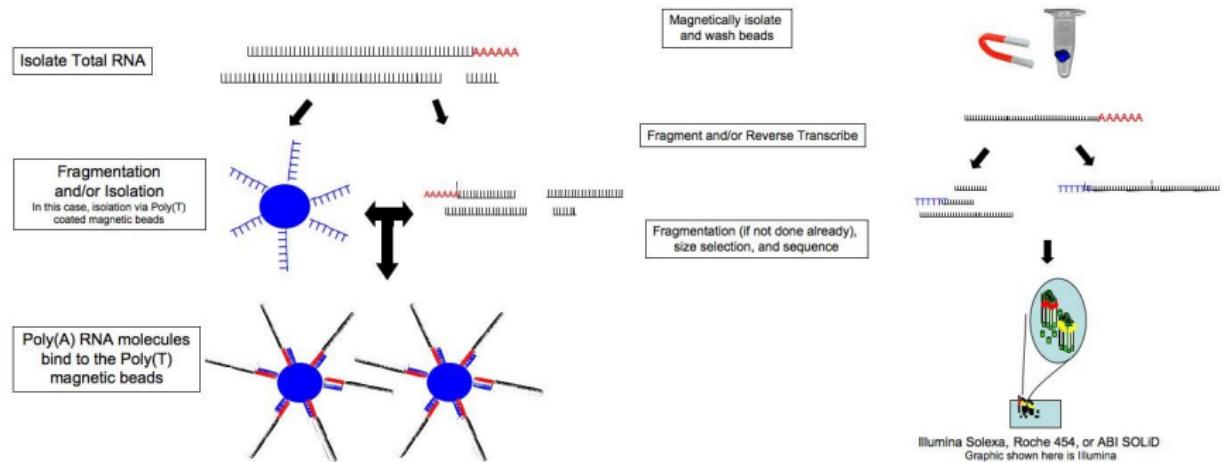
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## reverse transcription

Due to the 5' bias of randomly primed-reverse transcription as well as secondary structures influencing primer binding sites, hydrolysis of RNA into 200-300 nucleotides prior to reverse transcription reduces both problems simultaneously. However, there are trade-offs with this method where although the overall body of the transcripts are efficiently converted to DNA, the 5' and 3' ends are less so. Depending on the aim of the study, researchers may choose to apply or ignore this step.

Once the cDNA is synthesized it can be further fragmented to reach the desired fragment length of the sequencing system.





## size selection

When sequencing RNA other than mRNA, the library preparation is modified. The cellular RNA is selected based on the desired size range. For small RNA targets, such as miRNA, the RNA is isolated through size selection. This can be performed with a size exclusion gel, through size selection magnetic beads, or with a commercially developed kit.

Once isolated, linkers are added to the 3' and 5' end then purified.

The final step is cDNA generation through reverse transcription.



## DRSTM

As converting RNA into cDNA using reverse transcriptase has been shown to introduce biases and artifacts that may interfere with both the proper characterization and quantification of transcripts, single molecule Direct RNA Sequencing (DRSTM) technology was under development by Helicos (now bankrupt). DRSTM sequences RNA molecules directly in a massively-parallel manner without RNA conversion to cDNA or other biasing sample manipulations such as ligation and amplification.



# Transcriptome Assembly

- RNA-Seq
  - Reference genome
  - Reference transcriptome
- RNA-Seq
  - Reference genome
  - No reference transcriptome
- RNA-Seq
  - No reference genome
  - No reference transcriptome



# 转录组学 | RNA-Seq | Method | Transcriptome assembly

## Two methods

Two different assembly methods are used for producing a transcriptome from raw sequence reads: genome-guided and *de-novo*.



## genome-guided

An “easier” and relatively computationally cheaper approach is that of aligning the millions of reads to a “reference genome”. There are many tools available for aligning genomic reads to a reference genome, however, special attention is needed when aligning a transcriptome to a genome, mainly when dealing with genes having intronic regions. Several software packages exist for short read alignment, and recently specialized algorithms for transcriptome alignment have been developed, e.g. Bowtie for RNA-seq short read alignment, TopHat for aligning reads to a reference genome to discover splice sites, Cufflinks to assemble the transcripts and compare/merge them with others, or FANSe. These tools can also be combined to form a comprehensive system.

## *de novo*

This approach does not rely on the presence of a reference genome in order to reconstruct the nucleotide sequence. Due to the small size of the short reads, *de novo* assembly may be difficult, though some software does exist (Velvet (algorithm), Oases, and Trinity to mention a few), as there cannot be large overlaps between each read needed to easily reconstruct the original sequences. The deep coverage also makes the computing power to track all the possible alignments prohibitive. This deficit can be improved using longer sequences obtained from the same sample using other techniques such as Sanger sequencing, and using larger reads as a “skeleton” or a “template” to help assemble reads in difficult regions (e.g. regions with repetitive sequences).

## Notes

- assembly quality can vary a lot depending on which metric is used
- assemblies that scored well in one species did not really perform well in the other species
- the “most reliable” assembly could be then obtained by combining different approaches



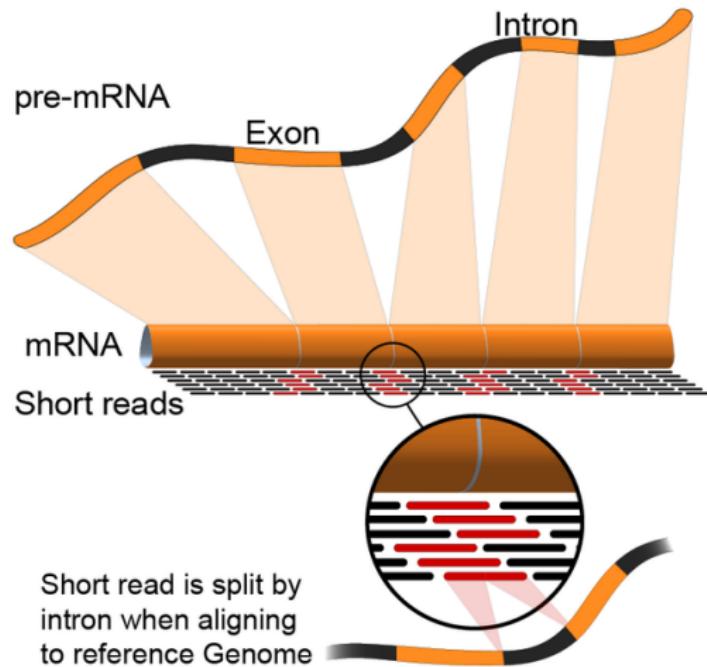
## junction

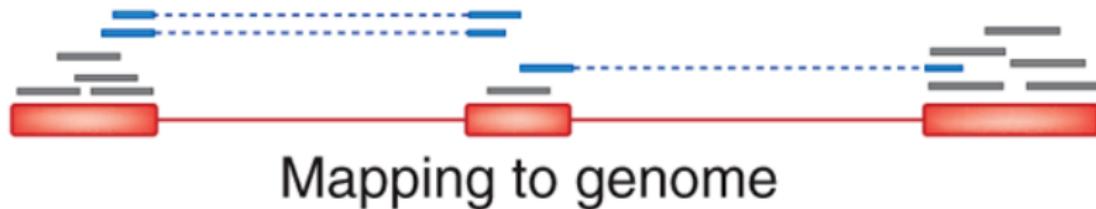
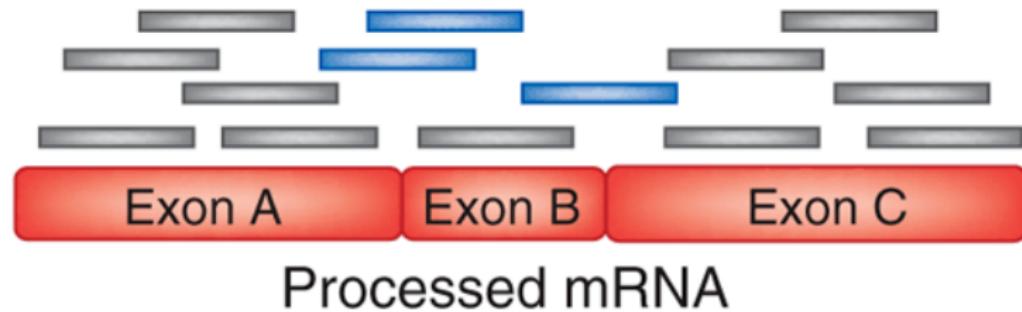
The created library and the short reads obtained cannot come from intronic sequences, so library reads spanning the junction of two or more exons will not align to the genome.

A possible method to work around this is to try to align the unaligned short reads using a proxy genome generated with known exonic sequences. This need not cover whole exons, only enough so that the short reads can match on both sides of the exon-exon junction with minimum overlap.



# 转录组学 | RNA-Seq | Method | Transcriptome assembly





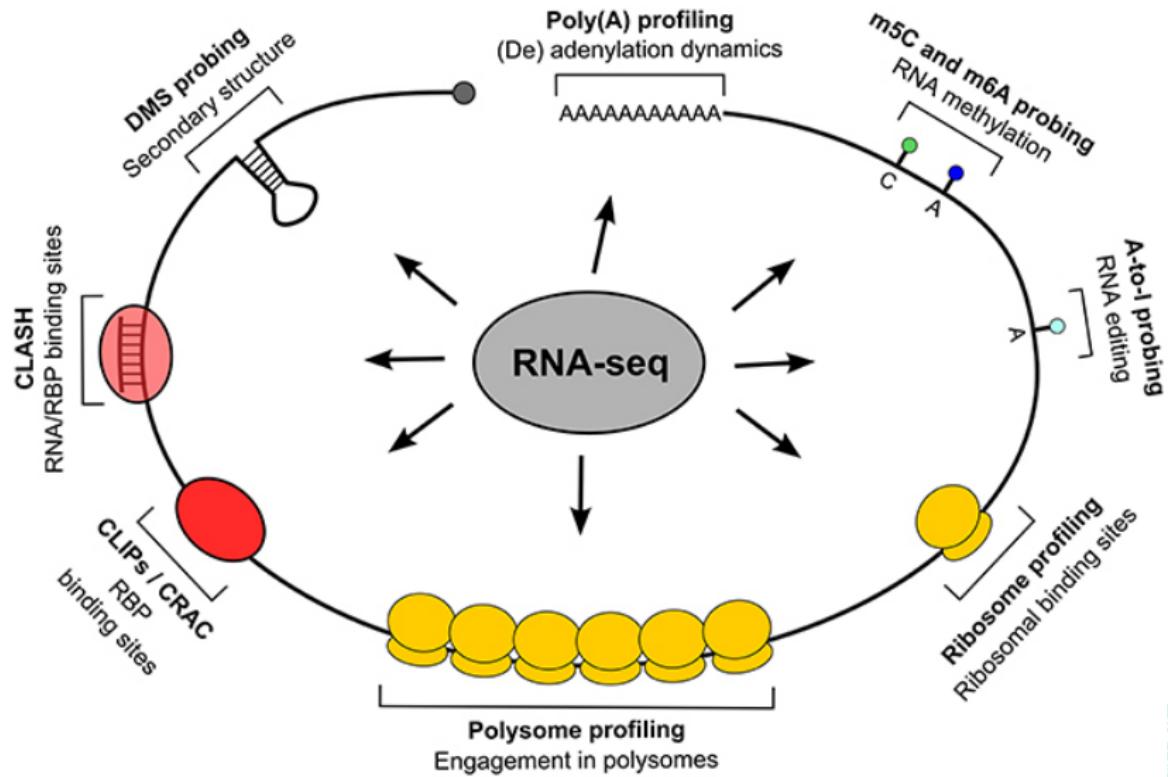
# 转录组学 | RNA-Seq | Method | Experimental considerations

## pros & cons

- Tissue specificity: Gene expression is not uniform throughout an organism's cells, it is strongly dependent on the tissue type being measured. RNA-Seq can provide a complete snapshot of all the transcripts being available at that precise moment in the cell.
- Time dependent: During a cell's lifetime and context, its gene expression levels change. Any single sequencing experiment will offer information regarding one point in time.
- Coverage: coverage/depth can affect the mutations seen.
- Subjectivity of the analysis: Numerous attempts have been taken to uniformly analyze the data. However, the results can vary due to the multitude of algorithms and pipelines available.
- Data management: The main issue with NGS data is the volume of data produced.
- Downstream interpretation of the data: Different layers of interpretations have to be considered when analyzing RNA-Seq data.

- RNA-Seq
  - Transcriptome assembly
    - Qualitative identification of expressed sequence
  - Differential expression analysis
    - Quantitative measurement of transcript expression
- RNA-Seq Applications
  - **Annotation:** Identify novel genes, transcripts, exons, splicing events, ncRNAs
  - Detecting RNA editing and SNPs
  - **Measurements:** RNA quantification and differential gene expression





# RNA-Seq applications

- Sequencing RNA transcripts, applications:
  - *de novo* transcriptome
  - **gene-wise differential expression**
  - novel splice variants
  - differential splicing
  - fusion genes
  - non-coding RNA
  - polyadenylation length
  - post-transcriptional modification
  - ...
- Differential expression analysis most common
  - Commonly called “DGE”



# RNA-seq Applications

- **Annotation**
  - Identify novel genes, transcripts, exons, splicing events, ncRNAs.
- Detecting RNA editing and SNPs.
- **Measurements: RNA quantification and differential gene expression**
  - Abundance of transcripts between different conditions



## Why do an RNA-seq experiment?

Detect differential expression

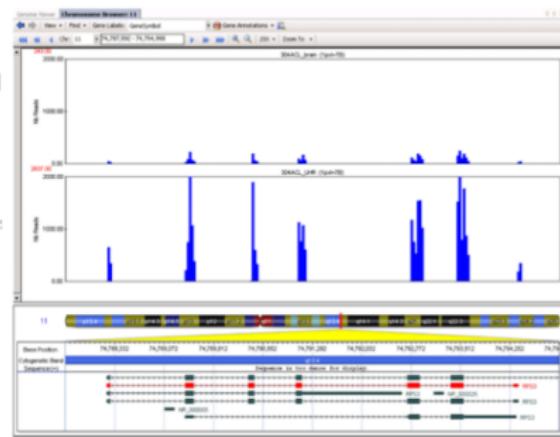
Assess allele-specific expression

Quantify alternative transcript usage

Discover novel genes/transcripts, gene fusions, circRNA

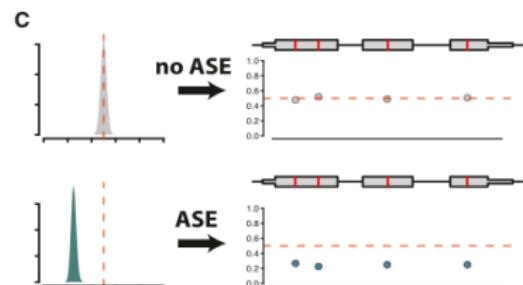
Profile transcriptome

Ribosome profiling to measure translation



## Why do an RNA-seq experiment?

- Detect differential expression
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## Why do an RNA-seq experiment?

Detect differential expression

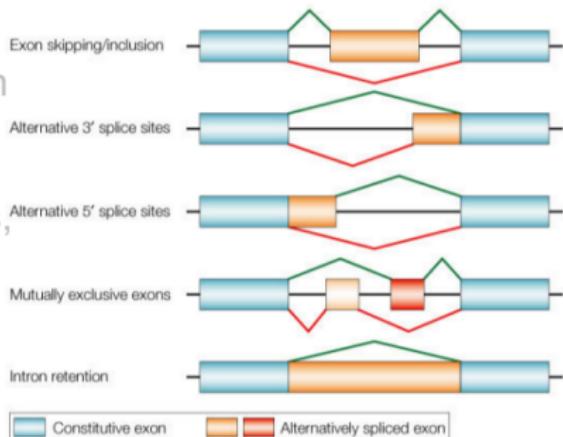
Assess allele-specific expression

Quantify alternative transcript usage

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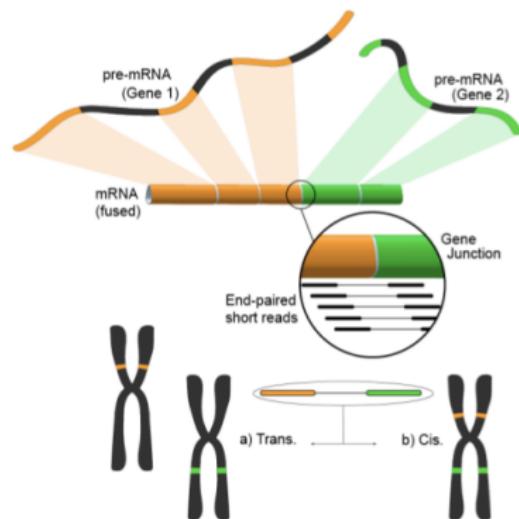
Profile transcriptome

Ribosome profiling to measure translation



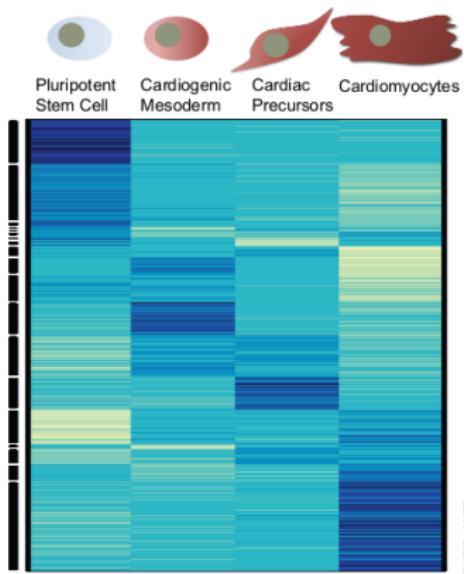
## Why do an RNA-seq experiment?

- Detect differential expression
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- Profile transcriptome
- Ribosome profiling to measure translation



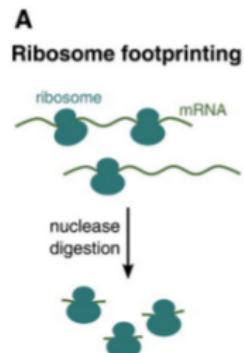
## Why do an RNA-seq experiment?

- Detect differential expression
- Assess allele-specific expression
- Quantify alternative transcript usage
- Discover novel genes/transcripts, gene fusions, circRNA
- Profile transcriptome**
- Ribosome profiling to measure translation



## Why do an RNA-seq experiment?

- Detect differential expression
- Assess allele-specific expression
- Quantify alternative transcript usage
- Discover novel genes/transcripts, gene fusions, circRNA
- Profile transcriptome
- Ribosome profiling to measure translation (Ribo-seq)



# Experimental design

- What are my goals?
  - Transcriptome assembly?
  - Differential expression analysis?
  - Identify rare transcripts?
- What are the characteristics of my system?
  - Large, complex genome?
  - Introns and high degree of alternative splicing?
  - No reference genome or transcriptome?



# Experimental Outputs

Left reads:

Input : 11607291  
 Mapped : 11606003 (100.0% of input)  
 of these: 57648 ( 0.5%) have multiple alignments (104 have >20)

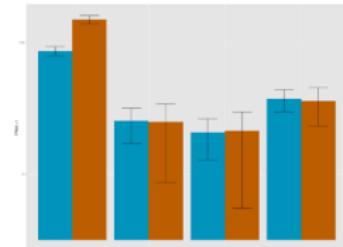
Right reads:

Input : 11607291  
 Mapped : 11606001 (100.0% of input)  
 of these: 57647 ( 0.5%) have multiple alignments (104 have >20)

100.0% overall read mapping rate.

Aligned pairs: 11604800  
 of these: 57644 ( 0.5%) have multiple alignments  
 324 ( 0.0%) are discordant alignments

100.0% concordant pair alignment rate.



Expression

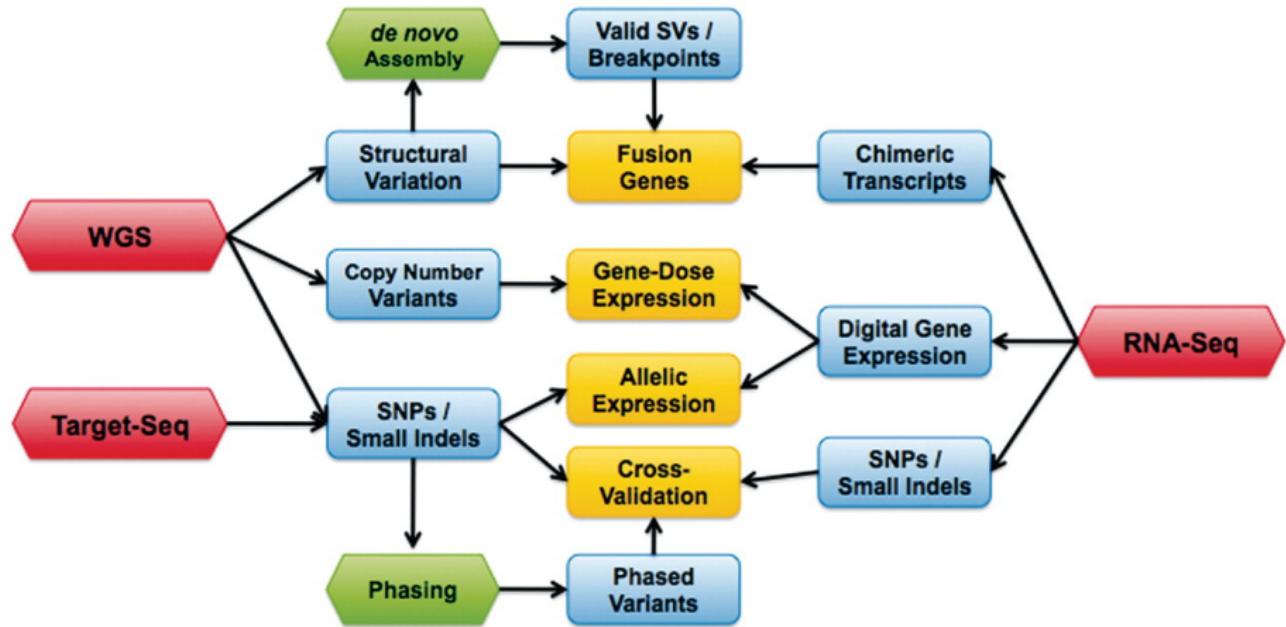
Differentially expressed

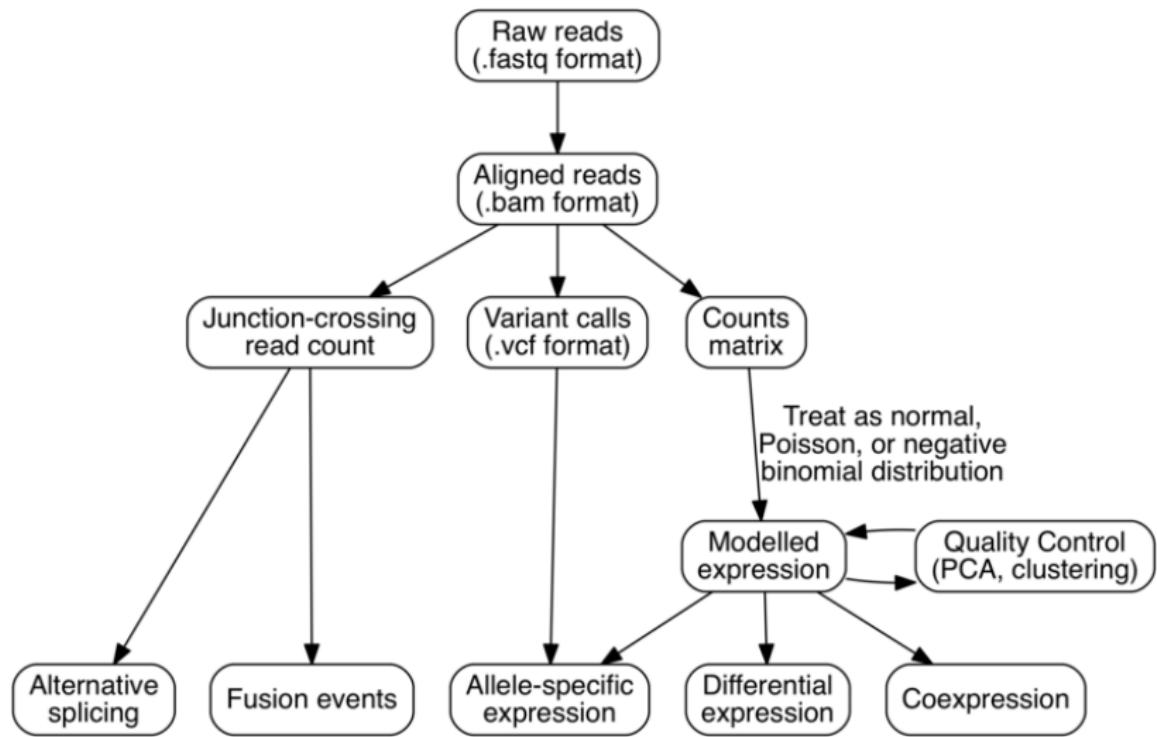
## Assembly



Splicing







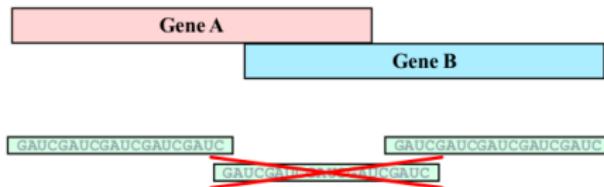
## Gene expression

- Which genes are expressed in what tissues, and at what levels.
- Measuring mRNA concentration levels is a useful tool in determining how the transcriptional machinery of the cell is affected in the presence of external signals (e.g. drug treatment), or how cells differ between a healthy state and a diseased state.
- Expression levels are expressed as Fragments Per Kilobase of transcript per Million mapped reads (FPKM).
- An R-based statistical package known as CummeRbund can be used to generate expression comparison charts for visual analysis.



## Measure expression levels in RNA-Seq data

- 1 Align read to reference genome
- 2 Measuring expression = counting aligned reads
  - ▶ Count in annotated exons
  - ▶ Positive integers (read counts of 3.1415 or  $-42$  are impossible)
  - ▶ Quantitative (read count has an absolute meaning)
- ▶ Observation (read count) must be statistically independent
  - ▶ No multi-map reads
  - ▶ Skip overlapping gene annotations



## Differential expression

RNA-Seq is generally used to compare gene expression between conditions, such as a drug treatment vs non-treated, and find out which genes are up- or down regulated in each condition.

Differently expressed genes can be identified by using tools that count the sequencing reads per gene and compare them between samples. The most commonly used tools for this type of analysis are DESeq and edgeR, packages from Bioconductor. Both these tools use a model based on the negative binomial distribution.



## Differential gene expression analysis tools

- ▶ Alignment
  - ▶ TopHat [15, 5]
  - ▶ STAR [3]
  - ▶ ... many many more
- ▶ Measuring expression (quantification)
  - ▶ HTSeq-count [2]
  - ▶ Cufflinks [16]
  - ▶ featureCounts [8]
- ▶ Group-wise comparison (hypothesis testing)
  - ▶ EdgeR [12]
  - ▶ DESeq2 [11]
  - ▶ Cuffdiff [14]



## Measure expression levels in RNA-Seq data

In Galaxy

- ▶ featureCounts [8]
  - ▶ Pro's
    - ▶ Fast
    - ▶ Flexible
    - ▶ Free (GPL)
    - ▶ Accepts both BAM and SAM files
    - ▶ Only requires name-sorted files when mate-pairs are counted together (name-sorting is slow)
  - ▶ Con's
    - ▶ Built-in name-sorting supports no threading – rather do this with samtools [7]

## Differential gene expression analysis

edgeR

- ▶ edgeR [12]
  - ▶ Differential gene expression analysis
  - ▶ Free R Package (GPL2)
  - ▶ Galaxy wrapper does normalizations for you
    - ▶ Use raw reads, do NOT use FPKM/RPKM!
- ▶ "Limma" for count data
  - ▶ Not Gaussian (normal) distributed like e.g. micro-array data – but negative binomial



# 转录组学 | RNA-Seq | Analysis | Absolute quantification of transcripts

## Absolute quantification of transcripts

It is not possible to do absolute quantification using the common RNA-Seq pipeline, because it only provides RNA levels relative to all transcripts. If the total amount of RNA in the cell changes between conditions, relative normalization will misrepresent the changes for individual transcripts. Absolute quantification of mRNAs is possible by performing RNA-Seq with added spike ins, samples of RNA at known concentrations. After sequencing, the read count of the spike ins sequences is used to determine the direct correspondence between read count and biological fragments.

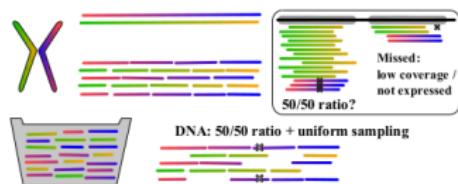


## SNV discovery

RNA-seq is limited to transcribed regions however, since it will only discover sequence variations in exon regions. This misses many subtle but important intron alleles that affect disease such as transcription regulators, leaving analysis to only large effectors. While some correlation exists between exon to intron variation, only whole genome sequencing would be able to capture the source of all relevant SNPs.



## Single Nucleotide Polymorphisms in RNA-Seq



- ▶ Major difference(s) between DNA-Seq:
  - ▶ Detected SNPs are expressed
    - ▶ Biological context
    - ▶ SNPs RNA-Seq only within exons and ncRNAs
    - ▶ Allele specific expression profiles
- ▶ Detection:
  - ▶ Expression affects coverage; in DNA-seq coverage should be uniform



## Single Nucleotide Polymorphisms in RNA-Seq

Using: Samtools, VarScan

reference

read1  
read2  
read3  
read4  
read5  
read6  
read7

read quality (q)

	A	C	T	G	A
read1	a	c	c	g	c
read2	a	c	t	g	a
read3	a	c	c	g	a
read4	a	c	c	g	a
read5	a	c	t	a	a
read6		c	c	g	a
read7			c	g	a
read quality (q)	0.99	0.99	0.85	0.8	0.99

aligned

q\*aligned

(1-q)\*aligned

exp match (abs)

exp mismatch (abs)

obs match

obs mismatch

P(obs|exp) fisher exact

P &lt; 0.05

5	6	7	7	7
4.95	5.94	5.95	5.6	6.93
0.05	0.06	1.05	1.4	0.07

5	6	6	6	7
0	0	1	1	0

5	6	2	6	6
0	0	5	1	1

1.000	1.000	0.049	0.538	0.500
REF	REF	SNP	REF	REF

{ Alignment }

{ Expected  
(based on quality) }

{ Observed }

{ Hypothesis testing }

Alignment

Expected  
(based on quality)

Observed

Hypothesis testing



## Single Nucleotide Polymorphisms in RNA-Seq

### Detection tools

- ▶ Alignment
  - ▶ TopHat [15, 5]
  - ▶ STAR [3]
  - ▶ ... many many more
- ▶ SNV calling
  - ▶ VarScan2 [6]
  - ▶ samtools [7]
  - ▶ exactSNP *(part of subread [9] package)*
  - ▶ GATK [17]



## Post-transcriptional edits

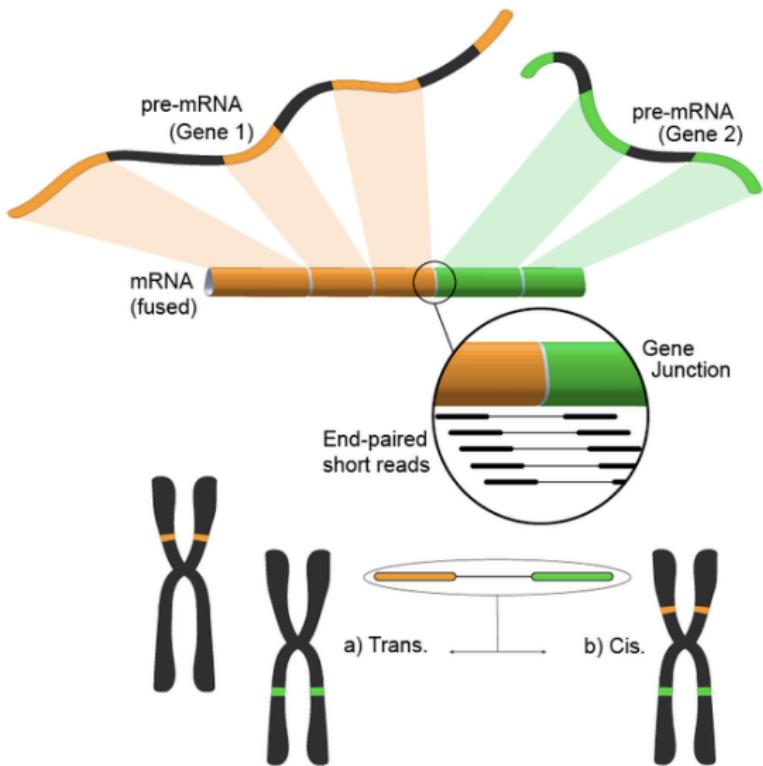
Having the matching genomic and transcriptomic sequences of an individual can also help in detecting post-transcriptional edits, where, if the individual is homozygous for a gene, but the gene's transcript has a different allele, then a post-transcriptional modification event is determined.

mRNA centric single nucleotide variants (SNVs) are generally not considered as a representative source of functional variation in cells, mainly due to the fact that these mutations disappear with the mRNA molecule, however the fact that efficient DNA correction mechanisms do not apply to RNA molecules can cause them to appear more often. This has been proposed as the source of certain prion diseases, also known as TSE or transmissible spongiform encephalopathies.

## Fusion gene detection

Caused by different structural modifications in the genome, fusion genes have gained attention because of their relationship with cancer. The ability of RNA-seq to analyze a sample's whole transcriptome in an unbiased fashion makes it an attractive tool to find these kinds of common events in cancer.

The idea follows from the process of aligning the short transcriptomic reads to a reference genome. Most of the short reads will fall within one complete exon, and a smaller but still large set would be expected to map to known exon-exon junctions. The remaining unmapped short reads would then be further analyzed to determine whether they match an exon-exon junction where the exons come from different genes. This would be evidence of a possible fusion event, however, because of the length of the reads, this could prove to be very noisy. An alternative approach is to use pair-end reads, when a potentially large number of paired reads would map each end to a different exon, giving better coverage of these events. Nonetheless, the end result consists of multiple and potentially novel combinations of genes providing an ideal starting point for further validation.



## Coexpression networks

Coexpression networks are data-derived representations of genes behaving in a similar way across tissues and experimental conditions. Their main purpose lies in hypothesis generation and guilt-by-association approaches for inferring functions of previously unknown genes. RNA-Seq data has been recently used to infer genes involved in specific pathways based on Pearson correlation, both in plants and mammals. The main advantage of RNA-Seq data in this kind of analysis over the microarray platforms is the capability to cover the entire transcriptome, therefore allowing the possibility to unravel more complete representations of the gene regulatory networks.

Co-expression modules may correspond to cell types or pathways. Highly connected intramodular hubs can be interpreted as representatives of their respective module.

## Application to genomic medicine

RNA-Seq data could help researchers interpreting the “personalized transcriptome” so that it will help understanding the transcriptomic changes happening therefore, ideally, identifying gene drivers for a disease. The feasibility of this approach is however dictated by the costs in terms of money and time.

RNA-Seq applications to the clinic have the potentials to significantly affect patient's life and, on the other hand, requires a team of specialists (bioinformaticians, physicians/clinicians, basic researchers, technicians) to fully interpret the huge amount of data generated by this analysis.



## Application to genomic medicine

Compared with microarrays, NGS technology has identified **novel and low frequency RNAs** associated with disease processes. This advantage aids in the diagnosis and possible future treatments of diseases, including cancer. Numerous studies have demonstrated NGS's ability to detect aberrant mRNA and small non-coding RNA expression in disease processes above that provided by microarrays. The lower cost and higher throughput offered by NGS confers another advantage to researchers.

The role of small non-coding RNAs in disease processes has also been explored in recent years.



## ENCODE & TCGA

A lot of emphasis has been given to RNA-Seq data after the Encyclopedia of the regulatory elements (ENCODE) and The Cancer Genome Atlas (TCGA) projects have used this approach to characterize dozens of cell lines and thousands of primary tumor samples, respectively.

RNA-Seq data provide a unique snapshot of the transcriptomic status of the disease and look at an unbiased population of transcripts that allows the identification of novel transcripts, fusion transcripts and non-coding RNAs that could be undetected with different technologies.



## ENCODE

ENCODE aimed to identify genome-wide regulatory regions in different cohort of cell lines and transcriptomic data are paramount in order to understand the downstream effect of those epigenetic and genetic regulatory layers.

## RNA Seq Atlas

RNA-Seq Atlas is a web-based repository of RNA-Seq gene expression profiles and query tools. The website offers free and easy access to RNA-Seq gene expression profiles and tools to both compare tissues and find genes with specific expression patterns.

## TCGA

TCGA aimed to collect and analyze thousands of patient's samples from 30 different tumor types in order to understand the underlying mechanisms of malignant transformation and progression.

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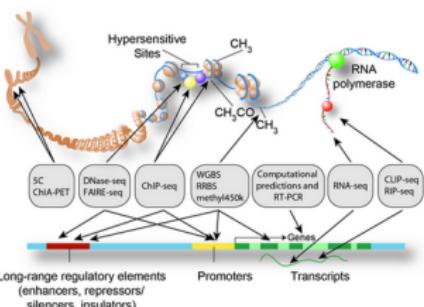
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ENCODE Data Encyclopedia Materials & Methods Help Search... 

## ENCODE: Encyclopedia of DNA Elements



The ENCODE (Encyclopedia of DNA Elements) Consortium is an international collaboration of research groups funded by the National Human Genome Research Institute (NHGRI). The goal of ENCODE is to build a comprehensive parts list of functional elements in the human genome, including elements that act at the protein and RNA levels, and regulatory elements that control cells and circumstances in which a gene is active.

Image credits: Darryl Leja (NHGRI), Ian Dunham (EBI), Michael Pazin (NHGRI)

### Quick Start

To find and download ENCODE Consortium data:

- Click the Data toolbar above and browse data
  - By assay
  - By biosample
  - By genomic annotations
- Enter search terms like "skin", "ChIP-seq", or "CTCF"

Additional help using the ENCODE Portal:

- Getting Started

### News Follow @EncodeDCC

**August 3rd, 2016:** With collaborations from the DAC (Data Analysis Center), a total of 336 Annotation File Sets of promoter-like and enhancer-like regions have been released! [read more]

**August 1st, 2016:** 191 new ENCODE experiments released in July - check them all out [here](#).

**July 21st, 2016:** Check out the latest GGR release from the Reddy lab, here on the portal. 84 ChIP-seq expts in A549 +/- dex treatment.

**July 20th, 2016:** Mouse e10.5 histone ChIP-seq dataset from the Ren lab available on the portal [here](#).



## ENCODE

DNA 元件百科全书 (Encyclopedia of DNA Elements, 简称为 ENCODE 项目) 是一个由美国国家人类基因组研究所 (NHGRI) 在 2003 年 9 月发起的一项公共联合研究项目，旨在找出人类基因组中所有功能组件。这是继完成人类基因组计划后国家人类基因组研究所开始的最重要的项目之一。

## 三个阶段

- 试验阶段：测试和比较现有方法以便严格分析一个所定义的人类基因组序列的一部分
- 技术发展阶段：分析整个基因组，并进行“额外中试规模研究”
- 生产阶段：2012 年 9 月 5 日，该项目的初步结果被整理为 30 篇论文并同时发表于多个刊物，包括 6 篇论文在《自然》、6 篇论文在《基因组生物学》及 18 篇论文在《基因组研究》上

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## Important features about the organization and function of the human genome

- The vast majority (80.4%) of the human genome participates in at least one biochemical RNA and/or chromatin associated event in at least one cell type. Much of the genome lies close to a regulatory event: 95% of the genome lies within 8kb of a DNA-protein interaction (as assayed by bound ChIP-seq motifs or DNaseI footprints), and 99% is within 1.7kb of at least one of the biochemical events measured by ENCODE.
- Primate-specific elements as well as elements without detectable mammalian constraint show, in aggregate, evidence of negative selection; thus some of them are expected to be functional.
- Classifying the genome into seven chromatin states suggests an initial set of 399,124 regions with enhancer-like features and 70,292 regions with promoters-like features, as well hundreds of thousands of quiescent regions. High-resolution analyses further subdivide the genome into thousands of narrow states with distinct functional properties.

## Important features about the organization and function of the human genome

- It is possible to quantitatively correlate RNA sequence production and processing with both chromatin marks and transcription factor (TF) binding at promoters, indicating that promoter functionality can explain the majority of RNA expression variation.
- Many non-coding variants in individual genome sequences lie in ENCODE-annotated functional regions; this number is at least as large as those that lie in protein coding genes.
- SNPs associated with disease by GWAS are enriched within non-coding functional elements, with a majority residing in or near ENCODE-defined regions that are outside of protein coding genes. In many cases, the disease phenotypes can be associated with a specific cell type or TF.

## Most striking finding

The most striking finding was that the fraction of human DNA that is biologically active is considerably higher than even the most optimistic previous estimates. In an overview paper, the ENCODE Consortium reported that its members were able to assign biochemical functions to **over 80% of the genome**. Much of this was found to be involved in controlling the expression levels of coding DNA, which makes up less than 1% of the genome.



## Most important new elements of the “encyclopedia”

- A comprehensive map of DNase 1 hypersensitive sites, which are markers for regulatory DNA that is typically located adjacent to genes and allows chemical factors to influence their expression. The map identified nearly 3 million sites of this type, including nearly all that were previously known and many that are novel.
- A lexicon of short DNA sequences that form recognition motifs for DNA-binding proteins. Approximately 8.4 million such sequences were found, comprising a fraction of the total DNA roughly twice the size of the exome. Thousands of transcription promoters were found to make use of a single stereotyped 50-base-pair footprint.



## Most important new elements of the “encyclopedia”

- A preliminary sketch of the architecture of the network of human transcription factors, that is, factors that bind to DNA in order to promote or inhibit the expression of genes. The network was found to be quite complex, with factors that operate at different levels as well as numerous feedback loops of various types.
- A measurement of the fraction of the human genome that is capable of being transcribed into RNA. This fraction was estimated to add up to **more than 75% of the total DNA**, a much higher value than previous estimates. The project also began to characterize the types of RNA transcripts that are generated at various locations.



# 教学提纲

## 1 转录组学概述

- 组学概述
- 转录组学
- 研究方法

## 2 RNA-Seq

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- **数据分析**
- 应用实例

## 3 顺反组

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- ChIP-Seq

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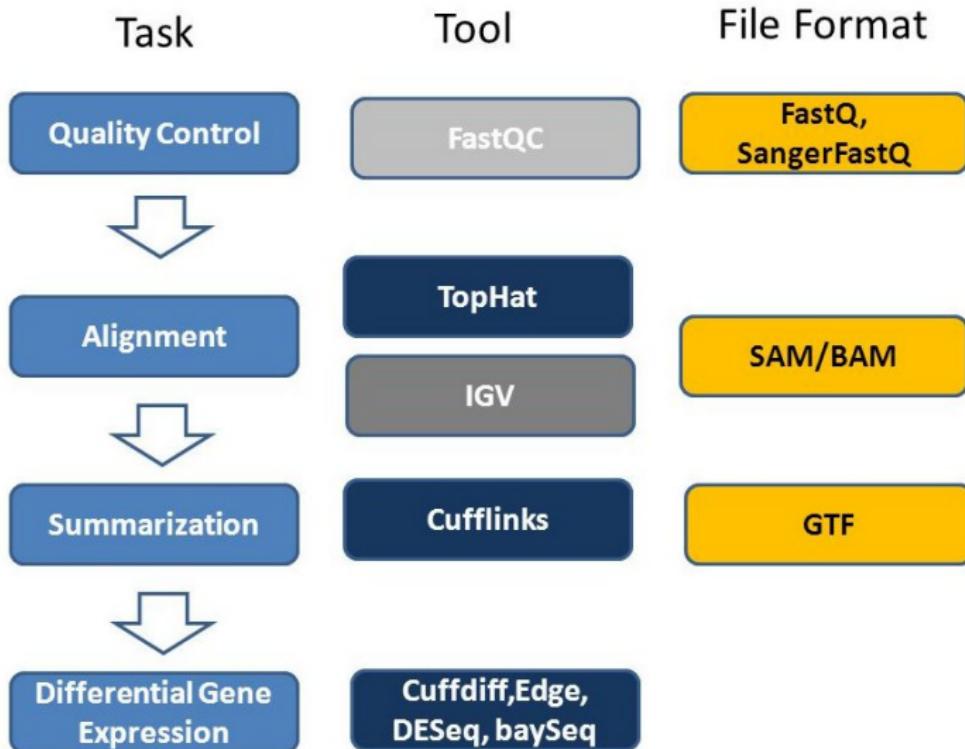
- 概述
- Methyl-Seq

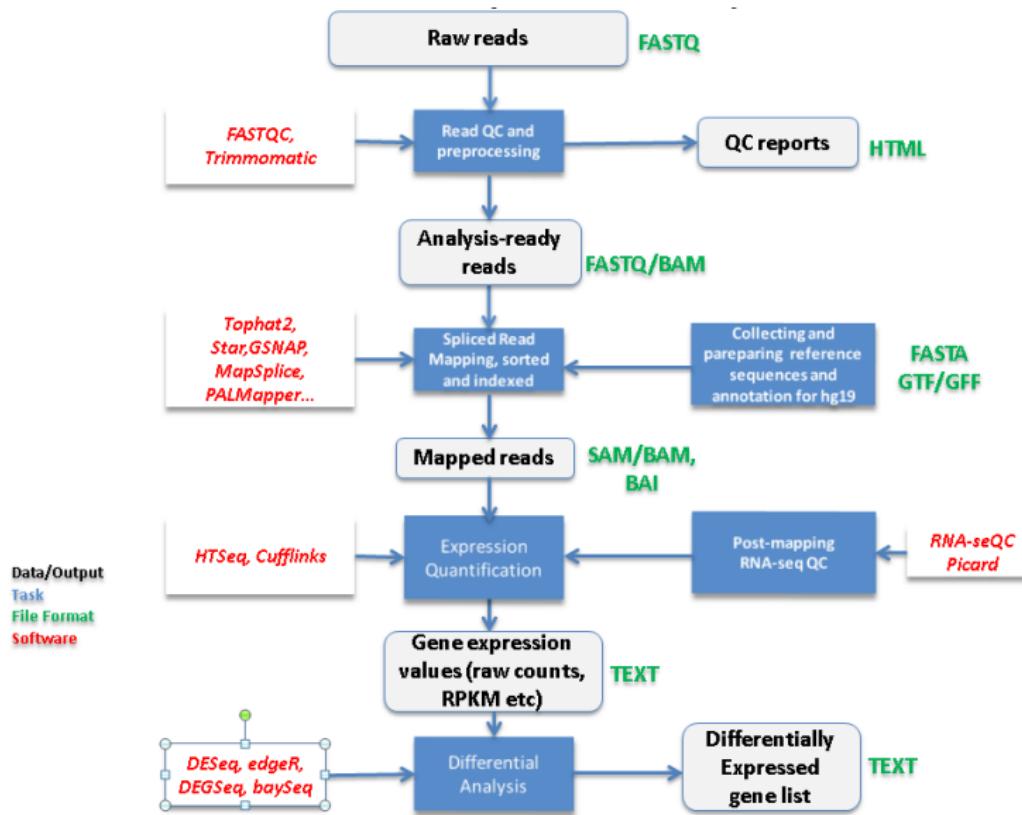
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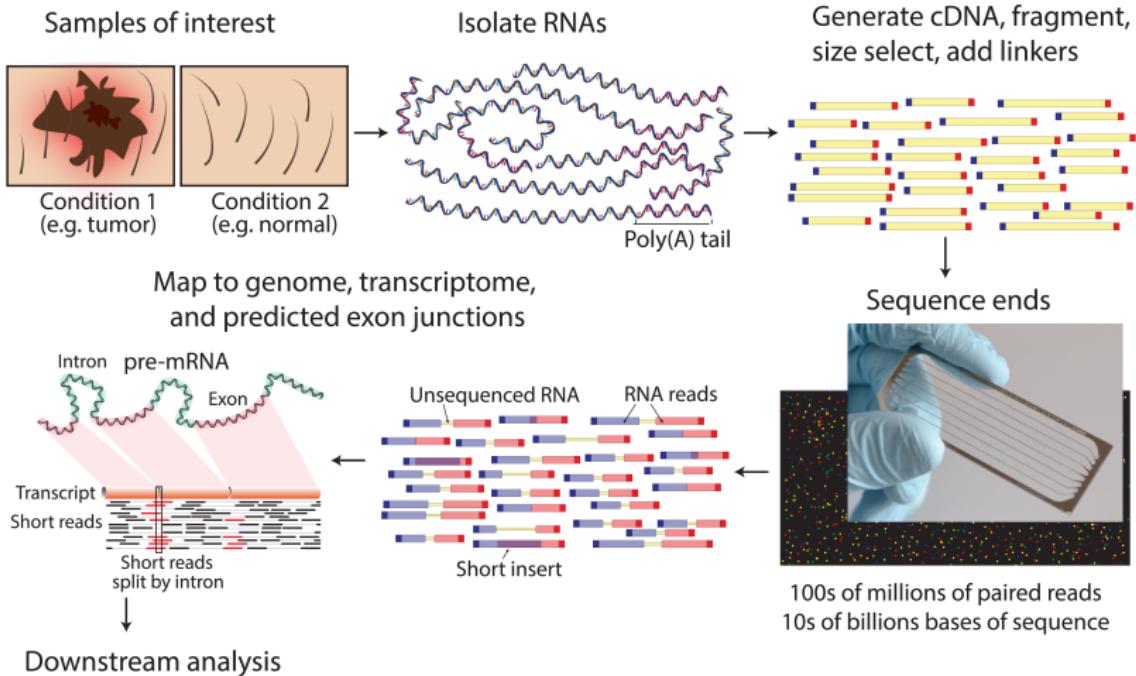


## RNASeq Tasks, Tools and File Formats

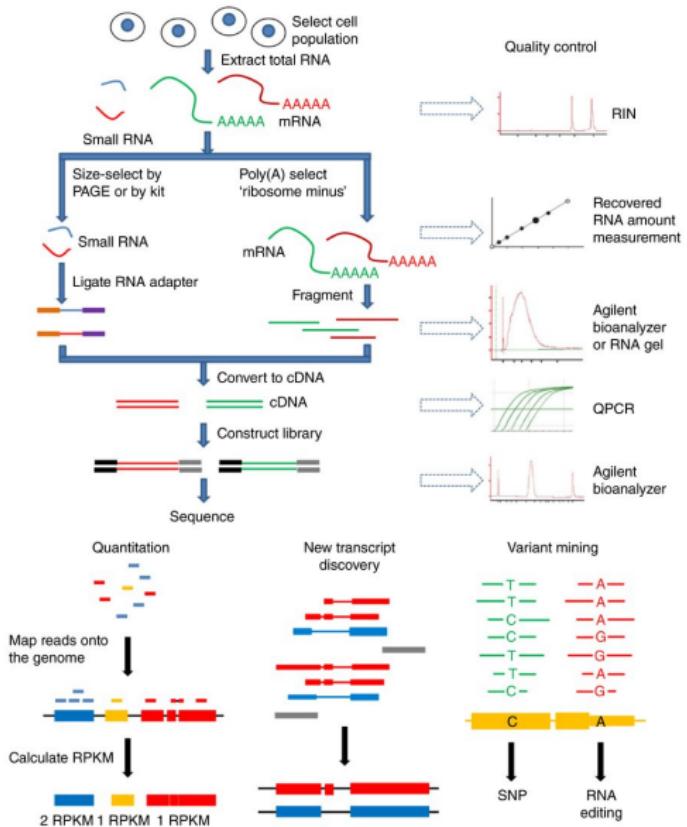


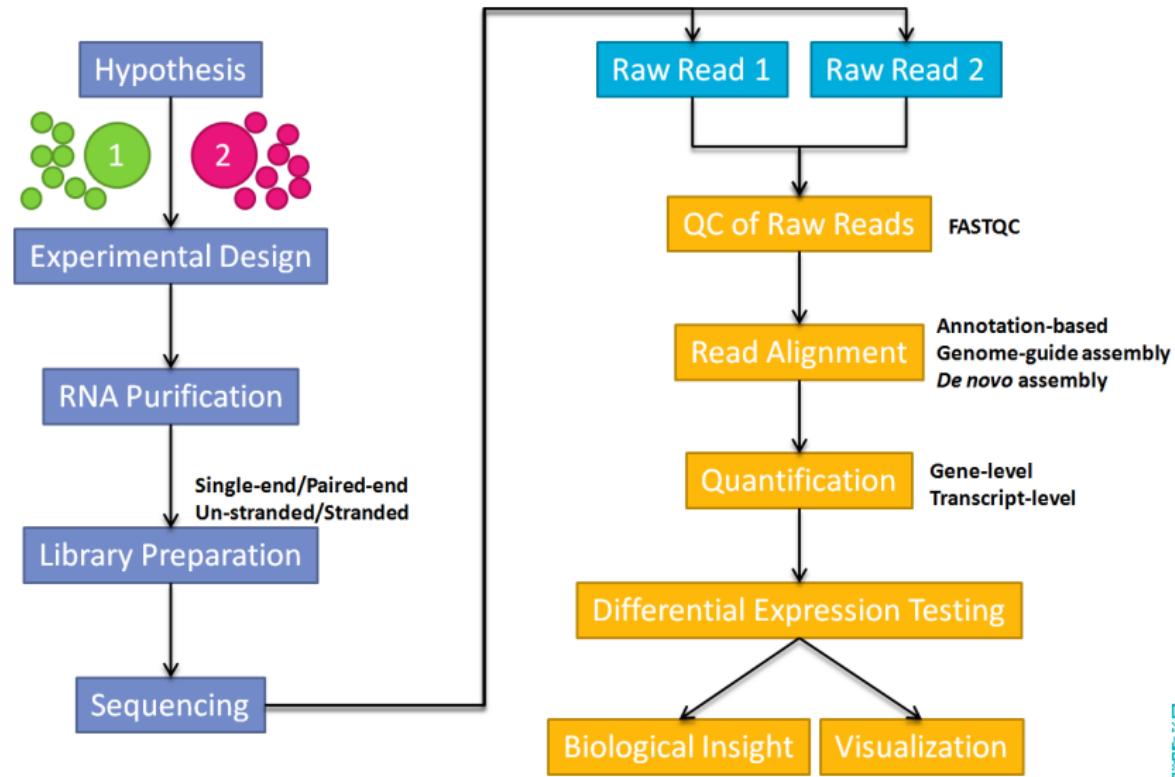


# 转录组学 | RNA-Seq | 分析 | 流程

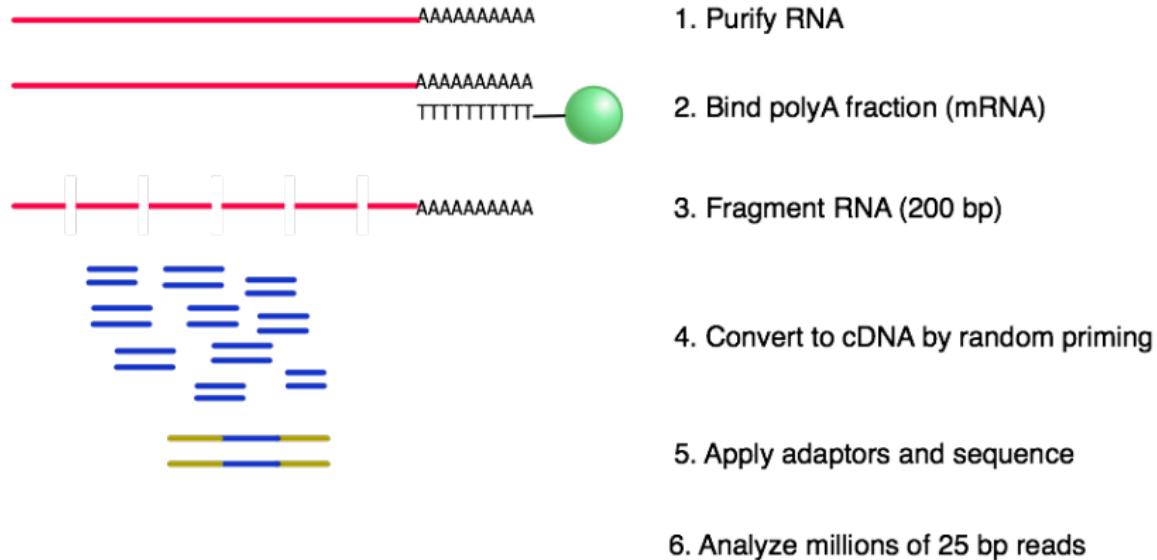


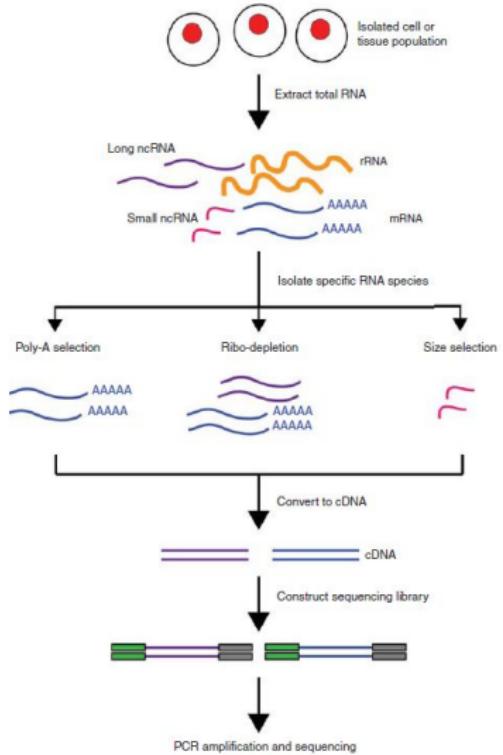
# 转录组学 | RNA-Seq | 分析 | 流程





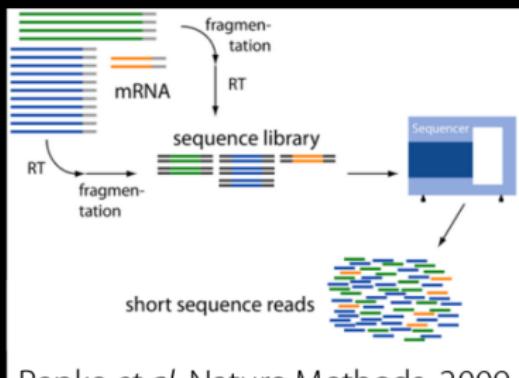
## Steps in Preparing an RNA-Seq Library





# RNA-Seq

- Deplete rRNA
- or select for polyadenylated RNA
- Fragmentation
- Reverse transcribe to cDNA
- Attach adaptor sequences
- Size selection
- Amplify by PCR
- High-throughput sequencing (eg Illumina)



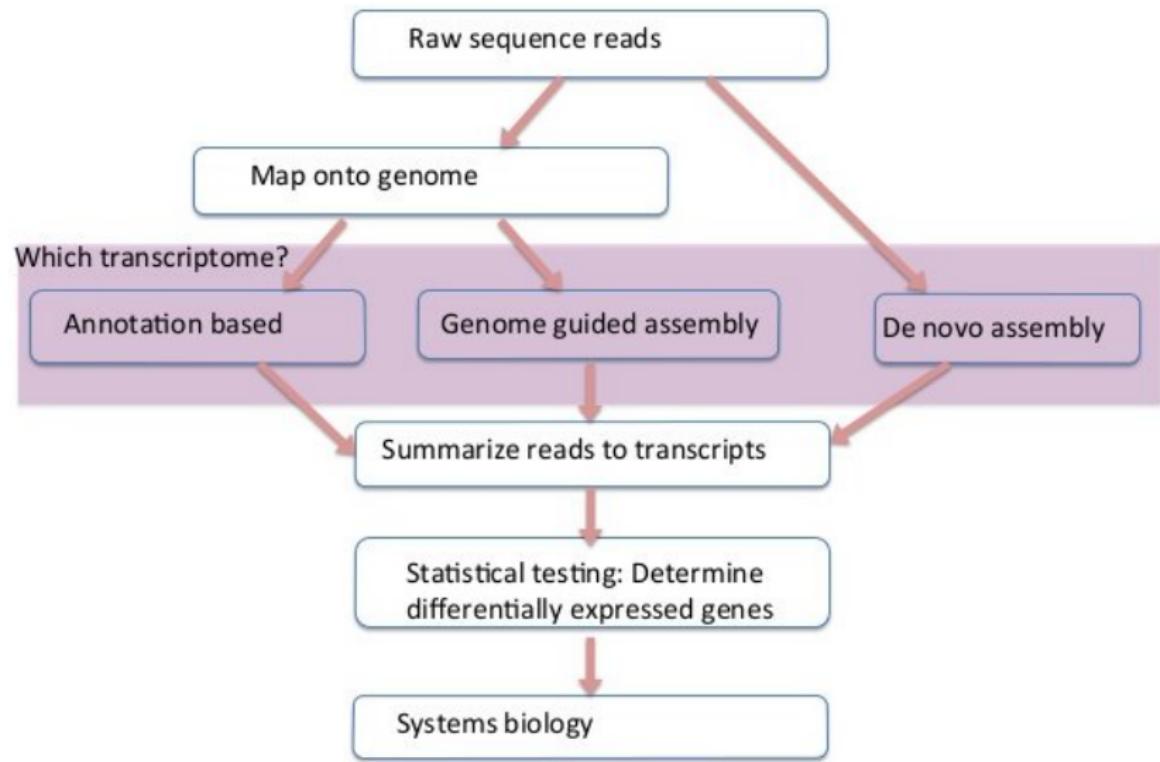
Pepke *et al*, Nature Methods, 2009

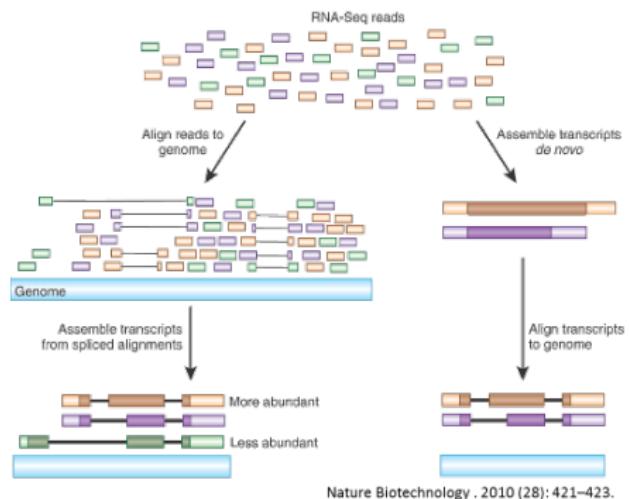


# RNA-Seq output

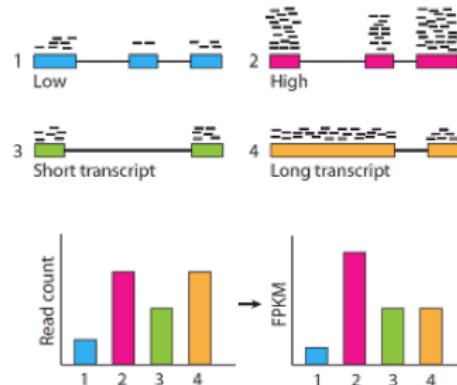
- Several million “reads” per sample
- Reads are RNA sequence starting from random locations within the original mRNA
- May read through into adaptor sequence
- Current typical length ~150 bases  
(really just needs to be long enough to locate in genome)





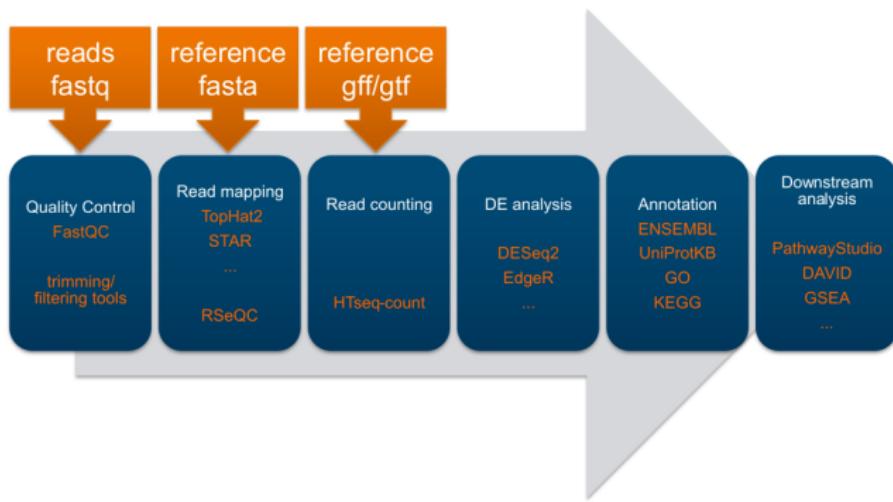
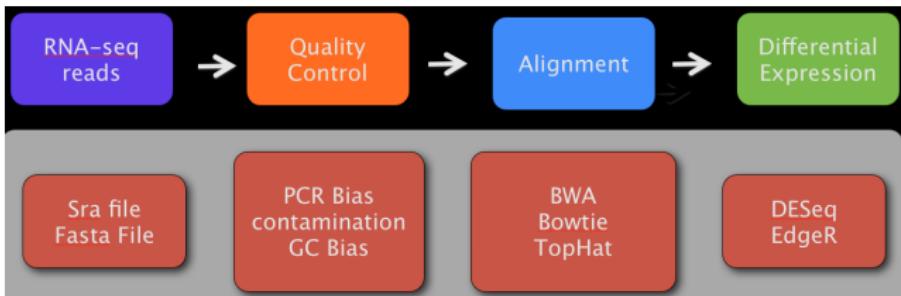


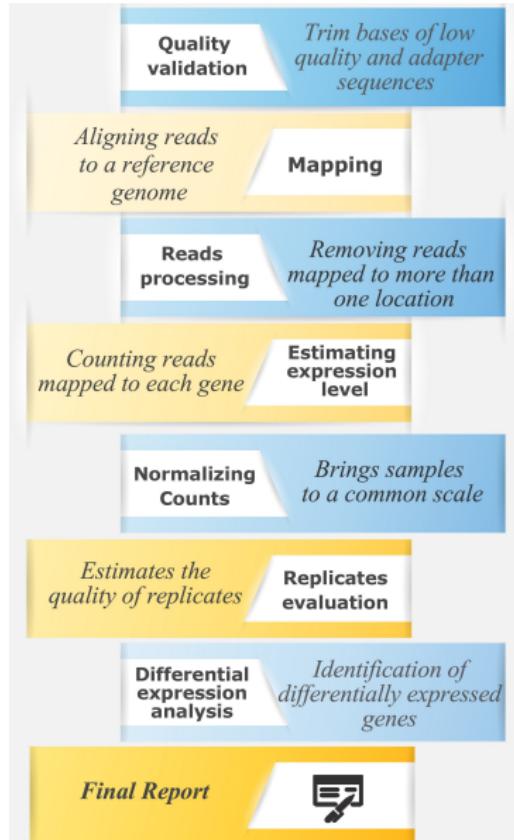
Nature Biotechnology . 2010 (28): 421–423.

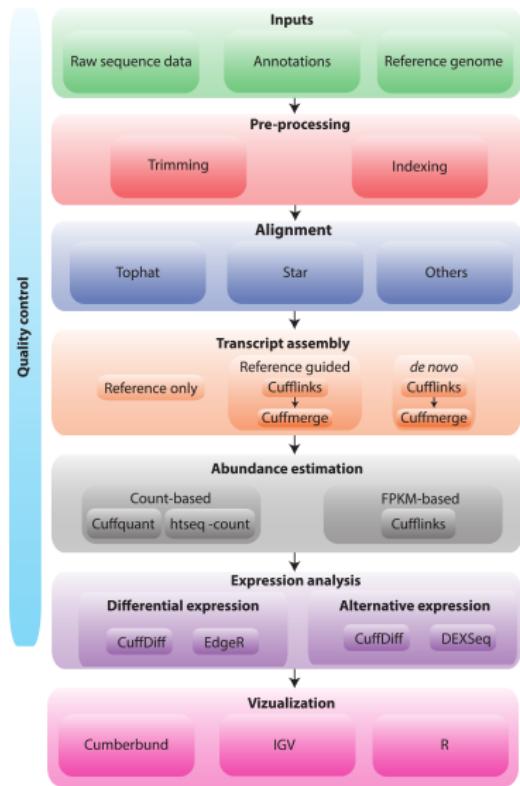


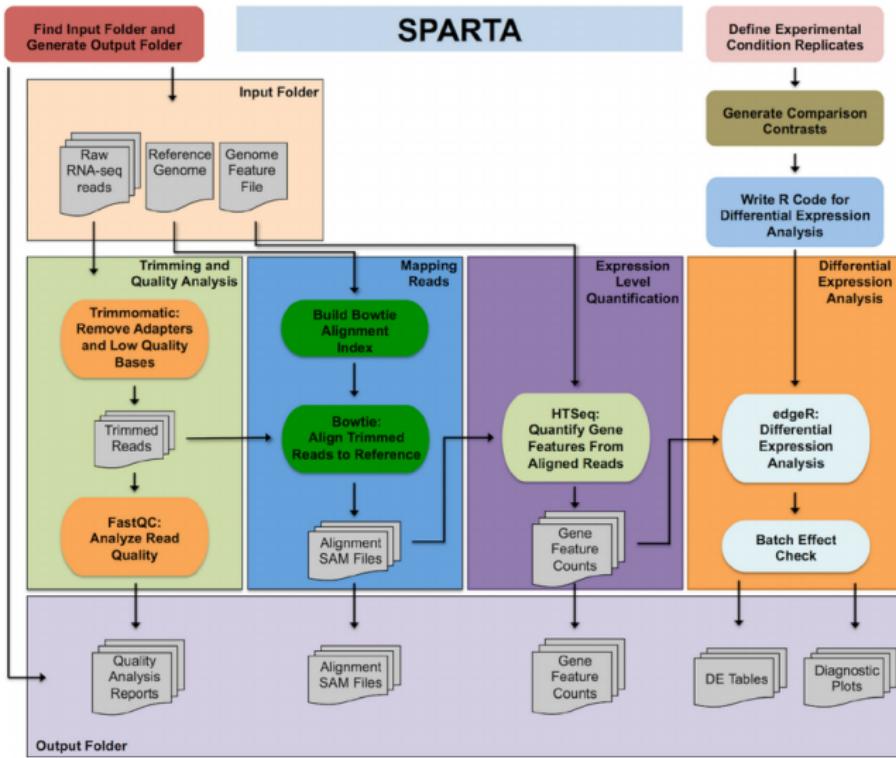
Nature Methods. 2011 (8): 469–477.



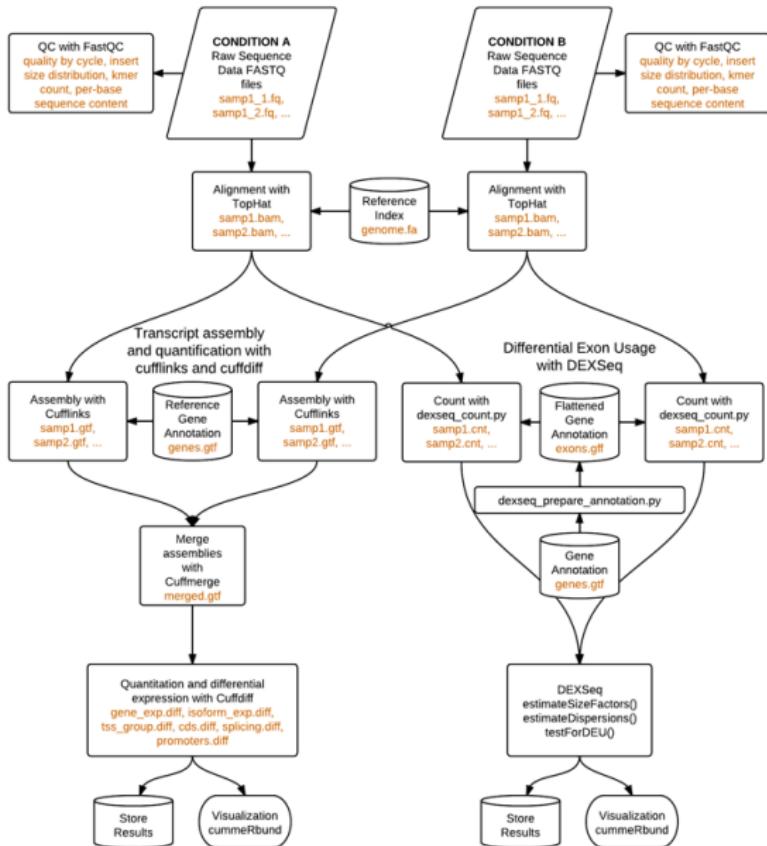








# 转录组学 | RNA-Seq | 分析 | 流程 | 生信

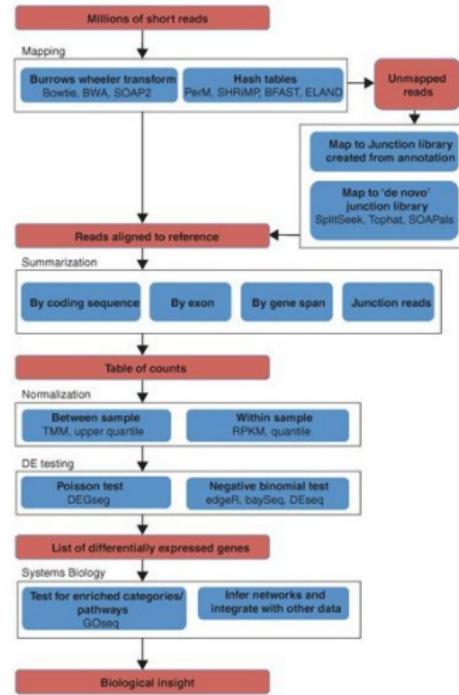


# RNA-seq workflows

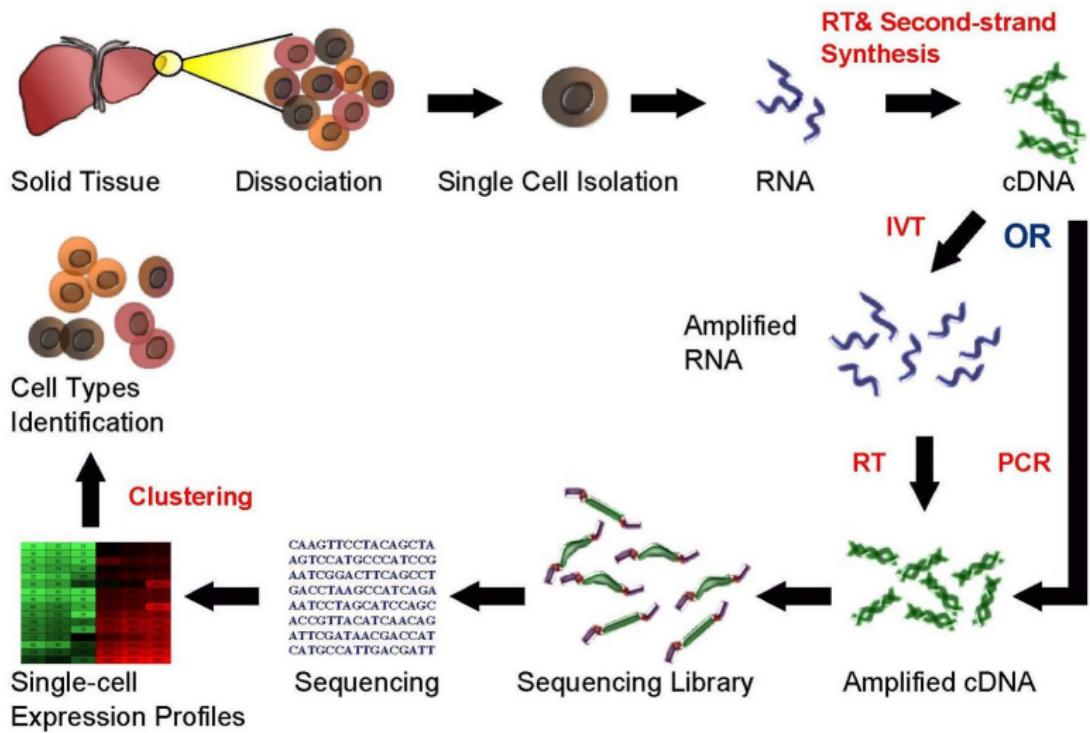
- Sequencing: obtain raw data (fastq format)
- Quality control (optional): FASTX
- Workflow 1: tophat2 (align) -> cufflinks (transcript assembly) -> cuffdiff (DEGs), cuffmerge (merge assemblies)

Workflow 2: bowtie2 (align) -> HTSeq-count (count by gene) -> edgeR or DESeq (DEGs)

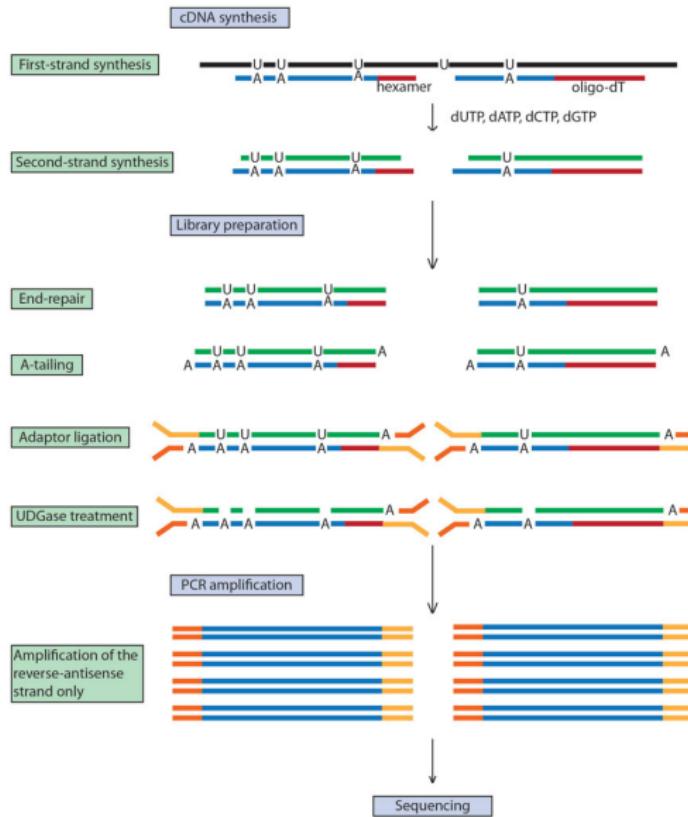
- Fusion detection (optional): “chimerascan” or “defuse”

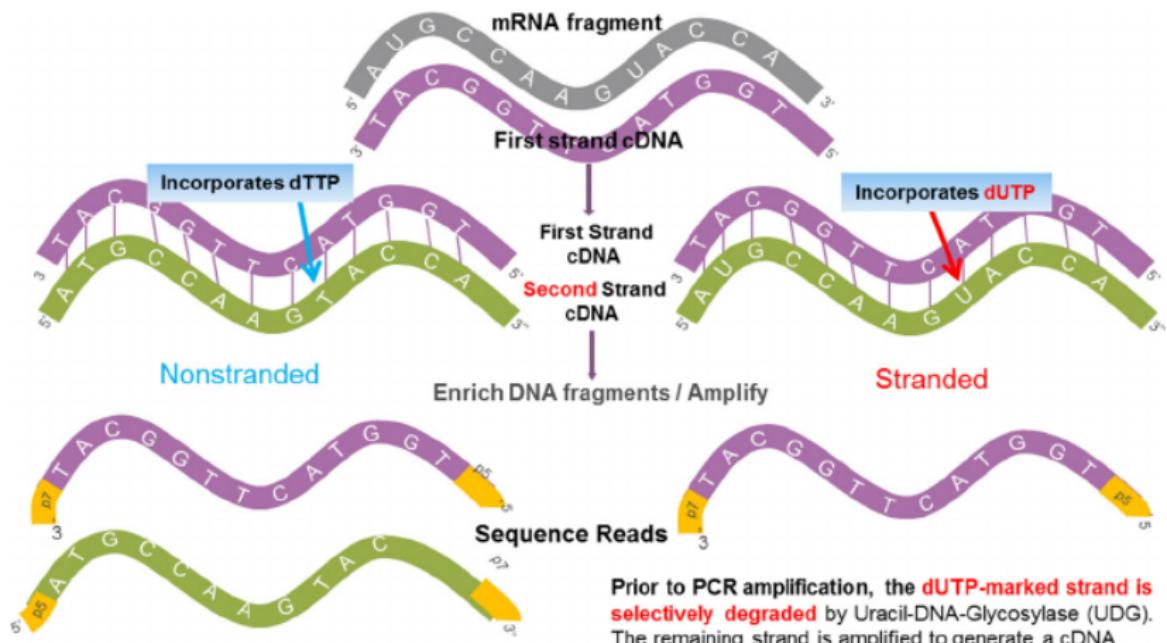


# Single Cell RNA Sequencing Workflow



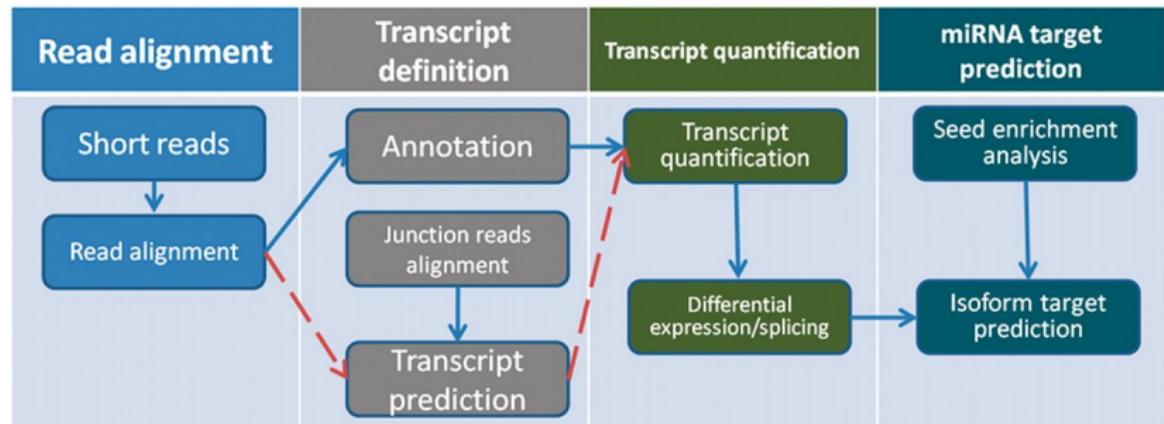
# 转录组学 | RNA-Seq | 分析 | 流程 | 补遗 | Stranded

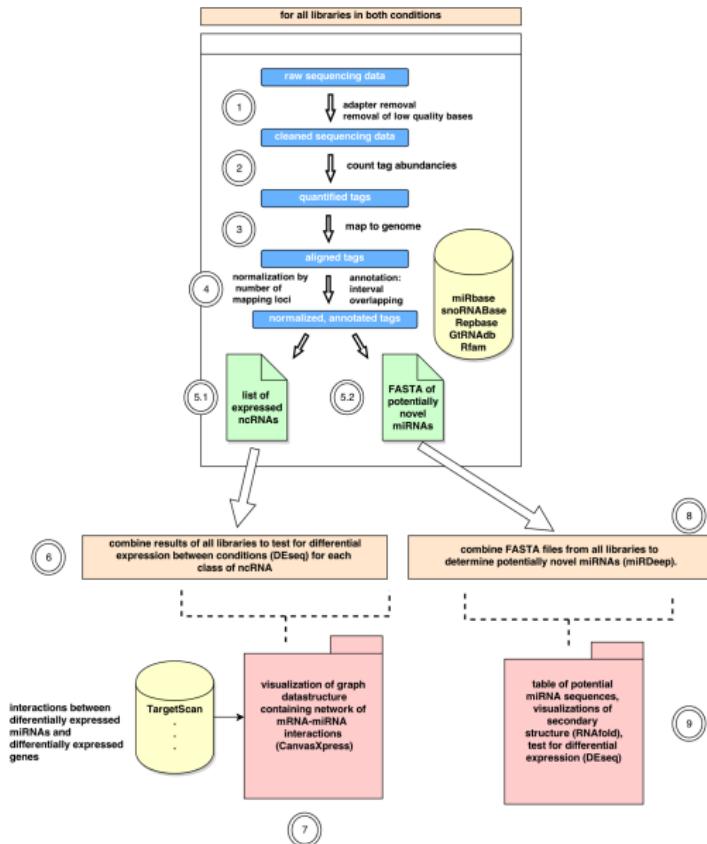


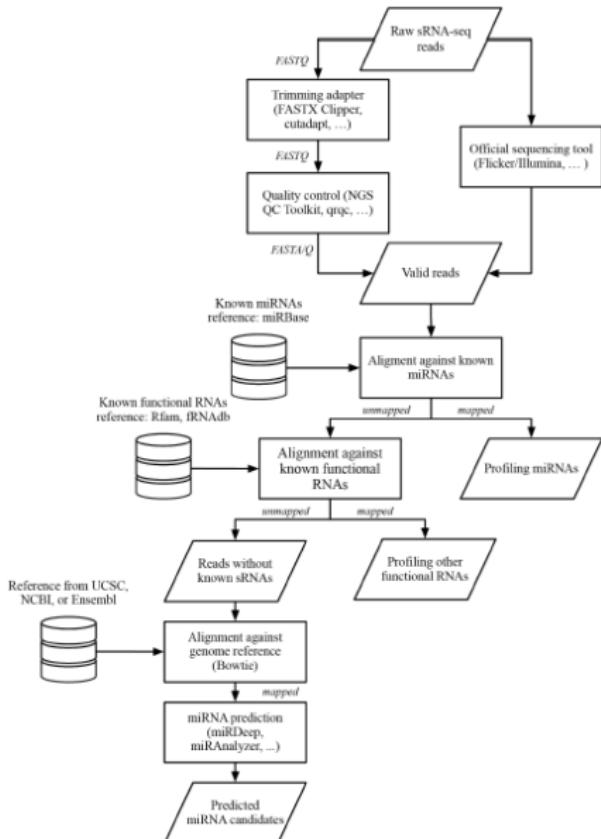


Prior to PCR amplification, the dUTP-marked strand is selectively degraded by Uracil-DNA-Glycosylase (UDG). The remaining strand is amplified to generate a cDNA library suitable for sequencing.









## Read counting options

Count per gene

**analysis with DESeq2, edgeR**



Count per transcript

**analysis with CummeRbund, DESeq2, edgeR**

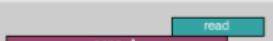
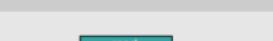
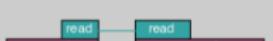
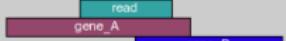
Count per exon

**analysis with DEXSeq**



## Tools: HTSeq-count

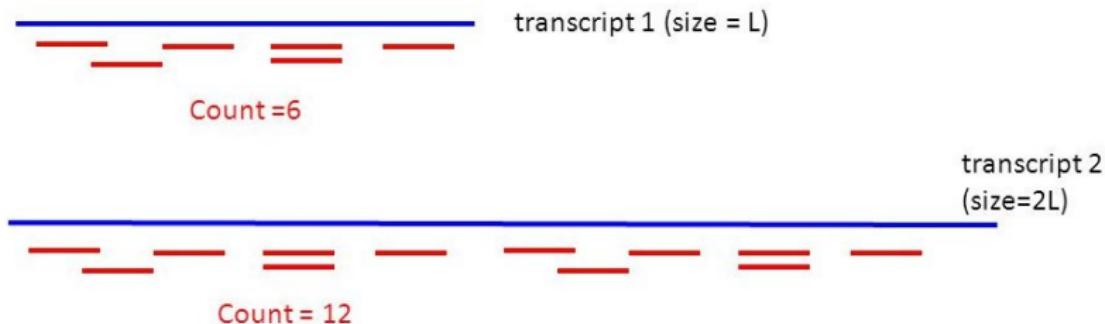
<http://www-huber.embl.de/users/anders/HTSeq/doc/count.html>

	union	intersection _strict	intersection _nonempty
 A single read overlaps with gene_A.	gene_A	gene_A	gene_A
 A single read spans gene_A.	gene_A	no_feature	gene_A
 A single read partially overlaps gene_A.	gene_A	no_feature	gene_A
 Two reads overlap with gene_A and gene_B respectively.	gene_A	gene_A	gene_A
 A single read spans both gene_A and gene_B.	gene_A	gene_A	gene_A
 A single read spans both gene_A and gene_B, but is ambiguous.	ambiguous	gene_A	gene_A
 A single read overlaps both gene_A and gene_B, but is ambiguous.	ambiguous	ambiguous	ambiguous



## Normalization for gene length and library size: RPKM / FPKM

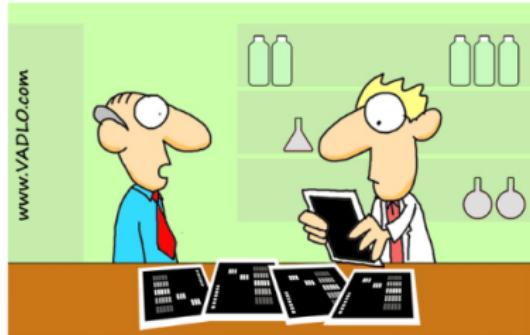
One sample, two transcripts



You can't conclude that gene 2 has a higher expression than gene 1!



## Normalization



"Data don't make any sense,  
we will have to resort to statistics."

Some samples are sequenced at higher depth than others

Normalization using the total counts:

total counts in sample  $j$  / total counts in a reference sample

But... longer genes/transcripts will generate more reads

**One proposed solution:**

**use RPKM = reads per kilobase per million mapped reads**



## Normalization: the problem

Number of reads (coverage) will not be exactly the same for each sample

**Problem:** Need to scale RNA counts per gene to total sample coverage

- **Solution** – divide counts per million reads

**Problem:** Longer genes have more reads, gives better chance to detect DE

- **Solution** – divide counts by gene length

Result = **RPKM** (Reads Per KB per Million)



## Normalization: classic (used by Cufflinks)

RPKM: Reads per kilobases per million mapped reads

**1kbp transcript with 2000 alignments in a sample of 10 million reads  
(out of which 8 millions are mapped)**

$$\text{RPKM} = 2000 / (1 * 8) = 250$$

by extension:

FPKM: Fragment per kilobases per million mapped reads

**a fragment is a pair of reads (Paired-end)**



## Other normalization methods

Sequencing depth, gene length, and count distribution are the main biases that must be accounted for in the normalization and/or differential expression calculations.

**Biological Replicates** are essential to increase the robustness of statistics

**FPKM** (Trapnell et al., 2010) - Fragments per Kilobase of exon per Million mapped reads, analogous to RPKM.

**Upper-quartile** (Bullard et al., 2010) - Counts are divided by upper-quartile of counts for transcripts with at least one read.

**TMM (EdgeR)** (Robinson and Oshlack, 2010) - Trimmed mean of M values.

**RLE (DESeq)** (Anders & Huber, 2010) – Relative Log Expression (Median of ratios)

**Quantiles**, as in microarray normalization (Irizarry et al., 2003).

**Many methods which is the best?**



**Table 3:** Summary of comparison results for the seven normalization methods under consideration

Method	Distribution	Intra-Variance	Housekeeping	Clustering	False-positive rate
TC	-	+	+	-	-
UQ	++	++	+	++	-
Med	++	++	-	++	-
DESeq	++	++	++	++	++
TMM	++	++	++	++	++
Q	++	-	+	++	-
RPKM	-	+	+	-	-

A '-' indicates that the method provided unsatisfactory results for the given criterion, while a '+' and '++' indicate satisfactory and very satisfactory results for the given criterion.

Both methods are found in Bioconductor packages (DESeq2 and EdgeR)



## Normalization: different goals

- **R/FPKM:** (Mortazavi et al. 2008)
  - **Correct for:** differences in sequencing depth and transcript length
  - **Aiming to:** compare a gene across samples and diff genes within sample
- **TMM:** (Robinson and Oshlack 2010)
  - **Correct for:** differences in transcript pool composition; extreme outliers
  - **Aiming to:** provide better across-sample comparability
- **TPM:** (Li et al 2010, Wagner et al 2012)
  - **Correct for:** transcript length distribution in RNA pool
  - **Aiming to:** provide better across-sample comparability
- **Limma voom (logCPM):** (Law et al 2013)
  - **Aiming to:** stabilize variance; remove dependence of variance on the mean



## Differential Expression

- Should we do differential expression on RPKM/FPKM or TPM?

Gene A (1kb) —————

Gene B (8kb) ——————



- Cufflinks: RPKM/FPKM
- LIMMA-VOOM and DESeq: TPM
- Power to detect DE is proportional to length
- Continued development and updates



# RPKM / FPKM / TPM

- **RPKM** (Reads per kilobase of transcript per million reads of library)
  - Corrects for total library coverage
  - Corrects for gene length
  - Comparable between different genes within the same dataset
- **FPKM** (Fragments per kilobase of transcript per million reads of library)
  - Only relevant for paired end libraries
  - Pairs are not independent observations
  - RPKM/2
- **TPM** (transcripts per million)
  - Normalises to transcript copies instead of reads
  - Corrects for cases where the average transcript length differs between samples



## RPKM:

### Reads Per Kilobase and Million mapped reads

Unit of measurement

$$RPKM = \frac{\# MappedReads * 1000bases * 10^6}{length\ of\ transcript * Total\ number\ of\ mapped\ reads}$$

- RPKM reflects the molar concentration of a transcript in the starting sample by normalizing for
  - RNA length
  - Total read number in the measurement
- This facilitates transparent comparison of transcript levels within and between samples

$$RPKM = \frac{\frac{number\ of\ reads\ of\ the\ region}{total\ reads}}{1,000,000} \times \frac{region\ length}{1,000}$$



## RPKM Example

Gene A 600 bases

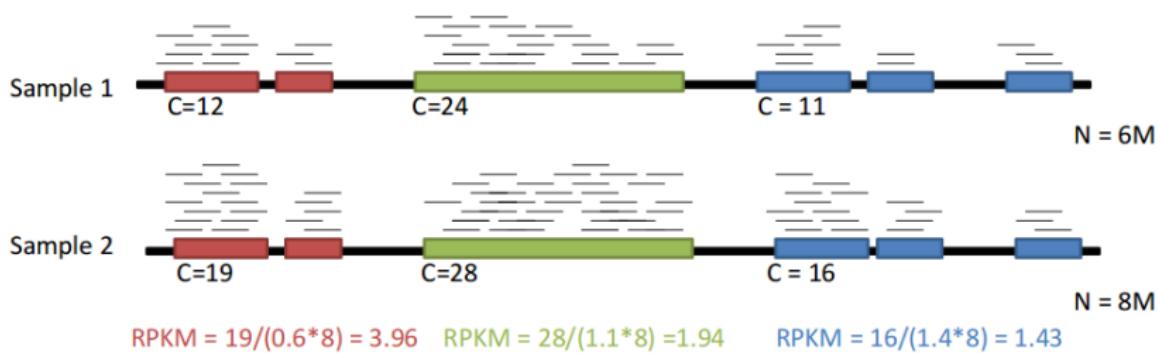
Gene B 1100 bases

Gene C 1400 bases

$$\text{RPKM} = 12/(0.6*6) = 3.33$$

$$\text{RPKM} = 24/(1.1*6) = 3.64$$

$$\text{RPKM} = 11/(1.4*6) = 1.31$$



## Reporting quantitative expression: FPKM/RPKM

- In NGS RNA-seq experiments, quantitative gene expression data is normalized for total gene/transcript length and the number of sequencing reads, and reported as
  - RPKM: Reads Per Kilobase of exon per Million mapped reads. Used for reporting data based on single-end reads
  - FPKM: Fragments Per Kilobase of exon per Million fragments. Used for reporting data based on paired-end fragments



## FPKM: Fragments per K per M

What's the difference between FPKM and RPKM?

- Paired-end RNA-Seq experiments produce two reads per fragment, but that doesn't necessarily mean that both reads will be mappable. For example, the second read is of poor quality.
- If we were to count reads rather than fragments, we might double-count some fragments but not others, leading to a skewed expression value.
- Thus, FPKM is calculated by counting fragments, not reads.

$$\text{RPKM} = \frac{\text{total exon reads}}{\text{mapped reads (millions)} * \text{exon length (KB)}}$$

$$\text{FPKM} = \frac{\text{total fragments}}{\text{mapped reads (millions)} * \text{exon length (KB)}}$$



## TPM

当我们进行 RNA-Seq 时，会使用 RPKM 或者 FPKM 来代表某个 gene 或是 isoform 的表达量多寡。可是当我们想要比较不同次实验内的某个基因，其表达量相比于“整体基因表达”而言，是否维持在“固定比例”时，便无法使用这样的计算方式。因此 Wagner *et. al.* 在 2012 年的时候提出 TPM (Transcript Per Million) 的概念来弥补这个缺点。



## TPM – Transcripts Per Million

Theory Biosci.  
DOI 10.1007/s12064-012-0162-3

SHORT COMMUNICATION

**Measurement of mRNA abundance using RNA-seq data:  
RPKM measure is inconsistent among samples**

Günter P. Wagner · Koryn Kin · Vincent J. Lynch

A slightly modified RPKM measure that  
accounts for differences in gene length  
distribution in the transcript population

TPM

$$= \frac{\frac{\text{total exon reads}}{\text{exon length (KB)}}}{\left( \frac{\text{GeneA mapped reads (millions)}}{\text{exon length (KB)}} + \frac{\text{GeneB mapped reads (millions)}}{\text{exon length (KB)}} + \frac{\text{GeneC mapped reads (millions)}}{\text{exon length (KB)}} + \dots \right)}$$

$$\text{TPM}_i = \left( \frac{\text{FPKM}_i}{\sum_j \text{FPKM}_j} \right) \cdot 10^6$$



假設某個生物具有4個基因，分別為A, B, C, D。然後我們做了3次的RNA-Seq實驗，將獲得的reads與每個基因進行比對，其比對的數目如下表所示。

	Replicate 1	Replicate 2	Replicate 3
Gene A (2kb)	10,000,000	12,000,000	30,000,000
Gene B (4kb)	20,000,000	25,000,000	60,000,000
Gene C (1kb)	5,000,000	8,000,000	15,000,000
Gene D (10kb)	0	0	1,000,000
Sum	35,000,000	45,000,000	106,000,000



# 转录组学 | RNA-Seq | 分析 | 术语 | TPM

根據RPKM的公式,

$$\text{RPKM} = \frac{\text{total exon reads}}{\text{mapped reads (millions)} * \text{exon length (KB)}}$$

我們來計算實驗1的Gene A的RPKM,

$$\text{RPKM} = \frac{10,000,000}{(10 + 20 + 5) * 2} = 142857$$

然後再將表格內所有的數值都轉換成RPKM之後，我們得到下方表格

	Replicate 1 (RPKM)	Replicate 2 (RPKM)	Replicate 3 (RPKM)
Gene A (2kb)	142857	133333	141509
Gene B (4kb)	142857	138889	141509
Gene C (1kb)	142857	177778	141509
Gene D (10kb)	0	0	943
Sum	428,571	450,000	425,470



我們再根據TPM的公式

TPM

$$= \frac{\frac{\text{total exon reads}}{\text{exon length (KB)}}}{\left( \frac{\text{GeneA mapped reads (millions)}}{\text{exon length (KB)}} + \frac{\text{GeneB mapped reads (millions)}}{\text{exon length (KB)}} + \frac{\text{GeneC mapped reads (millions)}}{\text{exon length (KB)}} + \dots \right)}$$

來計算實驗1的Gene A的TPM。

$$\text{TPM} = \frac{\frac{10,000,000}{2}}{\left( \frac{10}{2} + \frac{20}{4} + \frac{5}{1} + \frac{0}{10} \right)} = 333333$$

然後再將表格內所有的數值都轉換成TPM之後，我們得到下方表格

	Replicate 1 (TPM)	Replicate 2 (TPM)	Replicate 3 (TPM)
Gene A (2kb)	333333	296296	332594
Gene B (4kb)	333333	308642	332594
Gene C (1kb)	333333	395062	332594
Gene D (10kb)	0	0	2217
Sum	1,000,000	1,000,000	1,000,000



## 比较

比较 RPKM 和 TPM 的表格之后，可以发现 RPKM 在“Sum”这一行，三个实验中的数值均不同，因此我们很难直接利用 RPKM 数值去比较每个基因“相对于整体”的表达量多寡。然而 TMP 则一律为 1,000,000，也就是 1 million，意即 TPM 的定义（Transcript Per Million）。因此这些数值便可以直接比较，了解基因之间的相对表达量。



## Metrics

- RPKM (Reads Per Kilobase Million)
- FPKM (Fragments Per Kilobase Million)
- TPM (Transcripts Per Kilobase Million)

These three metrics attempt to normalize for sequencing depth and gene length.



## RPKM

Here's how you do it for RPKM:

- ① Count up the total reads in a sample and divide that number by 1,000,000 – this is our “per million” scaling factor.
- ② Divide the read counts by the “per million” scaling factor. This normalizes for sequencing depth, giving you reads per million (RPM)
- ③ Divide the RPM values by the length of the gene, in kilobases. This gives you RPKM.



## FPKM

FPKM is very similar to RPKM. RPKM was made for single-end RNA-seq, where every read corresponded to a single fragment that was sequenced. FPKM was made for paired-end RNA-seq. With paired-end RNA-seq, two reads can correspond to a single fragment, or, if one read in the pair did not map, one read can correspond to a single fragment. The only difference between RPKM and FPKM is that FPKM takes into account that two reads can map to one fragment (and so it doesn't count this fragment twice).



## TPM

TPM is very similar to RPKM and FPKM. The only difference is the order of operations. Here's how you calculate TPM:

- ➊ Divide the read counts by the length of each gene in kilobases. This gives you reads per kilobase (RPK).
- ➋ Count up all the RPK values in a sample and divide this number by 1,000,000. This is your “per million” scaling factor.
- ➌ Divide the RPK values by the “per million” scaling factor. This gives you TPM.

So you see, when calculating TPM, the only difference is that you normalize for gene length first, and then normalize for sequencing depth second. However, the effects of this difference are quite profound.

## Compare

When you use TPM, the sum of all TPMs in each sample are the same. This makes it easier to compare the proportion of reads that mapped to a gene in each sample. In contrast, with RPKM and FPKM, the sum of the normalized reads in each sample may be different, and this makes it harder to compare samples directly.

Here's an example. If the TPM for gene A in Sample 1 is 3.33 and the TPM in sample B is 3.33, then I know that the exact same proportion of total reads mapped to gene A in both samples. This is because the sum of the TPMs in both samples always add up to the same number (so the denominator required to calculate the proportions is the same, regardless of what sample you are looking at.)

With RPKM or FPKM, the sum of normalized reads in each sample can be different. Thus, if the RPKM for gene A in Sample 1 is 3.33 and the RPKM in Sample 2 is 3.33, I would not know if the same proportion of reads in Sample 1 mapped to gene A as in Sample 2. This is because the denominator required to calculate the proportion could be different for the two samples.

# 转录组学 | RNA-Seq | 分析 | 工具 | 概览

Workflow	Category	Package	Reference
Preprocessing of raw data	Raw data QC	FastQC HTQC	[8] [9]
	Read trimming	FASTX-Toolkit FLEXBAR	[10] [11]
Read alignment	Unspliced aligner	MAQ BWA Bowtie	[13] [14] [15]
	Spliced aligner	TopHat MapSplice STAR GSNAP	[16] [17] [18] [19]
RNA-seq specific quality control		RNA-SeQC RSQC	[20] [21]
		Qualimap 2	[22]
Transcriptome reconstruction	Reference-guided	Cufflinks Scripture StringTie	[24] [25] [26]
	Reference-independent	Trinity Oases	[27] [28]
		transAbYSS	[29]
Expression quantification	Gene-level quantification	ALEXA-seq Enhanced read analysis of gene expression (ERANGE)	[32] [33]
		Normalization by expected uniquely mappable area (NEUMA)	[34]
	Isoform-level quantification	Cufflinks StringTie RSEM	[24] [26] [35]
		Sailfish	[36]
Differential expression	Gene-level	NOIseq edgeR DESeq	[23] [39] [40]
	Isoform-level	SAMseq Cuffdiff EBSeq Ballgown	[41] [24] [42] [45]



## Quality control

- FastQC: FastQC is a quality control tool for high-throughput sequence data (Babraham Institute) and is developed in Java. Import of data is possible from FastQ files, BAM or SAM format. This tool provides an overview to inform about problematic areas, summary graphs and tables to rapid assessment of data. Results are presented in HTML permanent reports. FastQC can be run as a stand-alone application or it can be integrated into a larger pipeline solution.
- NGSQC: cross-platform quality analysis pipeline for deep sequencing data.



## Quality control

- RNA-SeQC: RNA-SeQC is a tool with application in experiment design, process optimization and quality control before computational analysis. Essentially, provides three types of quality control: read counts (such as duplicate reads, mapped reads and mapped unique reads, rRNA reads, transcript-annotated reads, strand specificity), coverage (like mean coverage, mean coefficient of variation, 5'/3' coverage, gaps in coverage, GC bias) and expression correlation (the tool provides RPKM-based estimation of expression levels). RNA-SeQC is implemented in Java and is not required installation, however can be run using the GenePattern web interface. The input could be one or more BAM files. HTML reports are generated as output.
- RSeQC: RSeQC analyzes diverse aspects of RNA-Seq experiments: sequence quality, sequencing depth, strand specificity, GC bias, read distribution over the genome structure and coverage uniformity. The input can be SAM, BAM, FASTA, BED files or Chromosome size file (two-column, plain text file). Visualization can be performed by genome browsers like UCSC, IGB and IGV. However, R scripts can also be used to visualization.

## NGS Data Quality Control

- FASTQ format
- Examine quality in an RNA-Seq dataset
- Trim/filter as we see fit, hopefully without breaking anything.

**Quality Control is not sexy.**

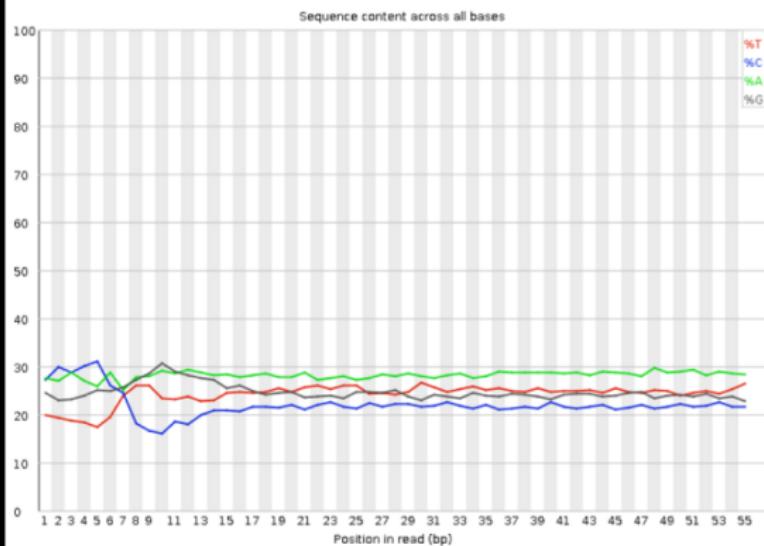
**It is vital.**



## NGS Data Quality: Sequence bias at front of reads?



Per base sequence content



From a sequence specific bias that is caused by use of random hexamers in library preparation.

Hansen, et al., "Biases in Illumina transcriptome sequencing caused by random hexamer priming" *Nucleic Acids Research*, Volume 38, Issue 12 (2010)



## Trimming and adapters removal

- FASTX: FASTX Toolkit is a set of command line tools to manipulate reads in files FASTA or FASTQ format. These commands make possible preprocess the files before mapping with tools like Bowtie. Some of the tasks allowed are: conversion from FASTQ to FASTA format, information about statistics of quality, removing sequencing adapters, filtering and cutting sequences based on quality or conversion DNA/RNA.
- PRINSEQ: PRINSEQ generates statistics of your sequence data for sequence length, GC content, quality scores, n-plicates, complexity, tag sequences, poly-A/T tails, odds ratios. Filter the data, reformat and trim sequences.
- cutadapt: Cutadapt finds and removes adapter sequences, primers, poly-A tails and other types of unwanted sequence from your high-throughput sequencing reads.

# Read Mapping

- Alignment algorithm must be
  - fast
  - able to handle SNPs, indels, and sequencing errors
  - allow for introns for reference genome alignment
- Input
  - fastq read library
  - reference genome index
  - insert size mean and stddev(for paired-end libraries)
- Output
  - SAM (text) / BAM (binary) alignment files



### *De novo* Splice Aligners that also use annotation optionally

- TopHat: TopHat is prepared to find de novo junctions. TopHat aligns reads in two steps. Firstly, unspliced reads are aligned with Bowtie. After, the aligned reads are assembled with Maq resulting islands of sequences. Secondly, the splice junctions are determined based on the initially unmapped reads and the possible canonical donor and acceptor sites within the island sequences.



## Genome-Guided assemblers

- Cufflinks: Cufflinks assembles transcripts, estimates their abundances, and tests for differential expression and regulation in RNA-Seq samples. It accepts aligned RNA-Seq reads and assembles the alignments into a parsimonious set of transcripts. Cufflinks then estimates the relative abundances of these transcripts based on how many reads support each one, taking into account biases in library preparation protocols.
- Scripture: Scripture is a method for transcriptome reconstruction that relies solely on RNA-Seq reads and an assembled genome to build a transcriptome *ab initio*. The statistical methods to estimate read coverage significance are also applicable to other sequencing data. Scripture also has modules for ChIP-Seq peak calling.

## Normalization, Quantitative analysis and Differential Expression

- Cufflinks/Cuffdiff: Cufflinks is appropriate to measure global *de novo* transcript isoform expression. It performs assembly of transcripts, estimation of abundances and determines differential expression (Cuffdiff) and regulation in RNA-Seq samples.
- DESeq: DESeq is a Bioconductor package to perform differential gene expression analysis based on negative binomial distribution.
- EdgeR: EdgeR is a R package for analysis of differential expression of data from DNA sequencing methods, like RNA-Seq, SAGE or ChIP-Seq data. edgeR employs statistical methods supported on negative binomial distribution as a model for count variability.
- DEGseq: DEGseq is an R package to identify differentially expressed genes from RNA-Seq data.
- baySeq: This package identifies differential expression in high-throughput ‘count’ data, such as that derived from next-generation sequencing machines, calculating estimated posterior likelihoods of differential expression (or more complex hypotheses) via empirical Bayesian methods.

## Analysis pipeline/Integrated solutions

- easyRNASeq: easyRNASeq calculates the coverage of high-throughput short-reads against a genome of reference and summarizes it per feature of interest (e.g. exon, gene, transcript). The data can be normalized as 'RPKM' or by the 'DESeq' or 'edgeR' package.
- Galaxy: Galaxy is a general purpose workbench platform for computational biology. There are several publicly accessible Galaxy servers that support RNA-Seq tools and workflows, including NBIC's Andromeda, the CBIIT-Giga server, the Galaxy Project's public server, the GeneNetwork Galaxy server, the University of Oslo's Genomic Hyperbrowser, URGI's server (which supports S-MART), and many others.
- GenePattern: GenePattern offers integrated solutions to RNA-Seq analysis.
- Taverna: Taverna is an open source and domain-independent Workflow Management System –a suite of tools used to design and execute scientific workflows and aid *in silico* experimentation.

## Visualization tools

- ngs.plot: Quick mining and visualization of next-generation sequencing data by integrating genomic databases. It allows to easily visualize NGS samples at functional genomic regions.
- GBrowse: GBrowse is a combination of database and interactive web pages for manipulating and displaying annotations on genomes.
- IGB: The Integrated Genome Browser (IGB, pronounced ig-bee) is an application intended for visualization and exploration of genomes and corresponding annotations from multiple data sources.
- IGV: The Integrative Genomics Viewer (IGV) is a high-performance visualization tool for interactive exploration of large, integrated genomic datasets.
- SeqMonk: SeqMonk is a program to enable the visualisation and analysis of mapped sequence data. It was written for use with mapped next generation sequence data but can in theory be used for any dataset which can be expressed as a series of genomic positions.
- Tablet: Tablet is a lightweight, high-performance graphical viewer for next generation sequence assemblies and alignments.

## RNA-Seq Databases

- ENCODE: Encyclopedia of DNA Elements
- RNA-Seq Atlas: A reference database for gene expression profiling in normal tissue by next-generation sequencing.
- SRA: The Sequence Read Archive (SRA) stores raw sequence data from “next-generation” sequencing technologies including 454, IonTorrent, Illumina, SOLiD, Helicos and Complete Genomics. In addition to raw sequence data, SRA now stores alignment information in the form of read placements on a reference sequence.



## Tuxedo

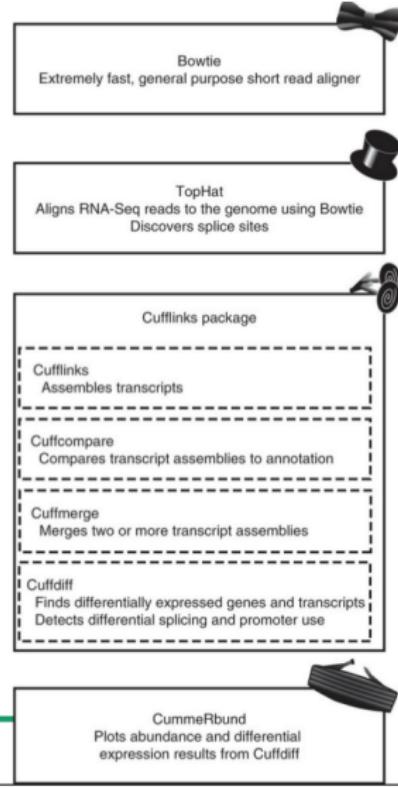
The RNA-seq pipeline “Tuxedo” consists of the **TopHat** spliced read mapper, that internally uses **Bowtie/Bowtie2** short read aligners, and several **Cufflinks** tools that allows one to assemble transcripts, estimate their abundances, and tests for differential expression and regulation in RNA-Seq samples.

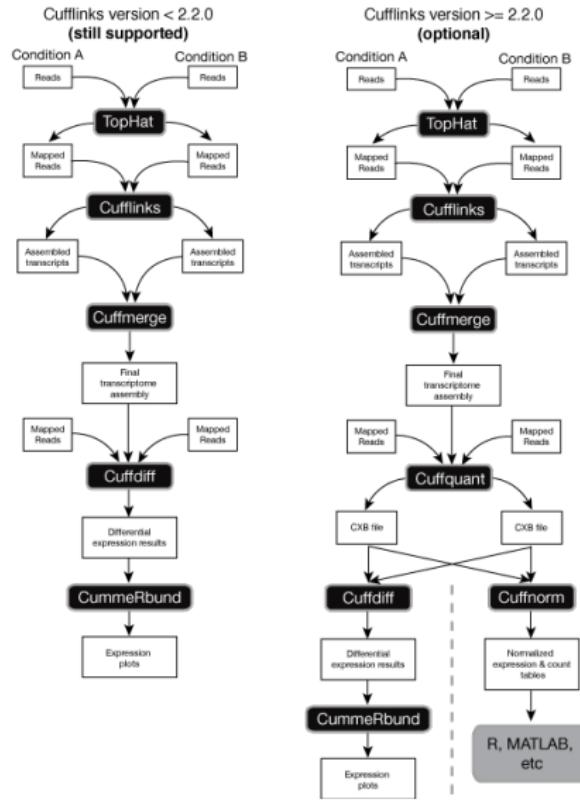
Tool	Tool description	
Bowtie	Ultrafast short read aligner	
Tophat	Aligns RNA-seq reads to the genome using Bowtie. Discovers splice sites	
Cufflinks package	Cufflinks	Assembles transcripts
	Cuffcompare	Compares transcript assemblies to annotation
	Cuffmerge	Merges two or more transcript assemblies
	Cuffdiff	Finds differentially expressed genes and transcripts. Detects differential splicing and promoter use



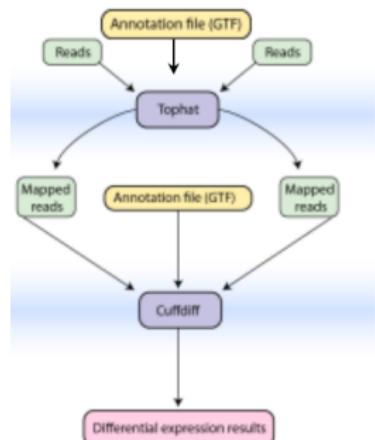
## The Tuxedo suite a complete solution (not the best anymore)

Bowtie  
TopHat  
Cufflinks  
**Cuffmerge**  
**Cuffdiff**  
CummRbund

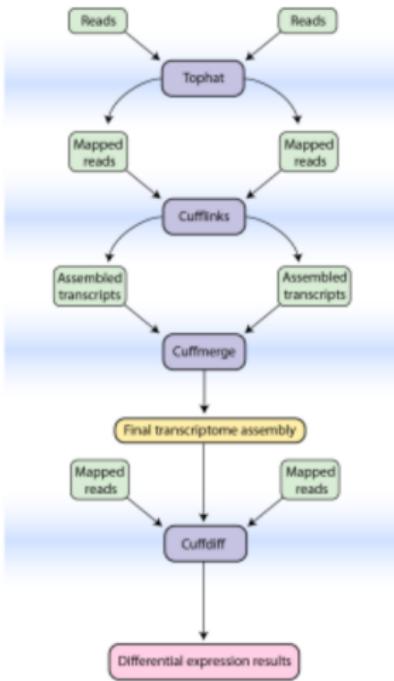




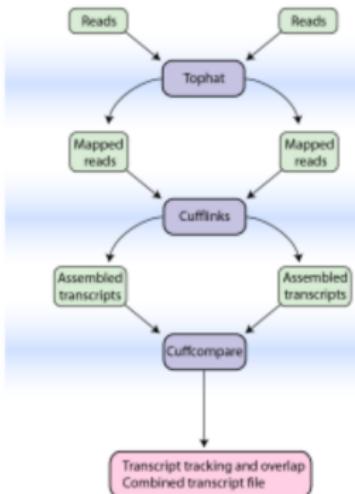
## Hands-on 1 Differential expression analysis

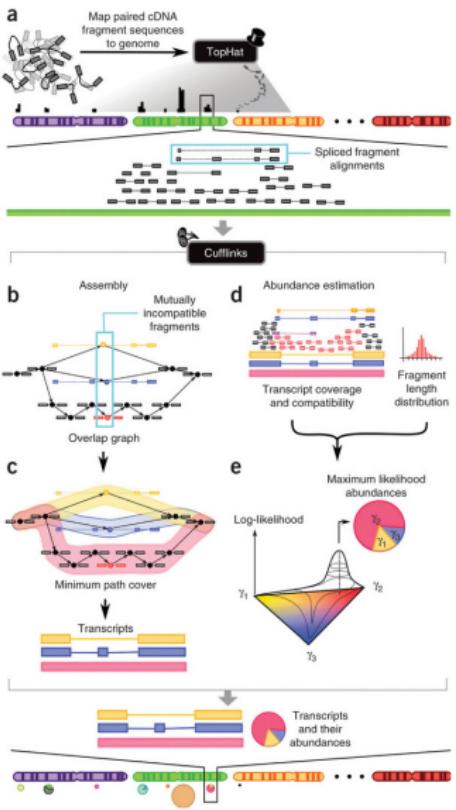


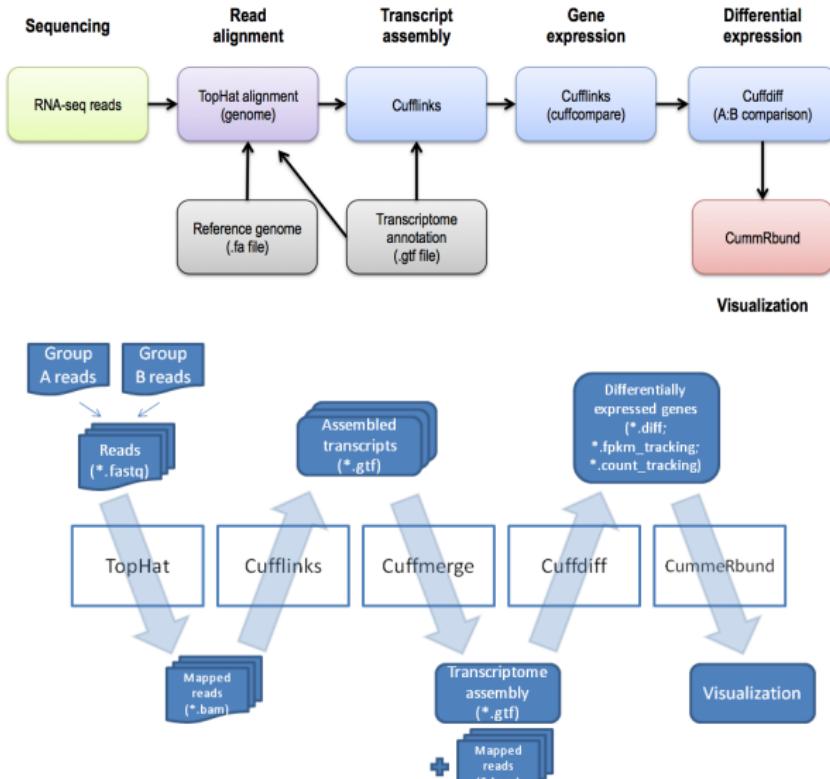
## Hands-on 2 Transcript assembly and differential expression analysis



## Hands-on 3 Transcript assembly and transcript comparison







## Bowtie: ultrafast short read alignment

Bowtie is an ultrafast and memory-efficient tool for aligning sequencing reads to long reference sequences. It is particularly good at aligning reads of about 50 up to 100s or 1,000s of characters, and particularly good at aligning to relatively long (e.g. mammalian) genomes. Bowtie 2 indexes the genome with an FM Index to keep its memory footprint small: for the human genome, its memory footprint is typically around 3.2 GB. Bowtie 2 supports gapped, local, and paired-end alignment modes.

## TopHat: alignment of short RNA-Seq reads

TopHat is a fast splice junction mapper for RNA-Seq reads. It aligns RNA-Seq reads to mammalian-sized genomes using the ultra high-throughput short read aligner Bowtie, and then analyzes the mapping results to identify splice junctions between exons.

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## CummeRbund: visualization of RNA-Seq differential analysis

CummeRbund is an R package that is designed to aid and simplify the task of analyzing Cufflinks RNA-Seq output.



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## Cufflinks

Cufflinks is both the name of a suite of tools and a program within that suite. Cufflinks the program assembles transcriptomes from RNA-Seq data and quantifies their expression.

## Cuffcompare

Cuffcompare helps you compare the transcriptomes assembled from different RNA-Seq libraries and assess the quality of your assembly.

## Cuffmerge

Cuffmerge merges the assembled transcriptomes into a master transcriptome. This step is required for a differential expression analysis of the new transcripts you've assembled.

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## Cuffquant

Cuffquant computes the gene and transcript expression profiles and save these profiles to files that you can analyze later with Cuffdiff or Cuffnorm. It is recommended for analyses involving more than a handful of libraries.

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Cuffdiff is a highly accurate tool for performing the comparisons of expression levels of genes and transcripts.

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Cuffnorm normalizes a set of samples to be on as similar scales as possible, which can improve the results you obtain with other downstream tools.

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## Tophat

<http://ccb.jhu.edu/software/tophat/>

Two-step approach:

- (optional) Align to transcriptome first.
- Use bowtie to align whole reads, identify potential exon.
- Split left-over reads into small segments, align independently.
  - Make a database of splice junctions.
  - Map the reads to confirm the splice junctions.

Some considerations:

- Does not support soft-clipping

# Mapping with Tophat

- Initial Tophat run
- Determine insert size
- Rerun Tophat with correct insert size
- Review mapping statistics



# Tophat Output

- unmapped.bam (BAM)
- accepted\_hits.bam (BAM): a list of read alignments in BAM/SAM format
- junctions.bed (BED): list BED track of junctions reported by Tophat where each junction consists of two connected BED blocks where each block is as long as the max overhang of any read spanning junction
- deletions.bed (BED): mentions the last genomic base before the deletion
- insertions.bed (BED): mentions the first genomic base of deletion

23: Tophat2 on data 5, data 1, and data 4: unmapped bam			
24: C1_R1 accepted hits			
23: Tophat2 on data 5, data 1, and data 4: splice junctions			
22: Tophat2 on data 5, data 1, and data 4: deletions			
21: Tophat2 on data 5, data 1, and data 4: insertions			
130 regions, 1 comments format: bed, database: dm3 Log: tool progress Log: tool progress [2013-12-17 16:07:04] Beginning TopHat run (v2.0.10) —			
— [2013-12-17 16:07:04] Checking for Bowtie Bowtie version: 2.1.0.0 [2013-12-17 16:07:04] Checking for Samtools display at UCSC main test display in IGB Local Web display at Ensembl Current			
1.Chrom	2.Start	3.End	4.Name
track name=insertions description=Tophat ins chr2L	2575279	2575279	G



## Cufflinks

Input:

- Aligned reads.
  - Gmap / Gsnap.
  - Tophat.

What it can do:

- Assemble transcripts.
- Estimate transcript abundance.



## Cufflinks

Modes of operation:

- Use predefined transcripts.
- Assemble transcripts assisted by known transcripts.
- Assemble transcripts with no prior knowledge.

When to use:

- Only interested in expression.
- Alternative splicing.

Discover new transcripts (Cuffcompare).



## Cuffdiff

Find significant changes in transcript expression, splicing, and promoter use.

- Support multiple samples and replicates
- Models to estimate the distribution
  - pooled, per-condition, blind
- Output a number of statistic tests
  - fold change, p values, q values



# Differential Expression

- Cuffdiff (Cufflinks package)
  - Pairwise comparisons
  - Differential gene, transcript, and primary transcript expression
  - Easy to use, well documented
  - Input: transcriptome, SAM/BAM read alignments



# Cuffdiff output

- Genes: gene differential FPKM
- Isoforms: Transcript differential FPKM
- CDS: Coding sequence differential FPKM

[62: Cuffdiff on data 39, data 1, and others](#) / ×  
others: transcript FPKM tracking

[61: Cuffdiff on data 39, data 1, and others](#) / ×  
others: transcript differential expression testing

[60: Cuffdiff on data 39, data 1, and others](#) / ×  
others: gene FPKM tracking  
14,200 lines  
format: tabular, database: dm3  
cuffdiff v2.1.1 (4046M) cuffdiff --no-update-check -q --library-norm-method geometric --dispersion-method pooled -p 4 -c 10 --FDR 0.050000 --labels "C1","C2"  
/BIO/galaxy/files/003/dataset\_3778.dat  
/BIO/galaxy/files/003/dataset\_3789.dat, /BIO/galaxy/files/



1	2	3	4
tracking_id	class_code	nearest_ref_id	gene
128up	-	-	128



## Cuffdiff: differentially expressed genes

Column	Contents
test_stat	value of the test statistic used to compute significance of the observed change in FPKM
p_value	Uncorrected P value for test statistic
q_value	FDR-adjusted p-value for the test statistic
status	Was there enough data to run the test?
significant	and, was the gene differentially expressed?



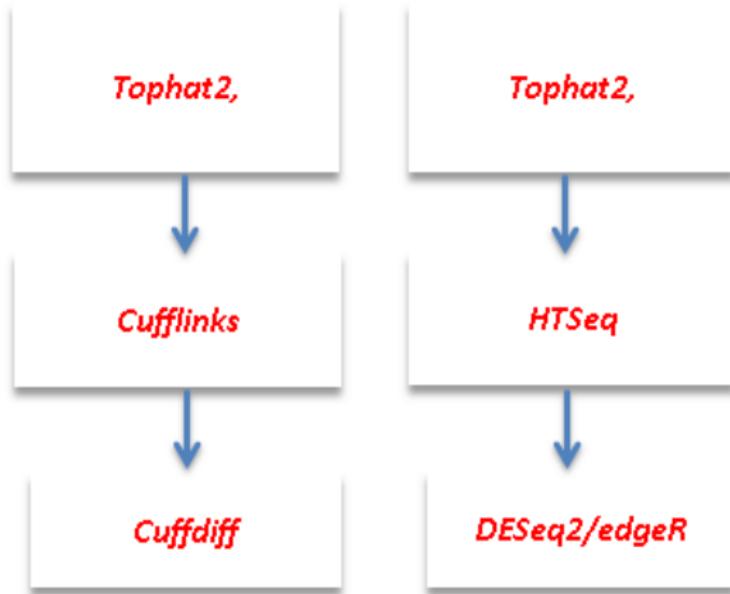
## Cuffdiff

- Column 7 ("status") can be FAIL, NOTEST, LOWDATA or OK
  - Filter and Sort → Filter
    - `c7 == 'OK'`
- Column 14 ("significant") can be yes or no
  - Filter and Sort → Filter
    - `c14 == 'yes'`

Returns the list of genes with

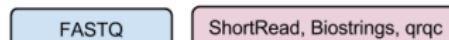
- 1) enough data to make a call, and
- 2) that are called as differentially expressed.



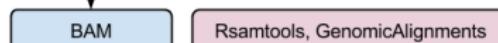


# 转录组学 | RNA-Seq | 分析 | 工具 | Pipeline | R/Bioconductor

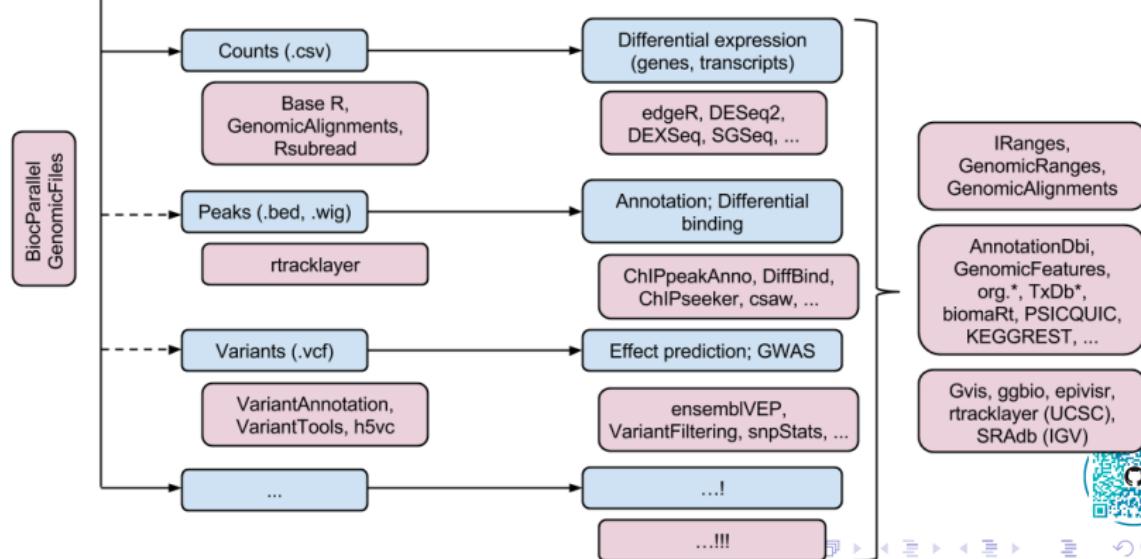
Sequencing



Alignment



Reduction



## Multiple testing problem

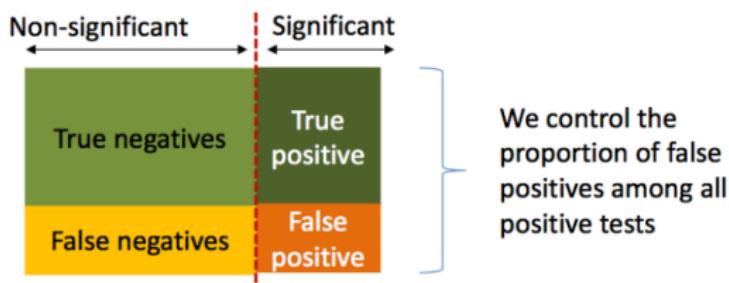
p-value: probability of observing a test statistic that is at least as extreme as the observed one if the null hypothesis were true.

In RNA-seq, we perform 1 test per gene

For example: ~20'000 human genes means ~1'000 significant tests (at  $P < 5\%$ ) expected by chance **even if there is NO differential expression!**

False discovery rate (FDR) correction

**For example Benjamini & Hochberg (1995) J. Roy. Stat. Soc. B**



## Correcting for multiple test

By default DESeq2 uses a FDR of 10%

This means that max 10% of the significant genes could be false positives

	<b>baseMean</b>	<b>log2FC</b>	<b>lfcSE</b>	<b>stat</b>	<b>pvalue</b>	<b>padj</b>
WBGene00000001	366.24625	0.73464	0.27865	2.63646	0.00838	0.02992
WBGene00000002	289.48852	-0.58337	0.32379	-1.80172	0.07159	0.16243
WBGene00000003	93.21683	0.11464	0.27268	0.42044	0.67417	0.79280
WBGene00000004	165.72585	-0.69165	0.32537	-2.12575	0.03352	0.09026
WBGene00000005	439.78883	-0.74071	0.29184	-2.53804	0.01115	0.03771
WBGene00000006	244.67827	-1.16500	0.40588	-2.87031	0.00410	0.01658
WBGene00000007	367.81227	-0.00548	0.38734	-0.01416	0.98870	0.99445
WBGene00000008	19.25137	-0.09673	0.56984	-0.16975	0.86521	0.92061

Adjusted p-values using  
Benjamini-Hochberg  
procedure



# After DGE RNA-seq?

You get your “gene list”, finished?

- Validate
- Typically expect some false-positives
- Genes not in your list may be differentially expressed

Important to always remember

- Your list of genes is produced with an arbitrary significance threshold!

Next?

- Gene-set enrichment tests
- Novel transcripts, novel splice-variants, ...



## Downstream analysis



You get your favorite DE gene list, what do you do next?

We want to annotate them functionally!

**Which biological functions (or pathways) are enriched among the highly differentially expressed genes?**

**Are there any common TF/enhancers controlling the expression of the most highly differentially expressed genes?**



**Shift focus from single genes to collections of genes (gene sets)**

Why gene set analysis?

**Genes are believed to work together**

**Many small, but concordant, effects may be detectable together  
even if they are not detectable individually!**

**Fewer gene sets than individual genes - less severe multiple testing problem.**



## A gene set, what's that?

A collection of genes that have something in common, e.g.,  
**genes that are part of the same pathway**  
**co-expressed genes**  
**genes with similar chromosomal positions**  
**genes that are known to be involved in some cancer type**

The gene sets have to be defined in advance (i.e., they are not generated in the gene set analysis).



## Gene sets and software tools

MSigDB (<http://www.broadinstitute.org/gsea/msigdb/index.jsp>)

GSEA (<http://www.broadinstitute.org/gsea/index.jsp>)

DAVID (<http://david.abcc.ncifcrf.gov>)

GO gene ontology (<http://www.geneontology.org>)

KEGG (<http://www.genome.jp/kegg/>)

Reactome (<http://www.reactome.org>)

Publications

Integrated in many software suits and commercial packages like  
GeneGo MetaCore, Pathway Studio, Ingenuity

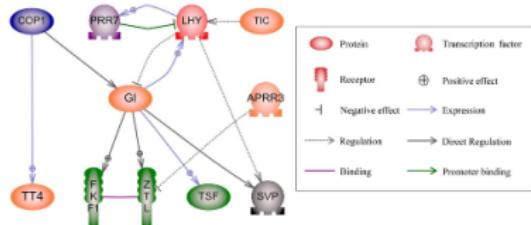
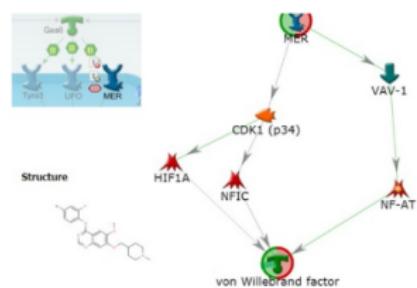
Where to find gene sets?

Some are available in R database packages (KEGG.db, GO.db,  
reactome.db)

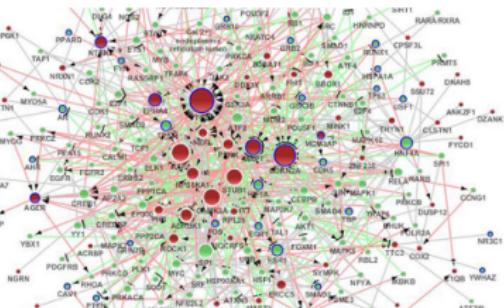


## Pathway analysis

Hoping for this...



You often get this...



## 1 转录组学概述

- 组学概述
- 转录组学
- 研究方法

## 2 RNA-Seq

- 概述
- 技术简介
- 数据分析
- 应用实例

## 3 顺反组

- 概述
- ChIP-Seq

## 4 表观遗传学

- 概述
- Methyl-Seq

## 5 回顾与总结

- 总结
- 思考题

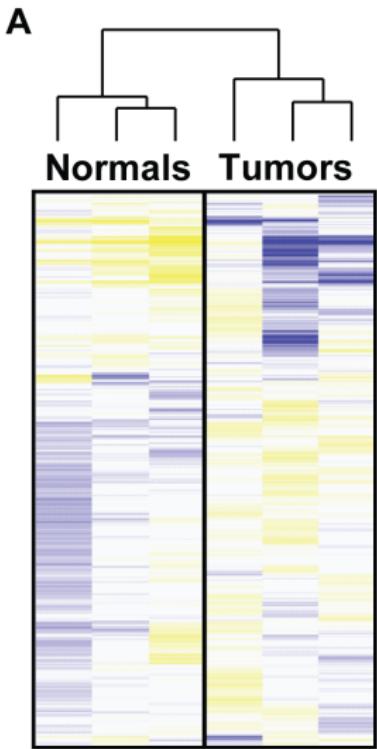


PLoS ONE, 2010

As an example of clinical applications, researchers at the Mayo Clinic used an RNA-Seq approach to identify differentially expressed transcripts between oral cancer and normal tissue samples. They also accurately evaluated the allelic imbalance (AI), ratio of the transcripts produced by the single alleles, within a subgroup of genes involved in cell differentiation, adhesion, cell motility and muscle contraction identifying a unique transcriptomic and genomic signature in oral cancer patients.

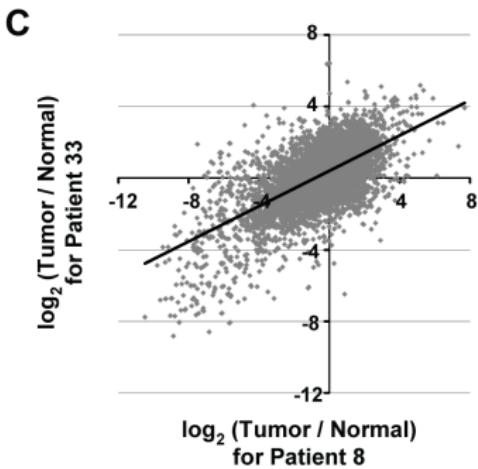
Tuch BB, Laborde RR, Xu X, et al. (2010). "Tumor transcriptome sequencing reveals allelic expression imbalances associated with copy number alterations". PLoS ONE. 5 (2): e9317.





**B**

8	1.00		
33	0.62	1.00	
51	0.51	0.46	1.00



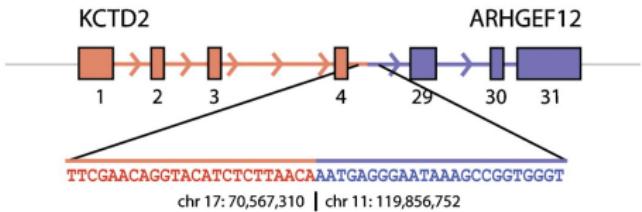
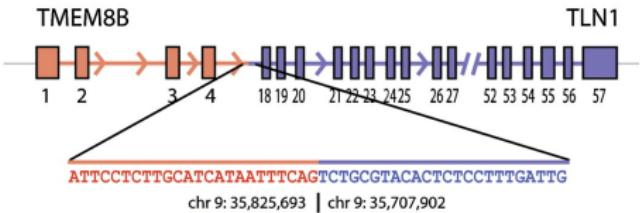
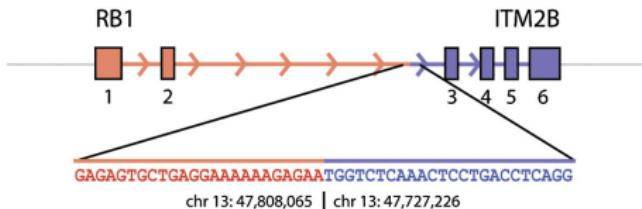
## Genome Research, 2010

Novel insight on skin cancer (melanoma) also come from RNA-Seq of melanoma patients. This approach led to the identification of eleven novel gene fusion transcripts originated from previously unknown chromosomal rearrangements. Twelve novel chimeric transcripts were also reported, including seven of those that confirmed previously identified data in multiple melanoma samples.

Berger MF, Levin JZ, Vijayendran K, et al. (April 2010). "Integrative analysis of the melanoma transcriptome". *Genome Res.* 20 (4): 413–27.



# 转录组学 | RNA-Seq | 实例 | fusion gene



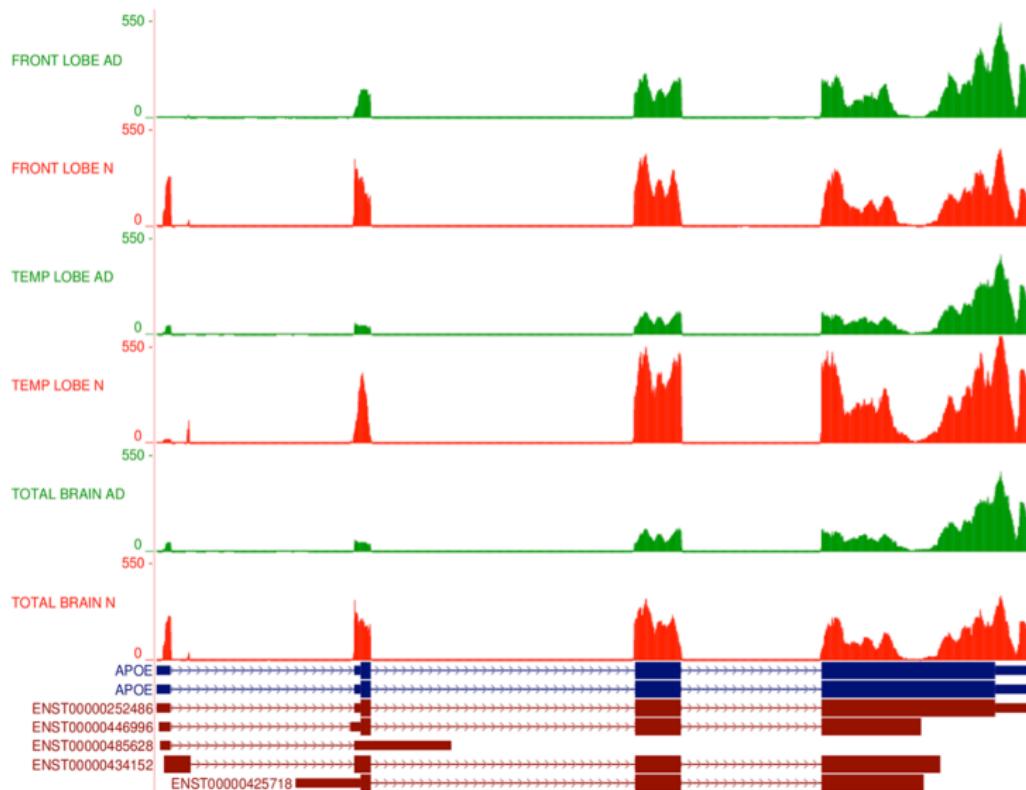
PLoS ONE, 2011

RNA-Seq has been used to study other important chronic diseases such as Alzheimer (AD) and diabetes. In the former case, Twine and colleagues compared the transcriptome of different lobes of deceased AD's patient's brain with the brain of healthy individuals identifying a lower number of splice variants in AD's patients and differential promoter usage of the APOE-001 and -002 isoforms in AD's brains.

Twine NA, Janitz K, Wilkins MR, Janitz M (2011). "Whole transcriptome sequencing reveals gene expression and splicing differences in brain regions affected by Alzheimer's disease". PLoS ONE. 6 (1): e16266.



# 转录组学 | RNA-Seq | 实例 | splice variant



Mol. Endocrinol, Cell Metab, 2012

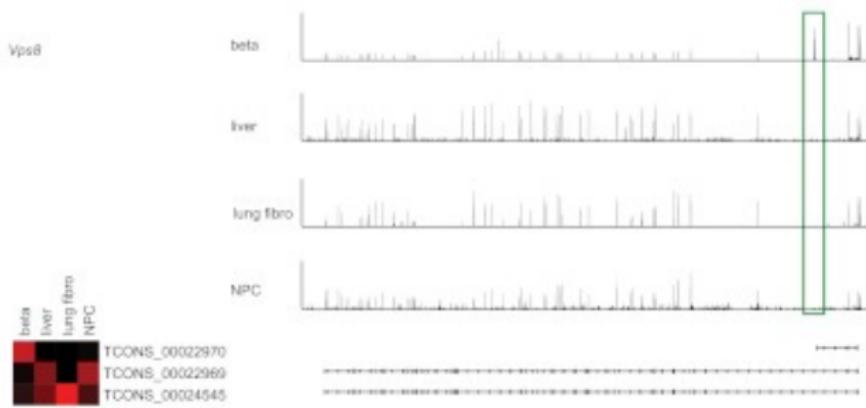
In the latter case, different groups showed the unicity of the beta-cells transcriptome in diabetic patients in terms of transcripts accumulation and differential promoter usage and long non coding RNAs (lncRNAs) signature.

Ku GM, Kim H, Vaughn IW, et al. (October 2012). "Research resource: RNA-Seq reveals unique features of the pancreatic  $\beta$ -cell transcriptome". Mol. Endocrinol. 26 (10): 1783–92.

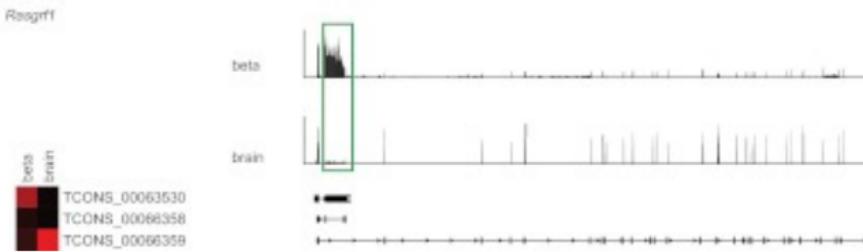
Morán I, Akerman I, van de Bunt M, et al. (October 2012). "Human  $\beta$  cell transcriptome analysis uncovers lncRNAs that are tissue-specific, dynamically regulated, and abnormally expressed in type 2 diabetes". Cell Metab. 16 (4): 435–48.

# 转录组学 | RNA-Seq | 实例 | splicing events and alternative promoter use

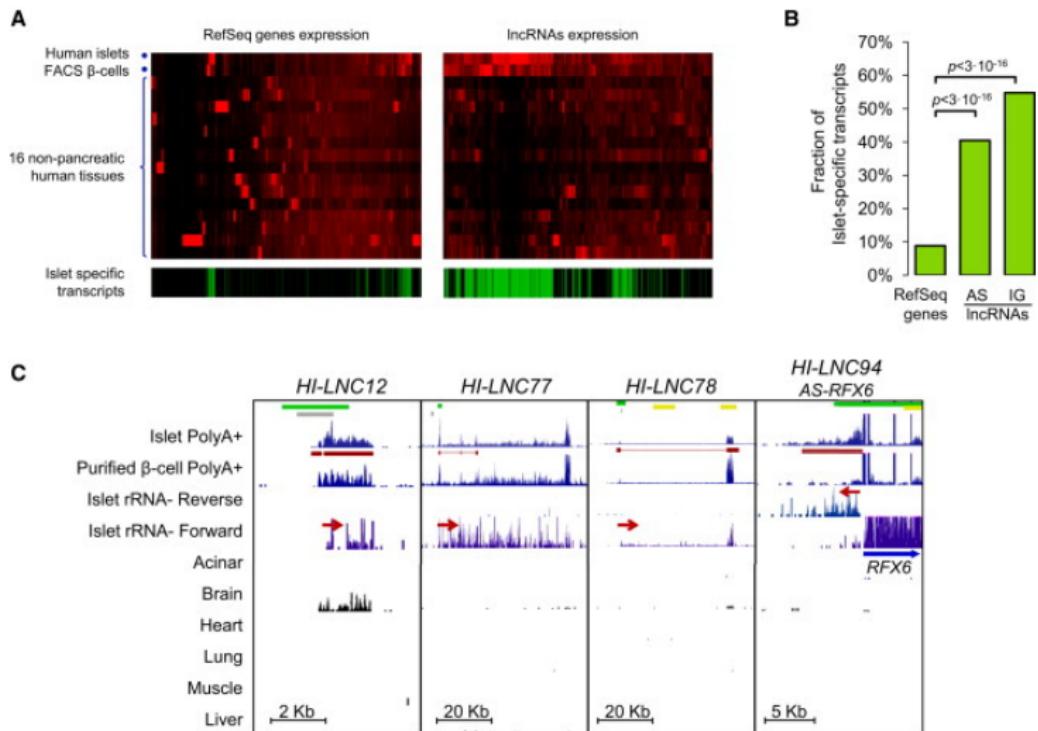
A



B



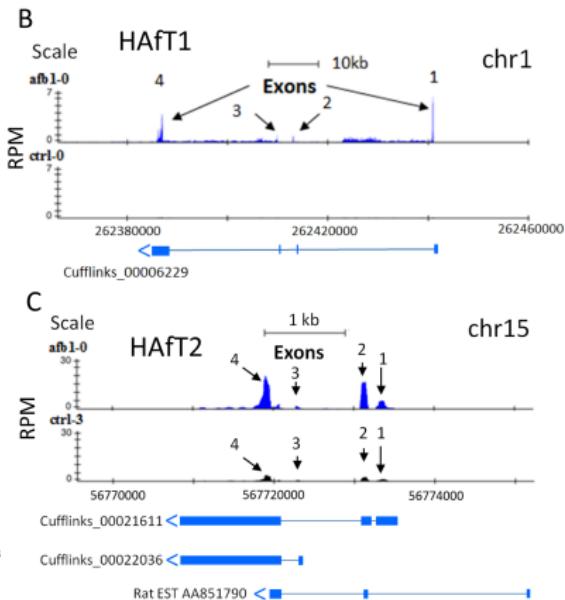
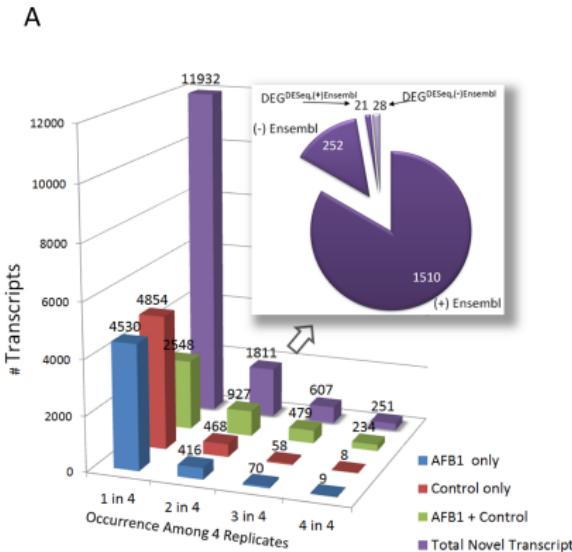
# 转录组学 | RNA-Seq | 实例 | lncRNA



PLoS ONE, 2013

NGS technology identified several previously undocumented differentially-expressed transcripts in rats treated with AFB1, a potent hepatocarcinogen. Nearly 50 new differentially-expressed transcriptions were identified between the controls and AFB1-treated rats. Additionally potential new exons were identified, including some that are responsive to AFB1. The next-generation sequencing pipeline identified more differential gene expressions compared with microarrays, particularly when DESeq software was utilized. Cufflinks identified two novel transcripts that were not previously annotated in the Ensembl database; these transcripts were confirmed using cloning PCR.

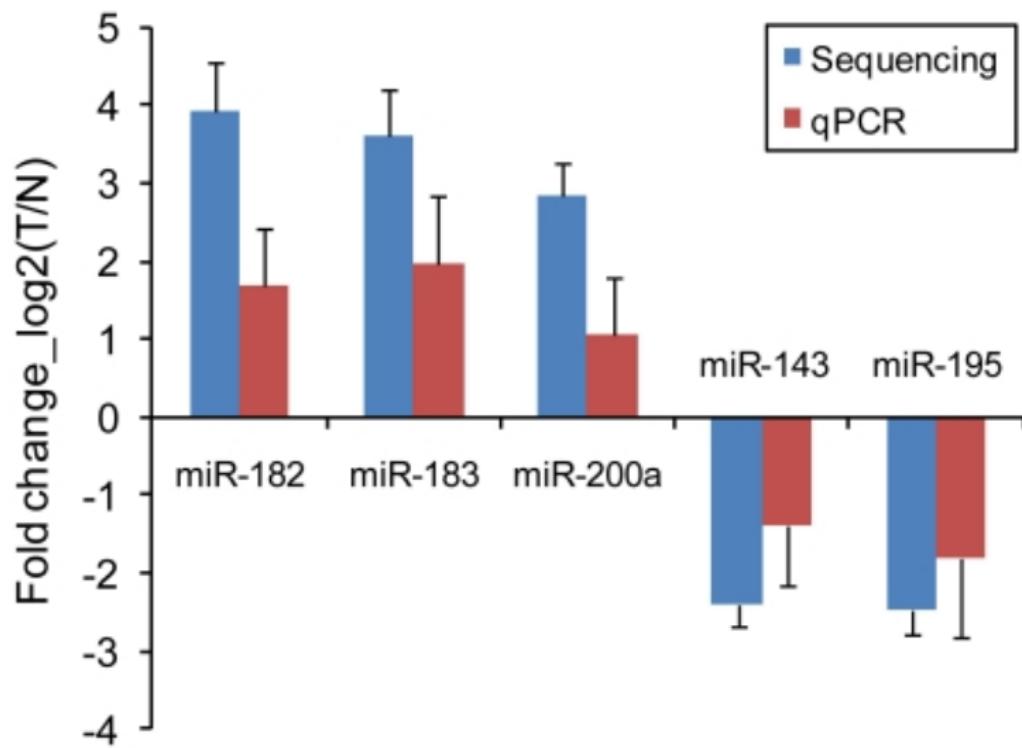
Merrick B. A.; Phadke D. P.; Auerbach S. S.; Mav D.; Stieglmeyer S. M.; Shah R. R.; Tice R. R. (2013). "RNA-seq profiling reveals novel hepatic gene expression pattern in Aflatoxin B1 treated rats". PLoS ONE. 8: e61768.



PLoS ONE, 2011

Han et al. (2011) examined microRNA expression differences in bladder cancer patients in order to understand how changes and dysregulation in microRNA can influence mRNA expression and function. Several microRNAs were differentially expressed in the bladder cancer patients. Upregulation in the aberrant microRNAs was more common than downregulation in the cancer patients. One of the upregulated microRNAs, has-miR-96, has been associated with carcinogenesis, and several of the overexpressed microRNAs have also been observed in other cancers, including ovarian and cervical. Some of the downregulated microRNAs in cancer samples were hypothesized to have inhibitory roles.

Han Y.; Chen J.; Zhao X.; Liang C.; Wang Y.; Sun L.; Jiang Z.; Zhang Z.; Yang R.; Chen J.; Li Z.; Tang A.; Li X.; Ye J.; Guan Z.; Gui Y.; Cai Z. (2011). "MicroRNA expression signatures of bladder cancer revealed by deep sequencing". PLoS ONE. 6: e18286.



# 教学提纲

## 1 转录组学概述

- 组学概述
- 转录组学
- 研究方法

## 2 RNA-Seq

- 概述
- 技术简介
- 数据分析
- 应用实例

## 3 顺反组

- 概述
- ChIP-Seq

## 4 表观遗传学

- 概述
- Methyl-Seq

## 5 回顾与总结

- 总结
- 思考题



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## 维基百科

顺反组（cistrome）指的是“全基因组尺度下反式作用因子的顺式作用靶点的集合，也可以说是在体情况下转录因子结合位点或组蛋白修饰在全基因组上的位置”。“顺反组”这一术语是 cistron（顺反子）和 genome（基因组）的混成词，最初由达纳-法伯癌症研究所和哈佛医学院的研究者命名。

染色质免疫沉淀等技术结合微阵列分析“ChIP-on-chip”或大规模并行 DNA 测序“ChIP-Seq”极大地方便了对转录因子及其它染色质相关蛋白的顺反组的定义。



## Wikipedia

The cistrome refers to “the set of cis-acting targets of a trans-acting factor on a genome-wide scale, also known as the *in vivo* genome-wide location of transcription factor binding-sites or histone modifications”. The term cistrome is a portmanteau of cistr (from cistron) + ome (from genome). The term cistrome was coined by investigators at the Dana-Farber Cancer Institute and Harvard Medical School.

Technologies such as chromatin immunoprecipitation combined with microarray analysis “ChIP-on-chip” or with massively parallel DNA sequencing “ChIP-Seq” have greatly facilitated the definition of the cistrome of transcription factors and other chromatin associated proteins.

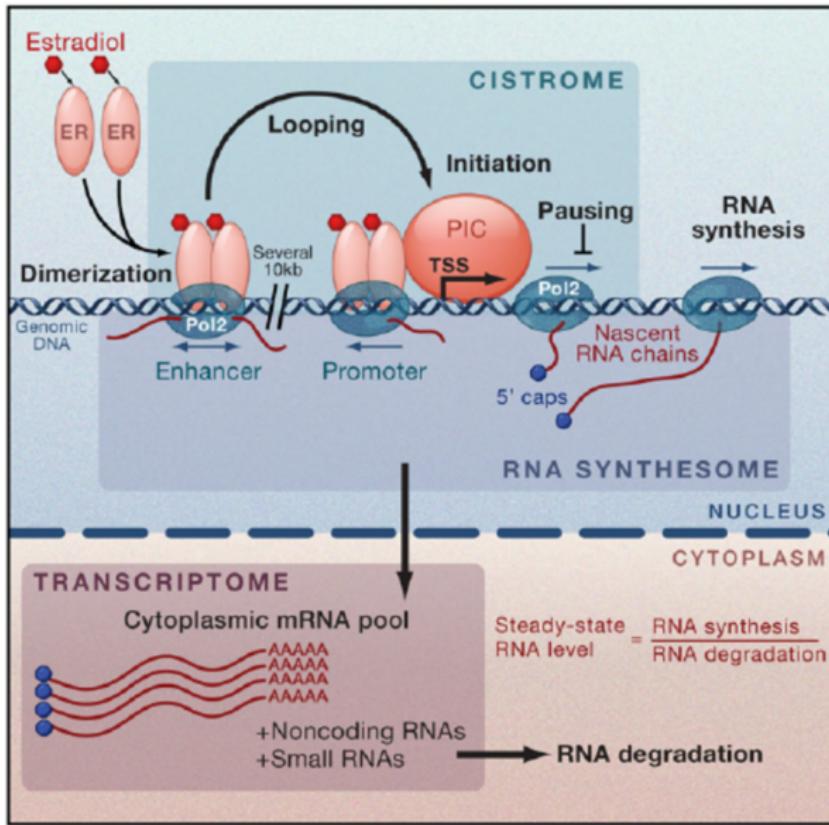


## 百度百科

顺反组 (cistrome) 是由 “Dana-Farber 癌症研究所” 与哈佛医学院的科学家提出的遗传学术语，用于定义一个反式 (trans) 调控因子在基因组 (genome) 范围内的作用对象——一组顺式 (cis) 作用元素。一些技术，例如免疫共沉淀与基因芯片结合的技术 (ChIP-on-chip)，已经被广泛的应用于发现转录因子以及其他染色质相关因子的顺反组。



# 顺反组 | 简介

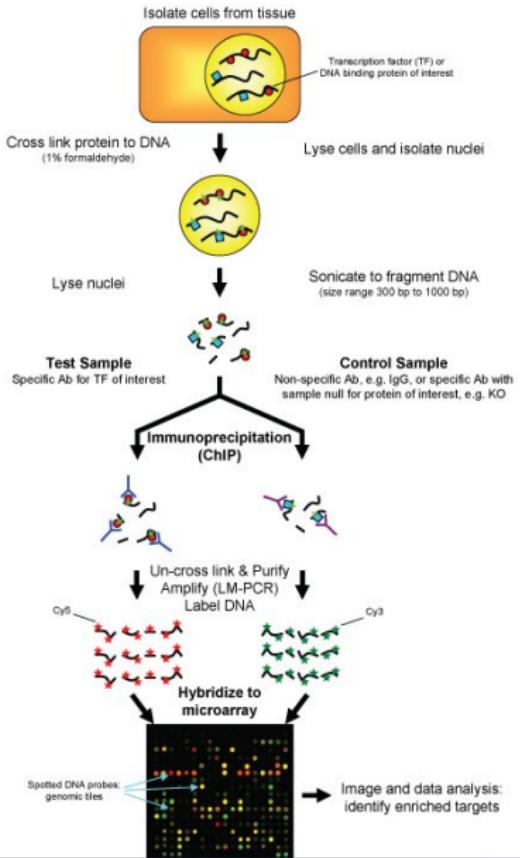


## ChIP-on-chip

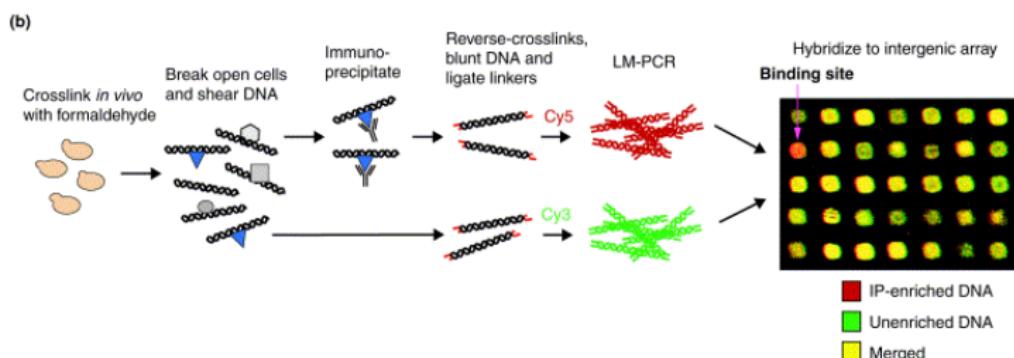
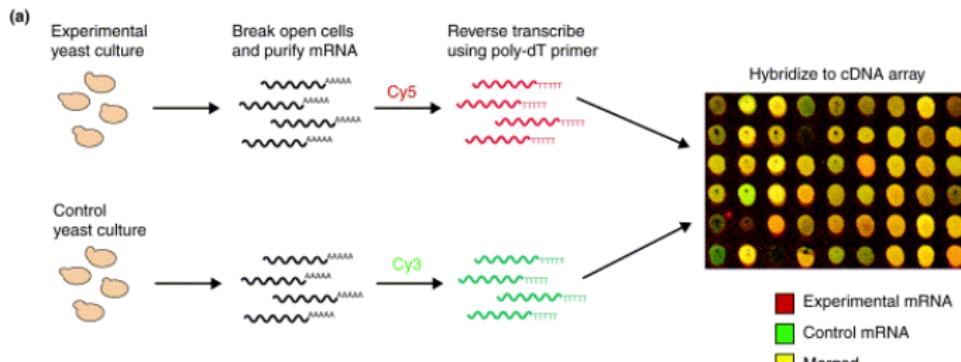
ChIP-on-chip (also known as ChIP-chip) is a technology that combines chromatin immunoprecipitation (“ChIP”) with DNA microarray (“chip”).

Like regular ChIP, ChIP-on-chip is used to investigate **interactions between proteins and DNA** *in vivo*. Specifically, it allows the identification of the cistrome, sum of binding sites, for DNA-binding proteins on a genome-wide basis. Whole-genome analysis can be performed to determine the locations of binding sites for almost any protein of interest. As the name of the technique suggests, such proteins are generally those operating in the context of chromatin. The most prominent representatives of this class are transcription factors, replication-related proteins, like Origin Recognition Complex Protein(Orc), histones, their variants, and histone modifications.

顺反组 | 研究方法 | ChIP-on-chip

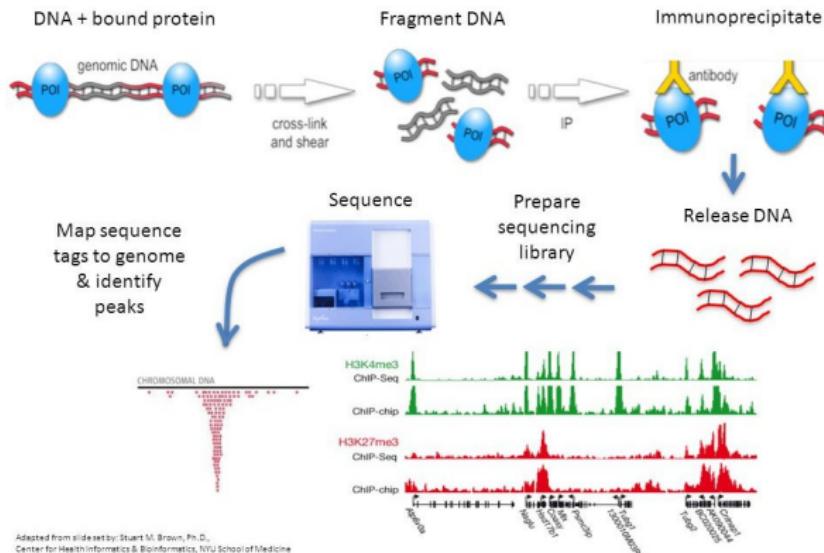


# 顺反组 | 研究方法 | ChIP-on-chip



## ChIP-Seq

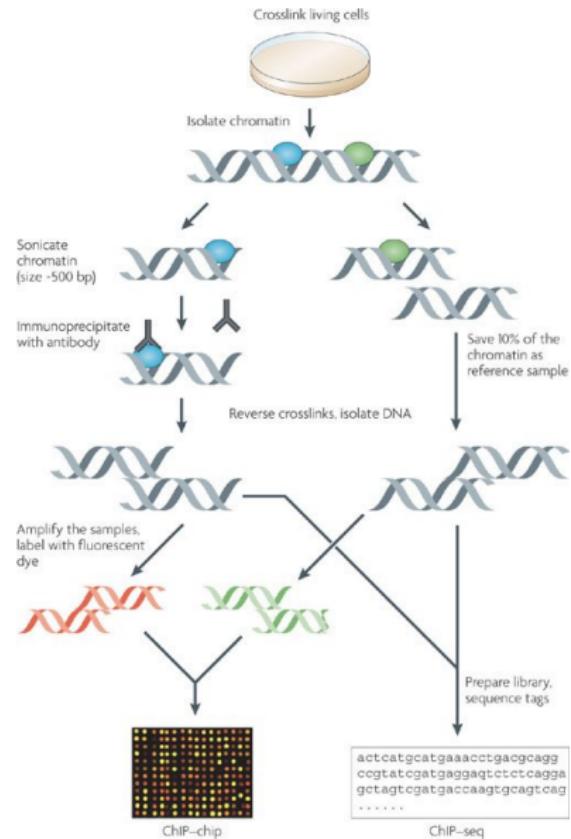
染色质免疫沉淀-测序（ChIP-sequencing，简称为 ChIP-seq）被用于分析**蛋白质与 DNA 的交互作用**。该技术将染色质免疫沉淀（ChIP）与大规模并行 DNA 测序结合起来以鉴定与 DNA 相关蛋白的结合部位。其可被用于精确绘制任意目的蛋白在全基因组上的结合位点。在此之前，ChIP-on-chip 是研究这些蛋白-DNA 联系的最常用的技术。



Adapted from slide set by Stuart M. Brown, Ph.D.,  
Center for Health Informatics & Bioinformatics, NYU School of Medicine



# 顺反组 | 研究方法 | ChIP-Seq vs. ChIP-chip



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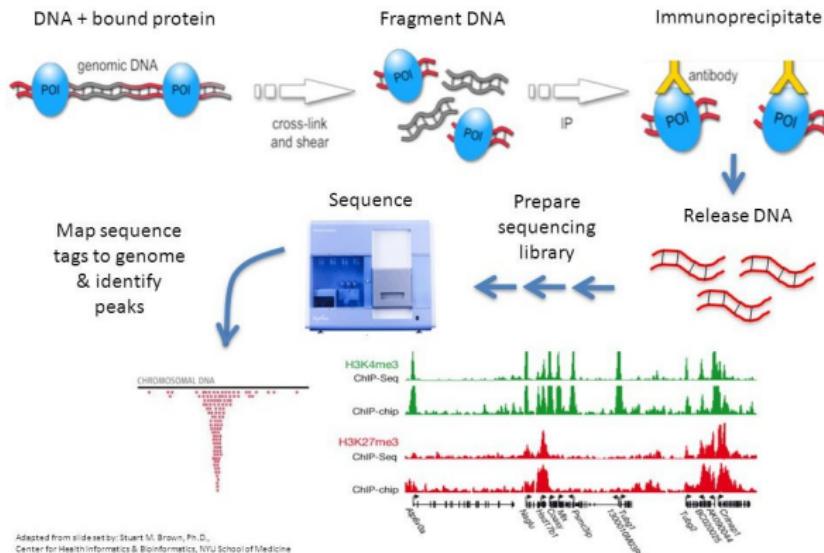
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## ChIP-Seq

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## ChIP-Seq

ChIP-sequencing, also known as ChIP-seq, is a method used to analyze protein interactions with DNA. ChIP-seq combines chromatin immunoprecipitation (ChIP) with massively parallel DNA sequencing to identify the binding sites of DNA-associated proteins. It can be used to map global binding sites precisely for any protein of interest. Previously, ChIP-on-chip was the most common technique utilized to study these protein-DNA relations.



## Uses

ChIP-seq is used primarily to determine how transcription factors and other chromatin-associated proteins influence phenotype-affecting mechanisms. Determining how proteins interact with DNA to regulate gene expression is essential for fully understanding many biological processes and disease states. This epigenetic information is complementary to genotype and expression analysis.

ChIP-seq technology is currently seen primarily as an alternative to ChIP-chip which requires a hybridization array. This necessarily introduces some bias, as an array is restricted to a fixed number of probes. Sequencing, by contrast, is thought to have less bias, although the sequencing bias of different sequencing technologies is not yet fully understood.

## Uses

Specific DNA sites in direct physical interaction with transcription factors and other proteins can be isolated by chromatin immunoprecipitation. ChIP produces a library of target DNA sites bound to a protein of interest *in vivo*.

Massively parallel sequence analyses are used in conjunction with whole-genome sequence databases to analyze the interaction pattern of any protein with DNA, or the pattern of any epigenetic chromatin modifications. This can be applied to the set of ChIP-able proteins and modifications, such as transcription factors, polymerases and transcriptional machinery, structural proteins, protein modifications, and DNA modifications.

As an alternative to the dependence on specific antibodies, different methods have been developed to find the superset of all nucleosome-depleted or nucleosome-disrupted active regulatory regions in the genome, like DNase-Seq and FAIRE-Seq.

## ChIP

ChIP is a powerful method to selectively enrich for DNA sequences bound by a particular protein in living cells. However, the widespread use of this method has been limited by the lack of a sufficiently robust method to identify all of the enriched DNA sequences. The ChIP process enriches specific crosslinked DNA-protein complexes using an antibody against the protein of interest. Oligonucleotide adaptors are then added to the small stretches of DNA that were bound to the protein of interest to enable massively parallel sequencing.



## Sequencing

After size selection, all the resulting ChIP-DNA fragments are sequenced simultaneously using a genome sequencer. A single sequencing run can scan for genome-wide associations with high resolution, meaning that features can be located precisely on the chromosomes. ChIP-chip, by contrast, requires large sets of tiling arrays for lower resolution.

There are many new sequencing methods used in this sequencing step. Then, the data collection and analysis software aligns sample sequences to a known genomic sequence to identify the ChIP-DNA fragments.



## Sensitivity

Sensitivity of this technology depends on the depth of the sequencing run (i.e. the number of mapped sequence tags), the size of the genome and the distribution of the target factor. The sequencing depth is directly correlated with cost. If abundant binders in large genomes have to be mapped with high sensitivity, costs are high as an enormously high number of sequence tags will be required. This is in contrast to ChIP-chip in which the costs are not correlated with sensitivity.



## Precision

Unlike microarray-based ChIP methods, the precision of the ChIP-seq assay is not limited by the spacing of predetermined probes. By integrating a large number of short reads, highly precise binding site localization is obtained. Compared to ChIP-chip, ChIP-seq data can be used to locate the binding site within few tens of base pairs of the actual protein binding site. Tag densities at the binding sites are a good indicator of protein-DNA binding affinity, which makes it easier to quantify and compare binding affinities of a protein to different DNA sites.

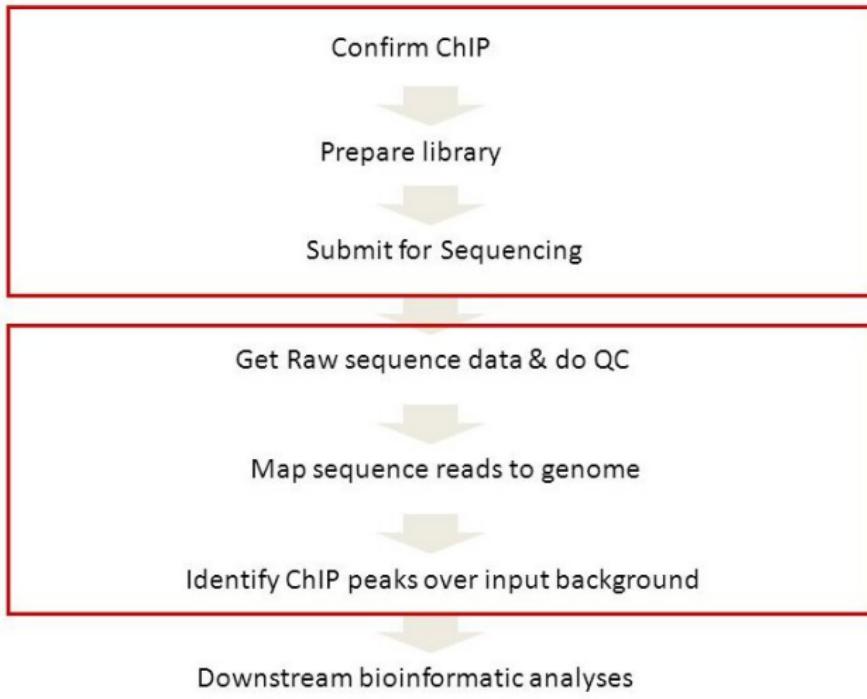


## Computational analysis

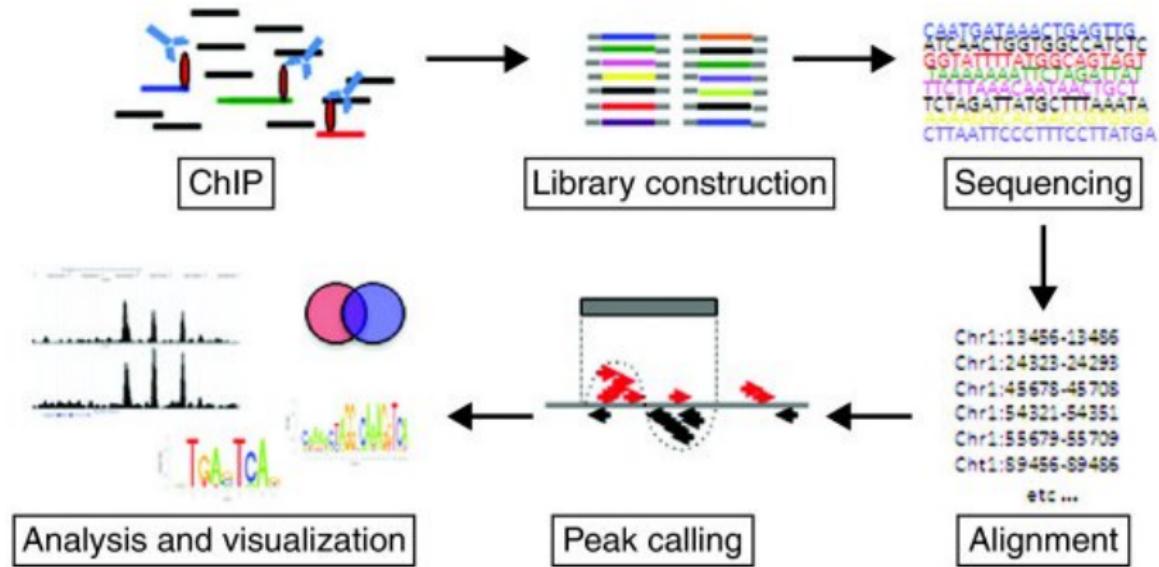
As with many high-throughput sequencing approaches, ChIP-seq generates extremely large data sets, for which appropriate computational analysis methods are required. To predict DNA-binding sites from ChIP-seq read count data, peak calling methods have been developed. The most popular method is MACS which empirically models the shift size of ChIP-Seq tags, and uses it to improve the spatial resolution of predicted binding sites.

Another relevant computational problem is Differential peak calling, which identifies significant differences in two ChIP-seq signals from distinct biological conditions. Differential peak callers segment two ChIP-seq signals and identify differential peaks using Hidden Markov Models. Examples for two-stage differential peak callers are ChIPDiff and ODIN.

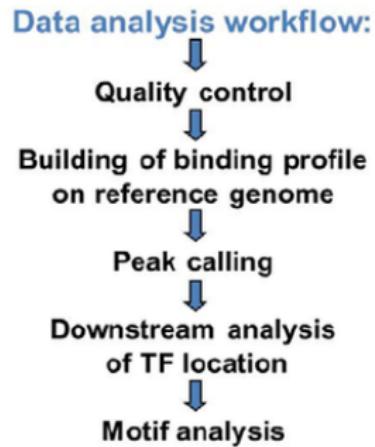
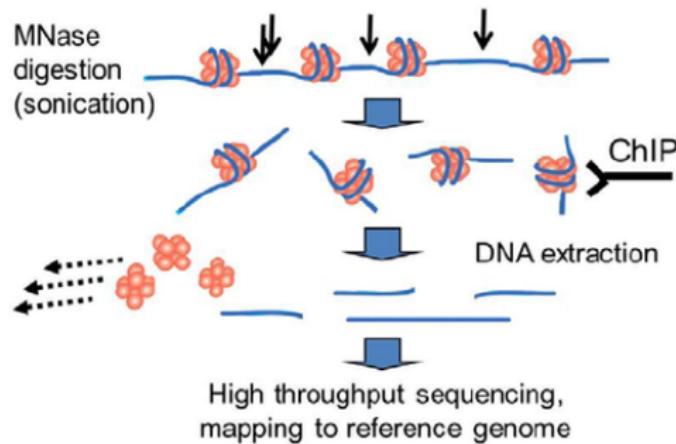
# ChIP-seq Workflow

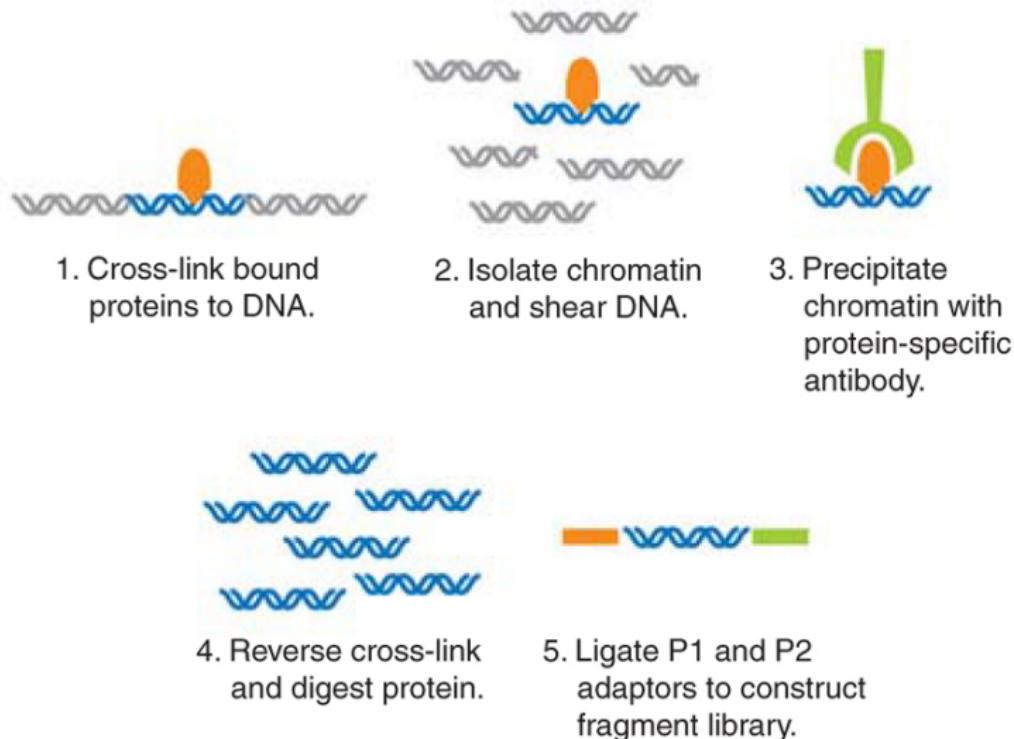


# 顺反组 | ChIP-Seq | 分析 | 流程

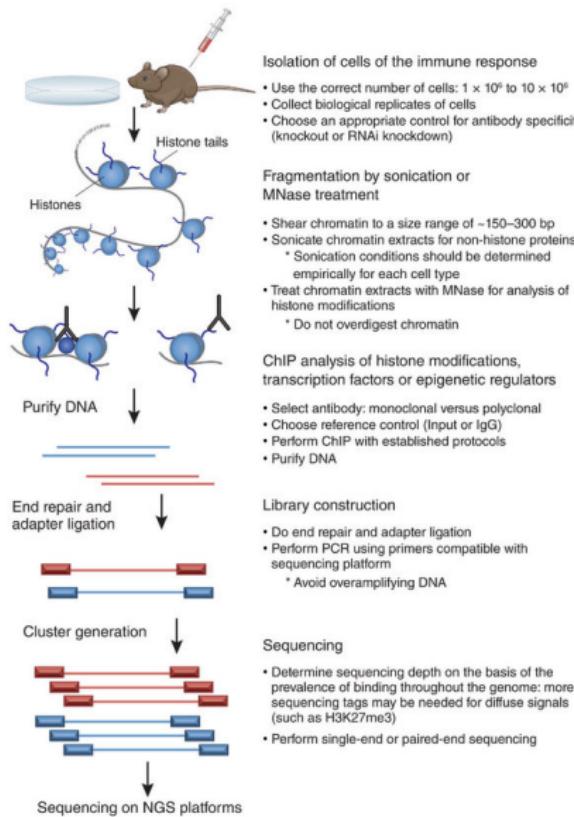


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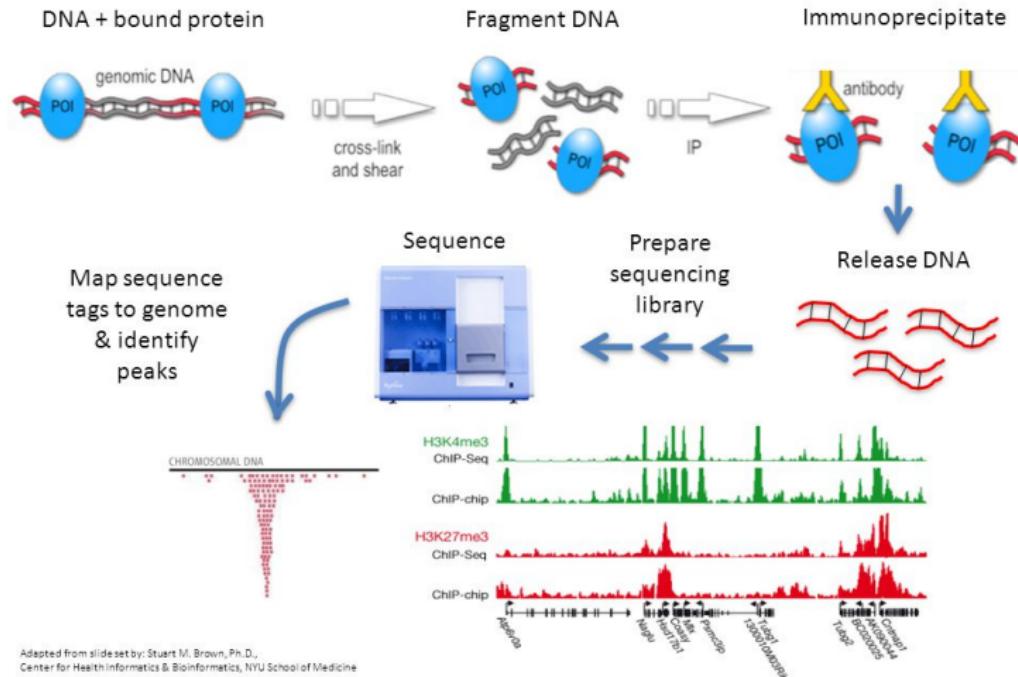




# 顺反组 | ChIP-Seq | 分析 | 流程 | 实验

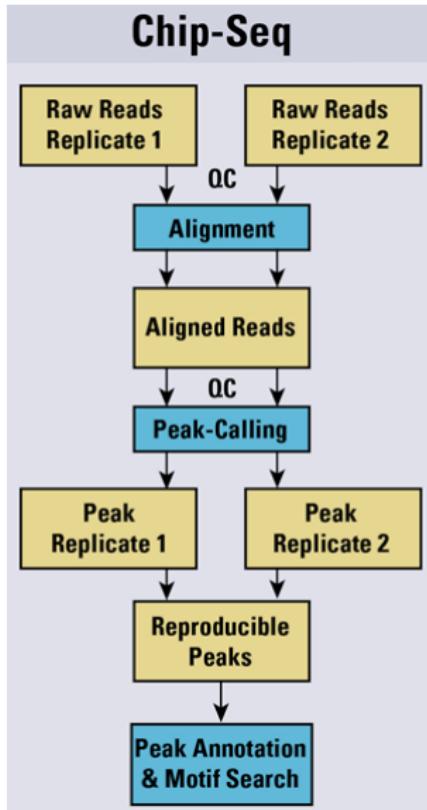


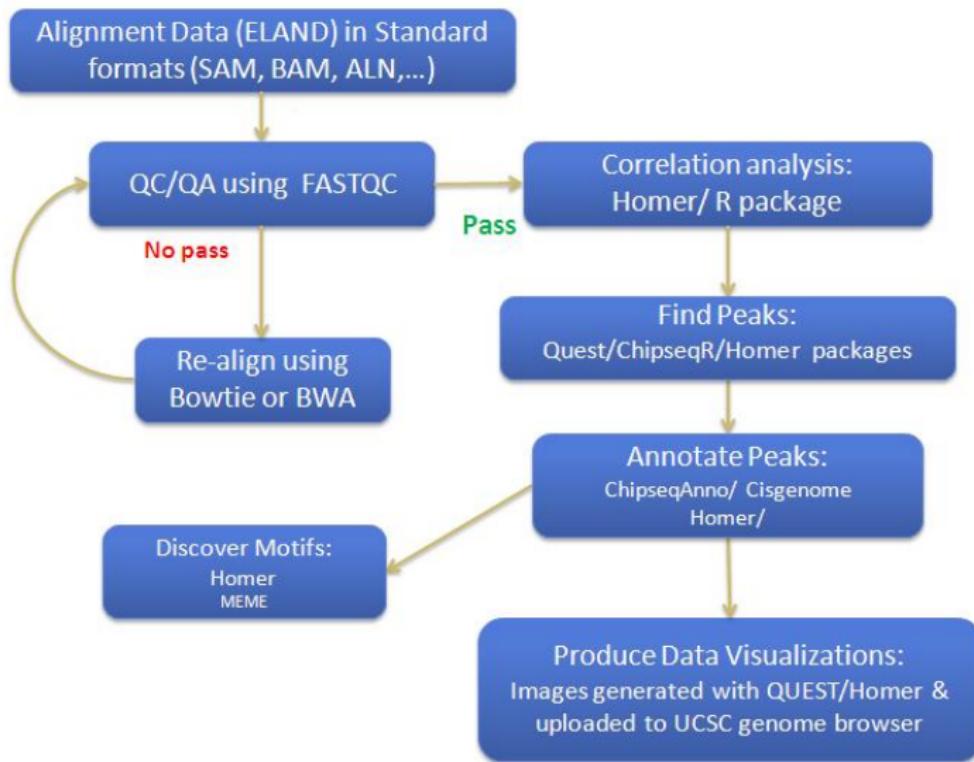
## ChIP-seq overview



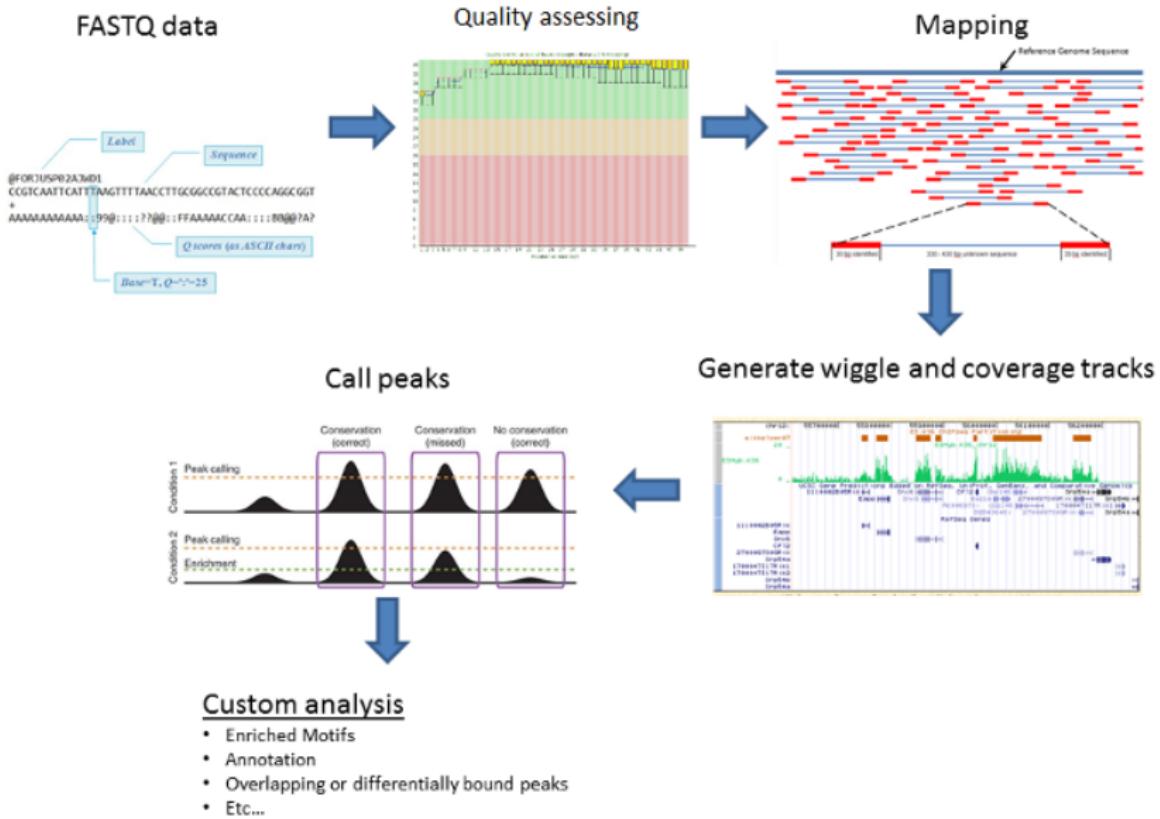
Adapted from slide set by: Stuart M. Brown, Ph.D.,  
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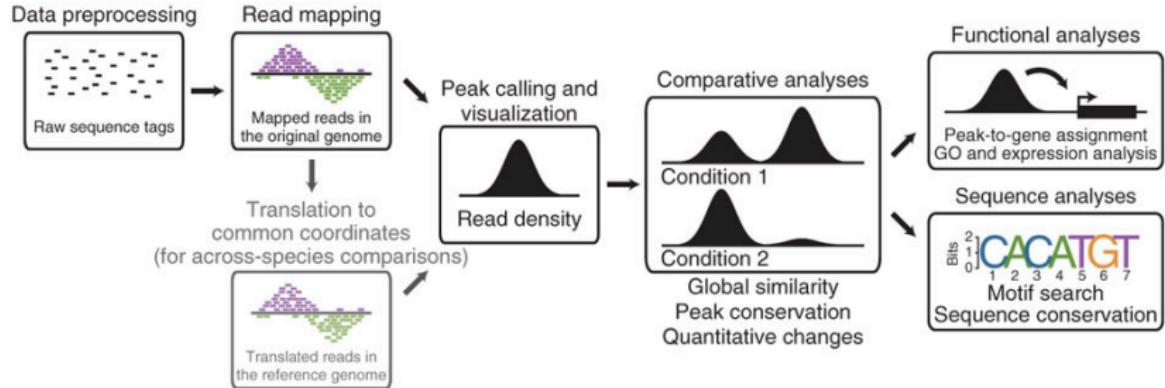




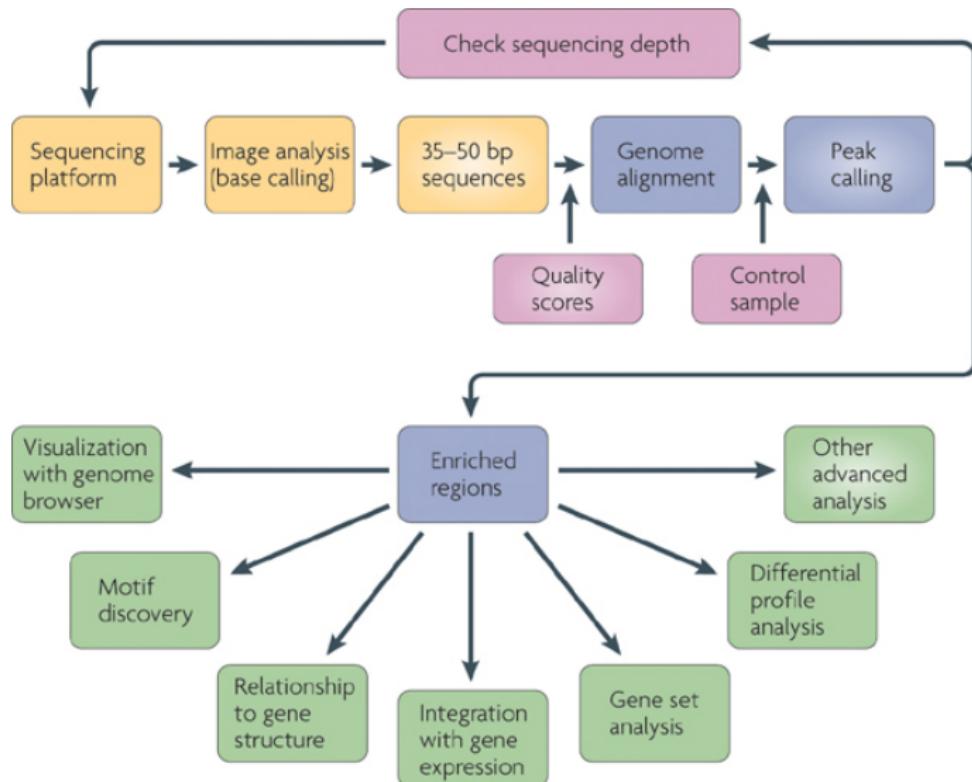
顺反组 | ChIP-Seq | 分析 | 流程 | 生信



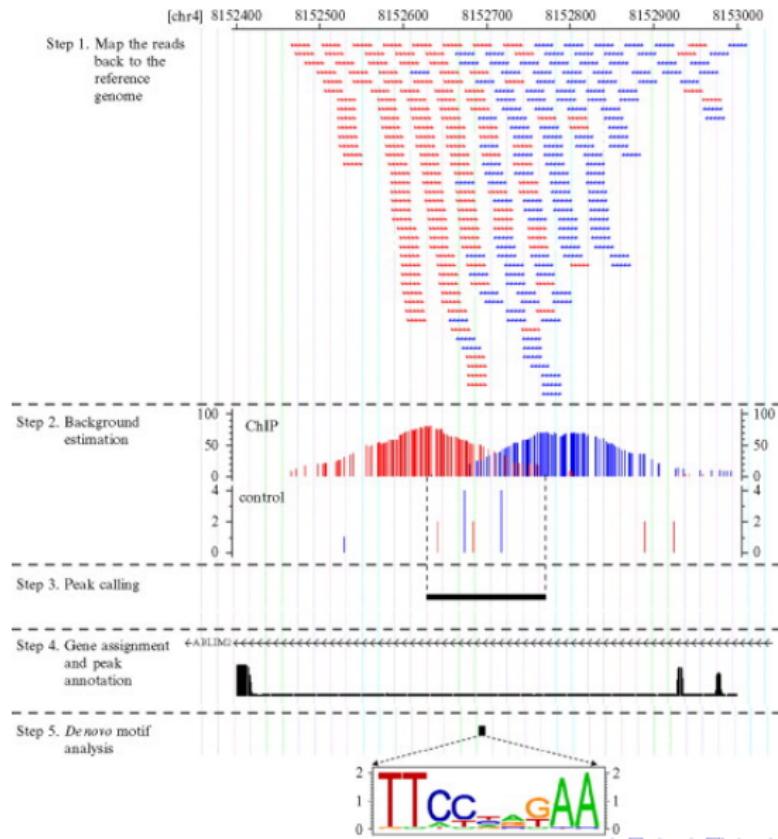
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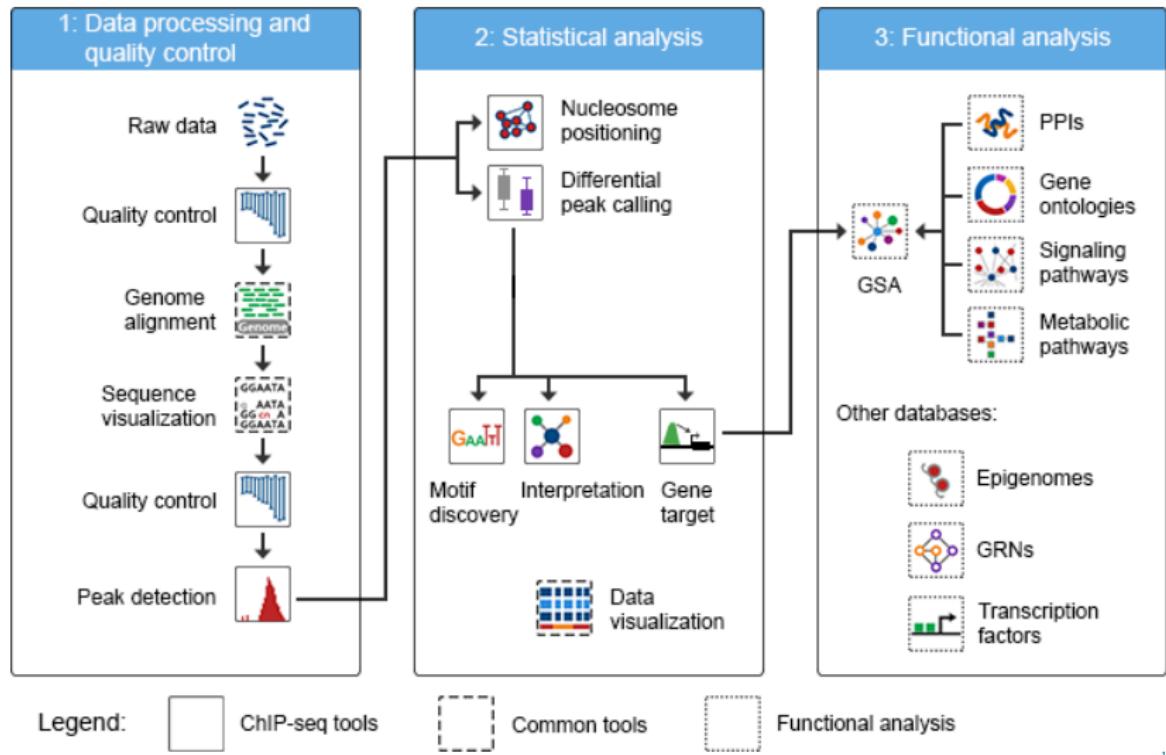


# 顺反组 | ChIP-Seq | 分析 | 流程 | 生信

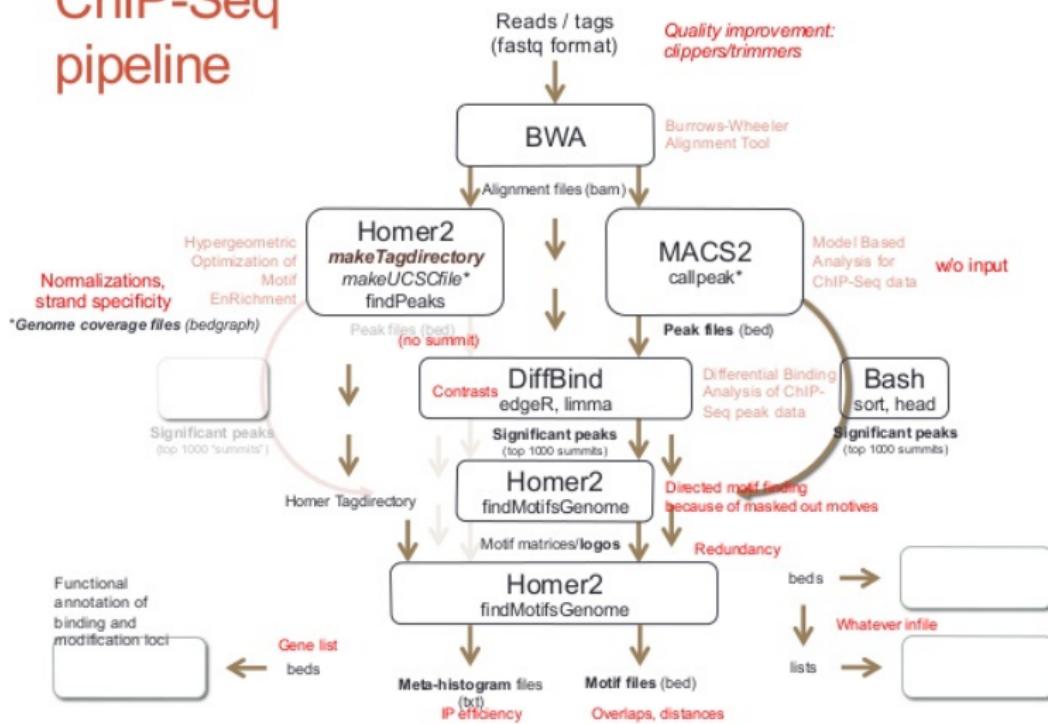


# 顺反组 | ChIP-Seq | 分析 | 流程 | 生信





## ChIP-Seq pipeline



## Peak calling

Peak calling 是一种用于鉴定经染色质免疫沉淀-测序或 MeDIP-测序实验后所得到的比对读段富集在基因组哪些区域中的一种计算方法。当免疫沉淀的蛋白质是一种转录因子时，那么 DNA 的富集区域就是转录因子结合位点 (TFBS)。主流的 Peak calling 软件有 MACS 等。

Peak calling 可应用于转录组/外显子组测序，亦可用于对 MeRIP-测序或 m6A-测序的 RNA 表观基因组测序数据进行分析；利用如 exomePeak 等的软件程序，可检测出转录后的 RNA 修饰位点。



## Peak calling

Peak calling is a computational method used to identify areas in a genome that have been enriched with aligned reads as a consequence of performing a ChIP-sequencing or MeDIP-seq experiment. These areas are those where a protein interacts with DNA. When the protein is a transcription factor, the enriched area is its transcription factor binding site (TFBS). Popular software programs include MACS.

Peak calling may be conducted on transcriptome/exome as well to RNA epigenome sequencing data from MeRIPseq or m6Aseq for detection of post-transcriptional RNA modification sites with software programs, such as exomePeak. Many of the peak calling tools are optimised for only some kind of assays such as only for transcription-factor ChIP-seq or only for DNase-seq. However new generation of peak callers such as DFilter are based on generalised optimal theory of detection and has been shown to work for nearly all kinds for tag profile signals from next-generation sequencing data. It is also possible to do more complex analysis using such tools like combining multiple ChIP-seq signal to detect regulatory sites.

## Differential peak calling

Differential peak calling is about identifying significant differences in two ChIP-seq signals. One can distinguish between one-stage and two-stage differential peak callers.

### One stage differential peak callers

One stage differential peak callers work in two phases: first, call peaks on individual ChIP-seq signals and second, combine individual signals and apply statistical tests to estimate differential peaks. DBChIP and MAnorm are examples for one stage differential peak callers.

### Two stage differential peak callers

Two stage differential peak callers segment two ChIP-seq signals and identify differential peaks in one step. They take advantage of signal segmentation approaches such as Hidden Markov Models. Examples for two-stage differential peak callers are ChIPDiff, ODIN, and THOR. Differential peak calling can also be applied in the context of analyzing RNA-binding protein binding sites.

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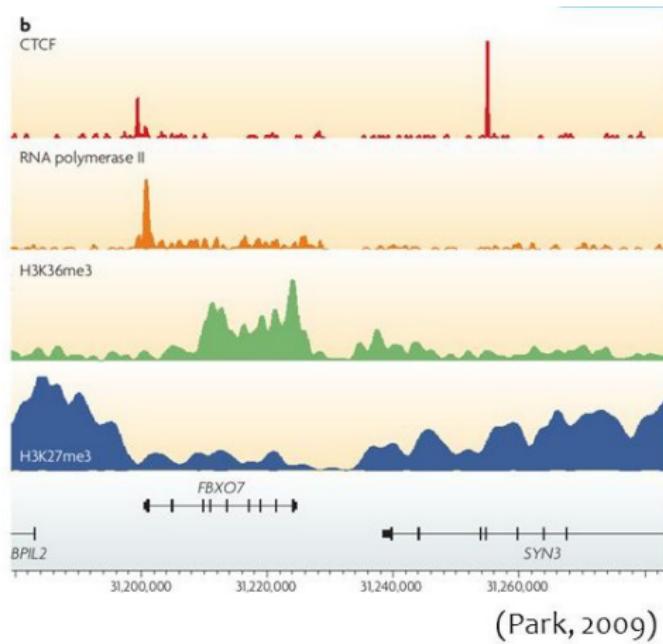
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# 顺反组 | ChIP-Seq | 分析 | Peak calling



Sharp (e.g. TF binding)

Mixture (e.g. polymerase binding)

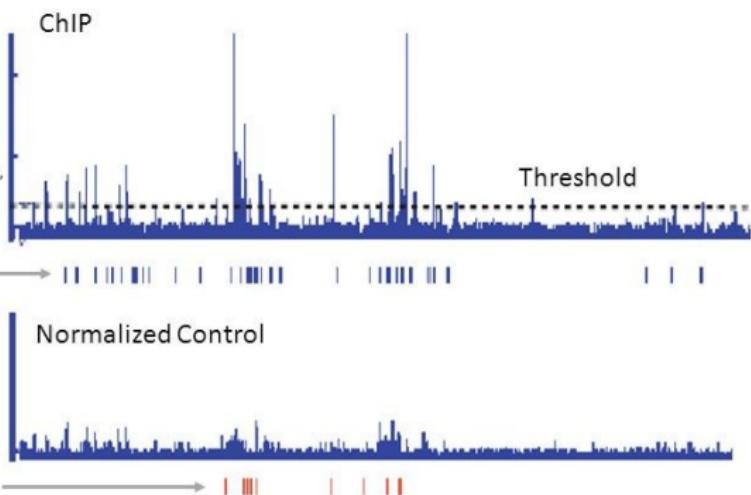
Broad (e.g. histone modification)



## Peak Calling

- Generate and threshold the signal profile and identify candidate target regions

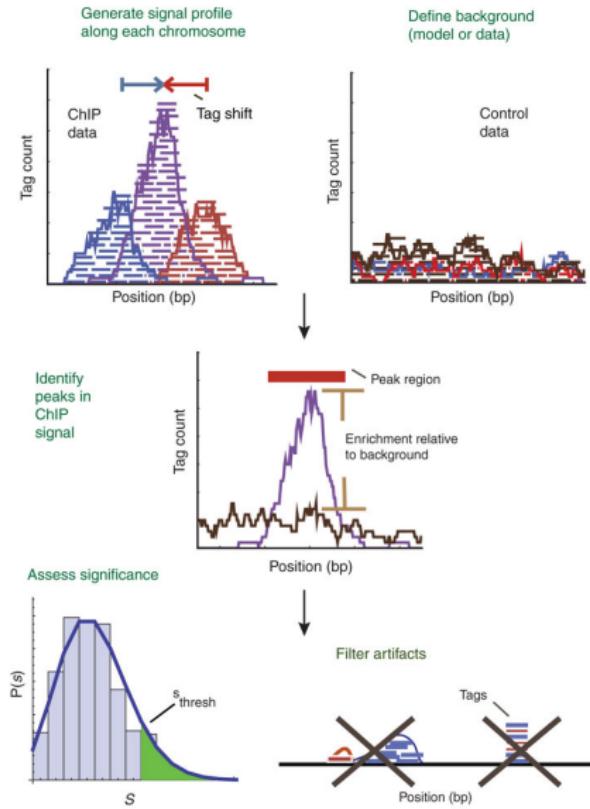
- Simulation (PeakSeq),
- Local window based Poisson (MACS),
- Fold change statistics (SPP)

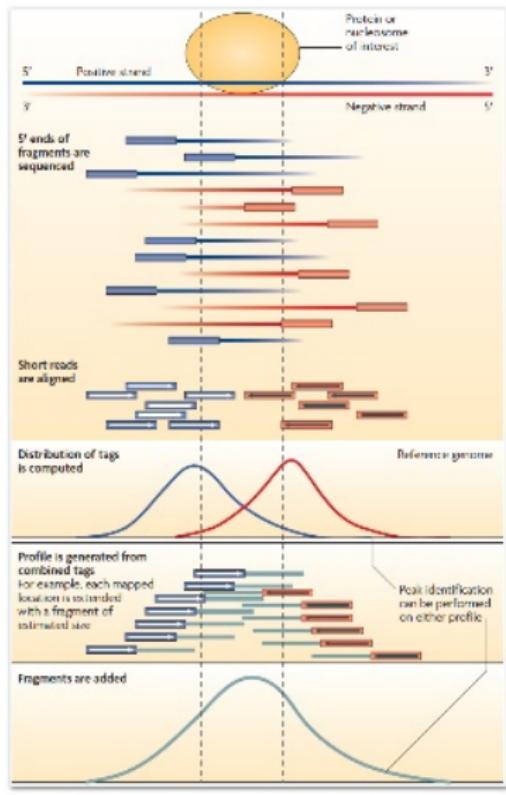


- Score against the control



# 顺反组 | ChIP-Seq | 分析 | Peak calling





## Chromatin immunoprecipitation (ChIP)

### Peak calling

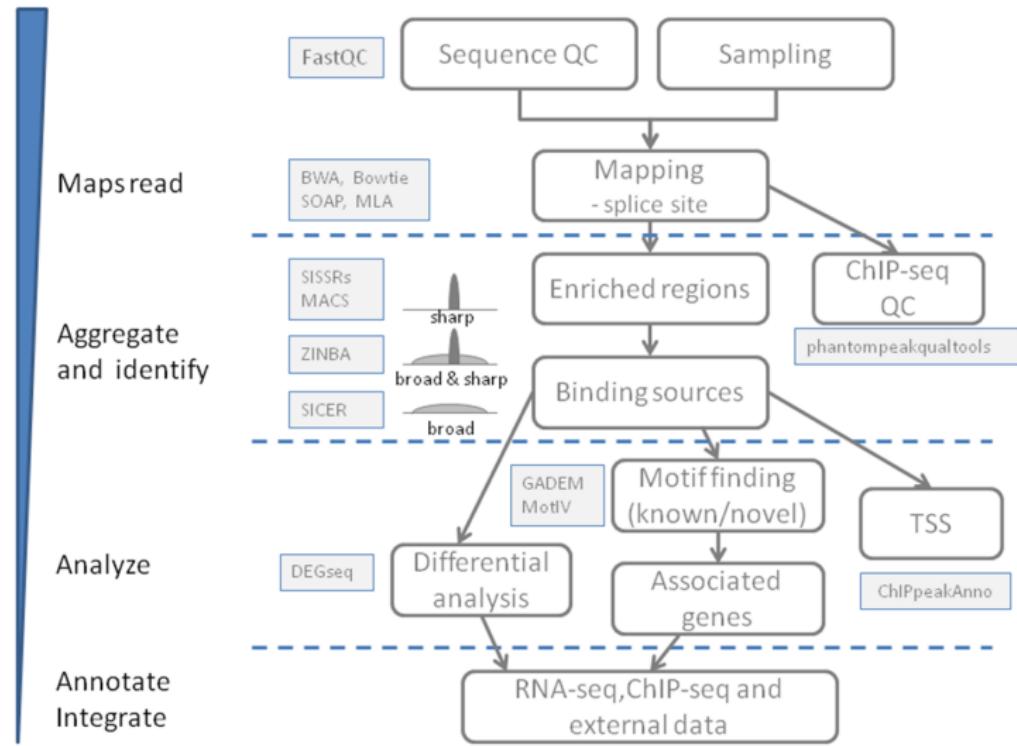
- Basic - regions are scored by the number of tags in a window of a given size.
- Each region is assessed by enrichment over control and minimum tag density.
- Advanced - take advantage of the directionality of the reads.

### Challenges

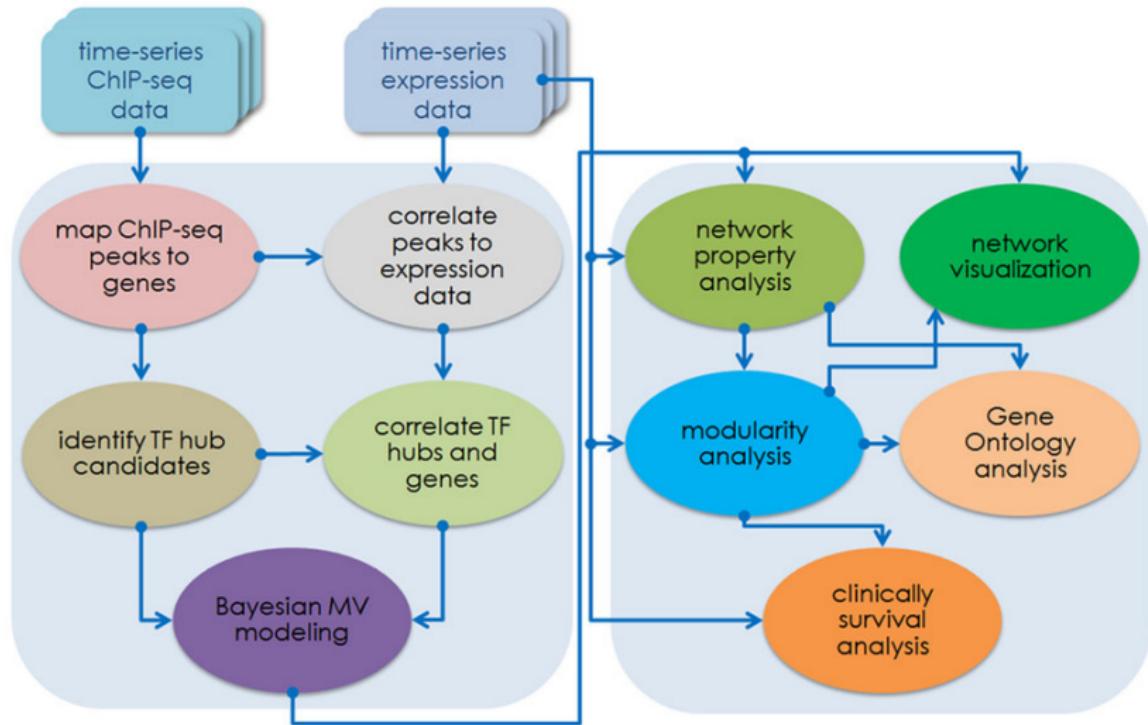
- Adjust for sequence alignability - regions that contain repetitive elements have different expected tag count
- Different ChIP-seq applications produce different type of peaks. Most current tools have been designed to detect sharp peaks (TF binding, histone modifications at regulatory elements)



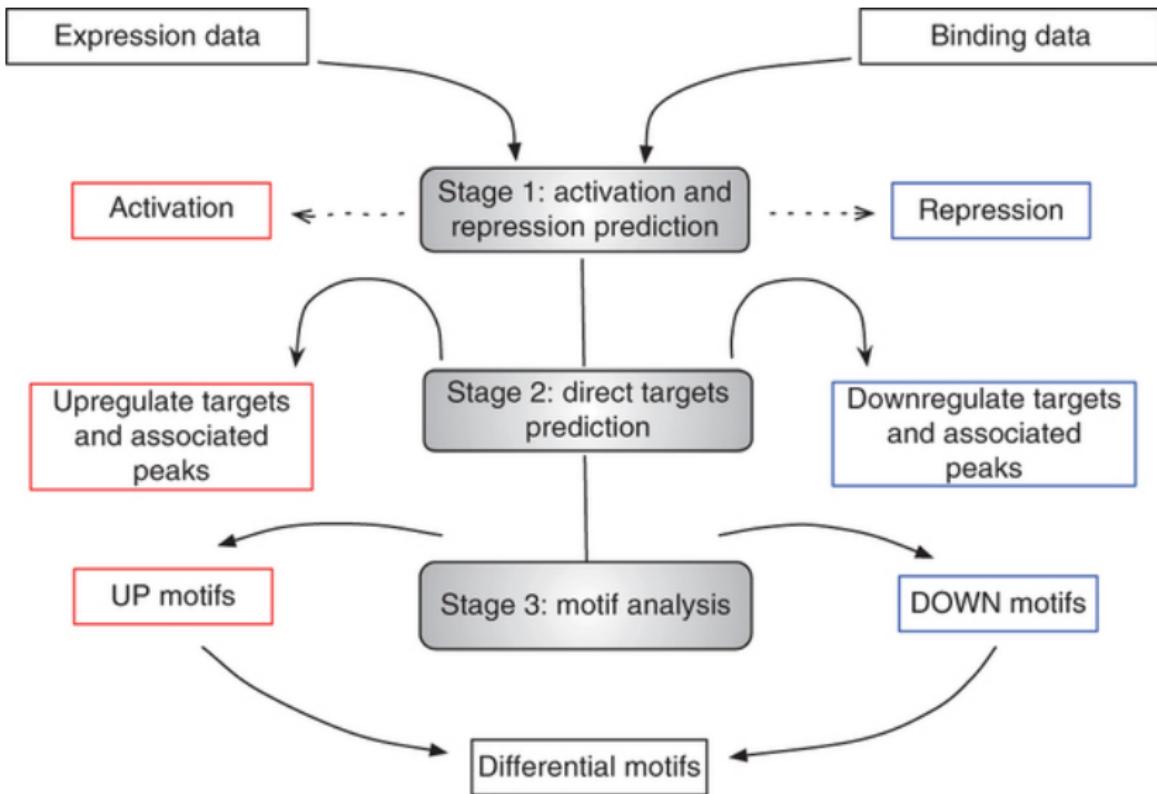
# 顺反组 | ChIP-Seq | 分析 | 应用

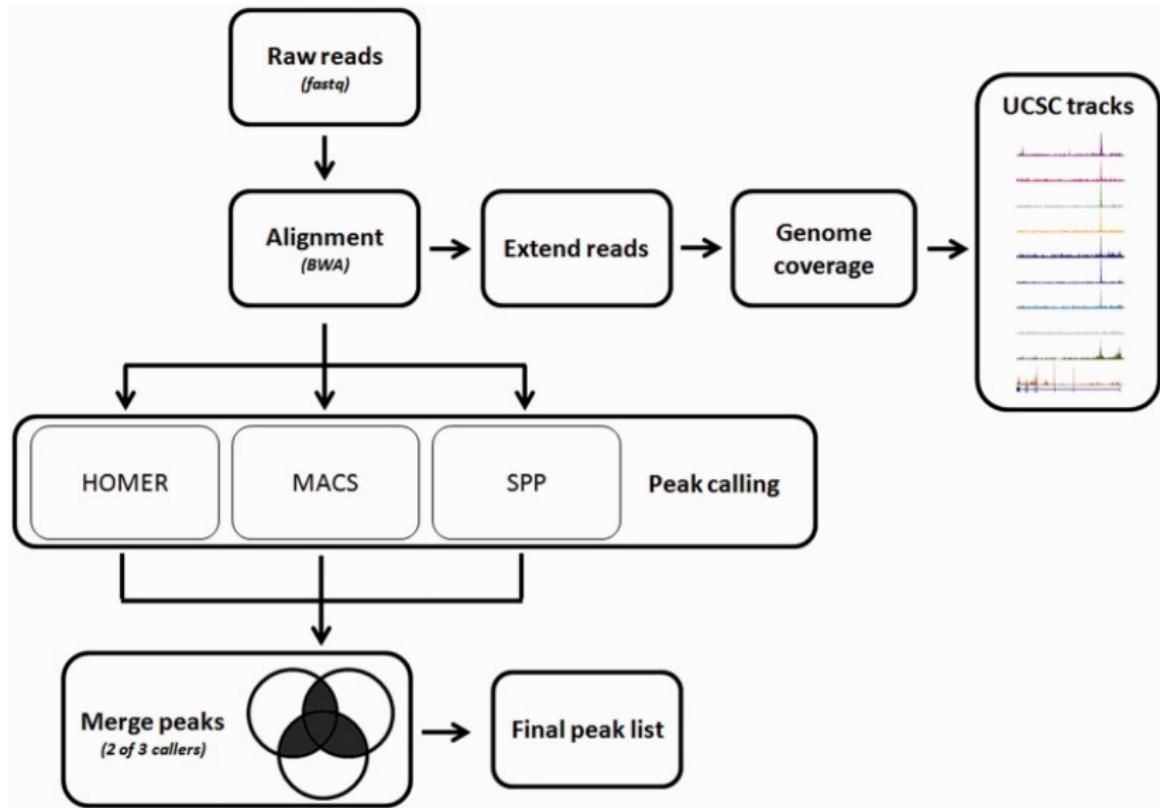


# 顺反组 | ChIP-Seq | 分析 | 应用



# 顺反组 | ChIP-Seq | 分析 | 应用





## MACS

Model-based Analysis of ChIP-Seq (MACS) empirically models the length of the sequenced ChIP fragments, which tends to be shorter than sonication or library construction size estimates, and uses it to improve the spatial resolution of predicted binding sites. MACS also uses a dynamic Poisson distribution to effectively capture local biases in the genome sequence, allowing for more sensitive and robust prediction. MACS compares favorably to existing ChIP-Seq peak-finding algorithms, is publicly available open source, and can be used for ChIP-Seq with or without control samples.



## PeakSeq

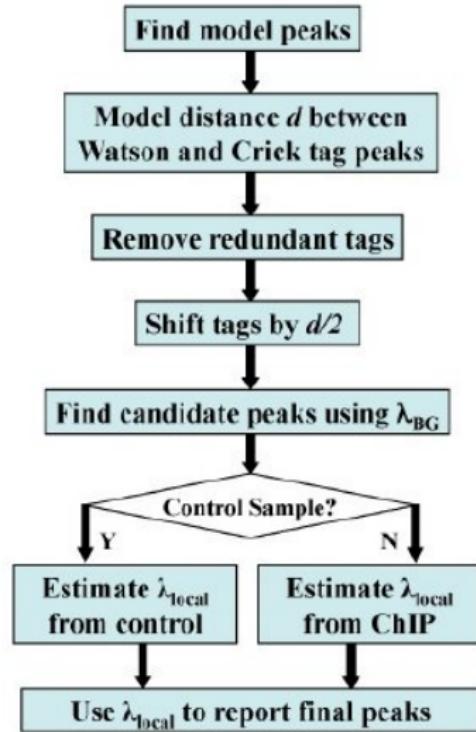
PeakSeq is a program for identifying and ranking peak regions in ChIP-Seq experiments. It takes as input, mapped reads from a ChIP-Seq experiment, mapped reads from a control experiment and outputs a file with peak regions ranked with increasing Q-values.



## HOMER

HOMER (Hypergeometric Optimization of Motif EnRichment) is a suite of tools for Motif Discovery and next-gen sequencing analysis. It is a collection of command line programs for unix-style operating systems written in Perl and C++. HOMER was primarily written as a *de novo* motif discovery algorithm and is well suited for finding 8-20 bp motifs in large scale genomics data. HOMER contains many useful tools for analyzing ChIP-Seq, GRO-Seq, RNA-Seq, DNase-Seq, Hi-C and numerous other types of functional genomics sequencing data sets.





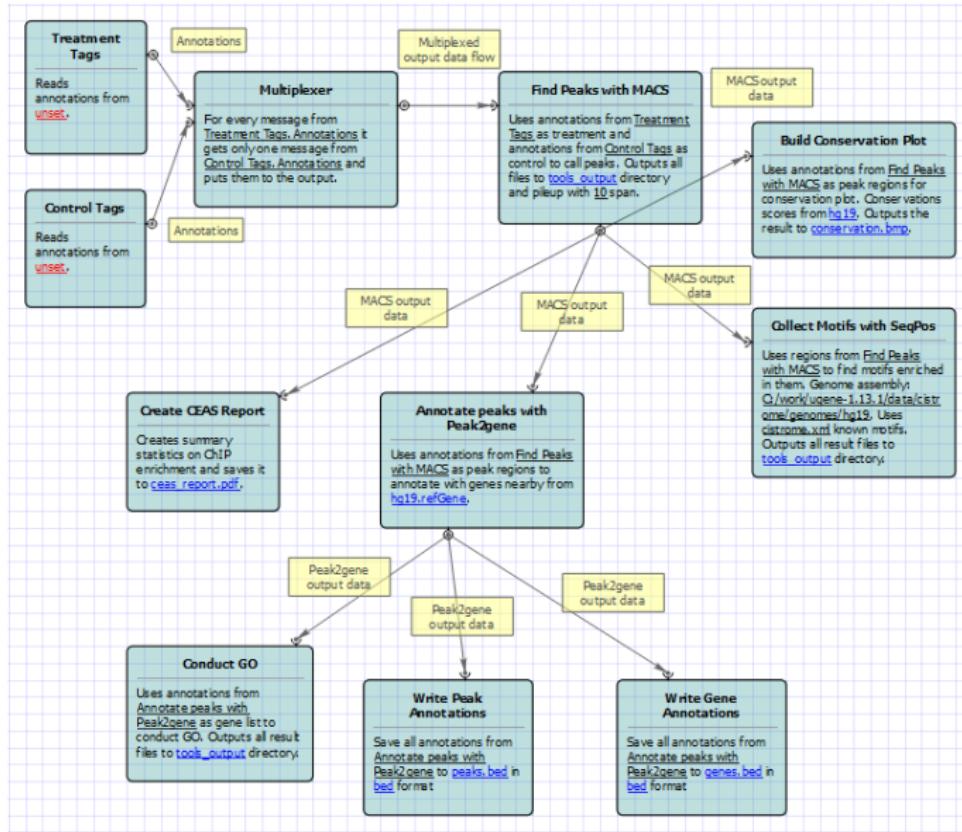
## MACS pipeline

### Output:

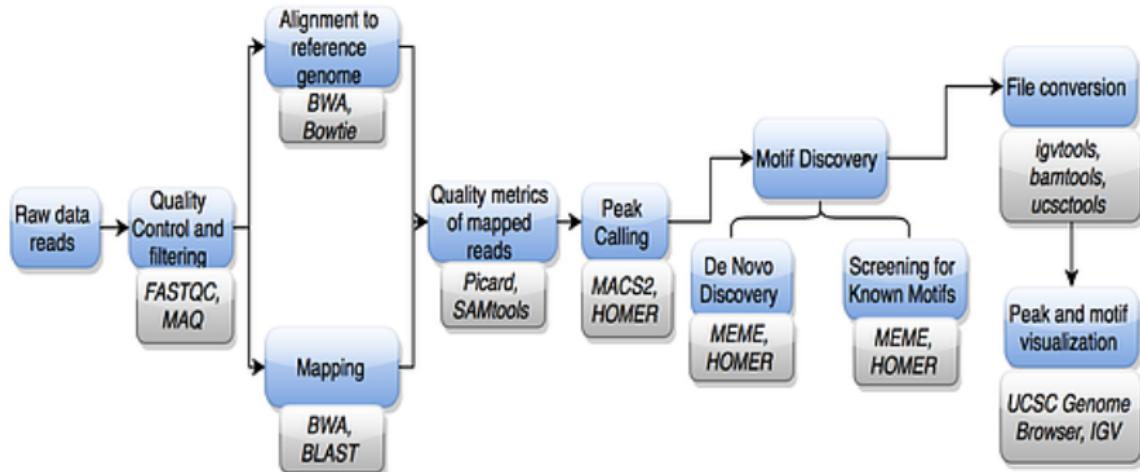
- Peak locations in BED and XLS format (genome browser)
- Tag count in wiggle format (genome browser)
- Bimodal model in R scripts



# 顺反组 | ChIP-Seq | 分析 | 工具 | MACS



## Motif Discovery and Analysis Using ChIP-seq



# The MEME Suite

Motif-based sequence analysis tools

**MEME Suite**  
4.11.2

► Motif Discovery

► Motif Enrichment

► Motif Scanning

► Motif Comparison

► Manual

► Guides & Tutorials

► Sample Outputs

► File Format Reference

► Databases

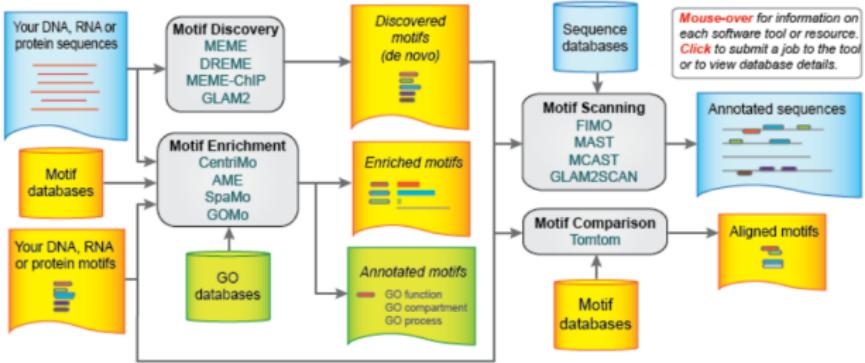
► Download & Install

► Help

► Alternate Servers

► Authors & Citing

► Recent Jobs



**MEME**  
Multiple Em for Motif Elicitation

**CentriMo**  
Local Motif Enrichment Analysis

**FIMO**  
Find Individual Motif Occurrences

**DREME**  
Discriminative Regular Expression Motif Elicitation

**AME**  
Analysis of Motif Enrichment

**MAST**  
Motif Alignment & Search Tool

**MEME-ChIP**  
Motif Analysis of Large Nucleotide Datasets

**SpaMo**  
Spaced Motif Analysis Tool

**MCAST**  
Motif Cluster Alignment and Search Tool

**GLAM2**  
Gapped Local Alignment of Motifs

**GOMo**  
Gene Ontology for Motifs

**GLAM2Scan**  
Scanning with Gapped Motifs

**Tomtom**  
Motif Comparison Tool

**GT-Scan**  
Identifying Unique Genomic Targets



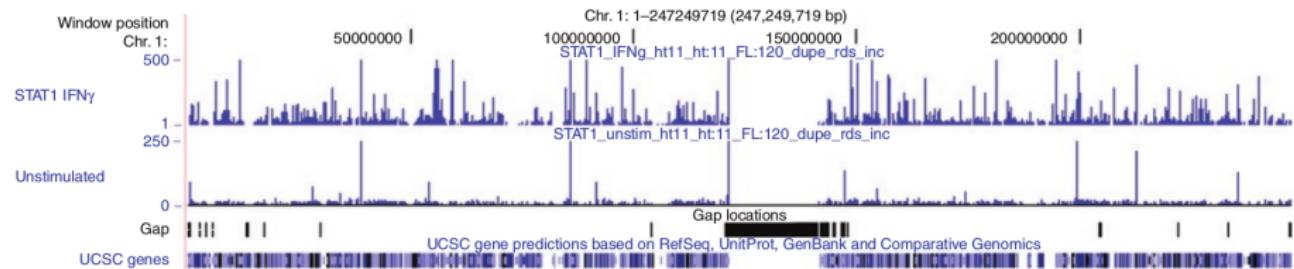
## Nature Methods, 2007

STAT1 DNA association: ChIP-seq was used to study STAT1 targets in HeLa S3 cells. The performance of ChIP-seq was then compared to the alternative protein-DNA interaction methods of ChIP-PCR and ChIP-chip.

ChIP-seq offers an alternative to ChIP-chip. STAT1 experimental ChIP-seq data have a high degree of similarity to results obtained by ChIP-chip for the same type of experiment, with >64% of peaks in shared genomic regions. Because the data are sequence reads, ChIP-seq offers a rapid analysis pipeline (as long as a high-quality genome sequence is available for read mapping, and the genome doesn't have repetitive content that confuses the mapping process) as well as the potential to detect mutations in binding-site sequences, which may directly support any observed changes in protein binding and gene regulation.

Robertson G et al.(2007) Genome-wide profiles of STAT1 DNA association using chromatin immunoprecipitation and massively parallel sequencing. Nature Methods 4: 651–657.

# 顺反组 | ChIP-Seq | 实例



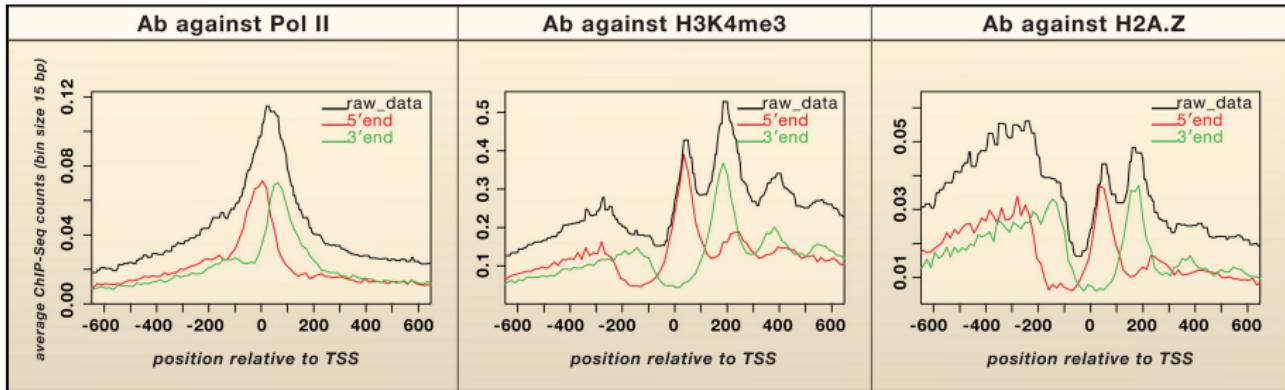
Cell, 2007

Nucleosome Architecture of Promoters: Using ChIP-seq, it was determined that Yeast genes seem to have a minimal nucleosome-free promoter region of 150bp in which RNA polymerase can initiate transcription.

Schmid et al. (2007) ChIP-Seq Data reveal nucleosome architecture of human promoters. Cell 131: 831–832



# 顺反组 | ChIP-Seq | 实例



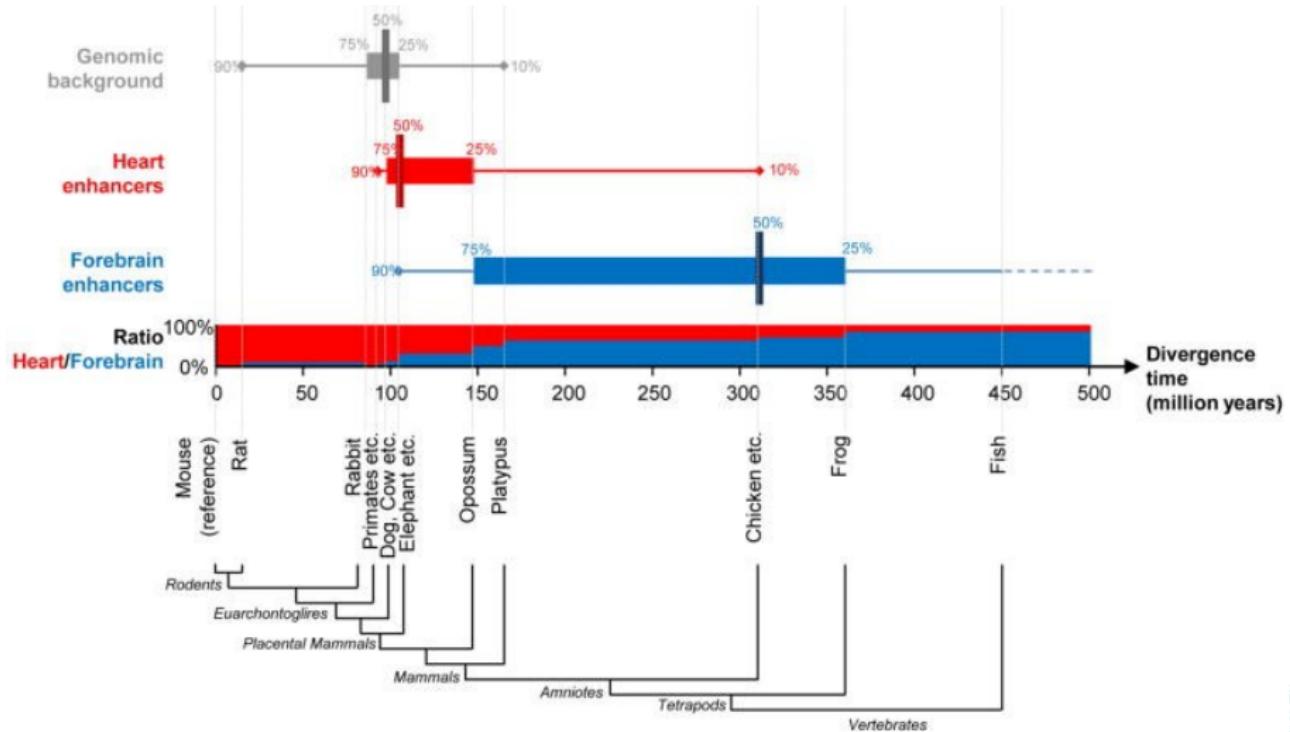
Nature Genetics, 2010

Transcription factor conservation: ChIP-seq was used to compare conservation of TFs in the forebrain and heart tissue in embryonic mice. The authors identified and validated the heart functionality of transcription enhancers, and determined that transcription enhancers for the heart are less conserved than those for the forebrain during the same developmental stage.

Blow, M. J., McCulley, D. J., Li, Z., Zhang, T., Akiyama, J. A., Holt, A., Plajzer-Frick, I., Shoukry, M., Wright, C., Chen, F., Afzal, V., Bristow, J., Ren, B., Black, B. L., Rubin, E. M., Visel, A., & Pennacchio, L. A. (2010). ChIP-seq identification of weakly conserved heart enhancers. Nature Genetics, 42, 806-810.



# 顺反组 | ChIP-Seq | 实例



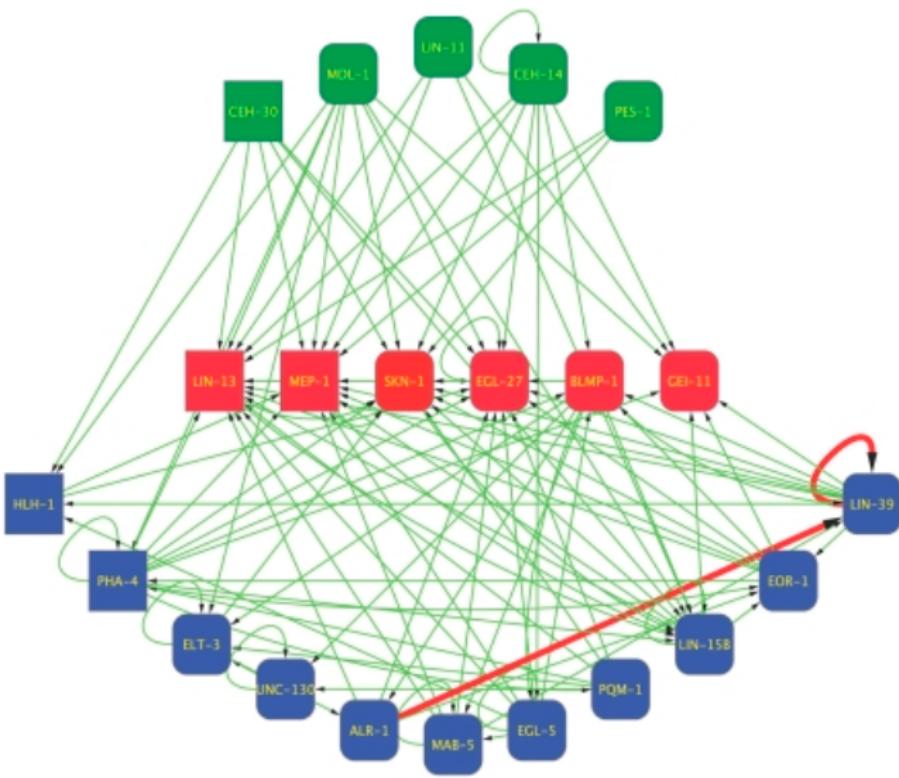
## Genome Research, 2011

Genome-wide ChIP-seq: ChIP-sequencing was completed on the worm *C. elegans* to explore genome-wide binding sites of 22 transcription factors. Up to 20% of the annotated candidate genes were assigned to transcription factors. Several transcription factors were assigned to non-coding RNA regions and may be subject to developmental or environmental variables. The functions of some of the transcription factors were also identified. Some of the transcription factors regulate genes that control other transcription factors. These genes are not regulated by other factors. Most transcription factors serve as both targets and regulators of other factors, demonstrating a network of regulation.

Niu, W., Lu, Z. J., Zhong, M., Sarov, M., Murray, J. I., Brdlik, C. M., Janette, J., Chen, C., Alves, P., Preston, E., Slightham, C., Jiang, L., Hyman, A. A., Kim, S. K., Waterston, R. H., Gerstein, M., Snyder, M., & Reinke, V. (2011). Diverse transcription factor binding features revealed by genome-wide ChIP-seq in *C. elegans*. *Genome Research*, 21, 245-254.



# 顺反组 | ChIP-Seq | 实例



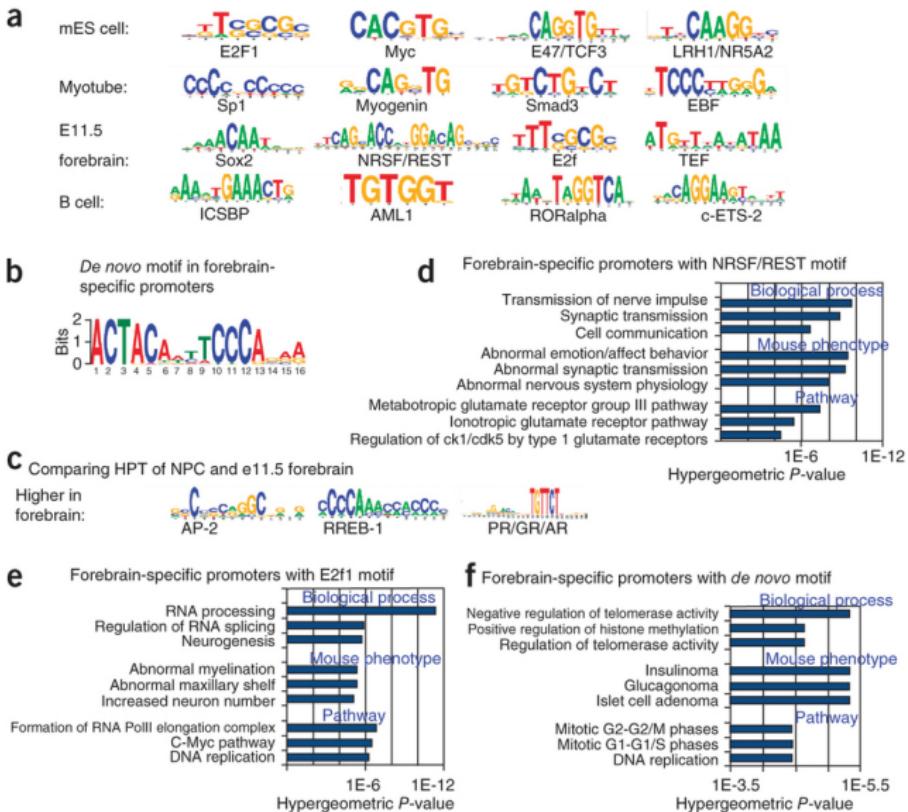
Nature Biotechnology, 2013

Inferring regulatory network: ChIP-seq signal of Histone modification were shown to be more correlated with transcription factor motifs at promoters in comparison to RNA level. Hence author proposed that using histone modification ChIP-seq would provide more reliable inference of gene-regulatory networks in comparison to other methods based on expression.

Vibhor Kumar, Masafumi Muratani, Nirmala Arul Rayan, Petra Kraus, Thomas Lufkin, Huck Hui Ng and Shyam Prabhakar. Uniform, optimal signal processing of mapped deep-sequencing data. Nature biotechnology, 2013.



# 顺反组 | ChIP-Seq | 实例



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- 组学概述
- 转录组学
- 研究方法

## 2 RNA-Seq

- 概述
- 技术简介
- 数据分析
- 应用实例

## 3 顺反组

- 概述
- ChIP-Seq

## 4 表观遗传学

- 概述
- Methyl-Seq

## 5 回顾与总结

- 总结
- 思考题



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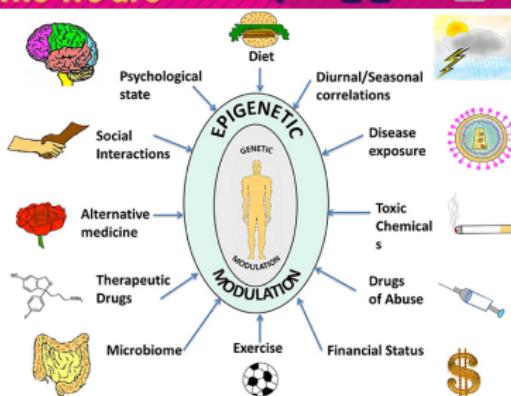
## 5 回顾与总结

- 总结
- 思考题



# EPIGENETICS

How the experiences  
of previous  
generations can  
affect who we are



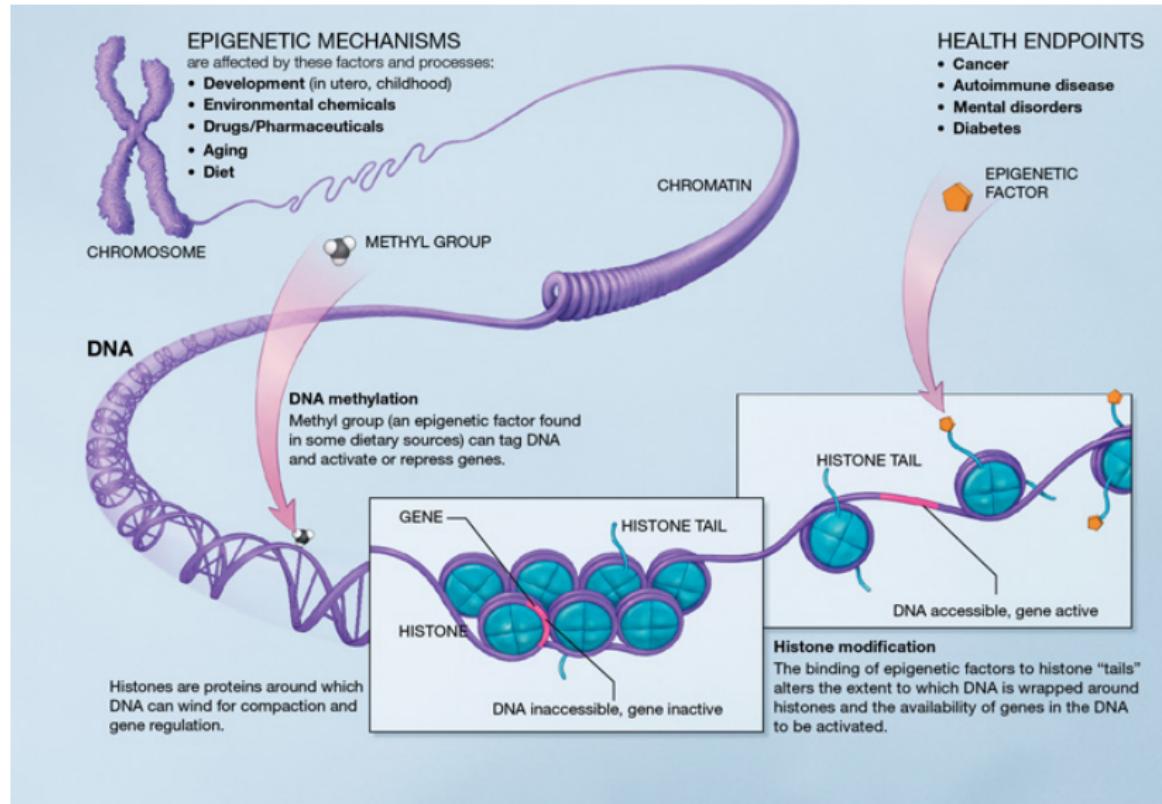
## 表观遗传学

表观遗传学 (epigenetics) 研究的是在不改变 DNA 序列的前提下，通过某些机制引起可遗传的基因表达或细胞表现型的变化。表观遗传学是 20 世纪 80 年代逐渐兴起的一门学科，是在研究与经典的孟德尔遗传学遗传法则不相符的许多生命现象过程中逐步发展起来的。

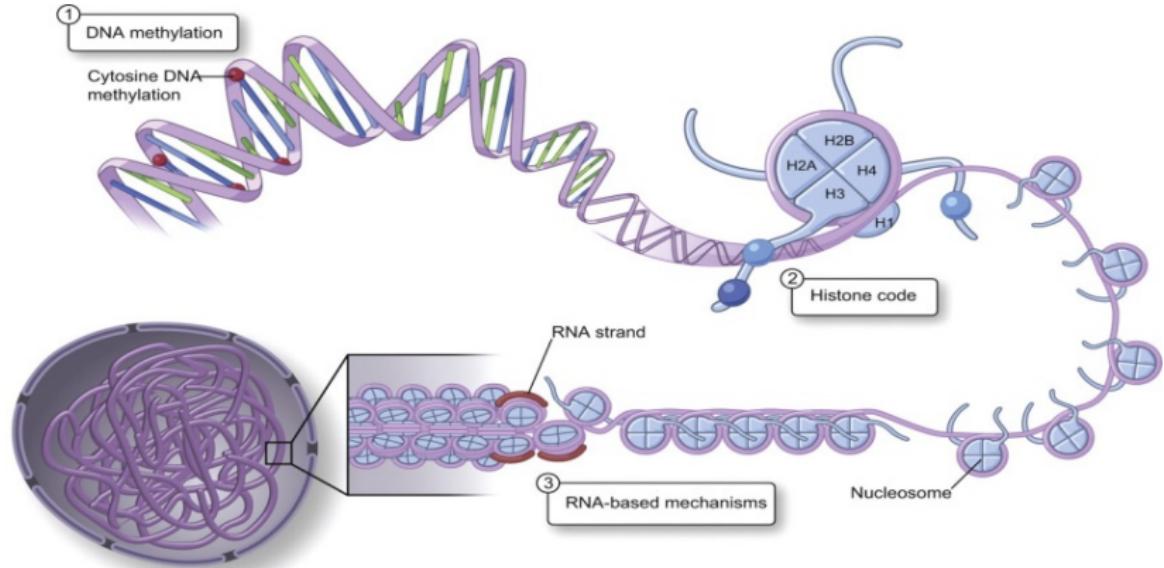
表观遗传现象包括 DNA 甲基化、组蛋白修饰、RNA 干扰等。与经典遗传学以研究基因序列影响生物学功能为核心相比，表观遗传学主要研究这些“表观遗传现象”建立和维持的机制。其研究内容主要包括两类，一类为基因选择性转录表达的调控，有 DNA 甲基化、基因印记、组蛋白共价修饰和染色质重塑；另一类为基因转录后的调控，包括基因组中非编码 RNA、微小 RNA、反义 RNA、内含子及核糖开关等。

表观遗传学指基因组相关功能改变而不涉及核苷酸序列变化，即“由染色体改变所引起的稳定的可遗传的表现型，而非 DNA 序列的改变”。

# 表观遗传学 | 简介



# 表观遗传学 | 简介



## DNA 甲基化

DNA 甲基化 (DNA methylation) 为 DNA 化学修饰的一种形式，能在不改变 DNA 序列的前提下，改变遗传表现。为外遗传编码 (epigenetic code) 的一部分，是一种外遗传机制。DNA 甲基化过程会使甲基添加到 DNA 分子上，例如在胞嘧啶环的 5' 碳上：这种 5' 方向的 DNA 甲基化方式可见于所有脊椎动物。特定胞嘧啶受甲基化的情形，可利用亚硫酸盐测序 (bisulfite sequencing) 方式测定。DNA 甲基化可能使基因沉默化，进而使其失去功能。

在人类细胞内，大约有 1% 的 DNA 碱基受到了甲基化。在成熟体细胞组织中，DNA 甲基化一般发生于 CpG 双核苷酸 (CpG dinucleotide) 部位；而非 CpG 甲基化则在胚胎干细胞中较为常见。

植物体内胞嘧啶的甲基化则可分为对称的 CpG (或 CpNpG)，或是不对称的 CpNpNp 形式 (C 与 G 是碱基；p 是磷酸根；N 指的是任意的核苷酸)。

## DNA 甲基化与肿瘤

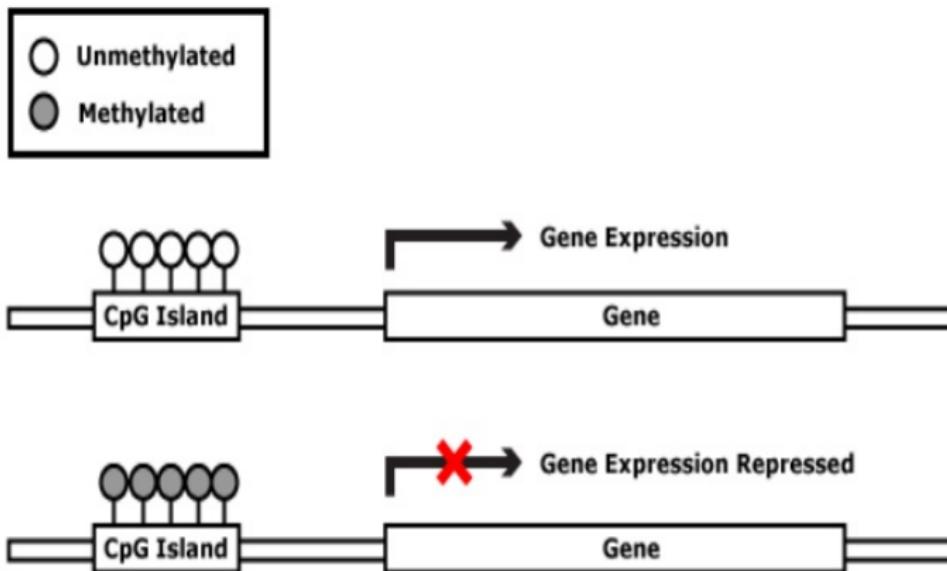
DNA 甲基化是一种基因转录的重要的调节器，许多证据已经证实，异常的 DNA 甲基化与不定期的基因沉默有关，若在启动子区域具有高水平的 5-甲基胞嘧啶，将发生基因沉默。

DNA 甲基化在胚胎发育期间是必需的，在体细胞中，DNA 甲基化的方式通常是高保真的传给子细胞。

异常的 DNA 甲基化模式与大量的人类恶性肿瘤有关，并发现其与正常组织相比存在两种不寻常的形式：超甲基化和低甲基化。超甲基化是主要的表观遗传修饰中的一种，其通过肿瘤抑制基因的启动子区抑制转录。超甲基化通常发生在启动子区的 CpG 岛，且与基因失活有关。整体的低甲基化也通过不同机制与癌症的发生和发展有关。



## DNA Cytosine Methylation



Mettivier, R. et al. Cyclical DNA methylation of a transcriptionally active promoter. *Nature* 452, 45–50 (2008).



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- 数据分析
- 应用实例

## 3 顺反组

- 概述
- ChIP-Seq

## 4 表观遗传学

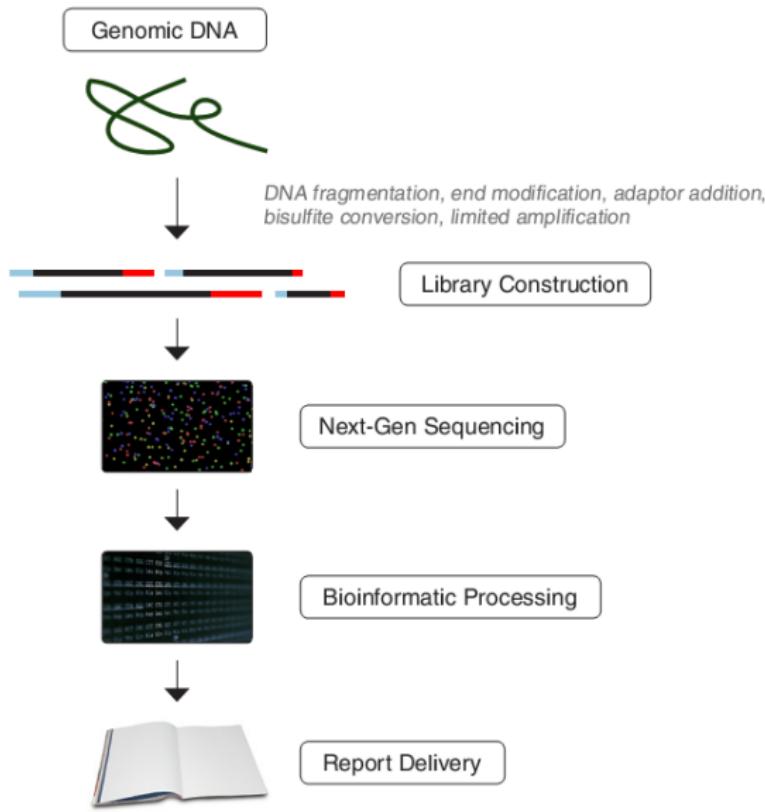
- 概述
- Methyl-Seq

## 5 回顾与总结

- 总结
- 思考题

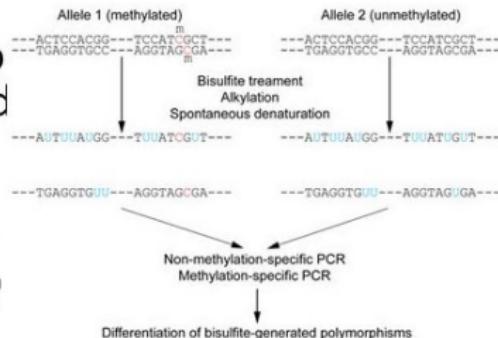
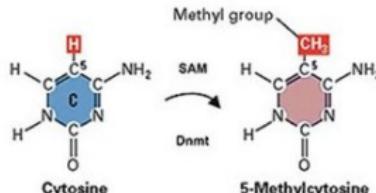


# 表观遗传学 | Methyl-Seq | 分析 | 流程



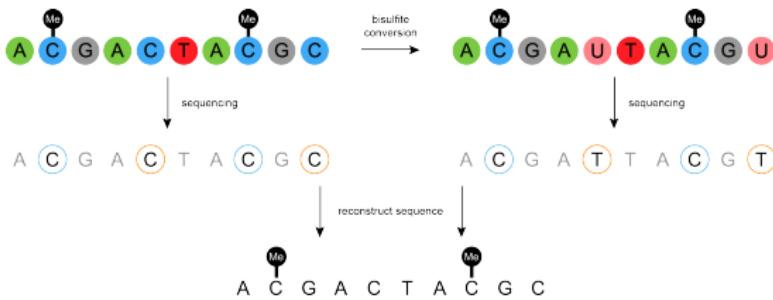
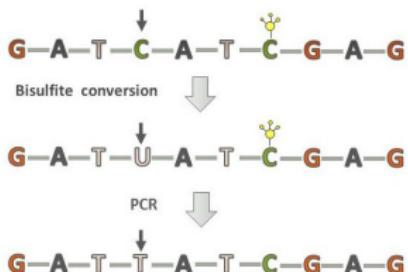
# Bisulfite sequencing

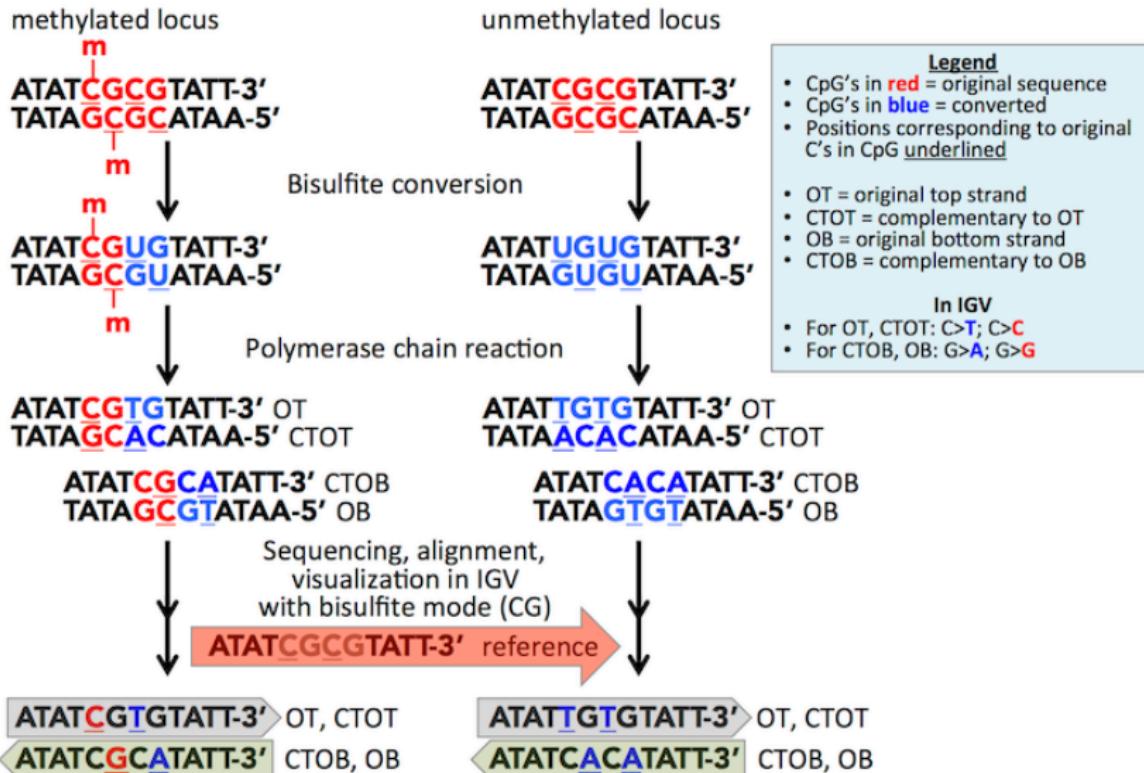
- To find out cytosines methylated at the carbon-5 position
    - Usually occurring at CpG, CpHpG and CpHpH nucleotide patterns

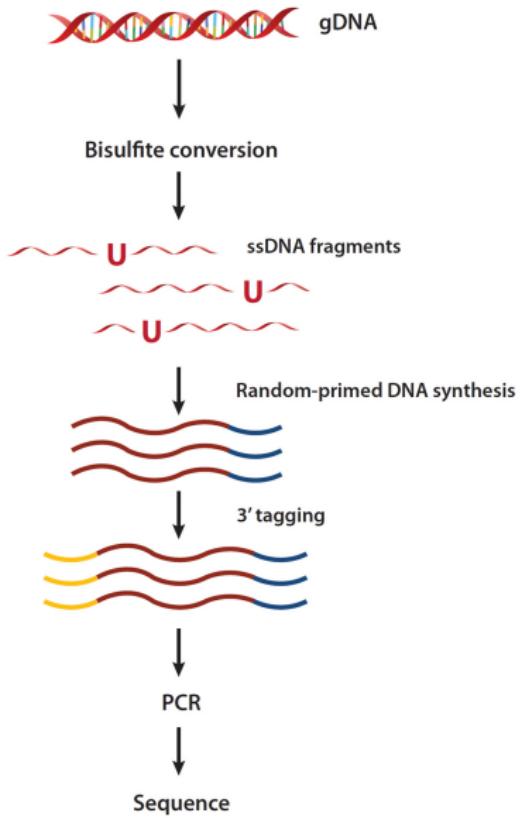


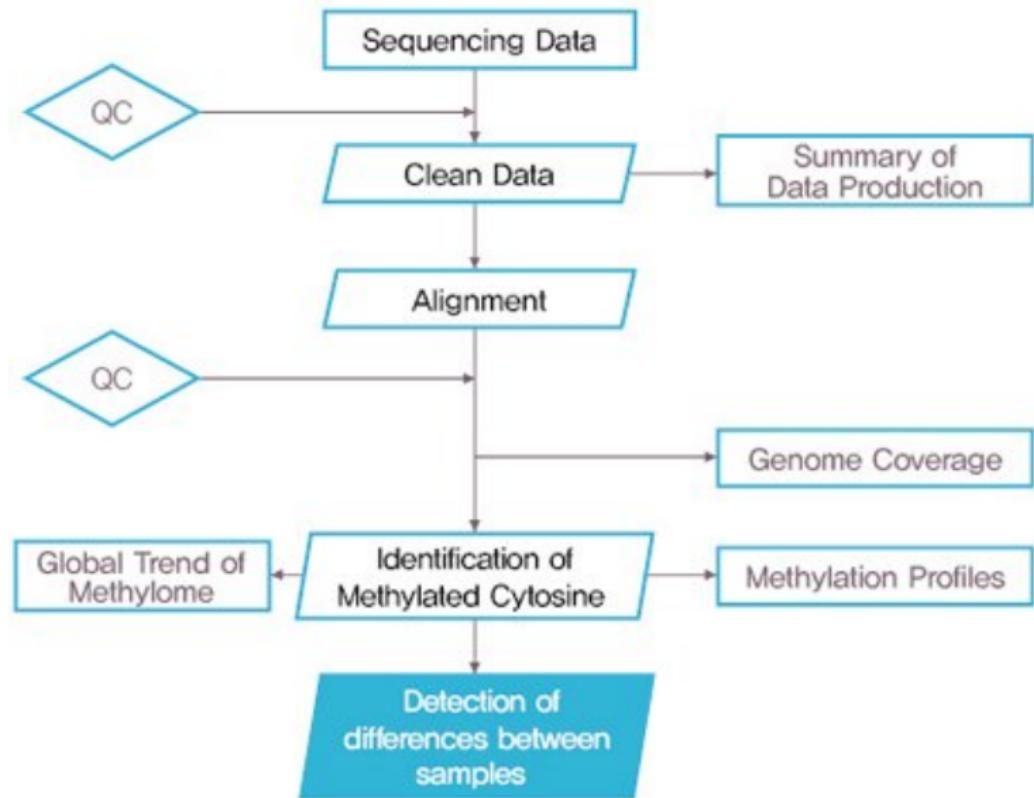
## METHYL-Seq

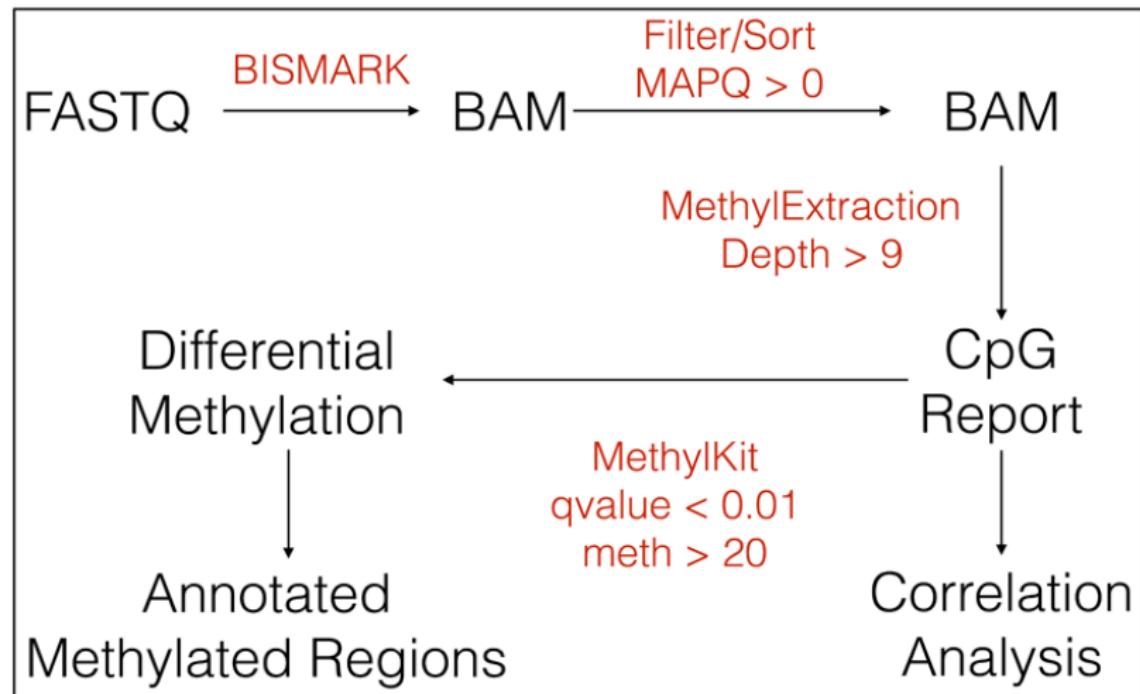
- Bisulfite Conversion



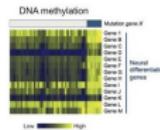
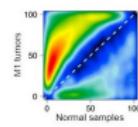
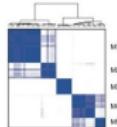
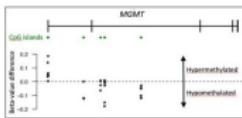








## Advanced methylation analysis



Data QC & visualization



Integration of  
methylation rate



Classification of  
methylation profiles

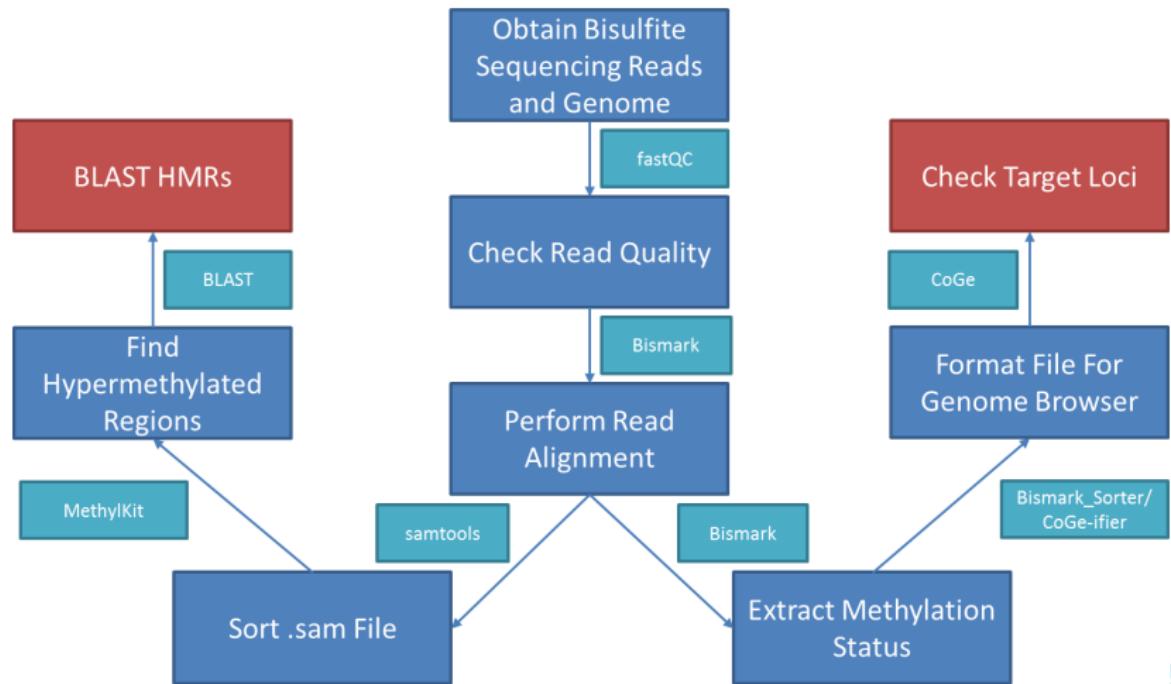


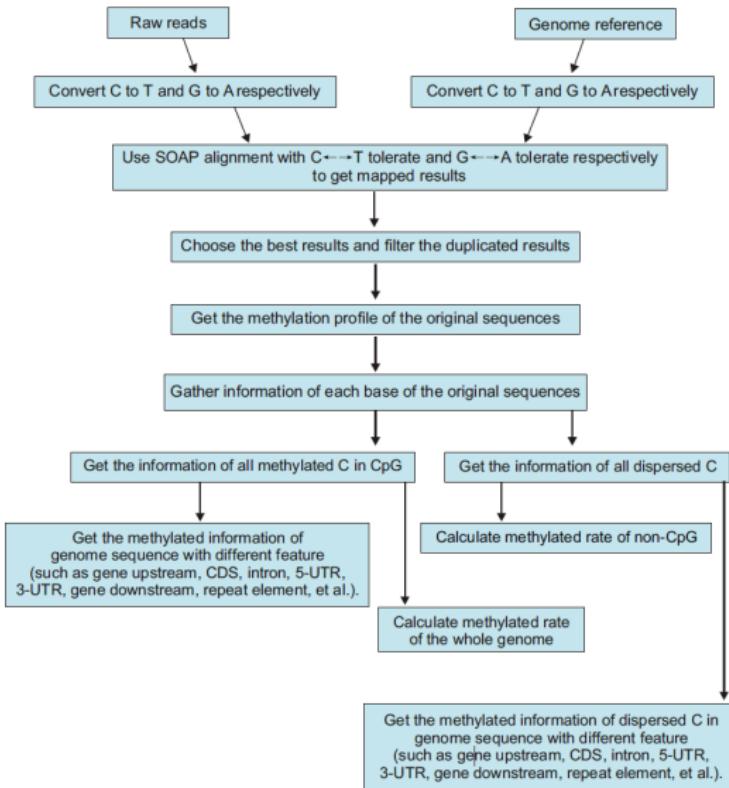
Differential methylation  
analysis



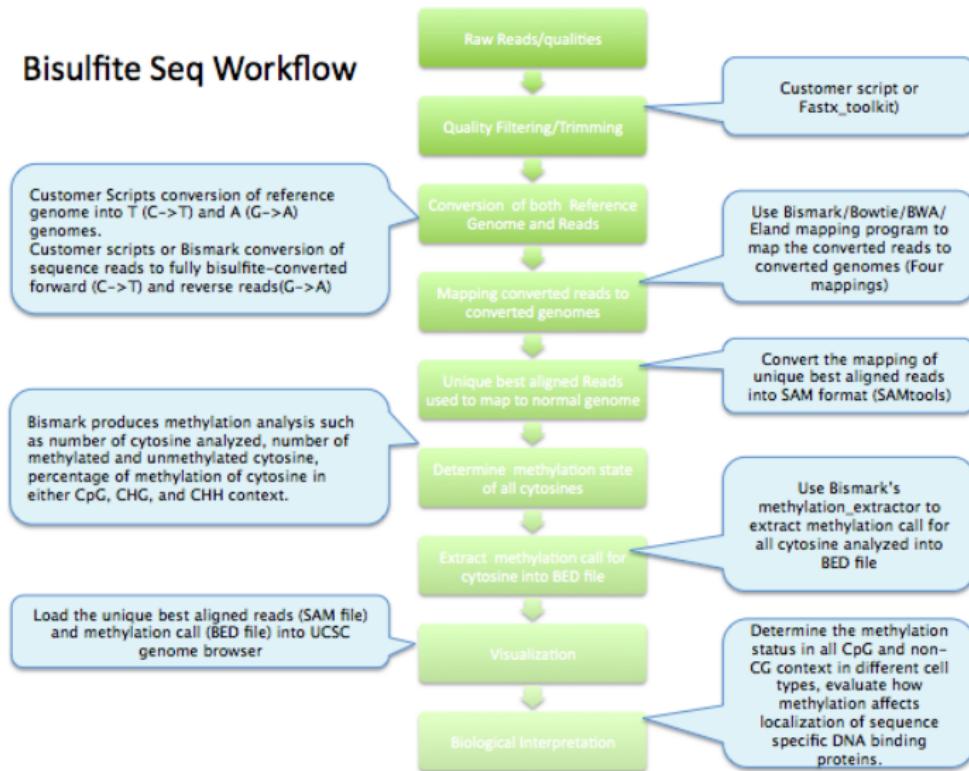
Pathways analysis,  
DMRs localization...

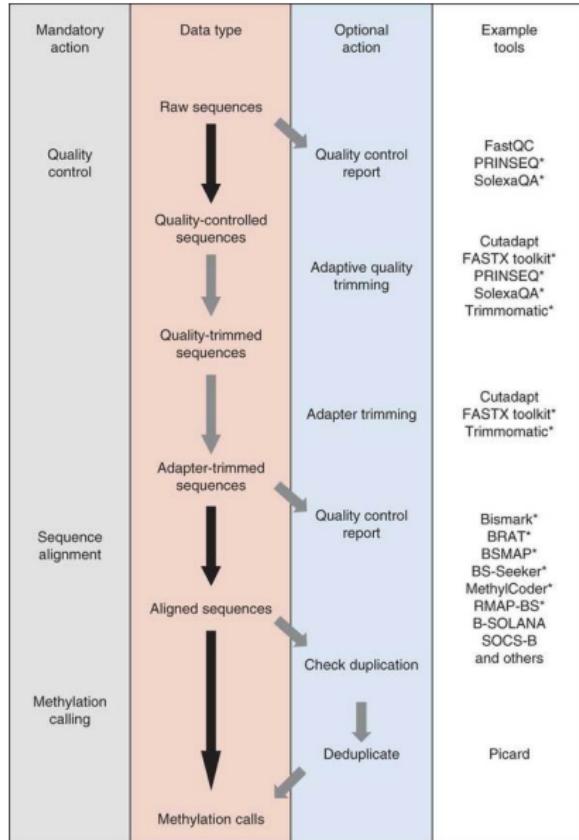




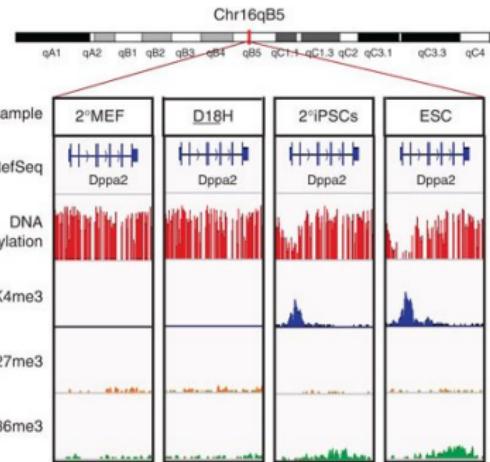
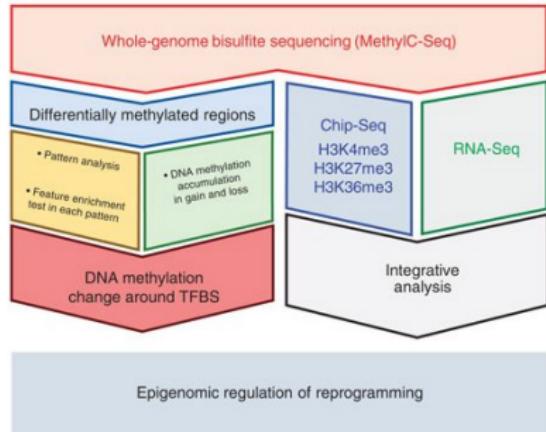


## Bisulfite Seq Workflow





# 表观遗传学 | Methyl-Seq | 分析 | 应用



## Bismark

Bismark is a program to map bisulfite treated sequencing reads to a genome of interest and perform methylation calls in a single step. The output can be easily imported into a genome viewer, such as SeqMonk, and enables a researcher to analyse the methylation levels of their samples straight away.

## bwa-meth

Fast and accurate alignment of BS-Seq reads.

## methylKit

methylKit is an R package for DNA methylation analysis and annotation from high-throughput bisulfite sequencing. The package is designed to deal with sequencing data from RRBS and its variants, but also target-capture methods such as Agilent SureSelect methyl-seq. In addition, methylKit can deal with base-pair resolution data for 5hmC obtained from Tab-seq or oxBs-seq. It can also handle whole-genome bisulfite sequencing data if proper input format is provided.

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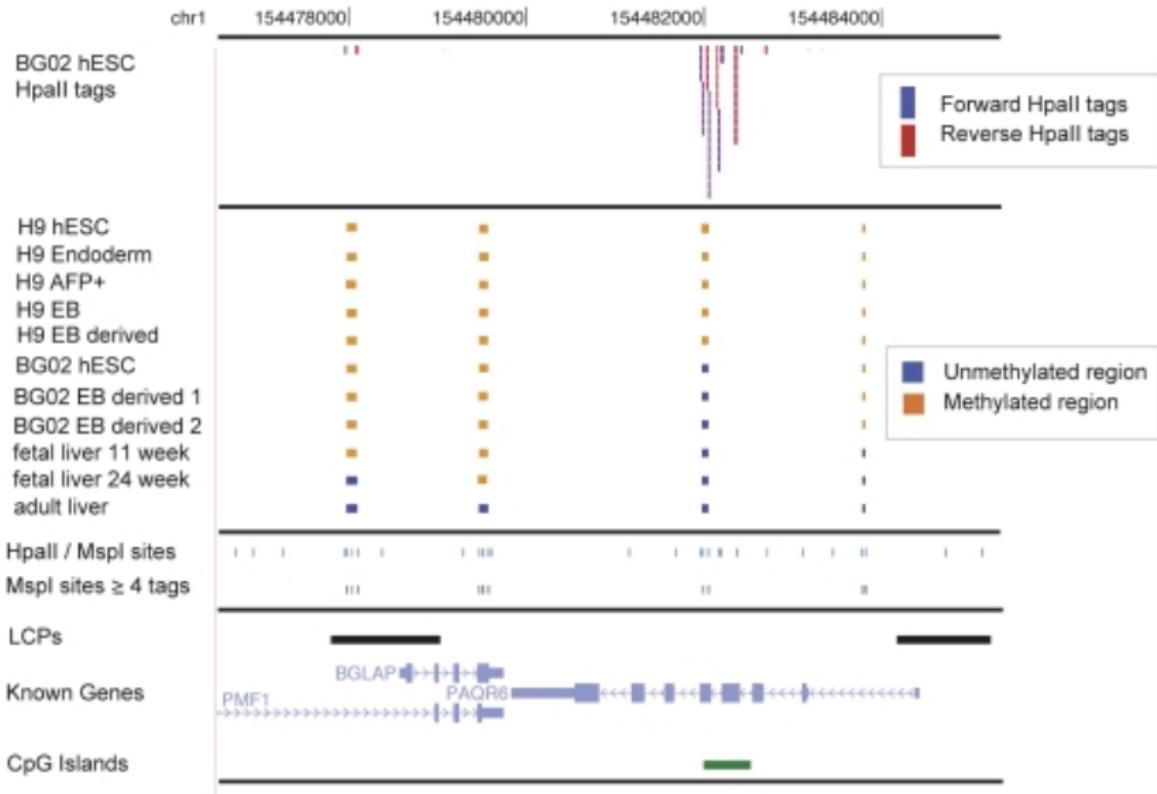
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## Genome Research, 2009

To investigate the role of DNA methylation during human development, we developed Methyl-seq, a method that assays DNA methylation at more than 90,000 regions throughout the genome. Performing Methyl-seq on human embryonic stem cells (hESCs), their derivatives, and human tissues allowed us to identify several trends during hESC and *in vivo* liver differentiation. Taken together, our results indicate that hESC differentiation has a unique DNA methylation signature that may not be indicative of *in vivo* differentiation.

Brunner AL, Johnson DS, Kim SW, Valouev A, Reddy TE, Neff NF, et al. Distinct DNA methylation patterns characterize differentiated human embryonic stem cells and developing human fetal liver. *Genome Res.* 2009;19: 1044–1056.

# 表观遗传学 | Methyl-Seq | 实例



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## 知识点

- 转录组学：定义，研究内容，研究方法
- RNA-Seq：实验流程，分析流程，主要应用
- RNA-Seq 数据分析：基本术语（RPKM/FPKM/TPM），常见工具，Tuxedo 套装
- 顺反组：定义，ChIP-Seq（流程，工具，Peak calling，应用）
- 表观遗传学：定义，Methyl-Seq（流程，工具）

## 技能

- 掌握 Tuxedo 套装的使用方法
- 对 RNA-Seq 测序数据进行完整分析
- 对 ChIP-Seq 测序数据进行完整分析
- 对 Methyl-Seq 测序数据进行完整分析

## 1 转录组学概述

- 组学概述
- 转录组学
- 研究方法

## 2 RNA-Seq

- 概述
- 技术简介
- 数据分析
- 应用实例

## 3 顺反组

- 概述
- ChIP-Seq

## 4 表观遗传学

- 概述
- Methyl-Seq

## 5 回顾与总结

- 总结
- 思考题



- ① 列举常见的组学并进行简介。
- ② 什么是转录组、转录组学？
- ③ 总结转录组学的研究内容和研究方法。
- ④ 总结 RNA-Seq 的实验流程和分析步骤。
- ⑤ 列举 RNA-Seq 的主要应用。
- ⑥ 举例说明 RPKM/FPKM/TPM 的计算方法。
- ⑦ 列举 RNA-Seq 数据分析的常用工具。
- ⑧ 简介 Tuxedo 套装中的各个组件。
- ⑨ 什么是顺反组、表观遗传学？
- ⑩ 总结 ChIP-Seq 的实验流程和分析步骤。
- ⑪ 总结 Methyl-Seq 的实验流程和分析步骤。



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