Introduction to Bioinformatics and Computational Biology

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Chapter 1

Course information

This is the course material for STAT115/215 BIO/BST282 at Harvard University.
All the YouTube videos in this course are organized under the 2021 STAT115 playlist.

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Chapter 2

Introduction

2.1 Brief history of bioinformatics

2.1.1 Protein structure wave

2.1.2 Gene expression wave

2.1.3 Genome sequencing wave

2.1.4 Big data challenge from sequencing

2.2 Should I take this course?

2.2.1 Bioinformatics vs computational biology

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2.3.1 Logistics

2.3.2 X Shirley Liu lab introduction

2.4 Lab 1

2.4.1 Introduction

2.4.2 Introduction to R

2.4.3 Introduction to Bash

2.4.4 Getting started with Cannon

Chapter 3

High throughput sequencing

3.1 Three generations of sequencing technologies

First generation sequencing is Sanger sequencing. It is the technology that was used to obtain the first human genome sequence.

Second generation sequencing is also called next generation sequencing (NGS) and is the start of high throughput sequencing. It is what scientists use most often nowadays, and Illumina is the market leader. Most of the rest of this course will cover data analysis using second generation sequencing.

Third generation sequencing is single-molecule sequencing. There are many new technologies still under active development, although none has reached market penetration.

3.2 FASTQ and FASTQC

NGS generates FASTQ files. FASTQC is an computational approach to evaluate the quality of your NGS data.

3.3 Early sequence alignment (1 with 1)

In the early days (1970s), scientists were not worried about having to align too many sequences. They wanted to find the best alignment between two

sequences. Many bioinformatics courses start with learning these, although it is not the main focus of our course. We included two videos in case you are interested.

The Needlemen-Wunsch algorithm is the earliest algorithm to find the alignment between two sequences and score their similarity.

When two sequences are long, and only a portion of them can align well with each other, the Smith-Waterman algorithm can find the best local sequence alignment. It is still considered the best alignment approach, although it is slow.

3.4 Sequence search algorihtms (1 with many)

With more and more sequences available in the public in the 1980s, scientists were interested in finding whether their newly sequenced string has been sequenced before in the public database. Therefore, the fast search algorithm BLAST was developed, using one sequence as the query to find similar sequences from a database.

3.5 Borrow-Wheeler Aligner (many with many)

With NGS, scientists need much faster search (aka mapping) algorithms in order to align the millions of sequences to the reference genome. The current best algorithm is called Borrow-Wheeler Aligner or BWA.

In order to understand BWA, we first need to introduce Borrows-Wheeler transformation and LF mapping

The basic idea of Borrows-Wheeler alignment

3.6 Alignment output

NGS raw data is in FASTQ. Alignment gives you SAM (alignment) or BAM (binary version of SAM) files which contain the sequence information in FASTQ and the mapping locations. BED file is the simpliest, although there is information loss.

Chapter 4

RNA-seq Quantification

4.1 Introduction to RNA-seq experiment

4.2 RNA quality control and experimental design

4.3 Alignment

4.4 RNA-seq QC

4.5 RNA-seq expression index

4.6 RSEM and Salmon

4.7 RNA-seq read distribution

4.8 Lab 2

4.8.1 STAR tutorial

4.8.2 RSeQC tutorial

4.8.3 RSEM/Salmon Tutorial

Chapter 5

Differential expression, FDR, GO, and GSEA

DESeq2 is a popular and accurate computational algorithm to detect differential gene expression from RNA-seq data. It includes many elegant quantitative considerations, such as:

- Normalize the gene read counts by library size and composition
- Model gene read counts with negative binomial distribution
- Use hierarchical modeling to stabilize the gene variance
- Use Benjamini-Hochberg to calculate control for false discovery rate of calling differentially expressed genes
- Filter lowly expressed genes to reduce the number of hypotheses to be tested

5.1 DESeq2 library normalization

5.2 DESeq2 variance stabilization

5.3 Multiple hypotheses testing and False Discovery Rate

5.4 DESeq2 gene filtering

5.5 Gene Ontology (GO analysis)

5.6 Gene Set Enrichent Analysis (GSEA)

5.7 DESeq2 tutorial

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Clustering

6.1 Heatmap and clustering quality

6.2 Hierarchical cluster

6.3 K means cluster

6.4 Pick K and consensus clustering

6.5 Batch effect removal

6.6 Lab3

6.6.1 PCA tutorial

6.6.2 Clustering tutorial

6.6.3 Combat tutorial

6.6.4 DESeq2 Tutorial

6.6.5 DAVID/GSEA Tutorial

Chapter 7

Dimension Reduction

RNA-seq samples have tens of thousands of genes, although many genes might not vary much between samples and many others have correlated gene expression. Dimension reduction techniques aim to reduce the dimension of representing each sample with tens of thousands of genes to much fewer demensions, e.g. 2 to 100.

7.1 Principal Component Analysis: idea behind PCA.

PCA / SVD automatically outputs PC1, PC2, PC3, etc, with earlier PCs capturing the highest level of variability in the original data. Each PC is a linear combination of raw gene expression, and is orthogonal to all other PCs.

7.2 Principal Component Analysis: PCA applications.

PCA is a widely used method to project samples with high dimensions (e.g. with gene expression data) onto two dimensions for better visualization. It is an intuitive way to identify sample clusters, and identify batch effect.

7.3 Multidimensional Scaling (MDS)

MDS can use differential ways to calculate pair-wise distance, then use lower dimensions to satisfy the pair-wise distance. PCA is a special case of MDS.

7.4 Linear discriminant Analysis (LDA)

LDA is not only a dimension reduction method, but also a supervised machine learning method.

Chapter 8

Classification

8.1 Introduction

Imagine you have RNA-seq of a collection of labeled normal lung and lung cancer tissues. Given a new sample of RNA-seq from the lung with unknown diagnosis, will you be able to predict based on the existing labeled samples and the expression data whether the new sample is normal or tumor? This is a sample classification problem, and it could be solved using **unsupervised** and **supervised** learning approaches.

Unsupervised learning is basically clustering or dimension reduction. You can use hierarchical clustering, MDS, or PCA. After clustering and projection the data to lower dimensions, you examine the labels of the known samples (hopefully they cluster into separate groups by the label). Then you can assign label to the unknown sample based on its distance to the known samples.

Supervised learning considers the labels with known samples and tries to identify features that can separate the samples by the label. Cross validation is conducted to evaluate the performance of different approaches and avoid over fitting.

StatQuest has done an amazing job with machine learning with a full playlist of well organized videos. While the full playlist is worth a full course, for the purpose of the course, we will just highlight a number of widely used approaches. They include logistic regression (this is considered statistical machine learning), K nearest neighbors, random forest, and support vector machine (these are considered computer science machine learning).

8.2 Supervised learning

8.3 Cross validation

8.4 Regression

8.5 Regularization

8.5.1 Ridge regression

8.5.2 LASSO regression

8.5.2.1 LASSO tutorial in R

8.6 KNN

8.7 Decision trees

8.8 Random forest

8.9 SVM

8.10 Lab 4

8.10.1 K-Nearest Neighbors tutorial

8.10.2 Regression/Ridge/LASSO Tutorial

8.10.3 Logistic Regression Tutorial

8.10.4 Support Vector Machine Tutorial

8.10.5 Random Forest Tutorial

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Module I Review

9.1 Module I review

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9.3 Analysis Scenario 2

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Transcription Factor Motif Finding

Chapter 11

Transcription Factor Motif Finding

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ChIP-seq, Expression Integration

12.1 Motif finding in eukaryotes, and ChIP-seq

12.2 MACS and ChIP-seq QC

12.3 Identify TF interactions from ChIP-seq motifs

12.4 TF target genes and expression integration

12.5 Lab 5

12.5.1 MACS Tutorial

12.5.2 ChIP-seq QC Tutorial

12.5.3 TF Motif Finding Tutorial

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Epigenetics, DNA Methylation

13.1 Intro to DNA Methylation

13.2 DNA Methylation Pattern and Function

13.3 DNA Methylation in Diseases

13.4 Techniques to Measure DNA Methylation

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Histone Modifications , Chromatin Accessibility

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Epigenetics, DNA Methylation

15.1 Intro to DNA Methylation

15.2 DNA Methylation Pattern and Function

15.3 DNA Methylation in Diseases

15.4 Techniques to Measure DNA Methylation

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Long Range Chromatin Interactions

16.1 Chromatin interactions

16.2 HiC

16.3 HiC contact map

16.4 HiC normalization

16.5 Fractal globule

16.6 Loops

16.7 Domains

16.8 Compartments

16.9 Phase separation

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Hidden Markov Model

17.1 Intro to HMM

17.2 Pb1: Forward & backward procedure

17.3 Pb2: Viterbi algorithm

17.4 Pb3: Parameter estimation

17.5 HMM application

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Module II Review

18.1 Module II Review

18.2 Practive Questions

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SNP and GWAS

19.1 SNP and LD

19.2 Family-based vs case-control association studies

19.3 GWAS studies and catalog

19.4 GTEx and eQTL

Chapter 20

GWAS and Epigenomics

20.1 Find tissue / cell type

20.2 Identify causal SNPs and genes

20.3 Predict phenotypes

Chapter 21

Single-cell RNA-seq (1)

21.1 Intro to scRNA-seq

21.2 Smart, Droplet, microwell, SCI-based

21.3 QC

21.4 Normalization

21.5 Imputation

21.6 Dimension reduction

21.7 Clustering

21.8 t-SNE and UMAP

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Single-cell RNA-seq (2)

22.1 Annotate scRNA-seq clusters

22.2 Differential expression

22.3 Batch effect removal

22.4 Pseudotime

22.5 Overload 10X

22.6 Other applications (CITE-seq, multi-seq, spatial transcriptomics)

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scATAC-seq

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Module III Review

24.1 Module III Review

Chapter 25

Cancer Genome Sequencing , Mutation analyses

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Cancer Subtyping, Survival Analyses

26.1 TCGA expression

26.2 Tumor subtypes

26.3 Survival analysis

26.4 GoF Oncogenes and LoF TS

26.5 Chromatin regulator mutations in cancer

26.6 DNA methylation and CIMP

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Targeted Therapy, Drug Resistance, Compound and Genetic Screens

Chapter 28

Cancer Immunotherapy (1)

28.1 Systemic immunotherapy

28.2 Personalized immunotherapy

28.3 HLA and neoantigens

28.4 Tumor immune deconvolution

28.5 T cell signaling (PD1/PDL1, etc)

28.6 Other immune-cells (scRNA-seq)

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Cancer Immunotherapy (2)

29.1 TCR analysis

29.2 BCR analysis

29.3 Microbiome

29.4 Immunotherapy response biomarkers

29.5 Targeted therapy as immune-modulators

29.6 Epigenetic therapy as immune-modulators

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CRISPR Screens

Chapter 31

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31.1 Module IV Review

31.2 Course Review