

Comp683: Computational Biology

Lecture 1

January 8, 2025

Outline for Today

- Introductions
- Course Logistics
- Bioinformatics vs computational biology
- Exciting problems for computational biology → key experimental modalities and associated computational challenges.

Class Meetings, Course Webpage

- We meet here in Fred Brooks 007 on Mondays and Wednesdays from 9:05am-10:20am
- Office Hours will be from 1-2 on Mondays in SN305.
- Dynamically-updated coursepage:
<https://github.com/natalies-teaching/comp683-2025>
- The course fulfills the **Applications** requirement for CS students
- Notes will be available at least an hour before the lecture in the git repo

Introductions

Let's introduce ourselves with the following info.

- Name
- Department, Grad or Undergrad?
- One thing you are hoping to learn about here and/or research interests

Prerequisites [informally]

- This is a graduate CS course, so I will not assume any knowledge of biology
- Mathematical Foundations: comfortable with linear algebra and probability
- Strong Programming (one of Python, Julia, R)
- Comfortable reading and ideally implementing ideas from research papers
- Feel free to chat with me if you feel weaker in one area, but still think that the course is beneficial for you.

Helpful References

We will mostly use research papers as references. I have listed a few books on the course webpage. In general, I find the following the most helpful for the machine learning and linear algebra side of things.

- Pattern Recognition and Machine Learning by Chris Bishop <https://www.microsoft.com/en-us/research/uploads/prod/2006/01/Bishop-Pattern-Recognition-and-Machine-Learning-2006.pdf>
- The Matrix Cookbook <http://matrixcookbook.com/>
- Spectral Learning on Matrices and Tensors
<https://arxiv.org/abs/2004.07984>

Course Structure

- Syllabus outlining everything available here ¹.
- Canvas site for turning in homework, posted announcements, etc,
- Components of grade:
 - **HW:** 20% each, a mixture of programming and light math to practice implementing and interpreting output of methods we will discuss.
 - **Project Proposal:** 10%. This is a writeup of your proposed project and a presentation to the class.
 - **Project Writeup and Final Presentation:** 30%. You will turn in a writeup, link to your code, and present to the class.
 - **Reading Questions:** 15% (over the entire semester). Complete the assigned set of questions twice over the semester for two papers of your choice.
 - **Class Attendance and Participation:** 5% There are many ways to be engaged. Find a way to engage with the material and your classmates that best works for you.

¹https://github.com/natalies-teaching/comp683-2025/blob/main/Syllabus_2025.pdf

Course Project Overview [keep it on your mind!]

- The goal is to ask a question, implement an idea, and apply it to a biological dataset
- I have compiled a list of publicly available datasets here,
<https://github.com/natalies-teaching/comp683-2025/blob/main/datasets.md>
- You can either propose a new method, or apply existing methods on data and interpret the results.
- Feel free to work alone or in teams of 2-3.
- Come talk to me if you need some ideas.

Course Project Writeup (May turn into published paper!)

This will be good practice in writing up research and putting your results in context in comparison to what has already been done.

- **Proposal:** You will write up a brief document of your scientific question, how it relates to what has been done, and perhaps some preliminary results
- **Project Writeup:** This will be structured like a regular research paper and will include background, results, discussion, and a link to your code.
- **Presenting Proposals and Write-ups:** You will present your project proposals (mid-semester) as well as your final project (end of semester).
- **Code Belonging to Your Project:** Create a git repository for your project and create a README with an example to run your method on a subset of data or to reproduce at least some of your results.

Example Project - Predicting Time to Labor From CyTOF Data

A good type of single-cell related project is predicting some clinical outcome from multiple patients.

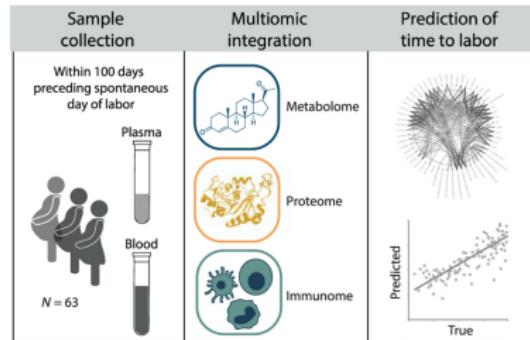


Figure: You would need to develop some approach to translate signals from either one modality or several into a model of time to labor. Image from <https://pubmed.ncbi.nlm.nih.gov/33952678/>.

Reading Summaries

You must complete this for twice over the semester for assigned papers.
Be prepared to participate in a discussion or to pose questions to your
classmates about these papers!

- Please explain in 2 sentences or less what the problem being solved is.
- What were the main contributions of the authors in this work? (You can answer in a few bullet points).
- Please describe 1-2 computational experiments that the authors implemented to test their method.
- Were the authors the first to attempt this particular problem? If not, did they compare their results to other baselines? Do you think that their evaluation was objective?
- Do you think that the authors provided enough evidence for why their developed method is an important contribution? If yes, please describe their reasoning here. If you do not think they adequately justified why they worked on this particular problem, please describe your thoughts on that here.
- What is one follow-up idea or extension from this work?

Homework

Two homework assignments, which will mostly be coding, visualization, and some light math. Homework can also be turned in through our sakai site.

- If I provide code to use with the homework assignment, it will be in Python. However you are free to submit your code in either Python, Julia, or R.
- Please submit your ultimate homework writeup as a PDF. I will provide a LaTeX template, but you can choose not to use it as necessary.

Homework Details, Continued

- You can send a link to your code (dropbox, google drive, git) labeled by hw problem, submit PDF writeup and code as zip, or if it is only a few lines you can paste it or add a screenshot to your writeup.
- It is ok to use thing implemented by other people (for example building a kNN graph using k-d tree, or PCA, etc). Just acknowledge where you got this code.
- ChatGPT: you can use it for syntax or to identify existing implementations of algorithms you might need. However, please write up your own solution yourself.

What is this course?

We will explore the mathematical foundations and theory of algorithms that commonly used to analyze modern biomedical datasets. This means that we will center lectures around a particular task, but dive into the mathematical and computational details as well.

What is this course (and what is it not)?

- This is **not** a course about bioinformatics pipelines or how to use packages
- This course does **not** serve as a comprehensive overview of computational biology and its evolution as a field
- The content here will be biased towards bioinformatics for single-cell data, the theory underneath the methods, combining datasets from multiple modalities, visualization, graph-representations of data, and how to benchmark and compare particular algorithms.
- Because we are combining theory with modern research, we will actively question what we are learning. (e.g. What could the authors have done better, are we convinced their approach is the best approach?)

Topic and Application Overview

- **Important Background:** Linear algebra, graph fundamentals, and graph signal processing.
- **Analysis of Single Cell Data:** Automated cell population discovery, imputation and batch effect correction, linking to external information, trajectory inference. Covering modalities such as flow and mass cytometry and single-cell RNA sequencing.
- **Benchmarking:** How do we objectively compare bioinformatics algorithms?
- **Combining Multiple Modalities:** How do we jointly represent biological samples or features?

Algorithms Span the Following Areas

- **Graph-based analysis of high-dimensional data.** We will get used to thinking about distances and how distances can be preserved. We will be frequently thinking about efficient ways to build graphs, diffusion on graphs, etc.
- **Numerical linear algebra.** Dimension reduction, matrix decomposition, spectral clustering, etc
- **Deep Learning.** We are at the beginning of a deep learning revolution in computational biology. It is just starting to make its entrance here (behind many other applications)

Let's get started with content now.

- A few examples of exciting advancements in technology, and how we can study biology.
- Bioinformatics vs computational biology
- Computational challenges and considerations in modern biology

Living in the high-throughput era of biomedicine

Several technologies exist with specific purposes. For example, they can be used to phenotype (identify) cells of particular types, study what the cells are secreting, or to understand spatial organizational patterns.

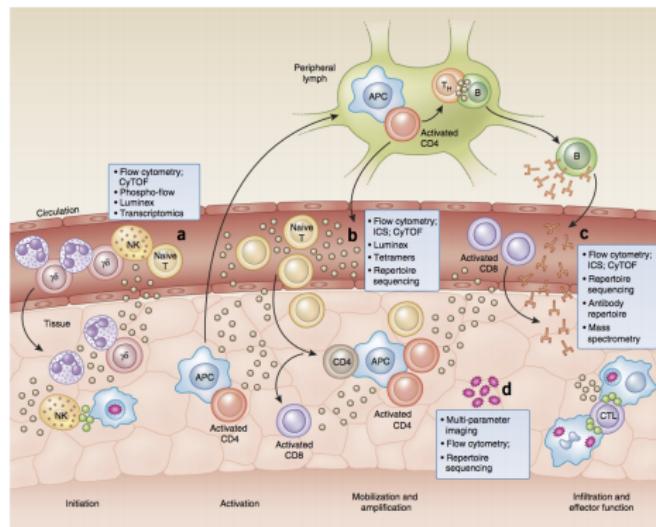


Figure: from Davis *et al.* 2018 'Systems Immunology, Just Getting Started'

Example : Studying the immune system gives rise to many problems in computational biology.

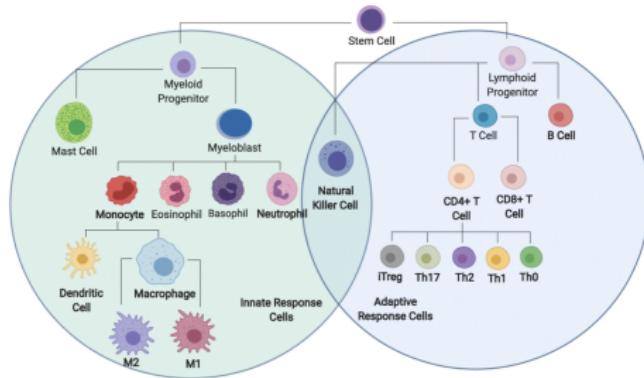


Figure: Torang *et al.* BMC Bioinformatics. 2019. Modern technologies help us to characterize the phenotype and function of these diverse immune cell types.

Single-Cell Data is a Dataset of Sets

In order to study the immune system, we must collect a lot of information.

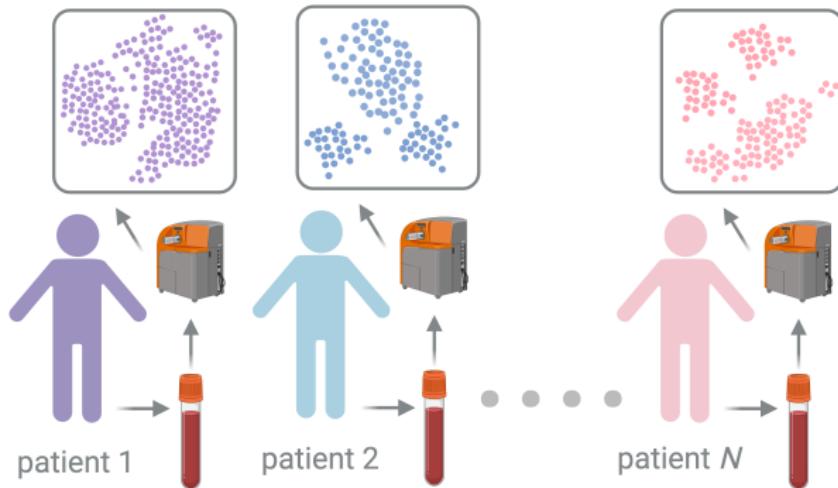


Figure: Each profiled sample contains many cells. Each cell is a d -dimensional feature vector.

Single-Cell Analysis to Understand COVID Severity

Single-cell gene and protein expression assays have been used in the past year to identify biomarkers of COVID severity.

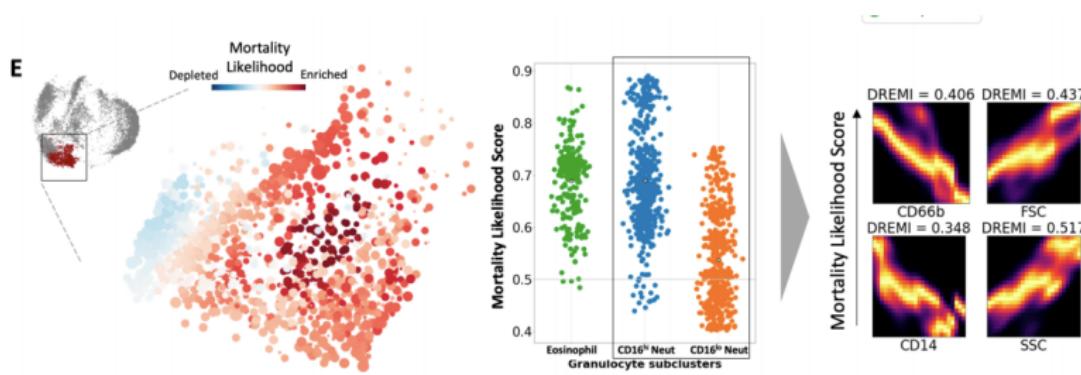


Figure: Kuchroo *et al.* Nature Biotechnology 2022. Understanding the Connection of Particular Cell-Populations with COVID severity.

Combining Multiple Biological Modalities

How do you determine a joint representation for a set of patients/samples/examples, according to multiple sources of information?

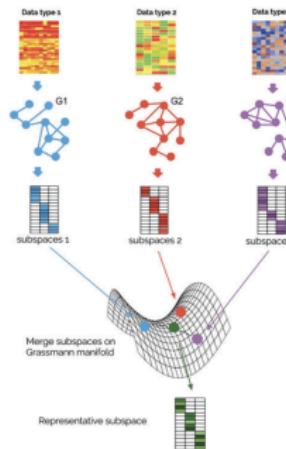


Figure: Ding *et al.* 2018. Bioinformatics.

Images of Tissues Coupled with Omics Measurements

Now we profile tissues with multiplexed imaging approaches to simultaneously measure several features in individual cells.

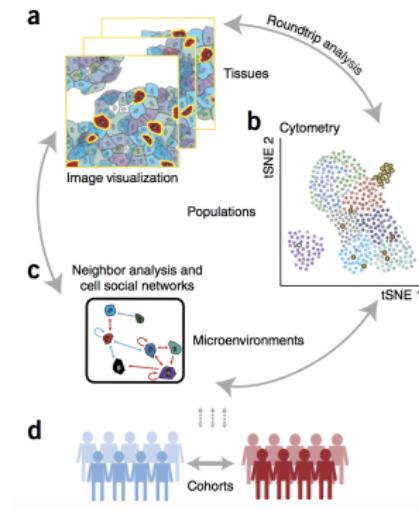


Figure: Schapiro *et al.* 2017. Nature Methods.

Spatial Proteomics as the 2024 Method of the Year.

Measure proteins in individual cells to infer how cells of particular types organize spatially and how this contributes to overall function.

[nature](#) > [nature methods](#) > [focus](#)

Focus | 10 December 2024

Method of the Year 2024: spatial proteomics

Spatial proteomics is our pick for Method of the Year 2024, for the impact that these technologies have had on the understanding of the organization, structure and function of complex tissues, including in global tissue atlas projects.



Figure: from Nature Methods

<https://www.nature.com/articles/s41592-024-02565-3>

Deep Learning Meets Structural Biology

- DeepMind used a deep learning approach to predict protein structure from amino acid sequence.
- Strong accuracy on this task can have important implications in applications, such as, drug discovery.

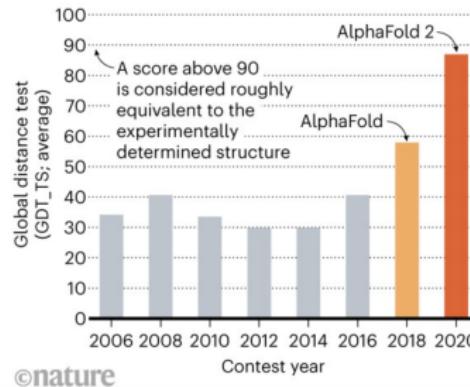


Figure: AlphaFold2 achieves state-of-the-art performance on the protein structure prediction problem in 2020.

Experimental vs Computationally Determined Protein Structures

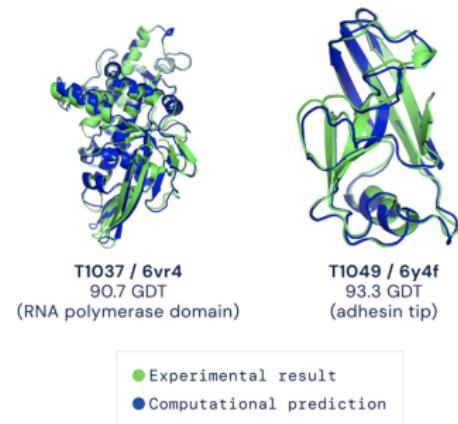


Figure: from DeepMind. Read more here,
<https://deepmind.com/blog/article/alphafold-a-solution-to-a-50-year-old-grand-challenge-in-biology>

The Difference Between Bioinformatics and Computational Biology

You may hear these terms used interchangeably, but there are subtle differences.

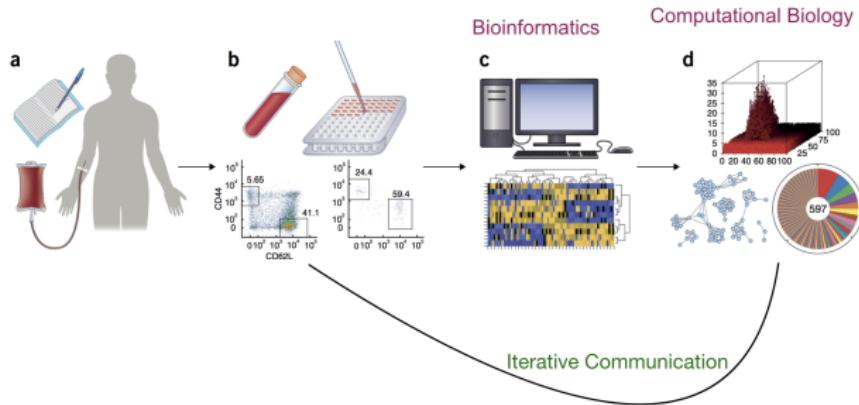


Figure: adapted from Davis *et al.* Nature Immunology 2018. Bioinformatics → software engineering and efficiently storing or representing information. Computational biology → modeling and prediction.

Official Definitions of Bioinformatics and Computational Biology

Bioinformatics: Research, development, or application of computational tools and approaches for expanding the use of biological, medical, behavioral or health data, including those to acquire, store, organize, archive, analyze, or visualize such data.

Computational Biology: The development and application of data-analytical and theoretical methods, mathematical modeling and computational simulation techniques to the study of biological, behavioral, and social systems.

Figure: NIH definitions of Bioinformatics and Computational Biology

Examples of Computational Problems Encountered with Current Biological Datasets.

Being a Computational Biologist in Practice...

- 'Featurizing' or defining a representation for a complex data type (e.g. single-cell data, images, counts of species in the microbiome).

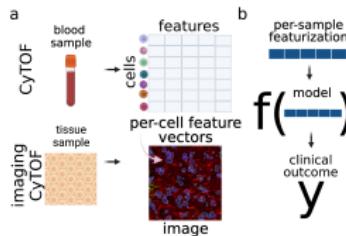


Figure: Example for single-cell modalities from blood or tissue samples. How do we represent disjoint cellular information into compact vector representation?

- Limited or missing data limits the application of sophisticated ML approaches developed for text or images.

Other Computational Problems and Practical Considerations

- **Limited Data and Model Instability** Many features, few samples/patients/examples can cause highly variable models, depending on which subset of the data were used for training.
- **Interpretability Enabling Effective Communication:** How do we best infer and communicate which features are driving the predictions of a model?
- **Integrating Multiple Profiled Modalities:** How do we best jointly integrate multiple different types of biological measurements? How do we infer importance of particular modalities and features within each modality?

Single Cell Data: Combining Potentially Millions of Cells

If you collect hundreds of thousands of cells over hundreds of patients, you quickly end up with millions of cells that you need to collectively consider identify clinically-predictive patterns.

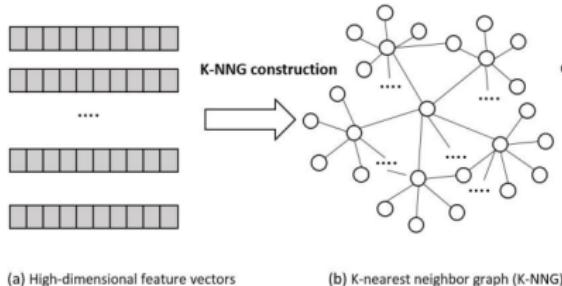


Figure: Tang *et al.* 2018. ArXiv. How do you calculate distances between millions of cells without computing all pairwise distances? How do you ensure that the representation preserves both local and global between-cell similarities?

Recap

Today

- Course Logistics
- Motivating Examples

Next time:

- Linear algebra review
- Building graphs from data
- Graph Laplacian + Diffusion