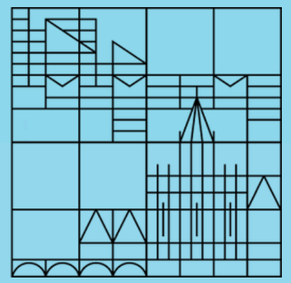
Universität Konstanz



UNIVERSITÄT KONSTANZ

Introduction to Network Science

Network Science of Socio-Economic Systems

Giordano De Marzo

About Me

- Postdoc at the Political Science department, University of Konstanz
- Junior Research Fellow at the Complexity Science Hub Vienna
- PhD in Physics at Sapienza University and Enrico Fermi Research Center (Rome)
- MSc and BSc in Theoretical Physics at Sapienza University

View from my room at Enrico Fermi Research Center

About Me

Research interests:

- Complex Digital Systems
- Social Networks
- Economic Complexity
- Artificial Neural Networks
- Large Language Models

email: giordano.de-marzo@uni-konstanz.de
website: giordano-demarzo.github.io
twitter: @GiordanoMarzo
room: D389

View from my room at Enrico Fermi Research Center

Outline

1. About this Course
2. Complex Networks
3. Network Science
4. A Network Science Experiment

About this Course

Course Objectives

By the end of this course, you will understand key concepts in network science, be able to analyse and model real networks, and apply these techniques to socio-economic systems.

- Grasp fundamental **network theory** concepts
- Analyse and model **network growth** processes
- Detect **communities** within networks
- Utilize **network ensembles** theory
- Apply network science to the analysis of **social** and **economic** systems

Course Assessment

- Students select a published article or a dataset from from those listed on the course website.
- The task is to replicate the analysis performed in the paper or apply network science to the analysis of the dataset.
- Results must be summarized in a report and discussed in a presentation.

The course grade is based on:

- the student **presentation** (35%)
- the **code** (15%)
- and on the **report** (50%)

Course Format

This course is structures as seminars and coding sessions

- 13 Theoretical seminars covering basics (the first 7) and more advanced (the following 6) topics in Network Science
- 7 Coding Sessions
- 1 Students Q&A session

The coding sessions are optional but strongly recommended!

I will upload slides and code on my website before each lesson

giordano-demarzo.github.io/teaching/network-science/

You can also look at last year website, the material will be more or less the same

giordano-demarzo.github.io/teaching/network-science-24/

Students Q&A

The last lecture will consist in a Q&A session

- you will present 2 or 3 slides about what you plan to do for the final project
- this presentation will not be graded
- this is a moment for you to ask me questions about your project and to understand if what you planned to do is reasonable

Final Report

I will upload datasets and papers on my website during the course

- the same dataset/paper can not be choose by more than one person
- you will have to communicate your choice by 22/01/2026
- first come first served, but there is plenty of choice for everybody

The report must be structured as a scientific paper and about **4/5 pages** long (including the bibliography). It must contain

- Abstract
- Introduction
- Results
- Discussion
- Methods
- References

Exam Dates

The dates of the exam are flexible

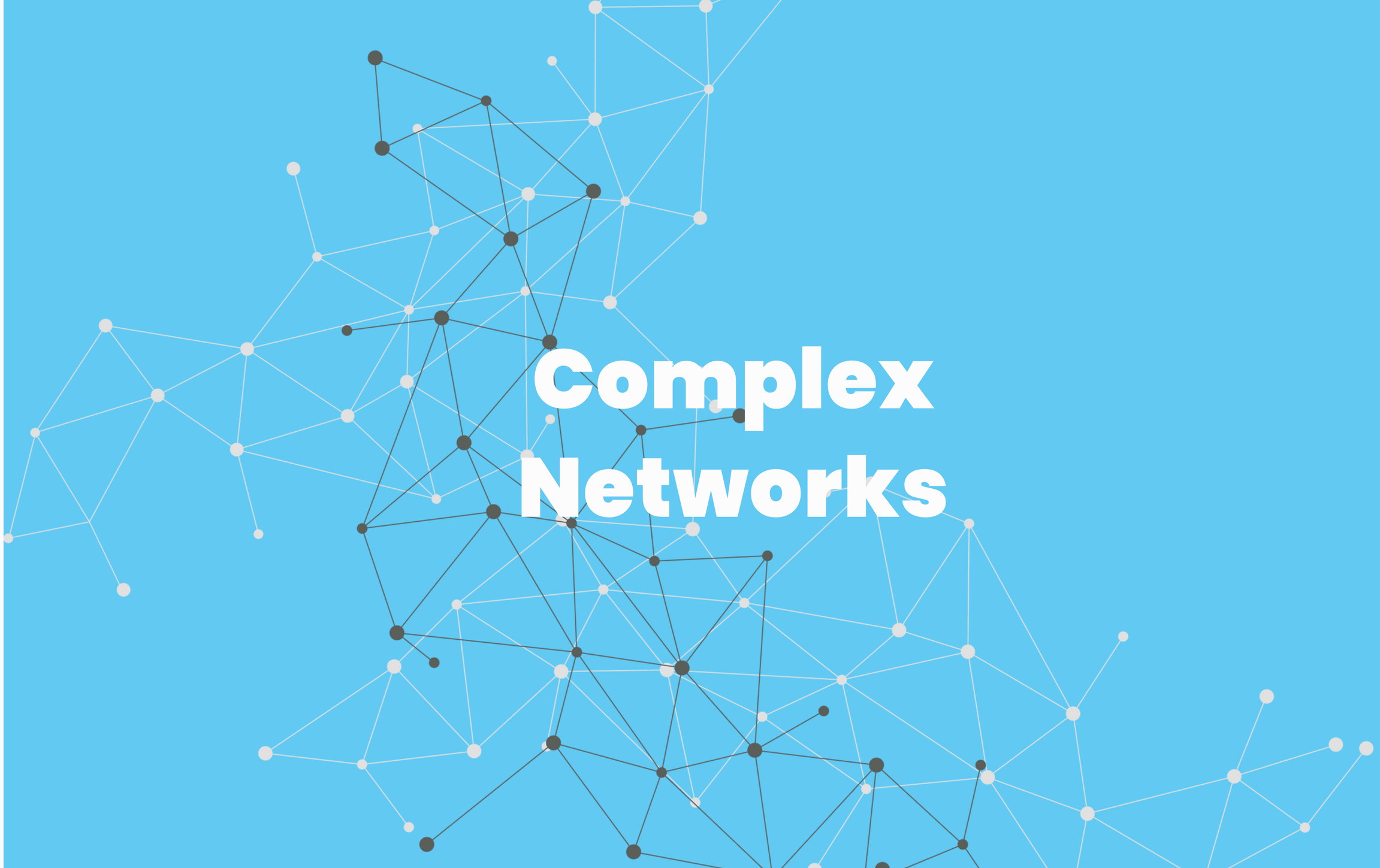
- I will create a form to select some exam dates that suits you
- ideally you should self-group into 2/3 people that wants to do the exam on the same day
- we can have an early exam day, as soon as the course ends
- we can also have a late exam session, just before the summer semester begins

Seminars Dates

October 29, 2025-Network Theory Basics
November 05, 2025-Random Graphs and Small World
November 12, 2025-Scale Free Networks
November 19, 2025-Measuring Nodes Centrality
November 26, 2025-Communities in Networks
December 3, 2025-Processes on Networks
December 10, 2025-Network Ensembles
December 17, 2025-Multilayer and Higher Order Networks
January 7, 2025-Economic and Financial Networks 1
January 14, 2026-Economic and Financial Networks 2
January 21, 2026-Social Networks
January 28, 2026-Advanced Topics in Network Science
February 04, 2026-Students Q&A

Coding Sessions Dates

October 29, 2025-Introduction to Network Science in Python
November 5, 2025-Analysis of real world networks
November 19, 2025-Centrality measures
November 26, 2025-Community detection algorithms
December 10, 2025-Configuration models
January 7, 2026-Analysis of the world trading network
January 21, 2026-Analysis of social networks


Complex
Networks

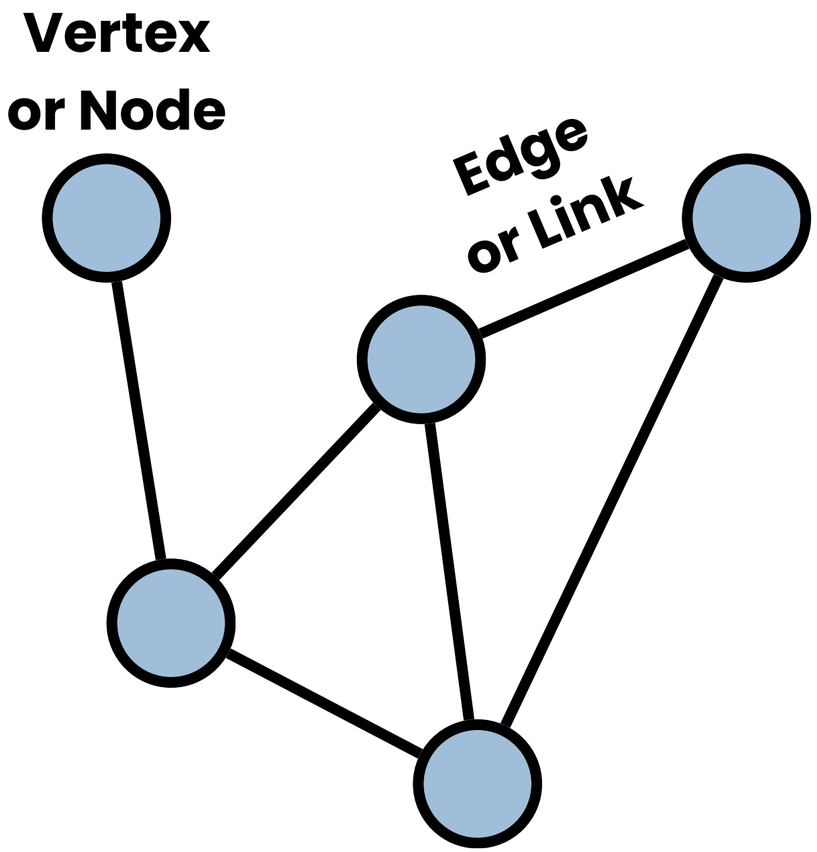
What is a Network?

A Network or Graph G(V, E) is a set of vertices or nodes V and and edges or links E

- nodes represent entities in the system (eg. people on a social network)
- edges represent connections among the nodes (eg. friendship in a social network)

We denote by

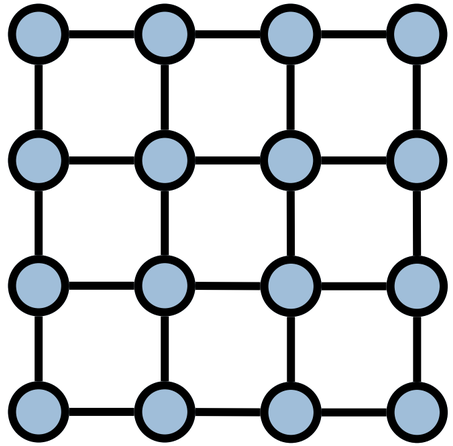
- N the number of nodes
- E the number of links



What is a Complex Network?

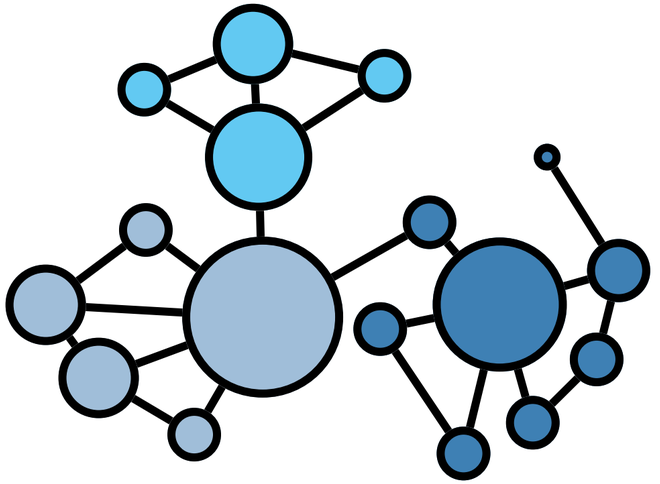
A grid or lattice is one of the simplest networks

- all nodes have the same degree
- no heterogeneity
- it repeats over and over without differences

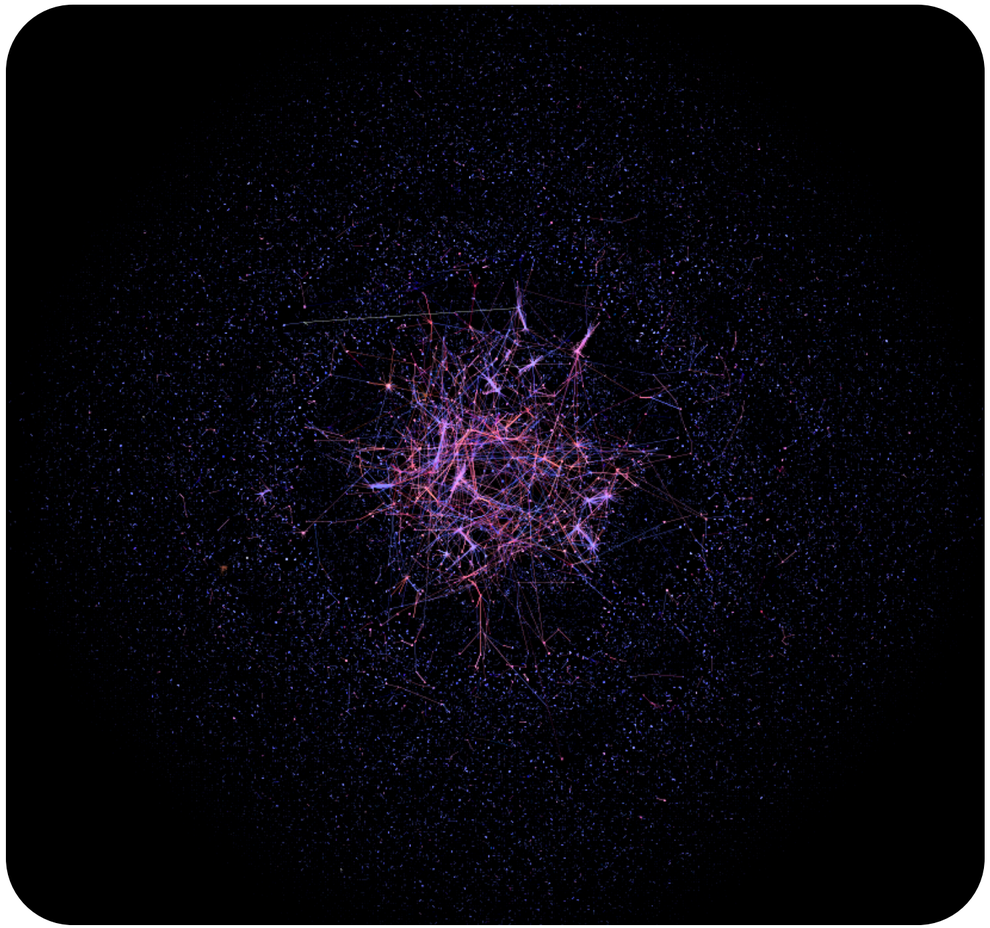


Defining Complex Networks is not easy

- degrees tend to be very heterogeneous
- nodes tend to form communities and more sophisticated structures



Social Networks



https://dhs.stanford.edu/gephi-workshop/twitter-network-gallery/

Human (online) societies can be described as a network

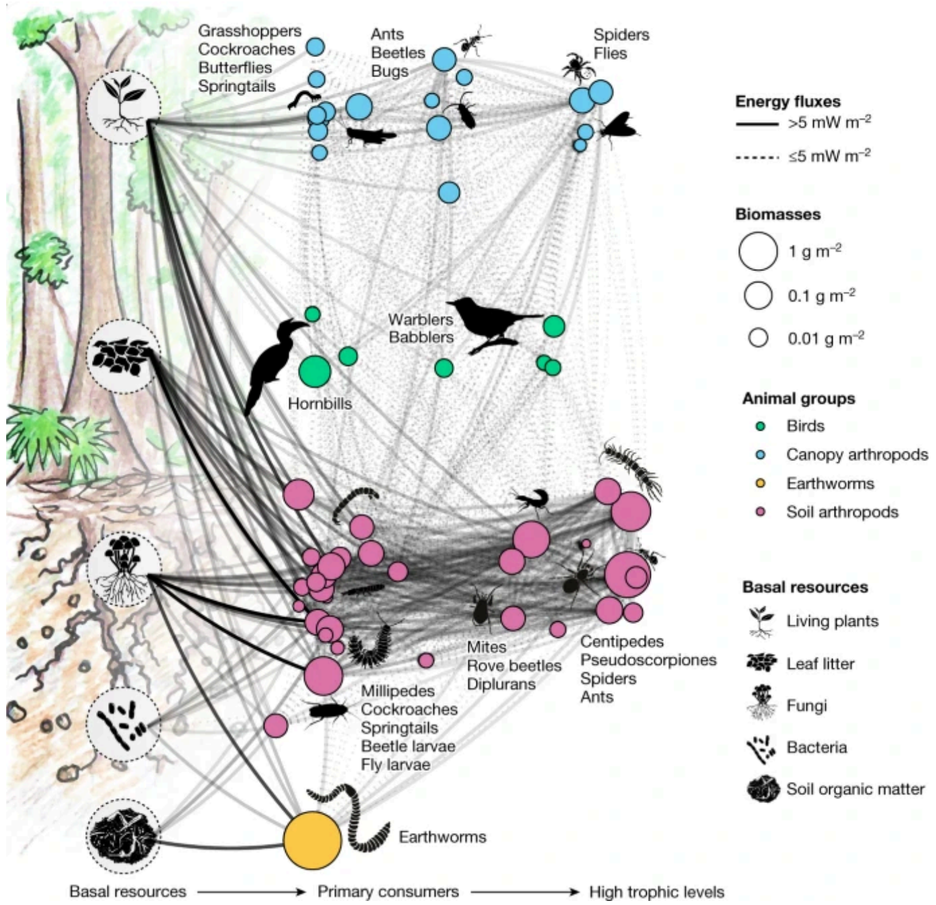
- nodes are individuals
- links represent some form of relation between the individuals
  - Facebook: friendship (undirected network)
  - Instagram: follow (directed network)

The image shows a network representation of 500M users on Twitter

Food Webs

Networks can be used to describe prey-predator relations, obtaining the so called food-webs

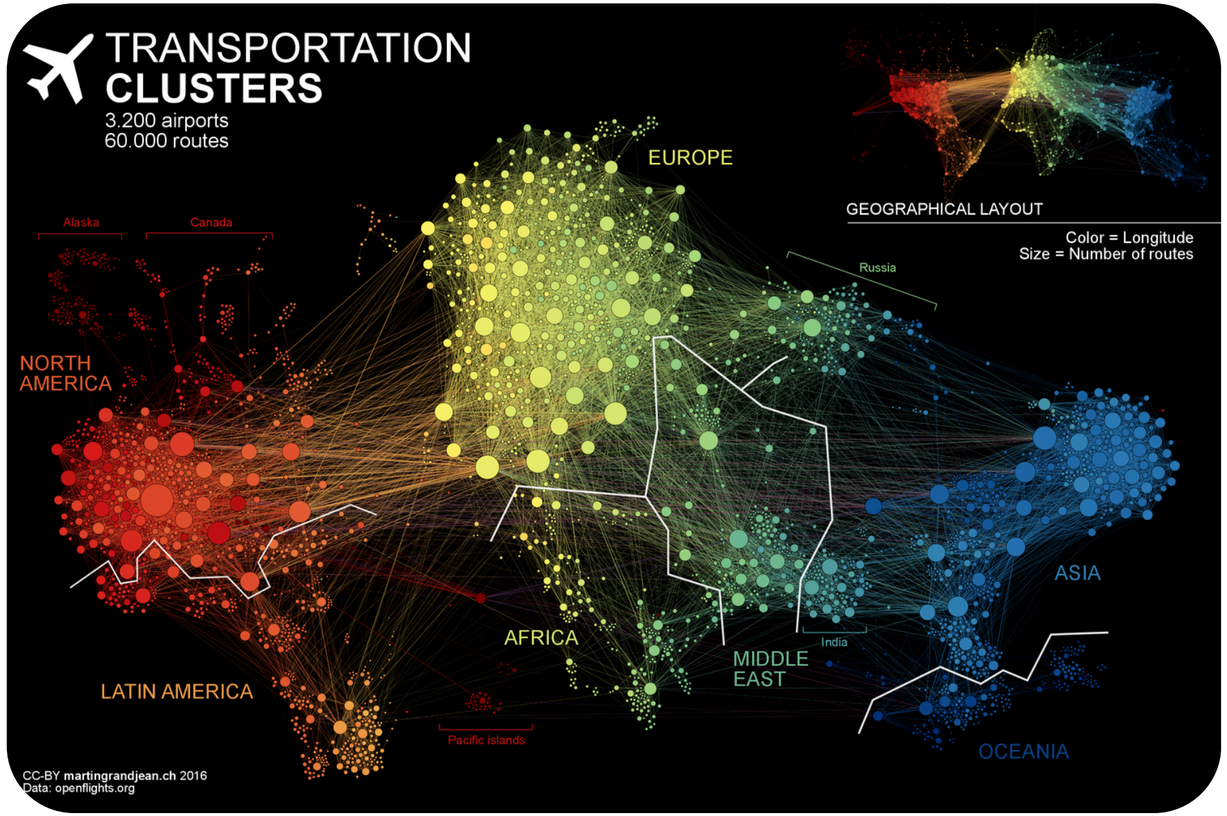
- nodes are animals or plants
- links represent who eats who relations
- the network is directed and can be weighted by the carbon transfer between the two species

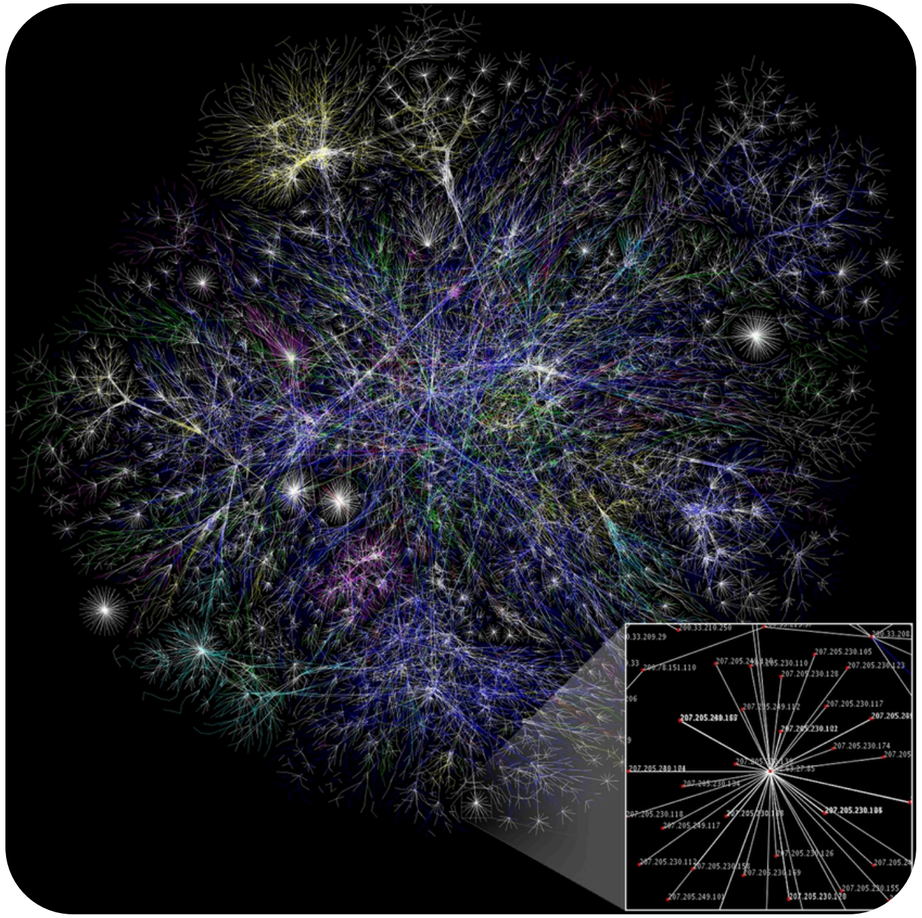


Potapov, A.M. et al. Rainforest transformation reallocates energy from green to brown food webs. Nature 627, 116–122 (2024).

Air Transportation Network

Airlines connect airports forming the air transportation network: nodes are airports, (directed) links represent flights between airports





Internet Backbone

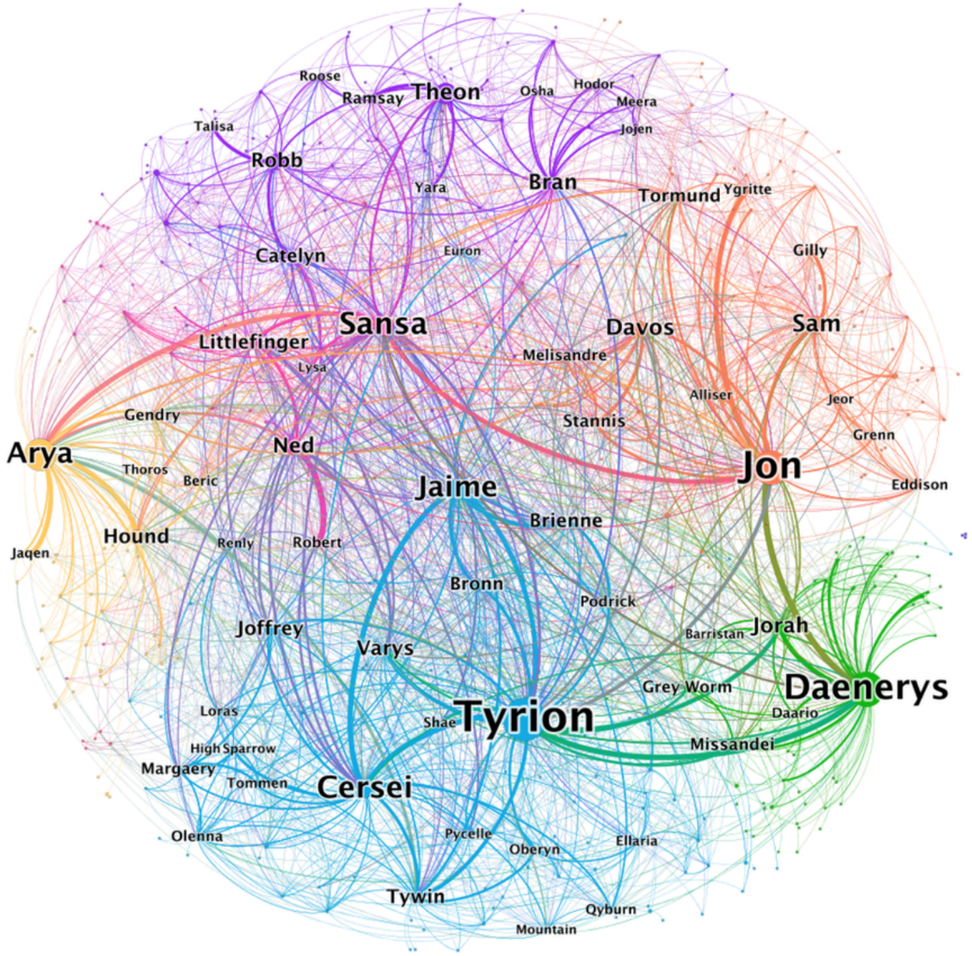
The global structure of the internet can be described as a network.

- Nodes are internet routers, data centers, servers
- Links are physical or logical connections (fiber optics, satellite links, etc.) that transfer data
- The network is directed
- The links can be weighted by bandwidth capacity or latency

Network of Thrones

We can build a network more or less out of everything. For instance we can visualize Game of Trones as a network

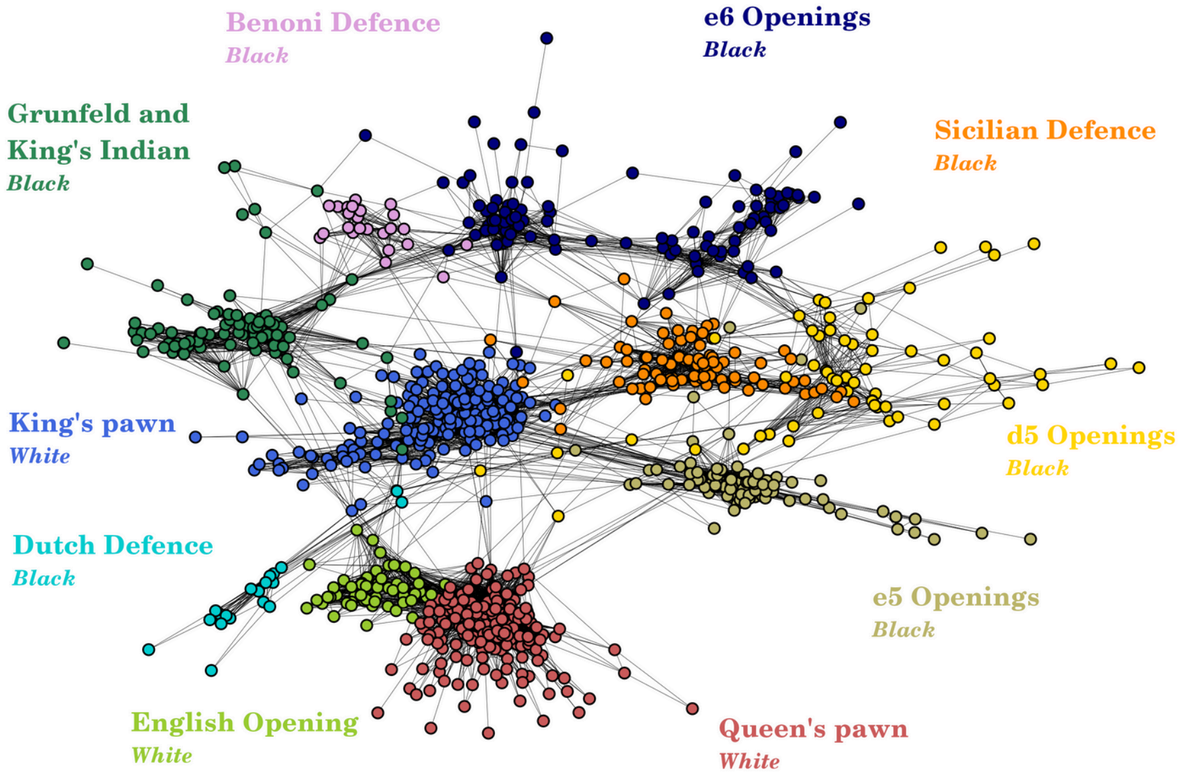
- nodes are characters
- links represent who co-appearances of two characters
- the weight gives the number of times two characters appeared together



networkofthrones.com

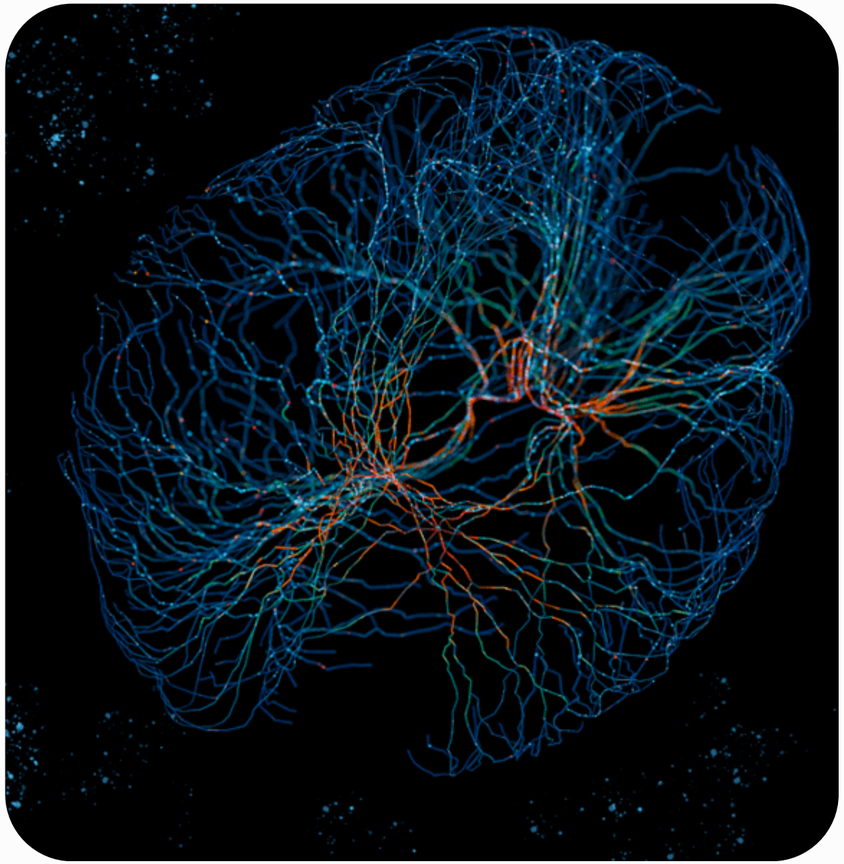
Chess Openings Network

Each dot is a specific chess opening, while (undirected) links represent similarity relations between these openings



De Marzo, Giordano, and Vito DP Servedio. "Quantifying the complexity and similarity of chess openings using online chess community data." Scientific Reports 13.1 (2023): 5327.

Neural Networks



https://news.mit.edu/2022/neural-networks-brain-function-1102

Networks describe both biological and artificial neural networks

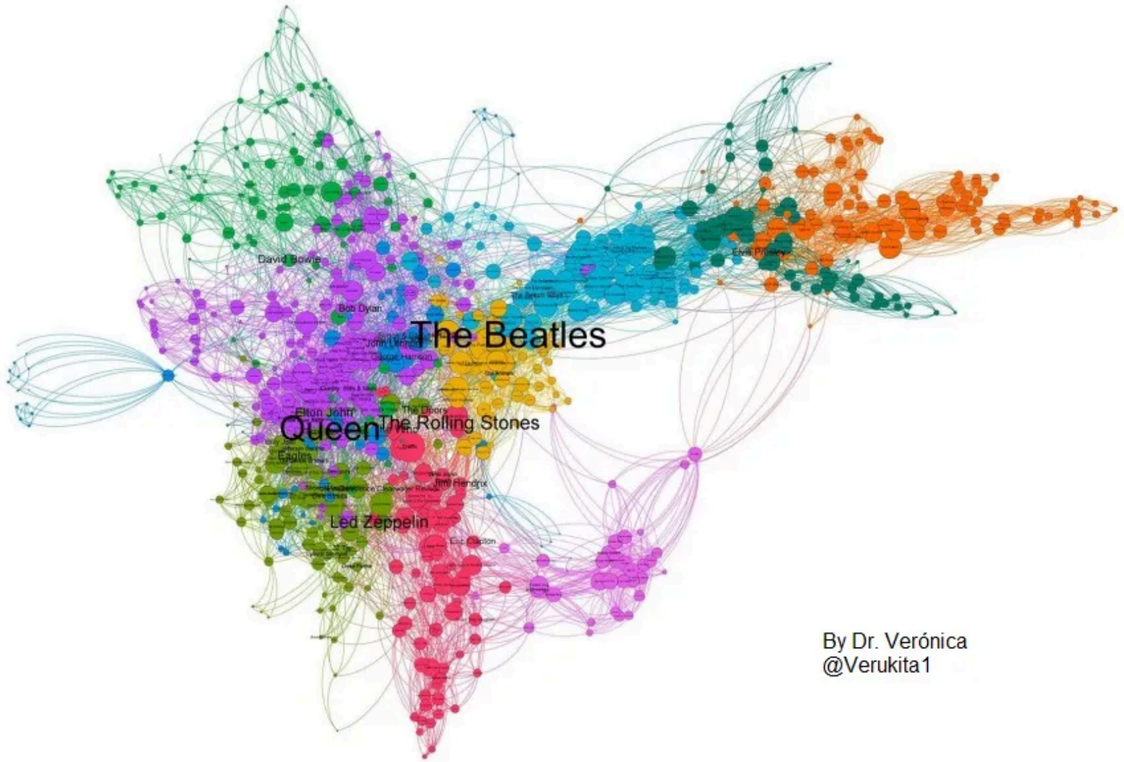
- Nodes are neurons (in biological networks) or artificial neurons (in artificial networks).
- Links are Synapses or weighted connections
- In both cases, the network is directed and weighted

Network
of Spotify Artists

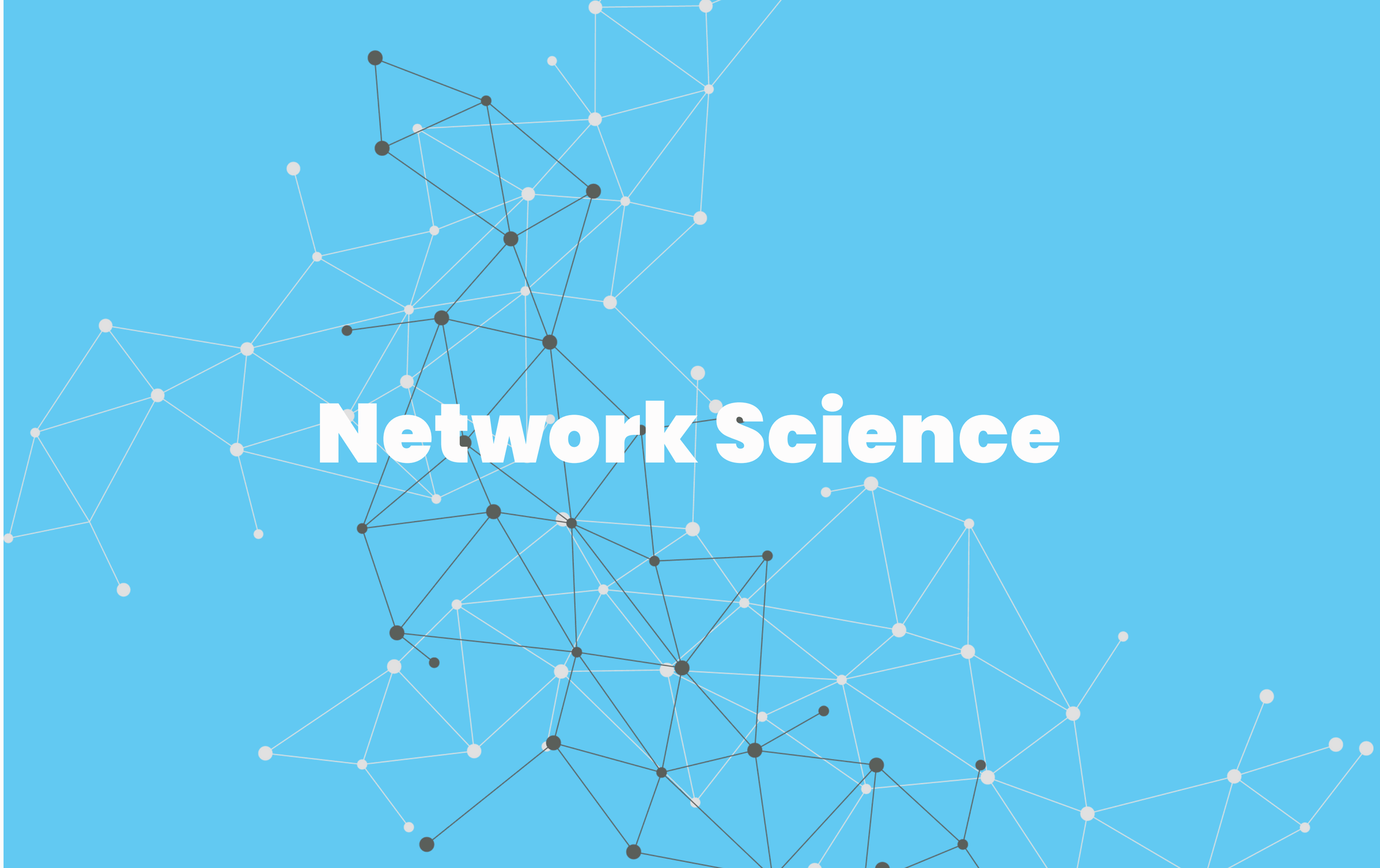
We can use network science to study music on Spotify

- nodes are artists
- links represent similarity between artists
- the weight gives the similarity score between them

You can try it with your favorite artist



https://labs.polsys.net/playground/spotify/.com


Network Science

What is Network Science?

Network Science is an interdisciplinary field that studies complex systems through their network structures

- Bridges mathematics, physics, computer science, sociology, biology, and economics
- focuses on the relationships between components (nodes) rather than individual components themselves
- analyzes both the topology (structure) and the processes (information flow, influence, etc.) occurring over networks

Research Questions

Network Dynamics

How do networks form and evolve over time? What are the processes leading to particular networks structures?

Processes on Networks

How does the network topology influences the process taking place on it? Examples can be epidemic spreading or opinion dynamics

Analysis of Real Networks

Which are the most influential nodes within a network? How resilient is a social or economic network? Which are the communities within a social network?

Network Dynamics

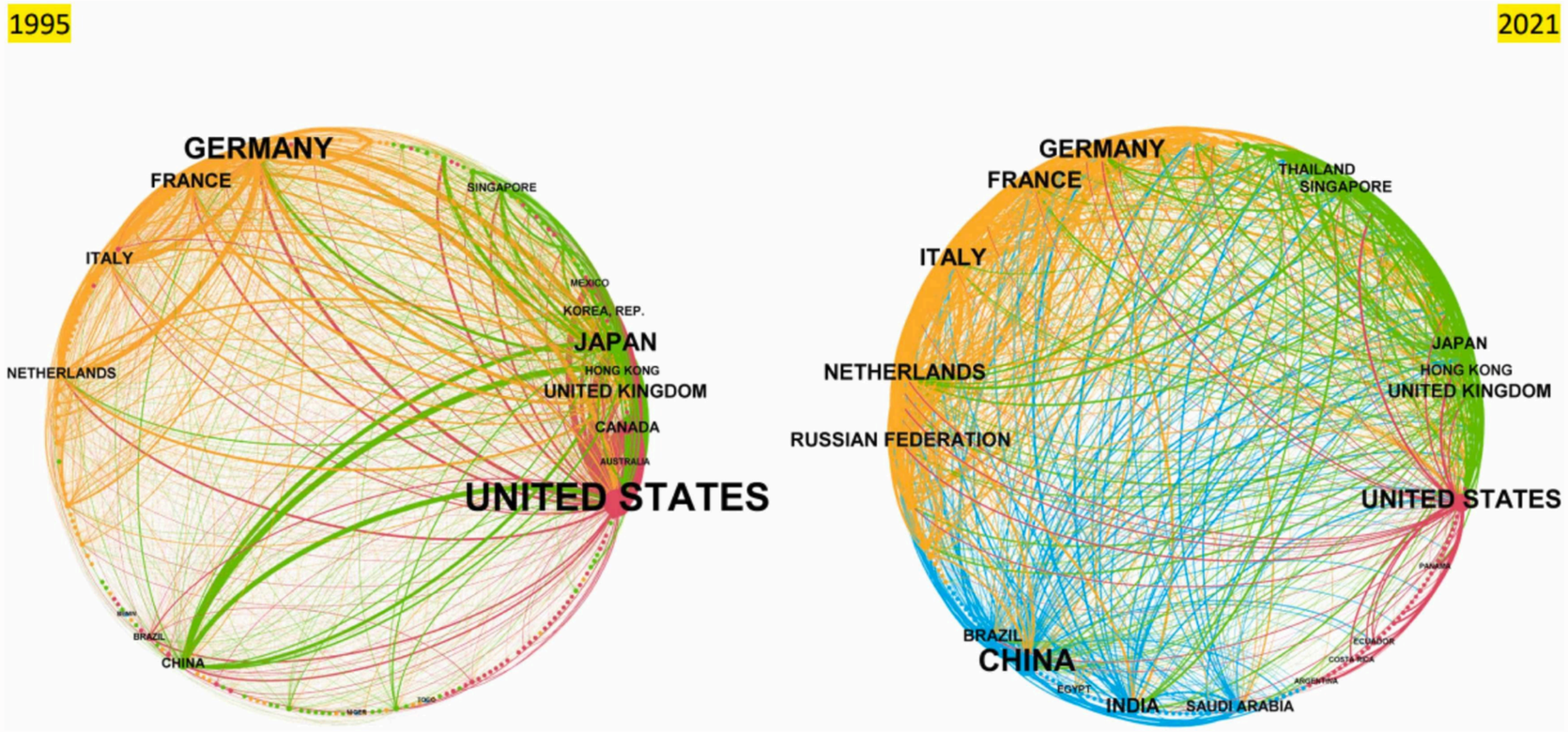
One of the main areas of network science is the study of Networks formation and dynamics

- many real world network from very different systems show similar statistical properties
- which are the growing mechanisms leading to many networks sharing similar characteristics?
- how do extremely complex structures like the internet can form from simple, pairwise interactions?

We will cover the main network growth processes in lectures 3 and 4

Network Dynamics

Evolution of the world trade network from 1995 to 2021



https://doi.org/10.1016/j.joitmc.2023.100009

Processes on Networks

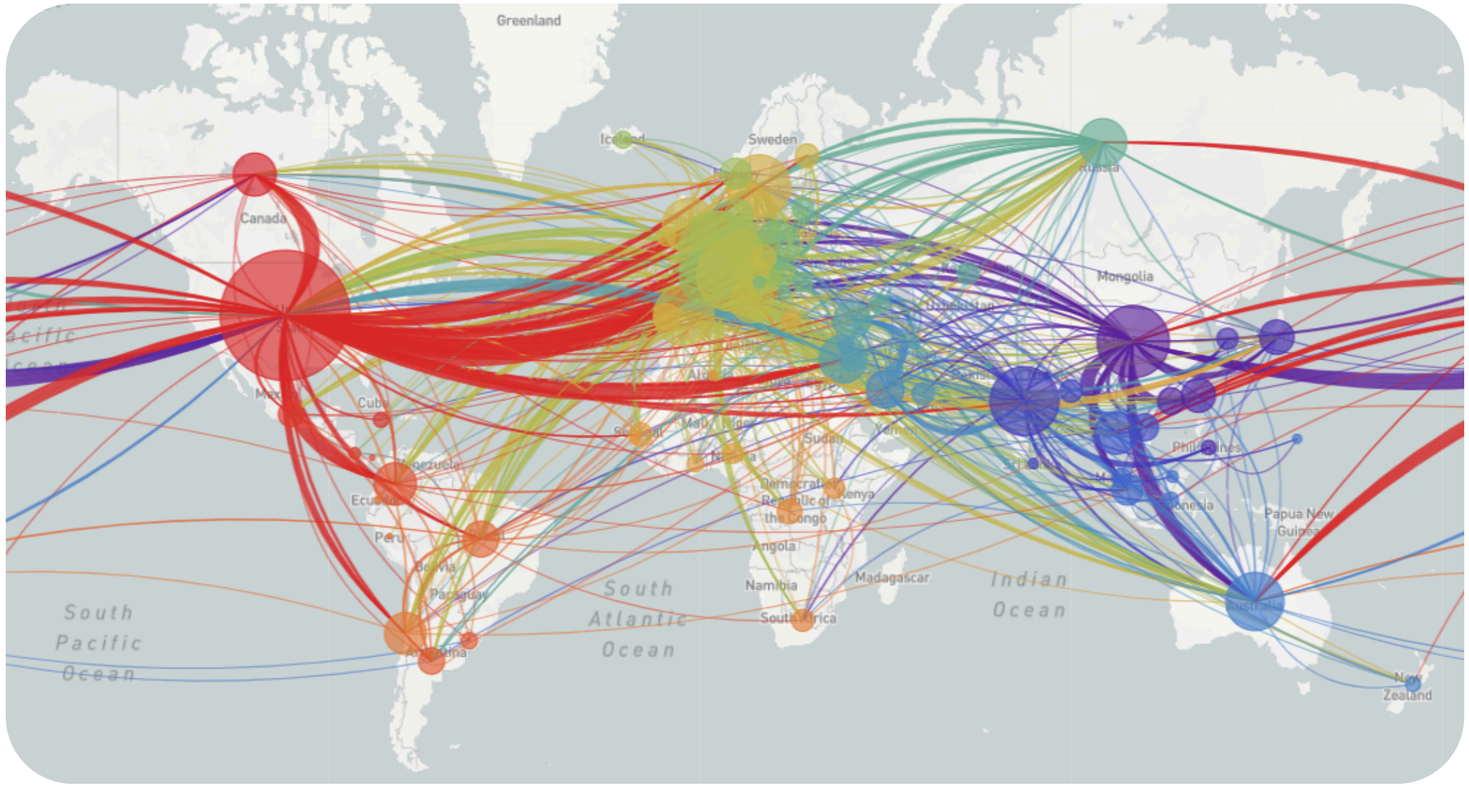
Not only a network can evolve, but processes can also take place on it, potentially shaping its growth process

- most interesting phenomena take place over network structures
- epidemic spreading is governed by transportation networks
- opinion dynamics take place on (online) social networks
- a process on a network can influence the network itself, for instance opinion dynamics may lead to the formation of a clustered social network

We will cover the main network processes in lecture 7

Processes on Networks

COVID-19 transmission network as of May 30, 2020



https://gwips.ucc.ie/covid19.html

Analysis of Real Networks

Network science can also be used to study and characterize real world networks and their components

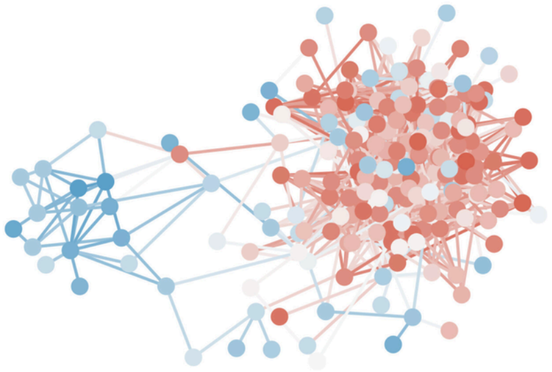
- centrality measures can help identify the most influential actors within a network
- community detection can spot groups within networks
- network based techniques can be used to understand the preferences and tastes of users
- the most significant links can be individuated and the resilience of an entire network can be computed

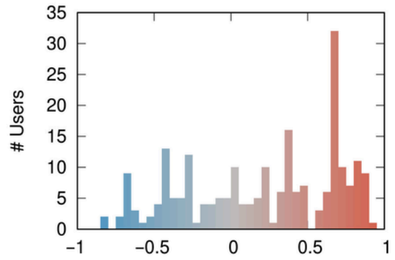
We will cover the main network processes in lectures 2, 5 and 6

Analysis of Real Networks

Debates networks happening on Twitter in the mid-2010s

Obamacare





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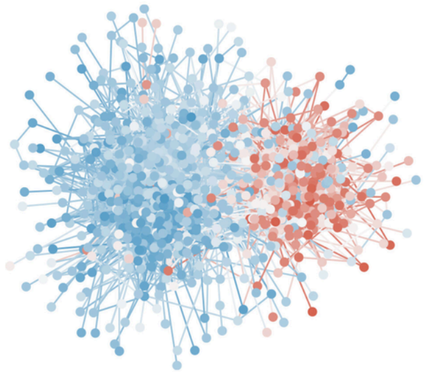
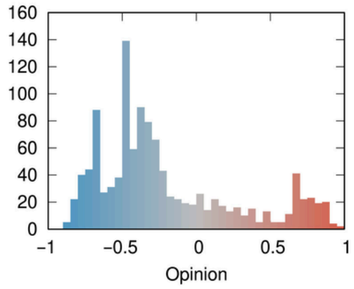
Gun control





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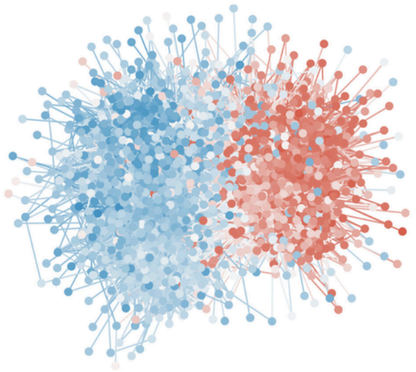
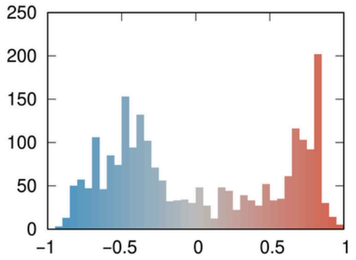
Abortion





16.71

https://doi.org/10.1126/sciadv.abq2044

A Network Science Experiment

The Research Question

Can we use network theory to understand which cocktails are closer to individuals' tastes?

Cocktail Project: a social experiment to validate network theory-based recommendations of cocktails

Giordano De Marzo[1,2,3,4], Vito D. P. Servedio[3], et al.[3]
[1] *Centro Ricerche Enrico Fermi, Piazza del Viminale, 1, I-00184 Rome, Italy*
[2] *Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy.*
[3] *Complexity Science Hub Vienna, Josefstädter Strasse 39, 1080, Vienna, Austria.*
[4] *Sapienza School for Advanced Studies, "Sapienza", P.le A. Moro, 2, I-00185 Rome, Italy.*

Cocktails Data

Cocktails

546 different drinks

Ingredients

1514 distinct ingredients

1 oz Gin

1 oz Campari

1 oz Sweet Vermouth

We use the **thecocktaildb.com** dataset.

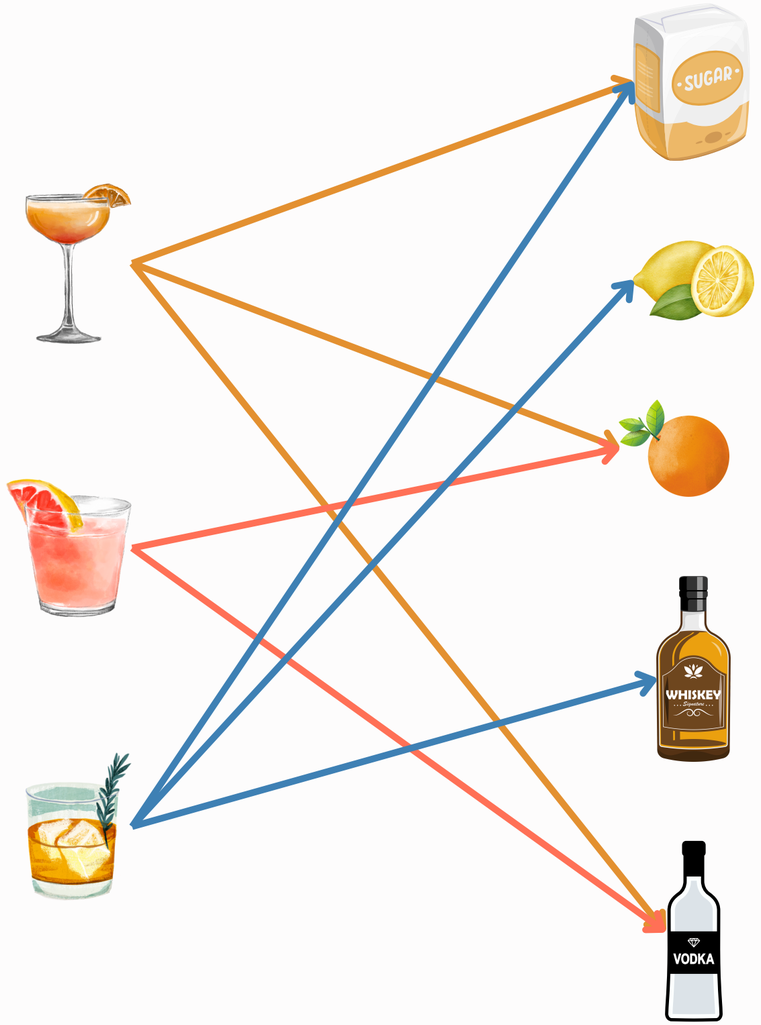
It provides

- ingredients
- procedure
- glass to be used
- cocktail image

A Bipartite Network

Recipes can be described as a bipartite network:

- one layer contains all drinks
- the other layer contains all ingredients
- an arrows connect cocktails to ingredients



Bipartite Network Projection

Starting from the bipartite network we can build a cocktail network by projecting it:

- cocktails sharing many cooccurences are similar
- ingredients used in many cocktails carry less information

Cocktail Network Matrix

$$M_{ck} = \frac{1}{d_k} \sum_i \frac{B_{ci} \cdot B_{ki}}{u_i}$$

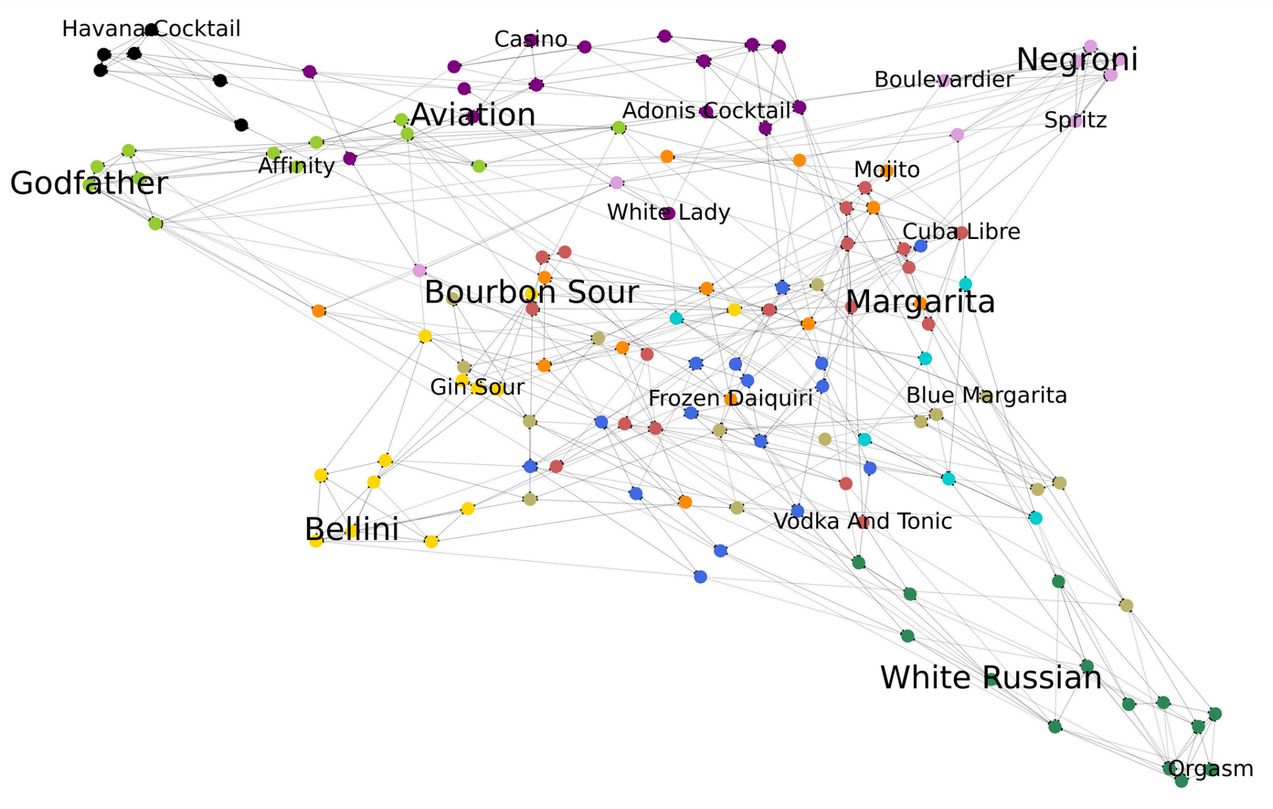
Cocktail-Ingredient bipartite matrix

Cocktail k diversification

Ingredient i ubiquity

Network of Cocktails

Cocktails that are close on the network have similar ingredients and thus similar taste



The Experiment

In order to understand if the cocktail network is meaningful we have to validate it.

We devised a social experiment where users drink cocktails based on the position on the network.

Initial Survey

Users fill an initial survey to asses their level of knowledge about cocktails

Initial Cocktails Rating

All users initially taste and rate the same five cocktails as a starting point for the recommendation algorithm

We also collect additional information to look for patterns in the network

Cocktails Recommendations

Next, cocktails are automatically assigned to users by means of a network based recommendation algorithm

Data Analysis and Dataset

After the experiment we analyze the data and we curate a dataset on cocktail ratings

Web App

Cocktail Orders

Orders are digitally managed and collected

Data Collection

Users rate cocktails directly on the app

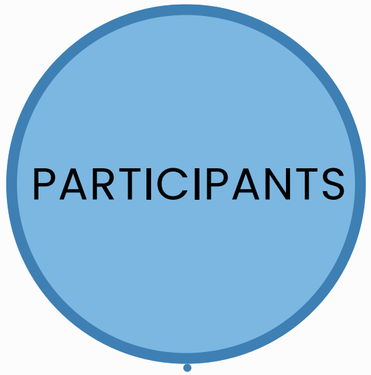
Cocktail Recommendations

Recommendations are fully automatized

Some Numbers

We already performed five experimental sessions in the past years

Around 250 different cocktails



More than 100 participants

Around 1000 ratings

Conclusions

Course Program

The first half of the course covers the main basic topics in network science. In the second half we will study more advanced topics with a focus on social and economic networks

Exam

Individual report and presentation. You can either reproduce a paper or analyze a network among those available on my website

Network Science

Network Science studies the dynamics of networks, the processes taking place on networks and the properties of nodes, links and structures within networks