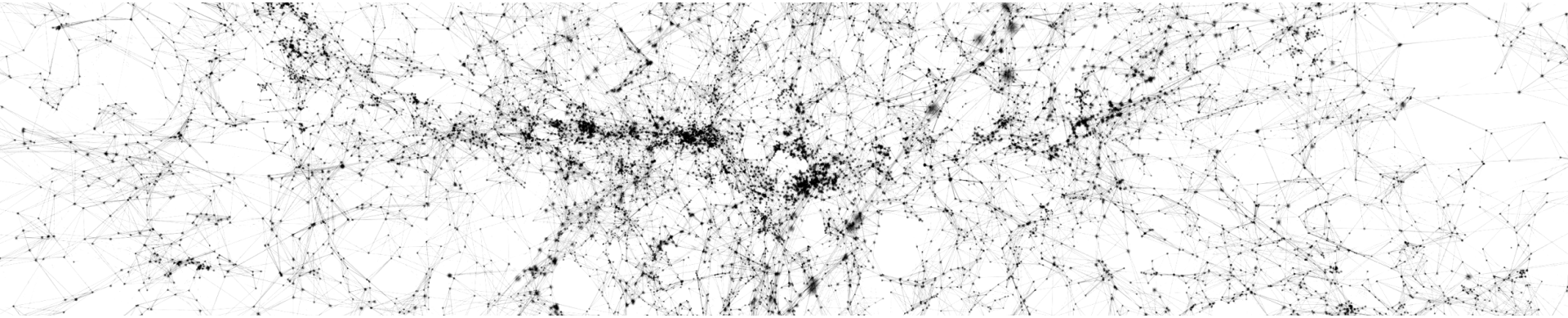
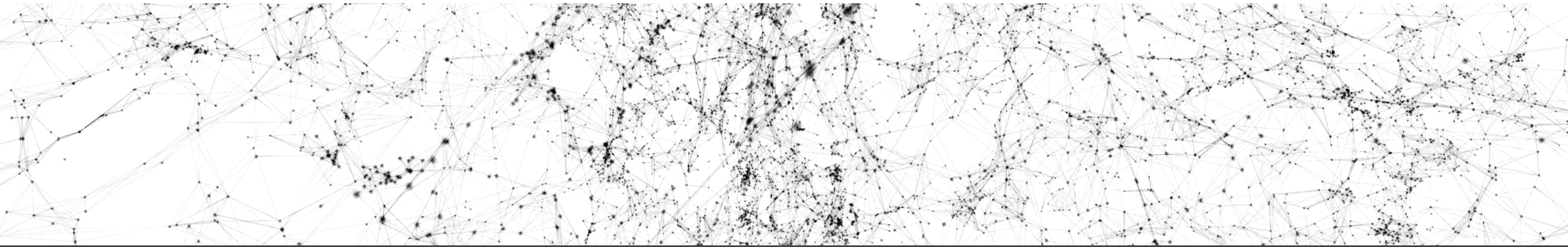


Network Science

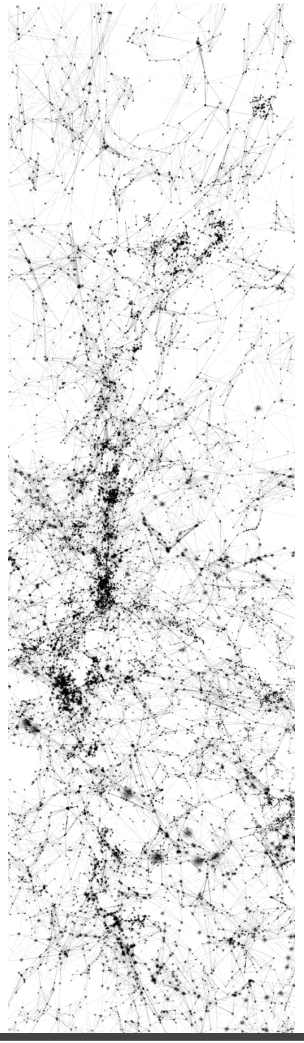
Analysis of Complex Interconnected Data

~~ Introduction ~~



Outline

- Introduction to the course
  - Complex systems is Physics
  - Societies as complex systems
  - Complex data everywhere and at every scale
  - Main tasks in complex data analysis
- Logistics of the course
  - General info
  - Who is in the class
  - What we will learn
  - Grading, deadlines, …



Why network science?

The world around us is interconnected, and complex systems arise in different fields.

Connections, interactions, relations are often present in real world data, and in many cases are key to understand the data.

"Learn how to see. Realize that everything connects to everything else."

— Leonardo da Vinci

Research disciplines

Analysis of complex interconnected data is multidisciplinary:

- Physics (complex systems)
- Sociology (social networks)
- Mathematics (graph theory)
- Data Mining (graph mining)
- Machine Learning (relational learning, graph neural networks)

And sometimes is considered as its own discipline coined as

Network Science or Science of Networks

Complex Systems in Physics

Study of complex systems has a long history in Physics, dating back to Aristotle's time, and more relevant than ever in this century

examples: deterministic chaos, quantum entanglement, spin glasses

"I think the next [21st] century will be the century of complexity"
— Stephen Hawking

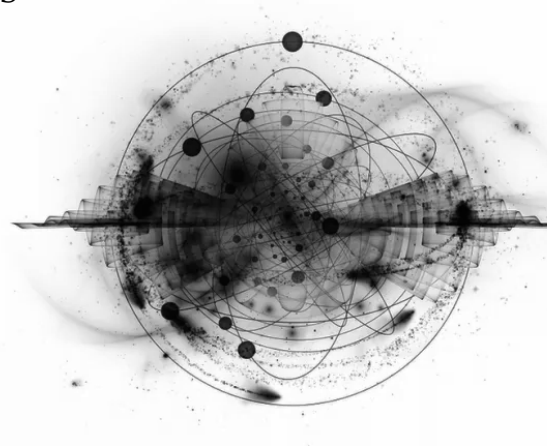
It is not limited to Physics phenomenons and even reaches the philosophy of science

In 'More is different',
— P. Anderson, Science (1972)
Condensed matter physicist who discusses emergent phenomena; limitations of reductionism and the existence of hierarchical levels of science

X	Y
solid state or many-body physics	elementary particle physics
chemistry	many-body physics
molecular biology	chemistry
cell biology	molecular biology
⋮	⋮
psychology	physiology
social sciences	psychology

Complex systems

- consists of many interconnected parts
- characterized by time-dependent interactions among their parts
- are not an aggregation of their separate parts
- when looked at as a whole gives non trivial insights
  - *Emergence*: a property not any of components have on their own, arising during a self-organization process
- often interactions change states of parts,
  and the states of the parts change the networks of interactions



com·plex

adjective
/ˌkäm'pleks,kəm'pleks,'käm,pleks/

1. consisting of many different and connected parts.
   "a complex network of water channels"
   synonyms: compound, composite, compounded, multiplex
   "a complex structure"

Society as a complex system

From early on when the field was being defined as an academic discipline, sociologist emphasized that social science should look at the society as a whole, rather than being limited to the specific actions of individuals.

Sociology studies the structure of social life, viewing the society as a complex system composed of individuals, who work together through relations, associations, and other forms of connections, and the evolution and dynamics within them affects our life.

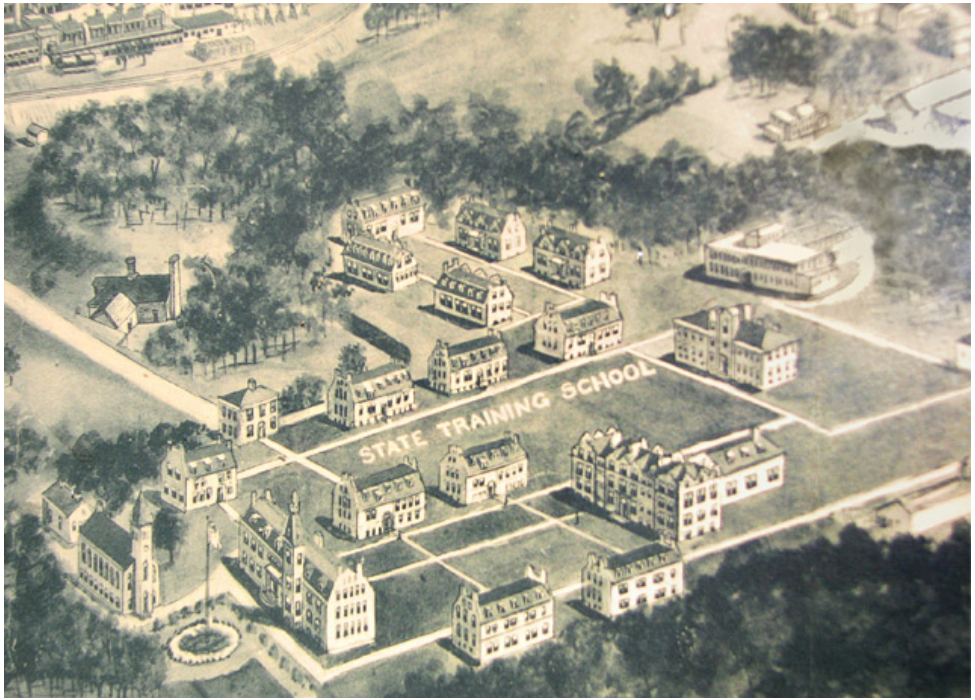
Social science should be holistic.
— Émile Durkheim (1895)
the principal architect of social science

French sociologist, formally established the academic discipline of sociology, insisted that society was more than the sum of its parts

What is society?
— Georg Simmel (1911)
forerunner of Structural functionalism

First generation of German sociologists, Sociology is the study of social interaction at the individual and small group level (dyad, triad...)

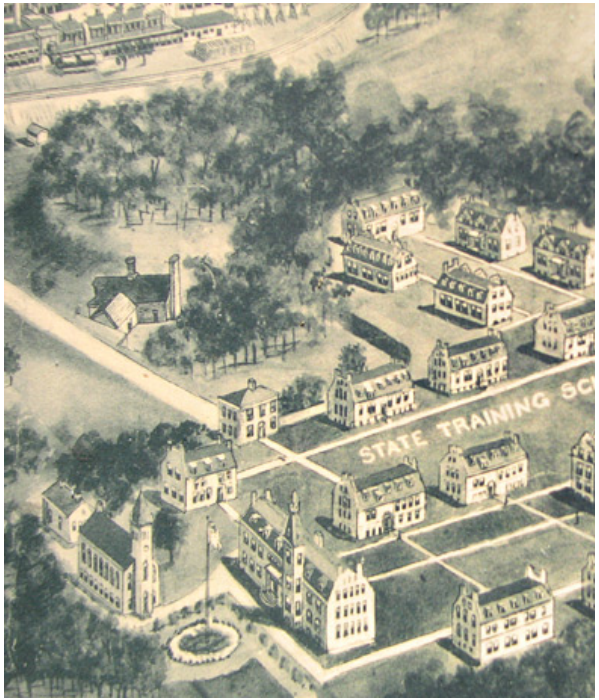
How to explain the pandemic of runaways?

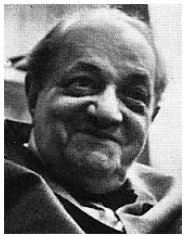


New York Training School for Girls

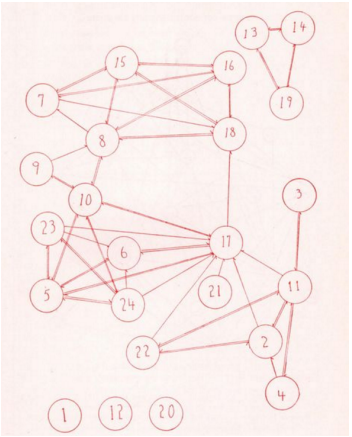
In 1932, within two weeks
14 girls ran away
(30x more than the average)

How to explain the pandemic of runaways?





Jacob L. Moreno,



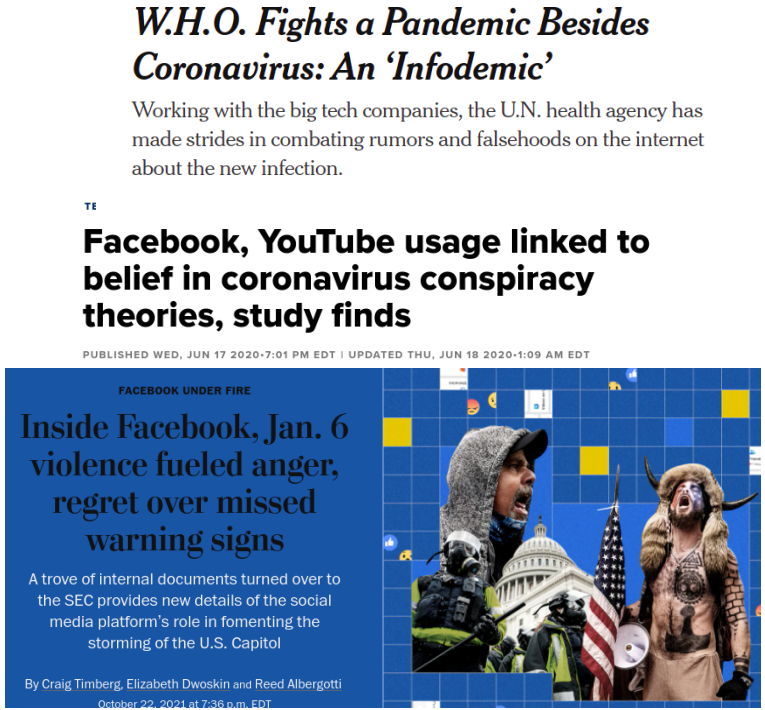
Mapped out the **channels for the flow of social influence and ideas,** and concluded that they **behaved based on how they are positioned in their social network**

Read more here

earliest graphical depictions of social networks (sociograms)

Who Shall Survive? (1934)

How to explain the pandemic of misinformation, fake news, conspiracy theories, populism, extremism, covid, …



W.H.O. Fights a Pandemic Besides Coronavirus: An 'Infodemic'

Working with the big tech companies, the U.N. health agency has made strides in combating rumors and falsehoods on the internet about the new infection.

TE

Facebook, YouTube usage linked to belief in coronavirus conspiracy theories, study finds

PUBLISHED WED, JUN 17 2020•7:01 PM EDT | UPDATED THU, JUN 18 2020•1:09 AM EDT

FACEBOOK UNDER FIRE

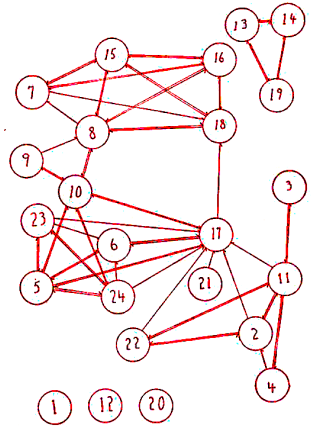
Inside Facebook, Jan. 6 violence fueled anger, regret over missed warning signs

A trove of internal documents turned over to the SEC provides new details of the social media platform's role in fomenting the storming of the U.S. Capitol

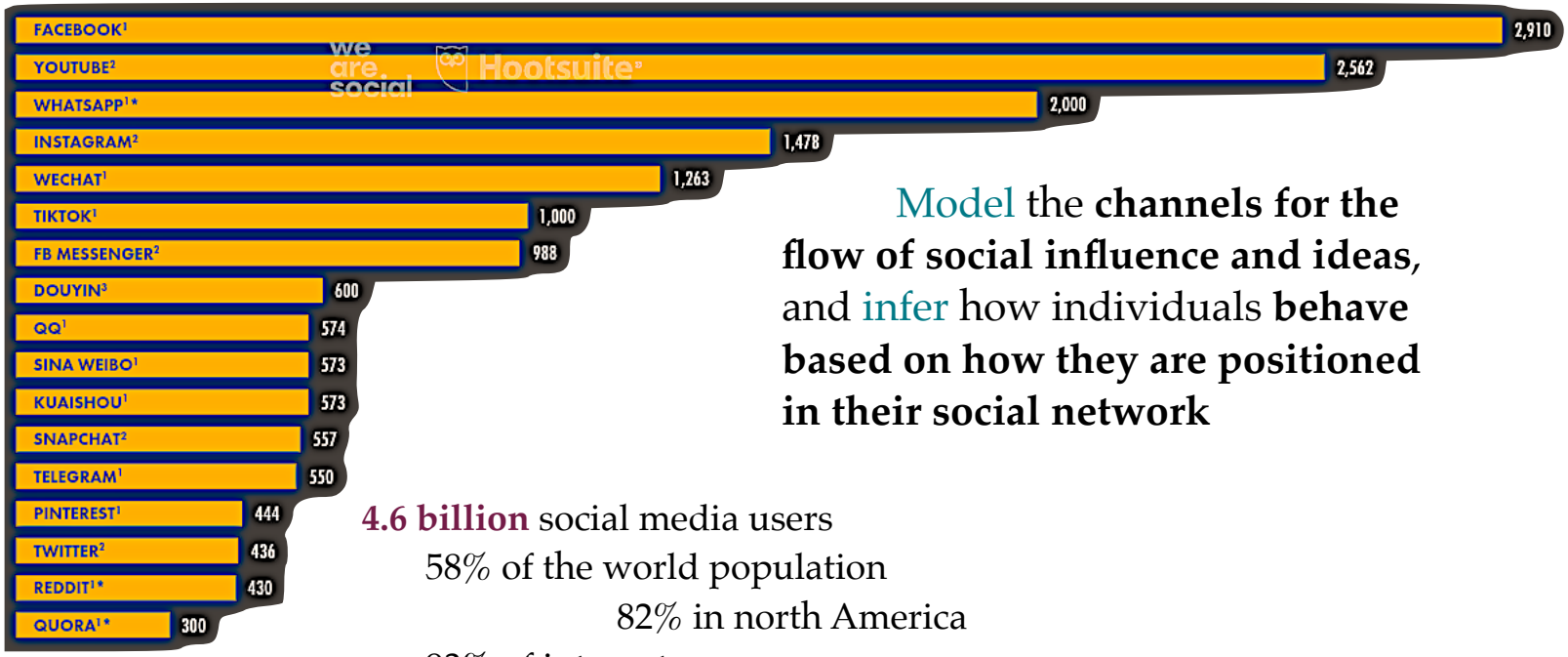
By Craig Timberg, Elizabeth Dwoskin and Reed Albergotti

October 22, 2021 at 7:36 p.m. EDT

Model the **channels for the flow of social influence and ideas,** and infer how individuals **behave based on how they are positioned in their social network**



How to explain the pandemic of misinformation, fake news, conspiracy theories, populism, extremism, covid, …



Model the **channels for the flow of social influence and ideas**, and infer how individuals **behave based on how they are positioned in their social network**

4.6 billion social media users

58% of the world population

82% in north America

93% of internet users

Model Complex Data as Graphs

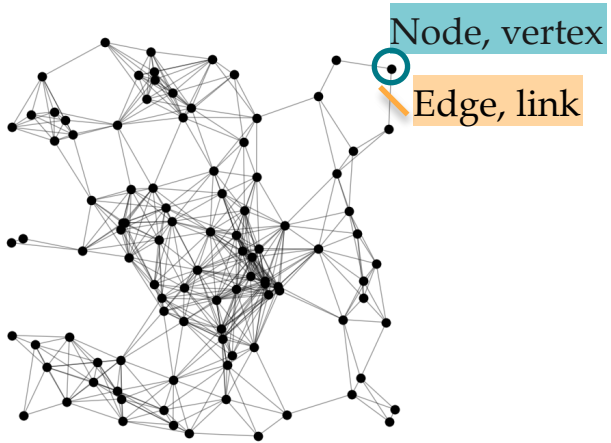
Represents interconnections between the datapoints as graphs or edge streams,

A (0,1) square matrix of size N (number of nodes)

$$A \in [0,1]^{N \times N}$$

$$A_{ij} = 1 \iff (i,j) \in E$$

$$G(V,E), E \subseteq \{(i,j) \mid (i,j) \in V^2\}$$



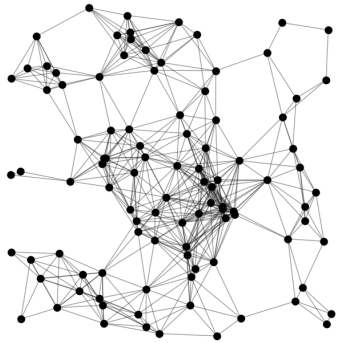
Extension: weighted, directed, signed, multi-edges and multi-type nodes (heterogenous), attributed (nodes and or edges have feature vectors), dynamic (sequence of graphs), multilayer networks (multi-view), hypergraphs (beyond pairwise relations), etc.

Model Complex Data as Graphs

Represents interconnections between the datapoints as graphs or edge streams,
this is different from and complementary to the data representation which considers data as a set of feature vectors (often iid) each a D-dimensional representation for a datapoint

connections & features of the instances are often **dynamic** and in interplay

similarity of individuals' characteristics motivates them to form relations (social selection) & characteristics of individuals is affected by the characteristics of their neighbours (social influence)



$$X = \begin{bmatrix} {x^{(1)}}^T \\ {x^{(2)}}^T \\ \vdots \\ {x^{(N)}}^T \end{bmatrix} = \begin{bmatrix} x_1^{(1)}, & x_2^{(1)}, & \cdots, & x_D^{(1)} \\ \vdots & \vdots & \ddots & \vdots \\ x_1^{(N)}, & x_2^{(N)}, & \cdots, & x_D^{(N)} \end{bmatrix} \in \mathbb{R}^{N \times D}$$

feature

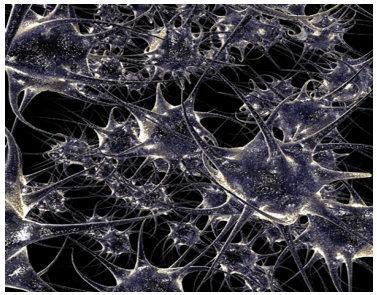
instance

Natural sciences

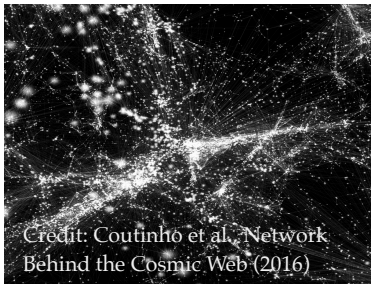
In natural sciences, we see connections between atoms, molecules, cells, organisms and even we have cosmic web.

Chemistry

Biology



Physics

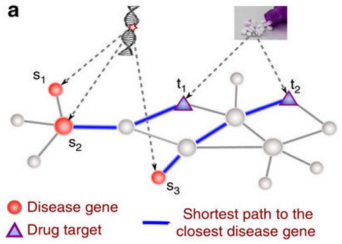


Check the interactive demo of galaxy networks here: https://cosmicweb.kimalbrecht.com/

Applied sciences

Interconnected systems exist in many applied sciences and other fields. There are numerous studies which show looking at these complex system, as a whole, gives us non trivial insights and is necessary to understand these systems.

Medicine

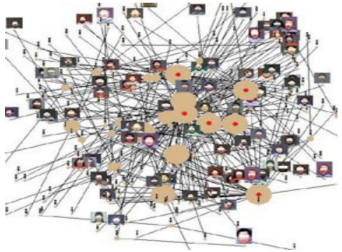


Disease Gene Network

Credit: Guney et al. (2016)

"the emergence of most diseases cannot be explained by single-gene defects, but involve the breakdown of the coordinated function of distinct gene groups"

Law



Criminal Network

Credit: Xu et al. (2005)

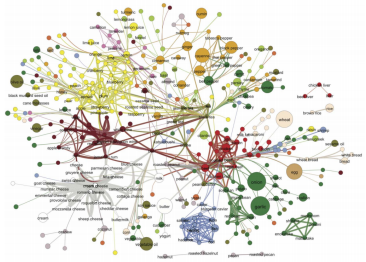
Economics

Trading Network

Credit: Adamic et al. (2017)

"strong feedback between the trading behaviour in buyers and sellers networks and the market conditions"

Culinary



Flavor Network

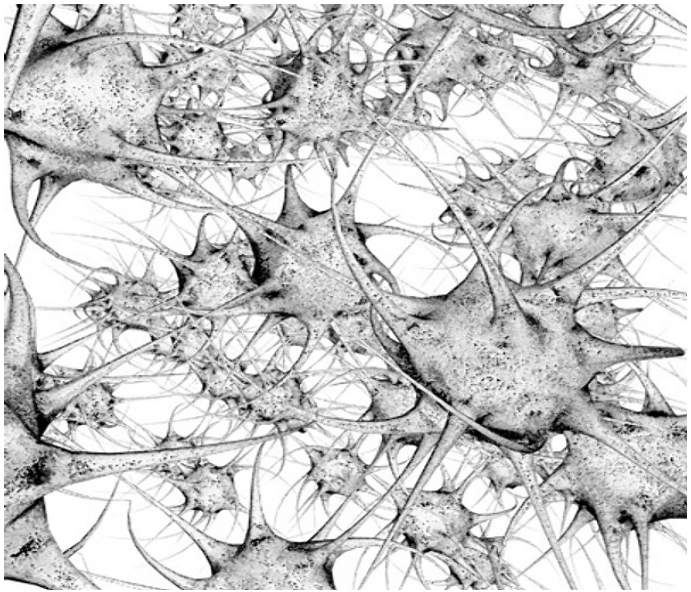
Credit: Ahn et al. (2011)

Read on food pairing theories and check out the interactive demo: https://foodgalaxy.jp/

Different scales

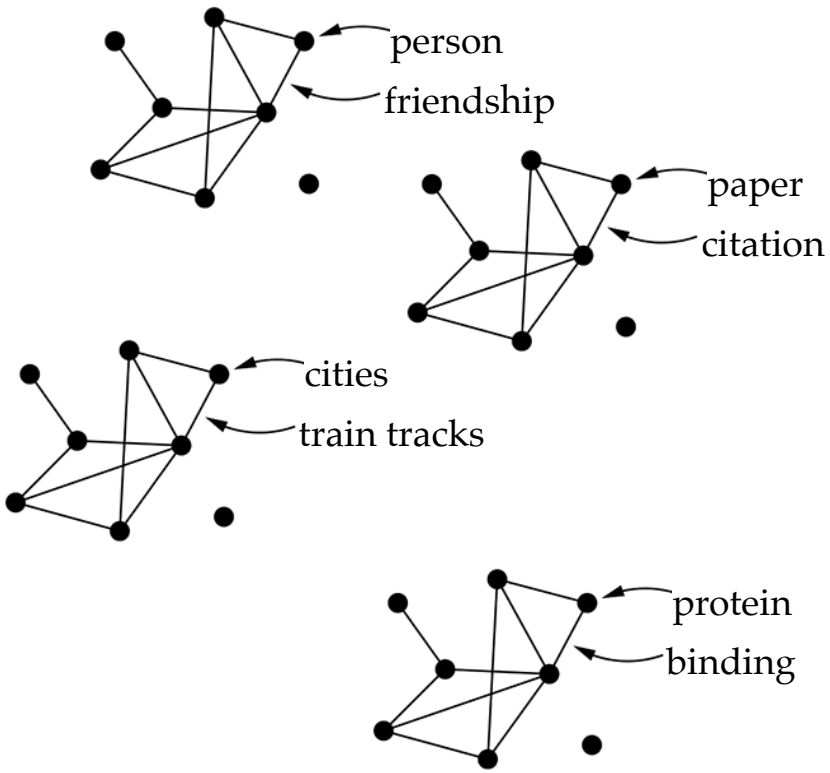
Interconnected systems exist at different scales, for instance in biology we have networks

- Within Cells
  - Protein-Protein Interaction Networks
  - Gene Interaction Networks
  - Metabolic Networks
- Between Cells
  - Cell Signalling Networks
  - Neural Networks
- Between Organisms
  - Food Webs
- Between Species
  - Species Interaction Networks



Benchmark graph datasets

	Network	Type	n	m
Social	film actors	undirected	449 913	25 516 482
	company directors	undirected	7 673	55 392
	math coauthorship	undirected	253 339	496 489
	physics coauthorship	undirected	52 909	245 300
	biology coauthorship	undirected	1 520 251	11 803 064
	telephone call graph	undirected	47 000 000	80 000 000
	email messages	directed	59 912	86 300
	email address books	directed	16 881	57 029
	student relationships	undirected	573	477
	sexual contacts	undirected	2 810	
Information	WWW `nd.edu`	directed	269 504	1 497 135
	WWW Altavista	directed	203 549 046	2 130 000 000
	citation network	directed	783 339	6 716 198
	Roget's Thesaurus	directed	1 022	5 103
	word co-occurrence	undirected	460 902	17 000 000
Technological	Internet	undirected	10 697	31 992
	power grid	undirected	4 941	6 594
	train routes	undirected	587	19 603
	software packages	directed	1 439	1 723
	software classes	directed	1 377	2 213
	electronic circuits	undirected	24 097	53 248
	peer-to-peer network	undirected	880	1 296
Biological	metabolic network	undirected	765	3 686
	protein interactions	undirected	2 115	2 240
	marine food web	directed	135	598
	freshwater food web	directed	92	997
	neural network	directed	307	2 359



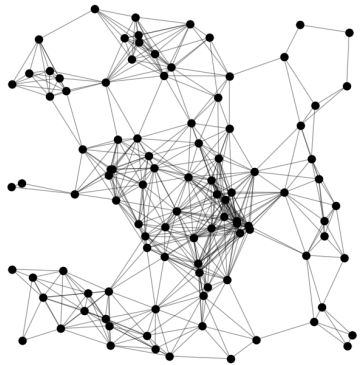
From: The structure and function of complex networks by Newman. SIAM review. 2003;45(2):167-256.

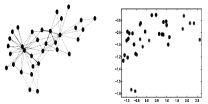
If interested, read part one of Newman's book on different types of network

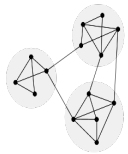
Graph Mining in CS

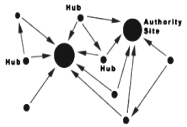
Analyzing, modelling complex data (not iid, structured)

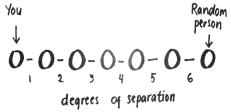
Comes as flavours of (statistical) relational learning, learning in structured settings, graph neural nets, graph representation learning, etc.











- Info. vs. Social Networks (Twitter) [Kwak et al.]
- **Signed** Networks [Leskovec et al.]
- Semantic Social Networks [Tang et al.]
- Four Deg. Of Separation [Backstrom et al.]
- Structural Diversity [Ugander et al.]
- Computational Social Science [Watts]
- **Network Embedding** [Perozzi et al.]

- Influence Max'n [Domingos & Kempe et al.]
- **Community Detection** [Girvan & Newman]
- Network Motifs [Milo et al.]
- Link Prediction [Liben-Nowell & Kleinberg]

- **HITS** [Kleinberg]
- **PageRank** [Page & Brin]
- Hyperlink Vector Voting [Li]

- **Small Worlds** [Migram]

- **Random Graph** [Erdos, Renyi, Gilbert]
- Degree Sequence [Tuttle, Havel, Hakami]

2015~2021

2010~2014

2005~2009

2000~2004

1998~1999

1997

1992

1970s

1960s

1950s

1930s

- **Graph Neural Networks**
- Deep Learning for Networks
- High-Order Networks [Benson et al.]

- Graph Evolution [Leskovec et al.]
- 3 Deg. Of Influence [Christakis & Fowler]
- Social **Influence** Analysis [Tang et al.]
- Six Deg. Of Separation [Leskovec & Horvitz]
- Network **Heterogeneity** [Sun & Han]
- Network **Embedding** [Tang & Liu]
- Computer Social Science [Lazer et al.]

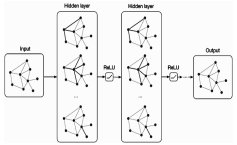
- **Small Worlds** [Watts & Strogatz]
- **Scale Free** [Barabasi & Albert]
- **Power Law** [Faloutsos x3]

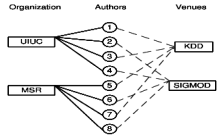
- Structural Hole [Burt]
- **Dunbar's Number** [Dunbar]

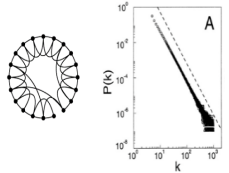
- The Strength Of **Weak Tie** [Granovetter]

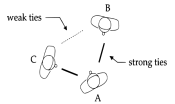
- **Homophily** [Lazarsfeld & Merton]
- Balance Theory [Heider et al.]

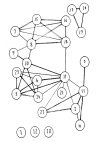
- **Sociogram** [Moreno]











Recent Trend: **Deep Learning for Graphs**

21st Century: **More CS**

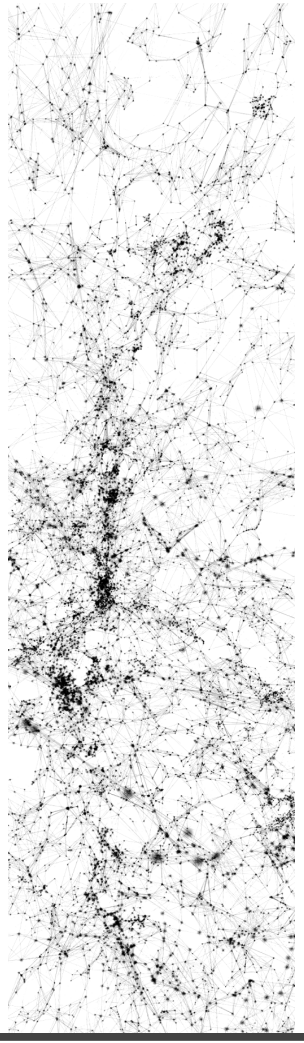
Late 20th Century: **CS & Physics**

20th Century: **Sociology**

Based on Slides from Jie Tang

Common tasks in network science

- Pattern & Anomaly Detection
- Modelling of Structure, Evolution, & Dynamics
- Measurements of Ranking & Similarity
- Clustering & Community Detection
- Prediction of Missing Link & Attributes
- Summarization, Visualization, & Layouts
- Temporal analysis of Evolution & Diffusion



Measurements of ranking & similarity

- Ranking: who is more important, or influential?
  - Degree Centrality, Betweenness Centrality, PageRank

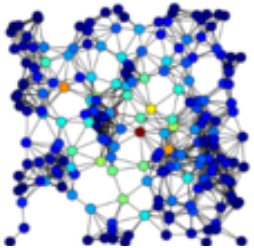
$$R : v \mapsto \mathbb{R}$$

- Similarity: how close are two nodes?
  - Shortest Path, Information Flow, common neighbours

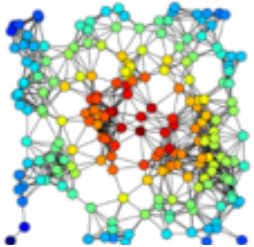
$$S : (u, v) \mapsto \mathbb{R}$$

Ranking nodes

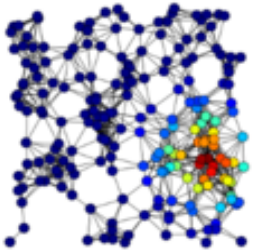
- Degree Centrality
  - marginals of the adjacency matrix
- Closeness Centrality
  - average length of the shortest paths
- Betweenness Centrality
  - number of shortest paths
- Eigenvector Centrality
  - connections to high-scoring nodes
  - e.g. Katz & PageRank



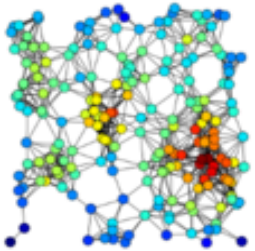
Betweenness



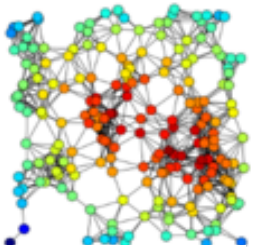
Closeness



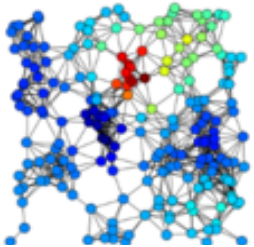
Eigenvector



Degree

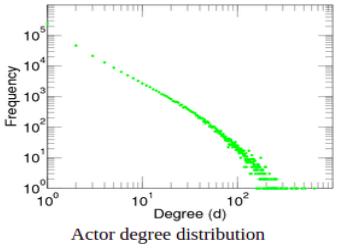


Harmonic

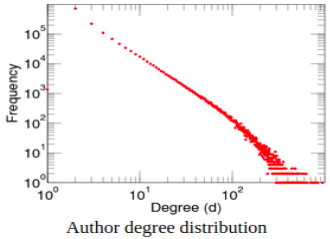


Katz

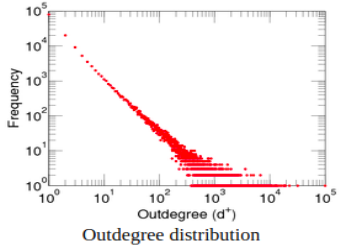
Degree distribution is heavy tailed [Example Pattern]



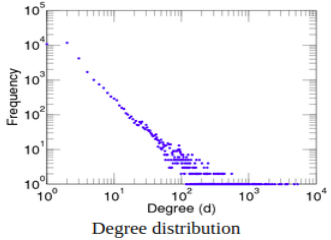
[Actor-Movies]



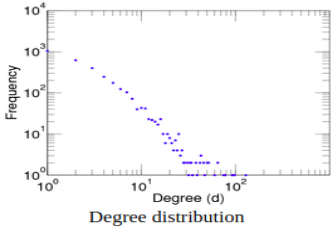
[Researcher-Publications]



[Wiki communications]



[Internet Topology]

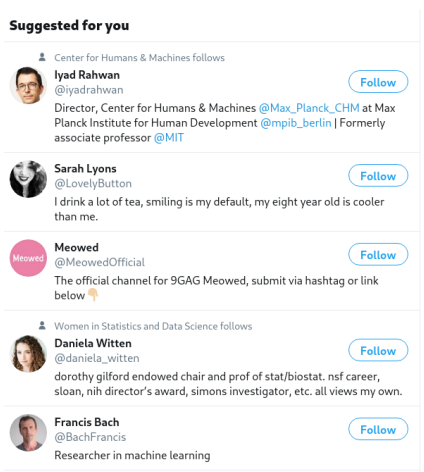


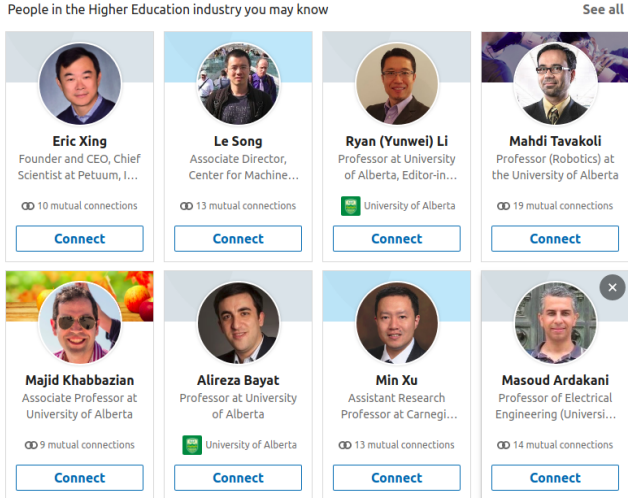
[Protein interactions]

Explore different datasets with precomputed statistics here: http://konect.cc/

Link Prediction [Example Task]

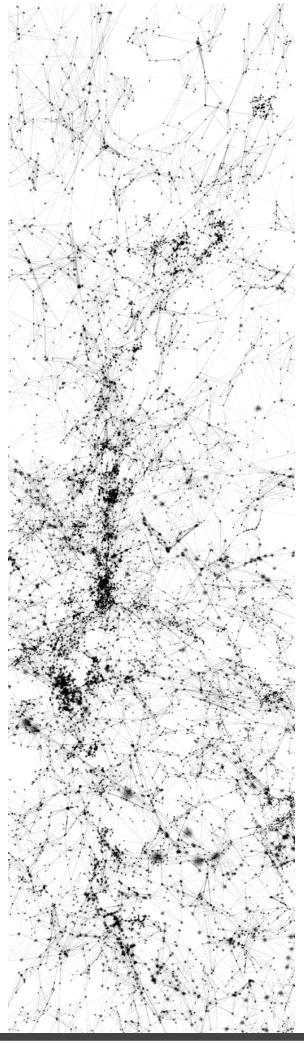
- Modelling of the network evolution
- Predict likely interactions, not explicitly observed
- Link recommendation: “friend” suggestion in social networks





Outline

- Introduction to the course
  - Complex systems is Physics
  - Societies as complex systems
  - Complex data everywhere and at every scale
  - Main tasks in complex data analysis
- Logistics of the course
  - General info
  - Who is in the class
  - What we will learn
  - Grading, deadlines, …



Logistics

Instructor: Reihaneh Rabbany [Office hours: Tuesdays 11:30-12:30pm, Zoom]

Teaching Assistant: Priyesh Vijayan

Project Advisor: Kellin Pelrine

Contact: **netscimcgill@gmail.com**

Course Website: www.reirab.com/comp599.html [has all the information needed, links and access restricted items are through Mycourses]

CDLab
McGill

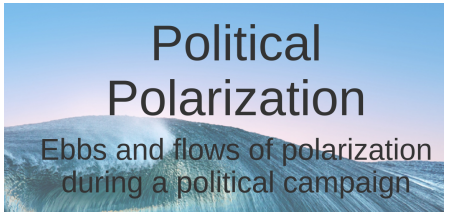
Theory
Algorithms for Analyzing
[Temporal] Graphs

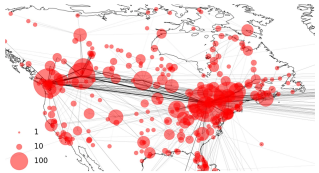
- Change point detection
- Anomaly detection
- Active Learning in Graphs
- Weak and Noisy Label/Data
- Graph representation learning
- Node classification and link prediction

Applications
health of online
societies and markets

- Crime
- Politics
- Epidemic

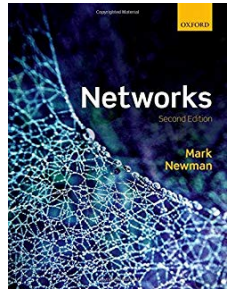
Infrared | AI for Humanity Mila

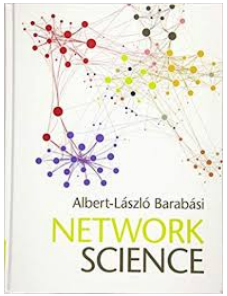


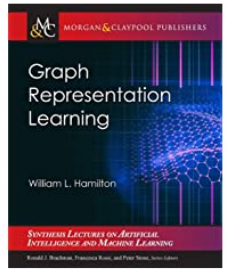


Reference Materials

- **Main textbooks**
  - **Networks: An Introduction** by M.E.J. Newman, ebook at library
  - **Network Science** by Albert-Barabasi, available online
  - **Graph Representation Learning Book** by William L. Hamilton, available online







- **Other textbooks**
  - **Networks, Crowds and Markets** by D. Easley and J. Kleinberg, available online
  - **Graph Representation Learning** by William L. Hamilton, available online
  - **Mining of Massive Datasets** by Jure Leskovec, Anand Rajaraman, Jeff Ullman, available online

- **Surveys and conference papers**
  - Web (WebConference, WSDM, ICWSM), Data (KDD, ICDM, SDM, ECML/PKDD, PAKDD), Learning (ICML, NeurIPS), Networks (ASONAM, NetSci, Complex Networks), ...

What we will learn

- Fundamental methods in each topic
  - Highly cited papers and basic concepts
- State of the art papers in each topic
  - Seminars on recent publications
- How to work with networked data
  - Assignments
- How to (attempt to) advance this area
  - Project

Grading details

- 50% project (10% proposal, 15% progress report, 25% final report)
- 30% assignments (3x10%)
- 10% presentations of assigned papers
- 10% reviewing assignments
  note: most of the grading is by peer-assessment
- bonus points:
  - 2 points for the best class presentation
  - 2 points for the best project proposal
  - 2 points for the best reviewer
  - 5 points for the best project
  - 1 point for each interesting point you share at the end of a class from the readings (for the current or previous lectures) which was not covered in the class

Project

- 50% project [specific writing format linked in the website]
  - 10% proposal
    - Writeup: 2 pages, describing what and why [8pt]
    - Presentation: 2 mins (2-3 slides) [2pt]
    - You will pitch this and get feedback
  - 15% progress report
    - Writeup: 4-5 pages, describing how and some preliminary results [12pt]
    - Presentation: 3 mins (3-4 slides) [3pt]
    - You will submit this and get feedback
  - 25% final report
    - Writeup: 8 pages, full project report [20pt]
    - Presentation: 7 mins (7-10 slides) [5pt]
    - You will submit this and get feedback and time to improve/respond before final submission
- Peer Reviewing [10%]: provide feedbacks on projects from other groups on each round
  - Proposal [2pt], progress [3pt], final [5pt]

Grading & policies

- 30% assignments (3x10%): basic programming with networked data
  - Assignment one: patterns in real world networks [explore]
  - Assignment two: random network and community detection [unsupervised]
  - Assignment three: node and link prediction [supervised]

Grading & policies

- 10% presentations of assigned readings (one/two presentations)
  - showing full understanding of the paper and related background
  - being able to answer questions
  - proper timing: each presentation is 20 minutes
  - proper depth/breath: covering with equal emphasis/time allocation: problem def, motivation & intuition, methodology, experiment setup (data, tasks, evaluation), findings & results
    - e.g. don't get tangled in explaining the theory of the method, loosing the big picture
- How you get marked?
  - Average score given by the listeners, peers and instructor

Collaboration

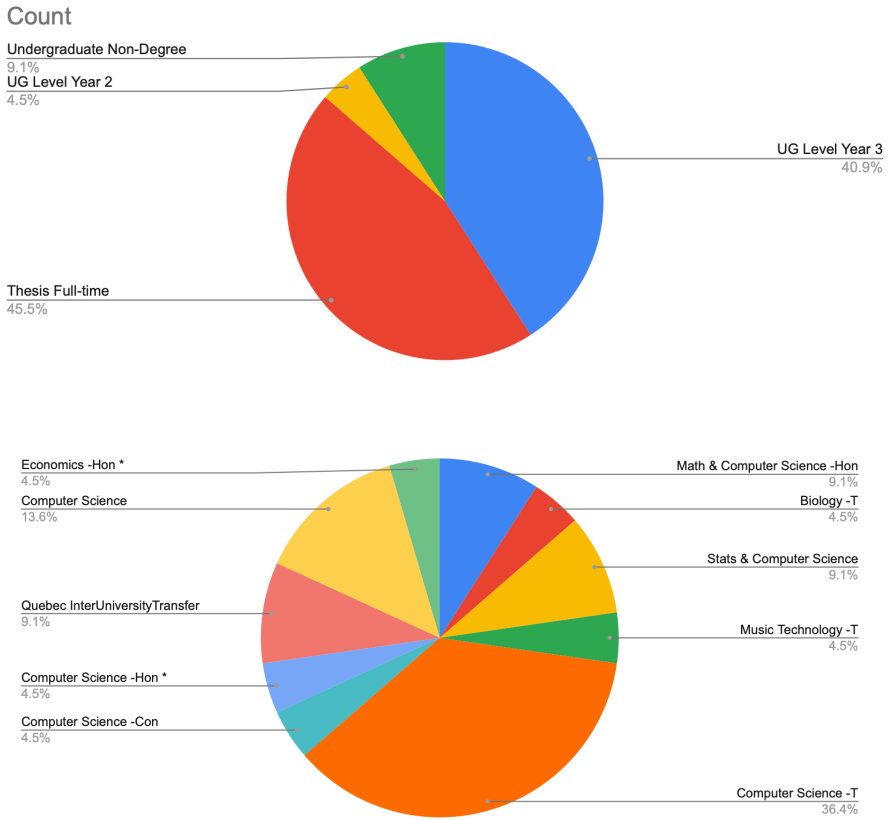
Welcome, but you need to acknowledge, cite any used resources

Do not copy and paste anything more than 3 consecutive words, in coding or write ups. This and other forms of plagiarism will be reported

Class composition

A Quick round of introductions

- Name
- Your background & interests
- Any particular reason for taking this class
- Python, linear algebra & ML background?



Further optional readings

- The first ideas: Six degrees of separation & small world experiment
  - First mentioned in a novel in 1929, then validated in real world through experiments in 1967
- Funding papers:
  - Emergence of scaling in random networks, 1999
  - On power-law relationships of the Internet topology, 1999
- Interesting read: More is different (loosely relevant)
- Watch:
  - Connected Movie
  - Mark Newman 1 - The Connected World
  - Networks are everywhere with Albert-László Barabási
  - Mark Newman - The Physics of Complex Systems

Childhood's end by Arthur C. Clarke