Network Theory and Dynamic Systems
01. Introduction to Network Science
SOSE 2025

Dr. -Ing. Stefania Zourlidou

Institute for Web Science and Technologies
Universität Koblenz

Objectives of this Lecture

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- Clarify the Course Objectives
- Software and Libraries
- An Introduction to Networks and Network Science
- Example of Networks

1. The Course and its Objectives

Course Description

- Networks are everywhere — in friendships, messages, computers, the internet, transport, and even inside our brains and bodies
- Networks help us understand how things are connected, from simple to very complex relationships
- In this course, we'll explore real-world networks (like social media and web networks) and learn basic tools to study and visualize them

Course Objectives

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- Understand the key ideas of network literacy
- Learn to work with networks using tools like Python (NetworkX)
- Identify the basic parts of a network: nodes, links, degree, connectivity, and more
- Study social networks and their small-world features
- Use centrality measures to find important nodes in a network
- Understand fun ideas like the friendship paradox (your friends have more friends than you!)
- Measure things like homophily (similarity) and clustering in networks
- Explore how things spread on networks — like diseases or rumors
- See how search engines use networks to rank web pages
- Discover how networks are used in biology, business, AI, social media, and more

Software

We will be using Python and the NetworkX (networkx.readthedocs.org) module. You can follow one or both of two approaches:

1. There are currently several free services to run Jupyter notebooks in the cloud, including:
   - Google Colab (colab.research.google.com)
   - Binder (mybinder.org)
   - Kaggle Kernels (www.kaggle.com/kernels)
   - Azure Notebooks (notebooks.azure.com)
   - Datalore (datalore.io)

Software

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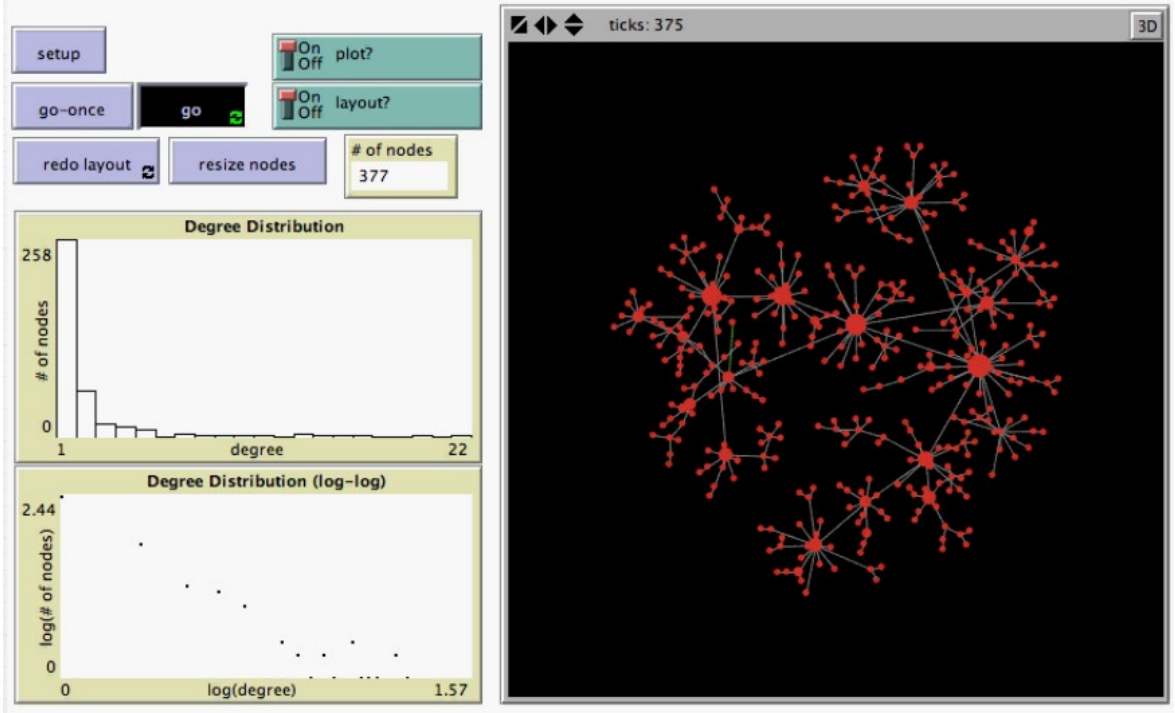
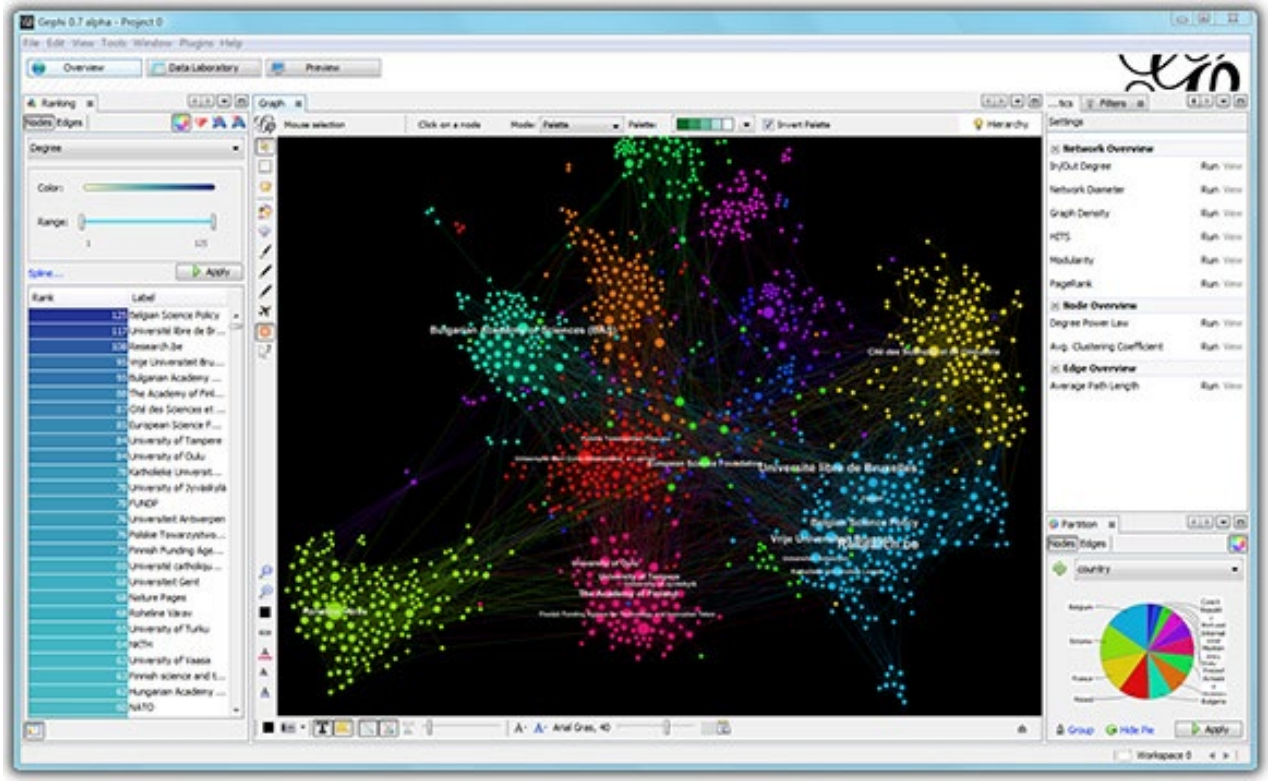
2. If you want to run Python on your own laptop and don't have Jupyter/IPython, we recommend installing Anaconda (Python 3): www.anaconda.com/distribution
3. I don't recommend using other Python distributions
4. This method is best if you're comfortable managing packages using tools like pip or conda

Important Notes

- Online (cloud-based) notebooks work too — but each one is different, and we can't test them all
- You may need to try a few, read instructions, or seek support to install packages
- Running Python locally can be tricky, especially on Windows
- The course team may not be able to help with technical issues on your setup

Other Software





- Gephi (gephi.org)
- NetLogo (ccl.northwestern.edu/netlogo)

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2. Introduction to Networks

Networks

- Networks are present in all aspects of our lives:
  - networks of friends
  - of communications
  - of computers
  - the Web
  - of transportation
  - of brain cells
  - of proteins, etc.

Networks Are Part of Everyday Life

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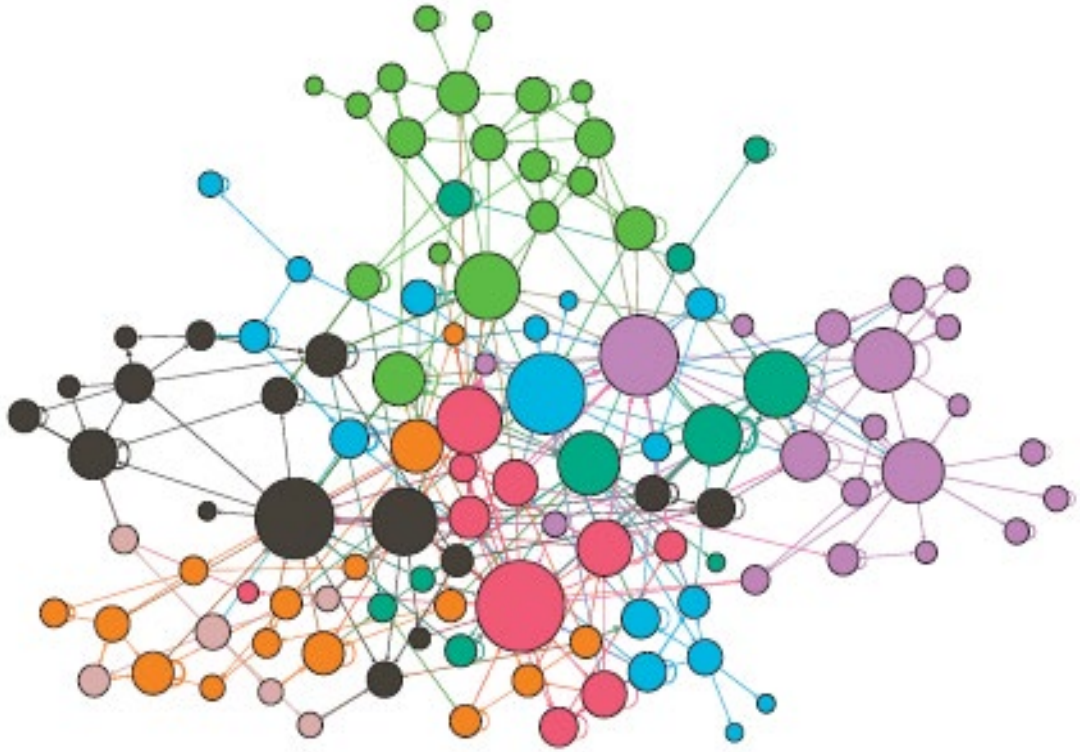
- We use networks all the time — like when we chat on Facebook or Twitter, shop on Amazon, search on Google, or book flights
- Most of us don't even realize networks are working behind the scenes
- Knowing how networks work is important for many careers — in tech, marketing, business, design, biology, the arts, and more



A network map of chapters, sections, and subsections of Textbook [1], highlighting the interconnectedness through links, node colors, and sizes

A World Without Networks

- No friendships, no roads connecting places, and every computer works alone
- Nothing spreads — no news, no events, no connections
- It would be a lonely and disconnected world
- Networks make life dynamic — they enable events, communication, and sharing of knowledge

Why Networks Matter

- Networks are the foundation of how we connect and communicate
- Biological networks help our bodies grow and work
- Neural networks in the brain make thinking and awareness possible
- Information and transport networks help people and ideas move and spread across the world

How Networks Help Us Understand Complexity

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- Networks break down complex systems into simple parts: nodes (things) and links (connections)
- They ignore small details and focus on how things interact
- This makes networks useful in many fields to study complex systems

The Structure of Networks: What Makes Up a Network?

- Networks consist of nodes (e.g., people, cities, genes) and links (e.g., relationships, interactions)
- Nodes represent entities within a system, while links represent the connections between them
- In network diagrams:
  - Node color can show different groups or types
  - Node size often shows how many connections it has — bigger means more important or influential

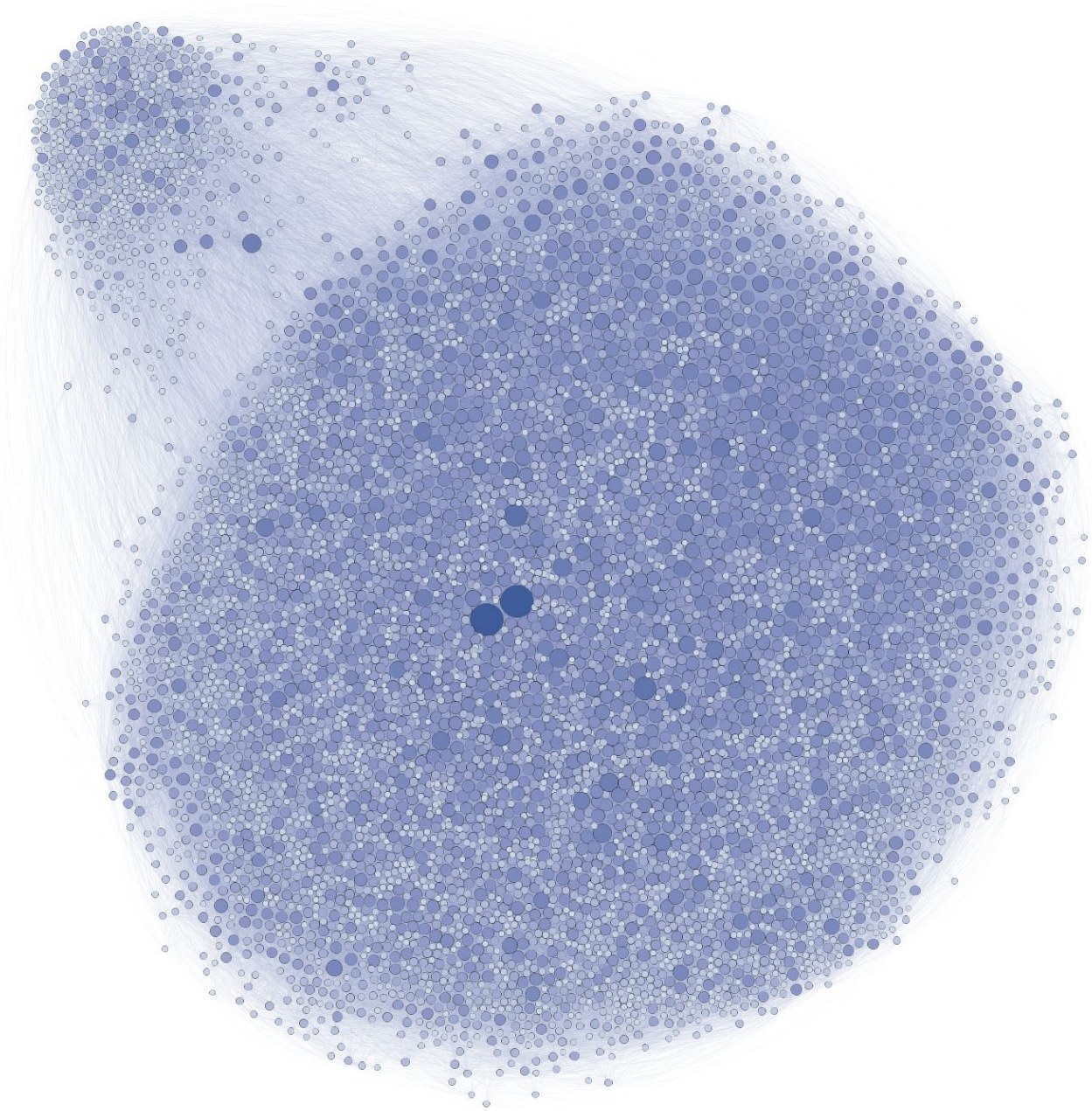
Network Analysis: Studying Networks of All Sizes

- Both small and large networks provide valuable insights into structural dynamics
- Small networks let us look closely at each connection
- Large networks help us find big patterns and overall structure
  - The course Textbook [1] provides data for network examples on a public GitHub repository for practical exploration

3. Examples of Networks

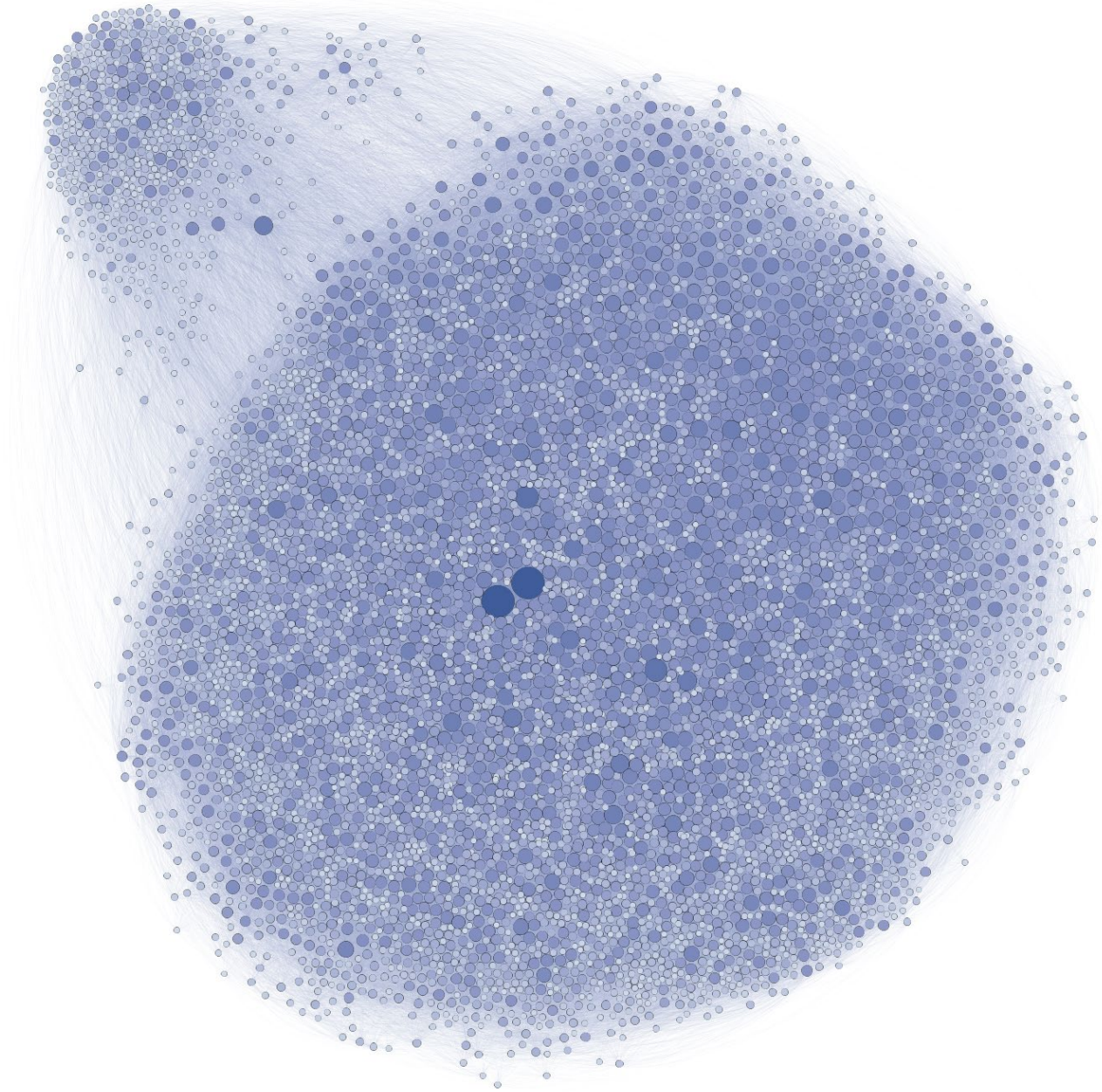
Social Networks

- Facebook users at Northwestern University
  - What do nodes represent?
  - What do links represent?
  - Do links have direction?
  - Do links have weights?
  - Larger, darker nodes have more connections; what does that represent?
  - What do the two clusters tell us?

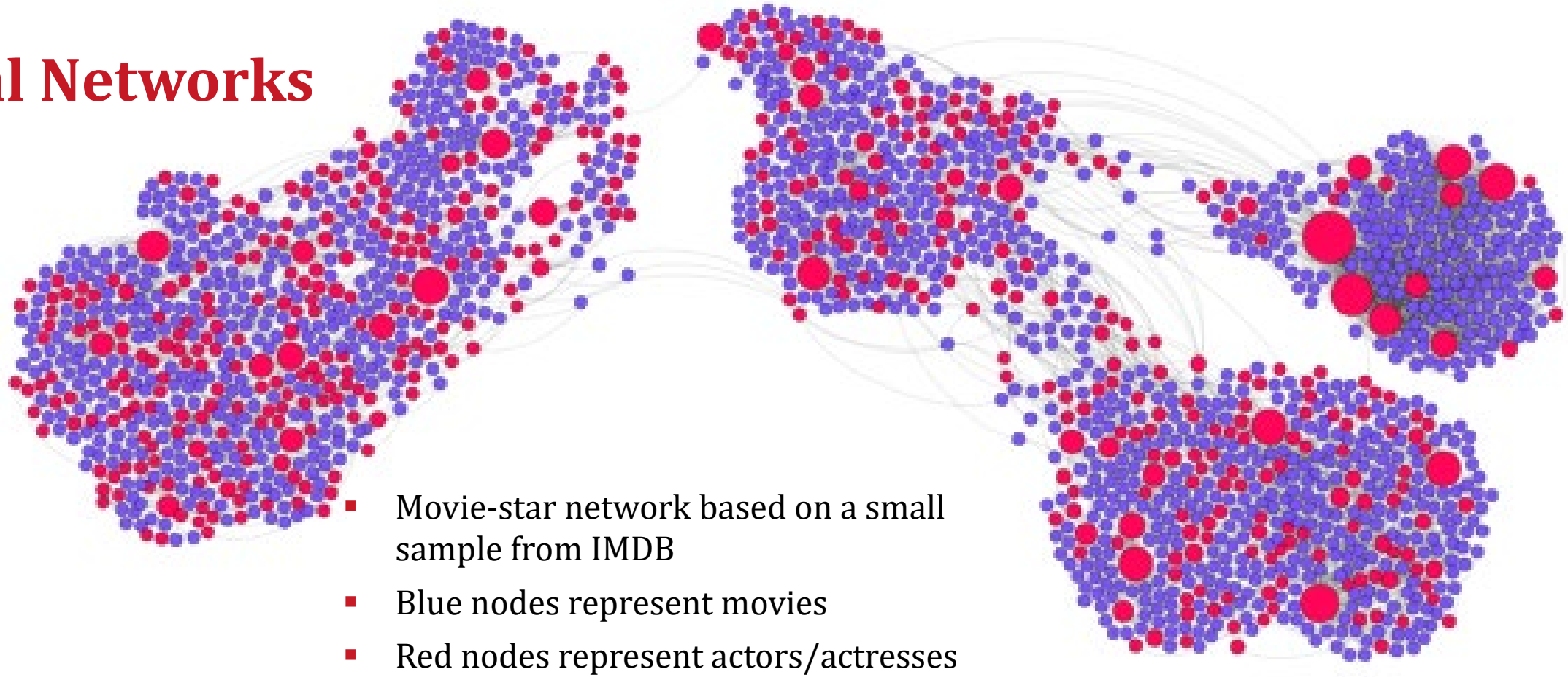


Social Networks

- What do nodes represent? People
- What do links represent? Facebook friend connections
- Do links have direction? No
- Do links have weights? No
- Larger, darker nodes have more connections; what does that represent? More connections
- What do the two clusters tell us? Undergraduate students are more likely to be friends with other undergraduates than with graduate students

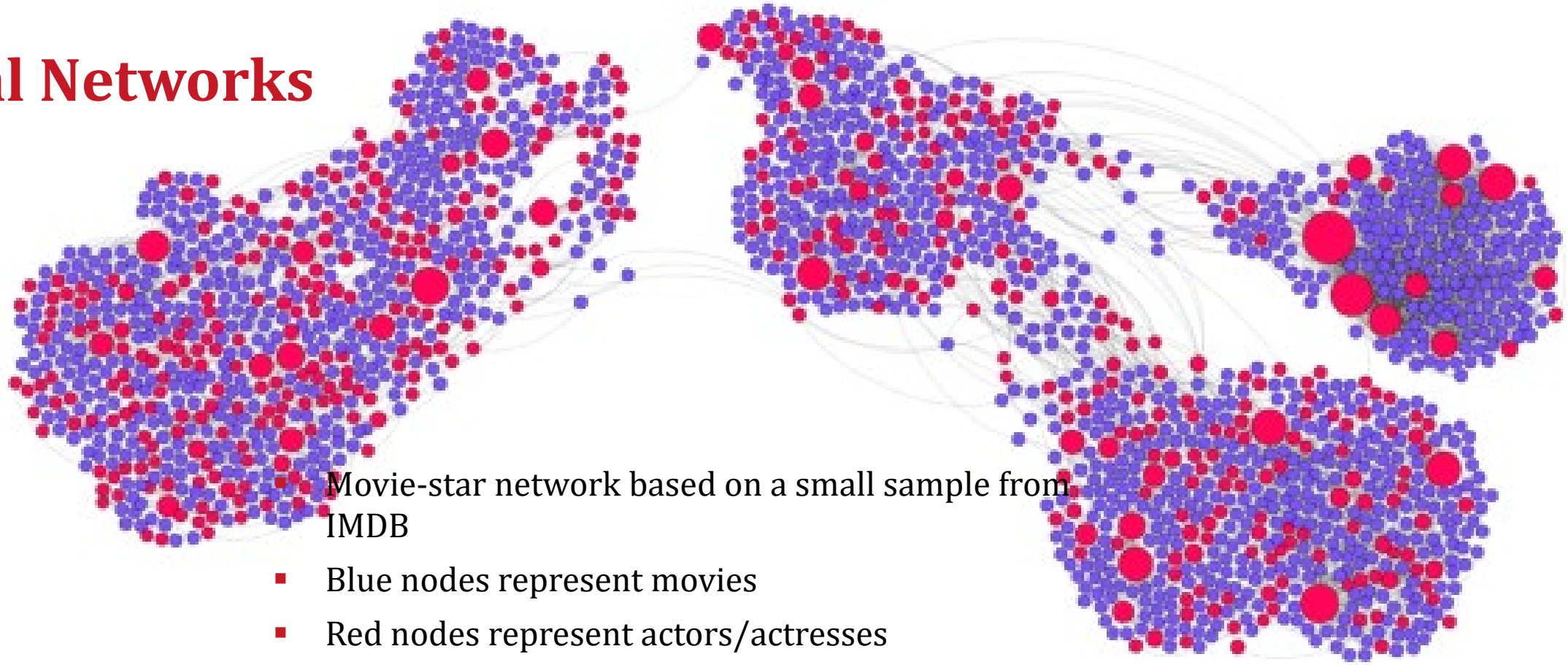


Social Networks



- Movie-star network based on a small sample from IMDB
- Blue nodes represent movies
- Red nodes represent actors/actresses
- What do links represent?
- Do links have direction?
- Do links have weights?
- Larger nodes have more connections; what does that mean?
- What do the clusters represent?

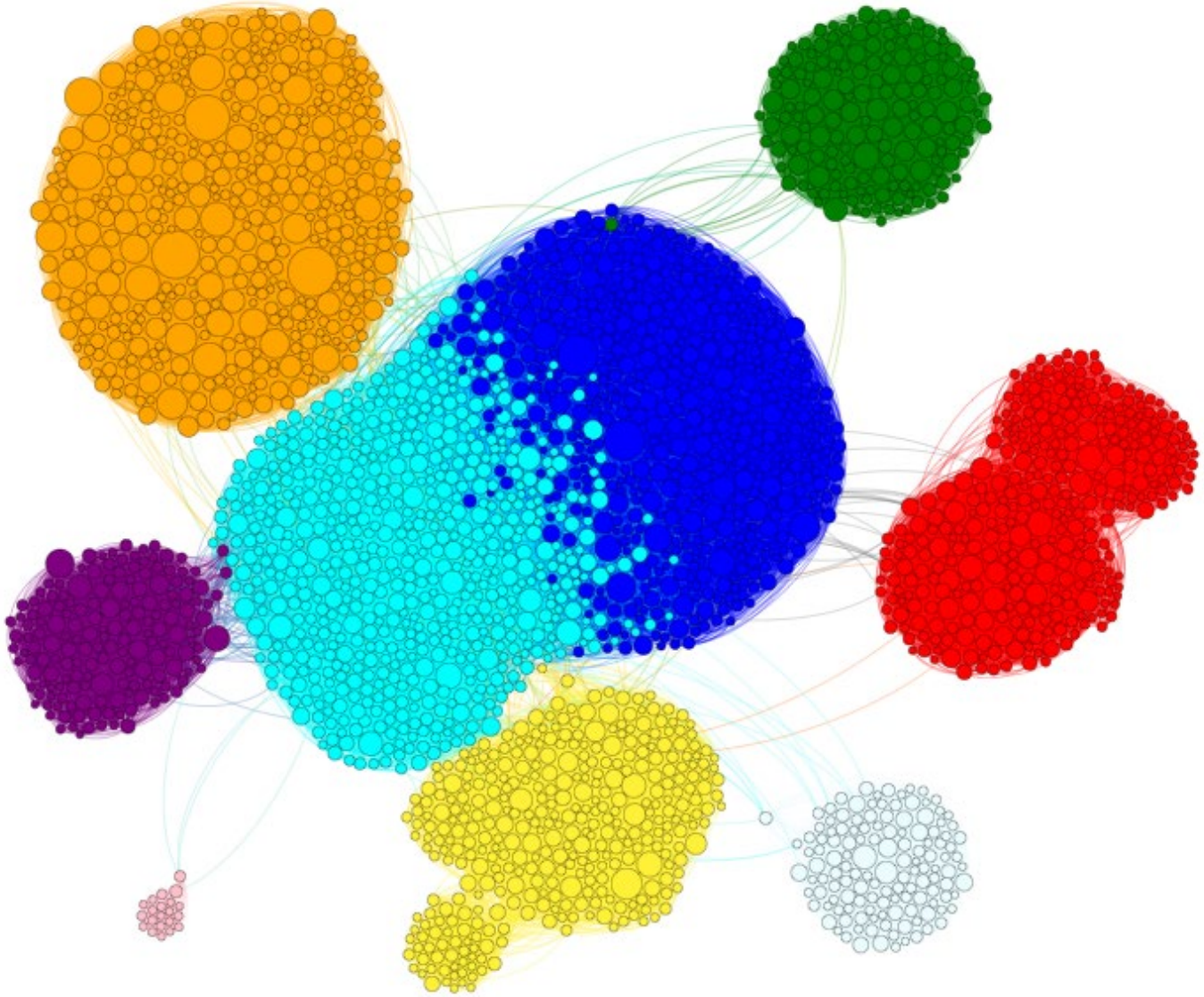
Social Networks



- Movie-star network based on a small sample from IMDB
  - Blue nodes represent movies
  - Red nodes represent actors/actresses
  - What do links represent? An actress and a movie in which she has starred
  - Do links have direction?
  - Do links have weights?
  - Larger nodes have more connections; what does that mean? Stars acted in many movies
  - What do the clusters represent?

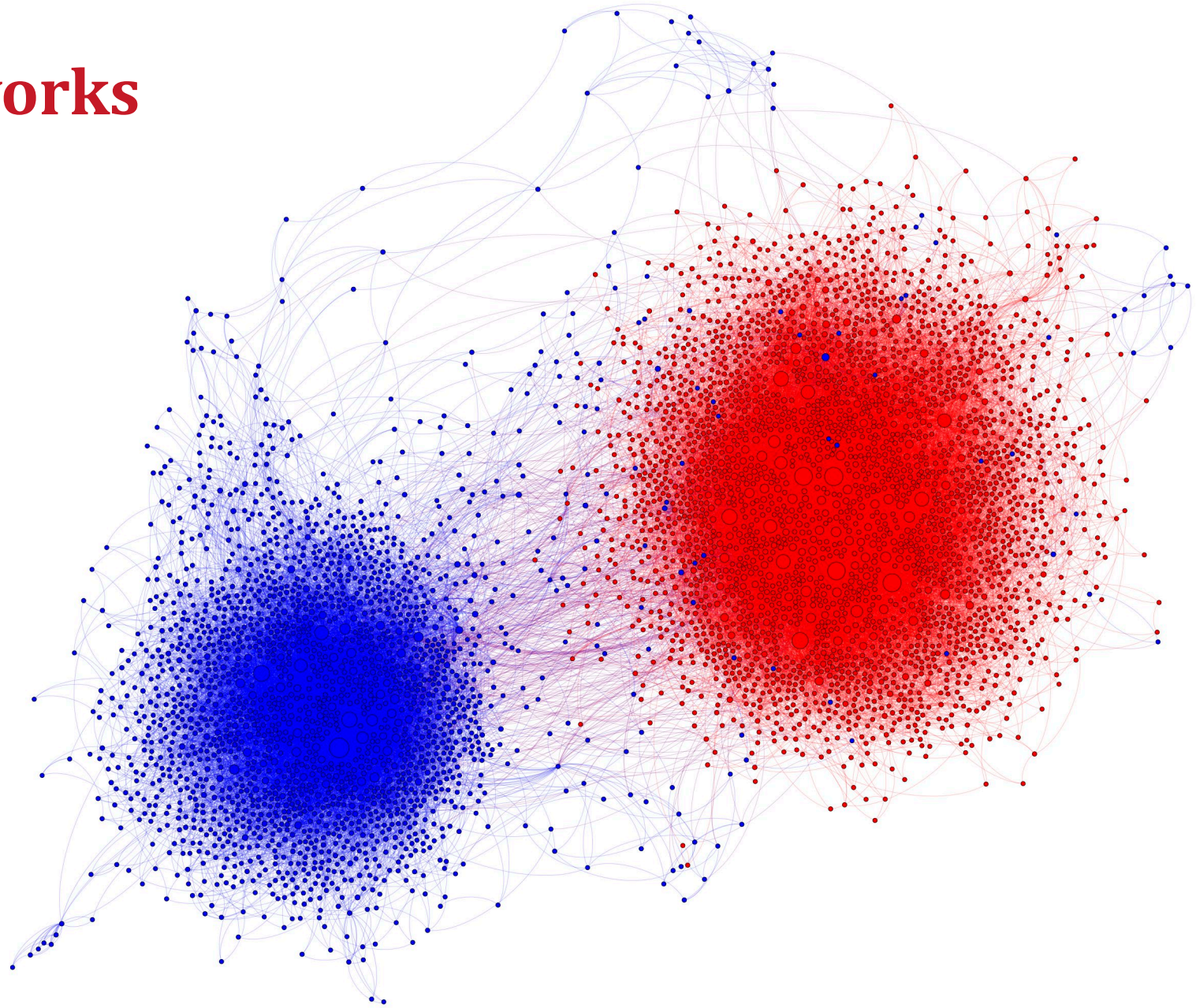
Social Networks

- Movie co-star network based on a small sample from IMDB
- What do nodes represent? Actors
- What do links represent? Co-starring in at least one movie
- Do links have direction?
- Do links have weights?
- Larger nodes have more connections; what does that mean?
- What do the clusters represent?



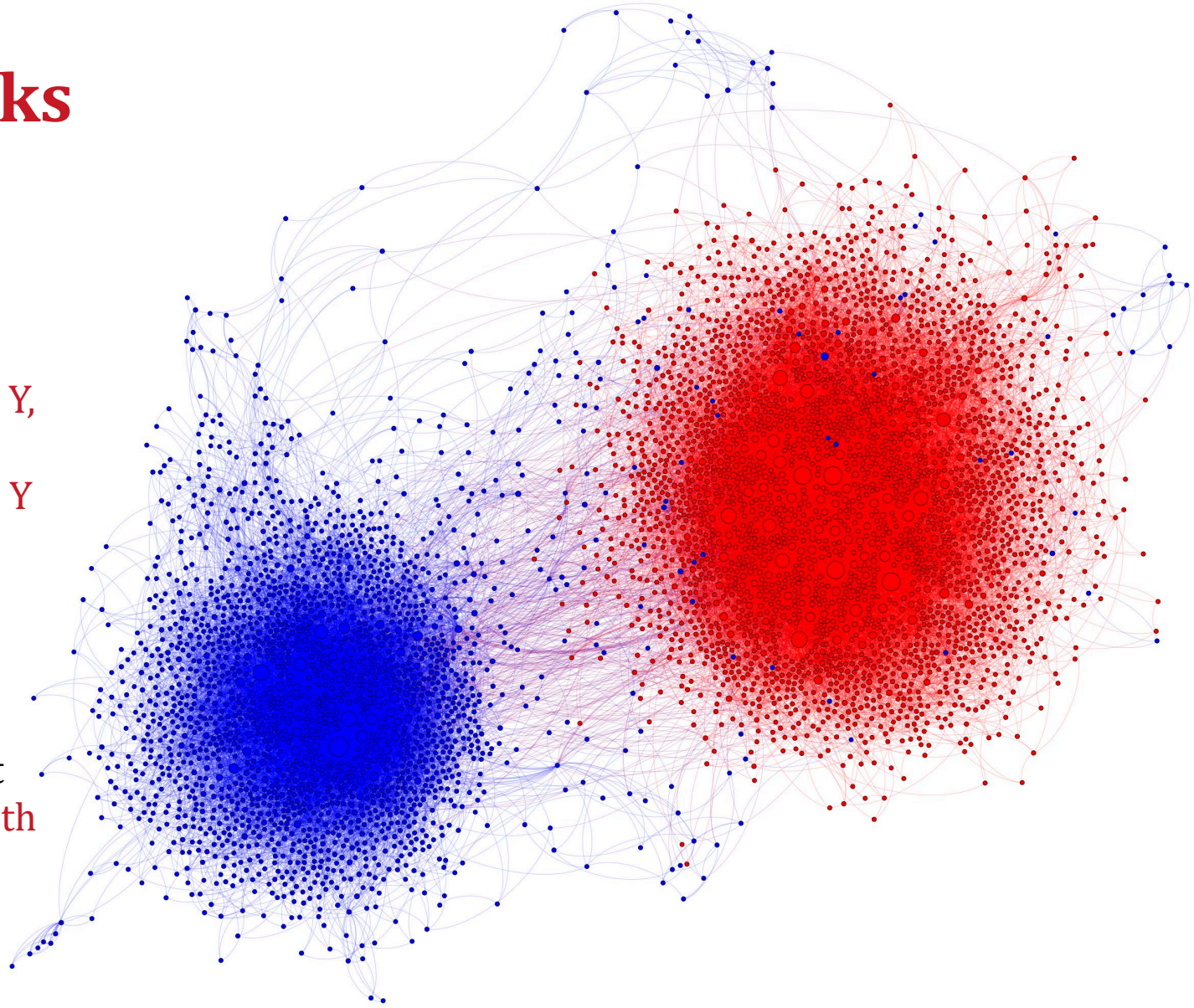
Communication Networks

- Retweet network on Twitter, based on political posts during 2010 US election
- What do nodes represent?
- What do links represent?
- Do links have direction?
- Do links have weights?
- Larger nodes have more connections; what does that mean?
- What do the clusters and colors represent?

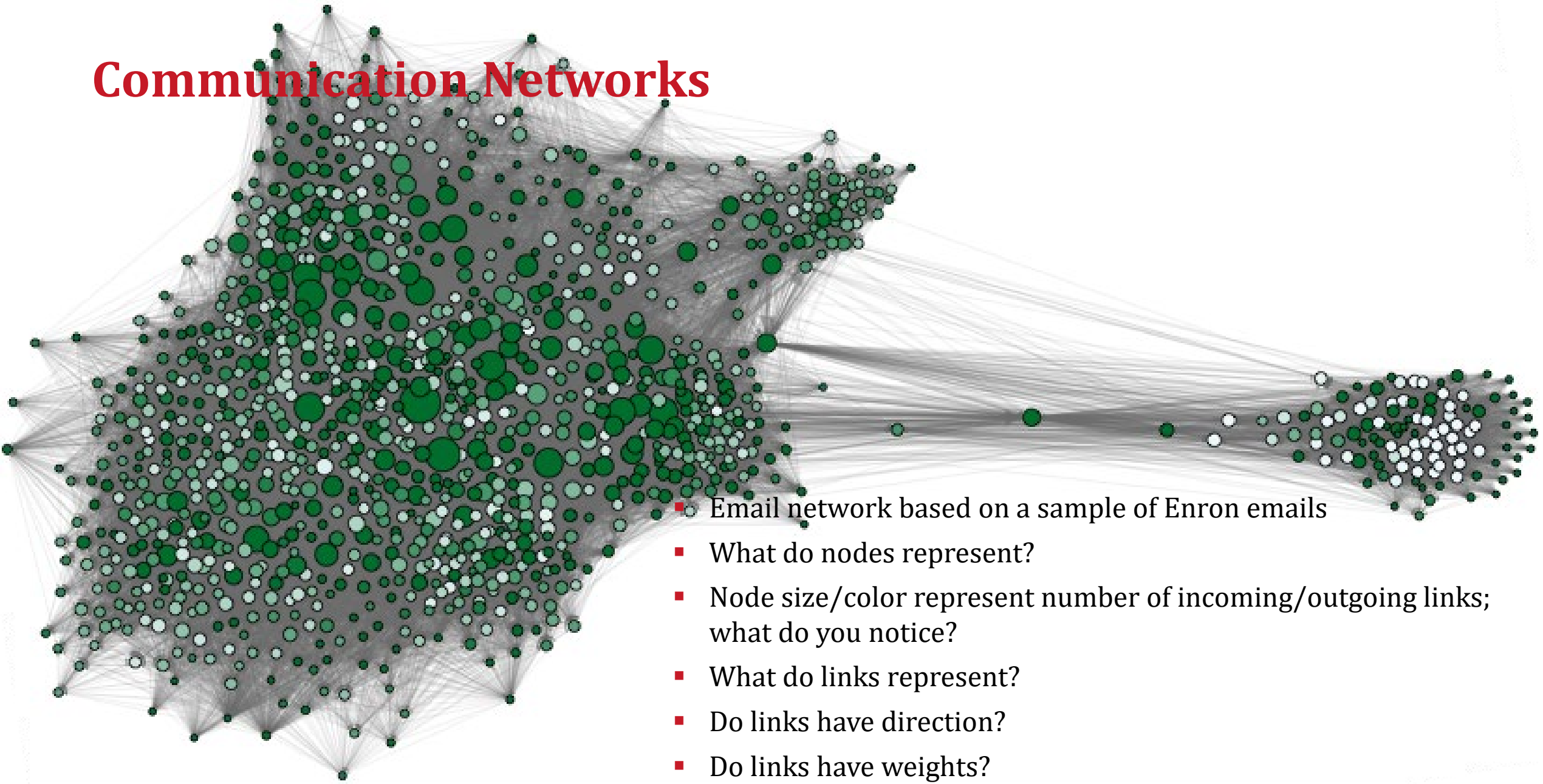


Communication Networks

- Retweet network on Twitter, based on political posts during 2010 US election
- What do nodes represent? People
- What do links represent? When X retweets Y, we draw a directed link from Y to X, to indicate that a message has propaged from Y to X.
- Do links have direction?
- Do links have weights?
- Larger nodes have more connections; what does that mean? Larger nodes are those with more outgoing links,
- What do the clusters and colors represent? Conservative users (red nodes) mostly retweet messages from other conservatives, while progressive users (blue nodes) similarly share progressive content

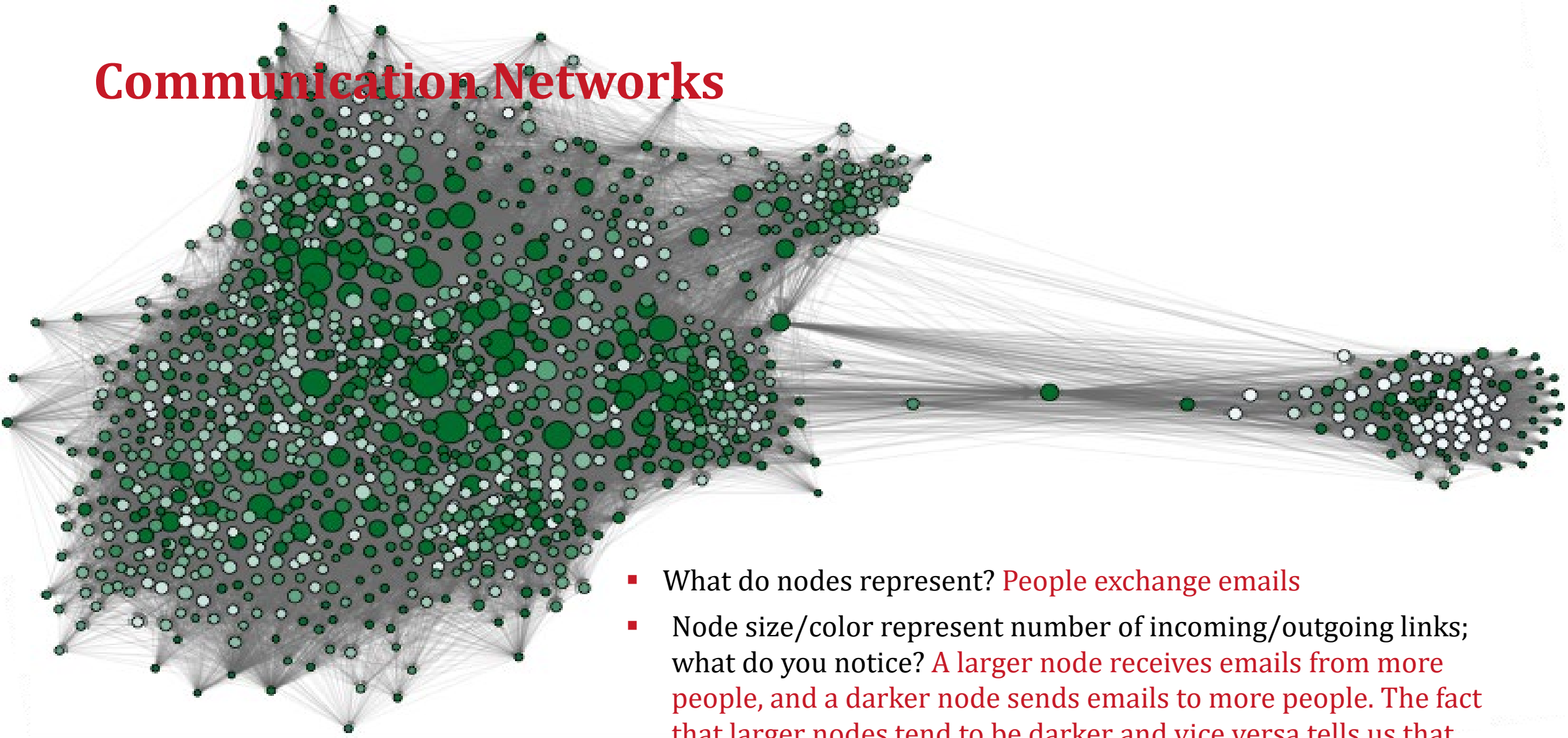


Communication Networks



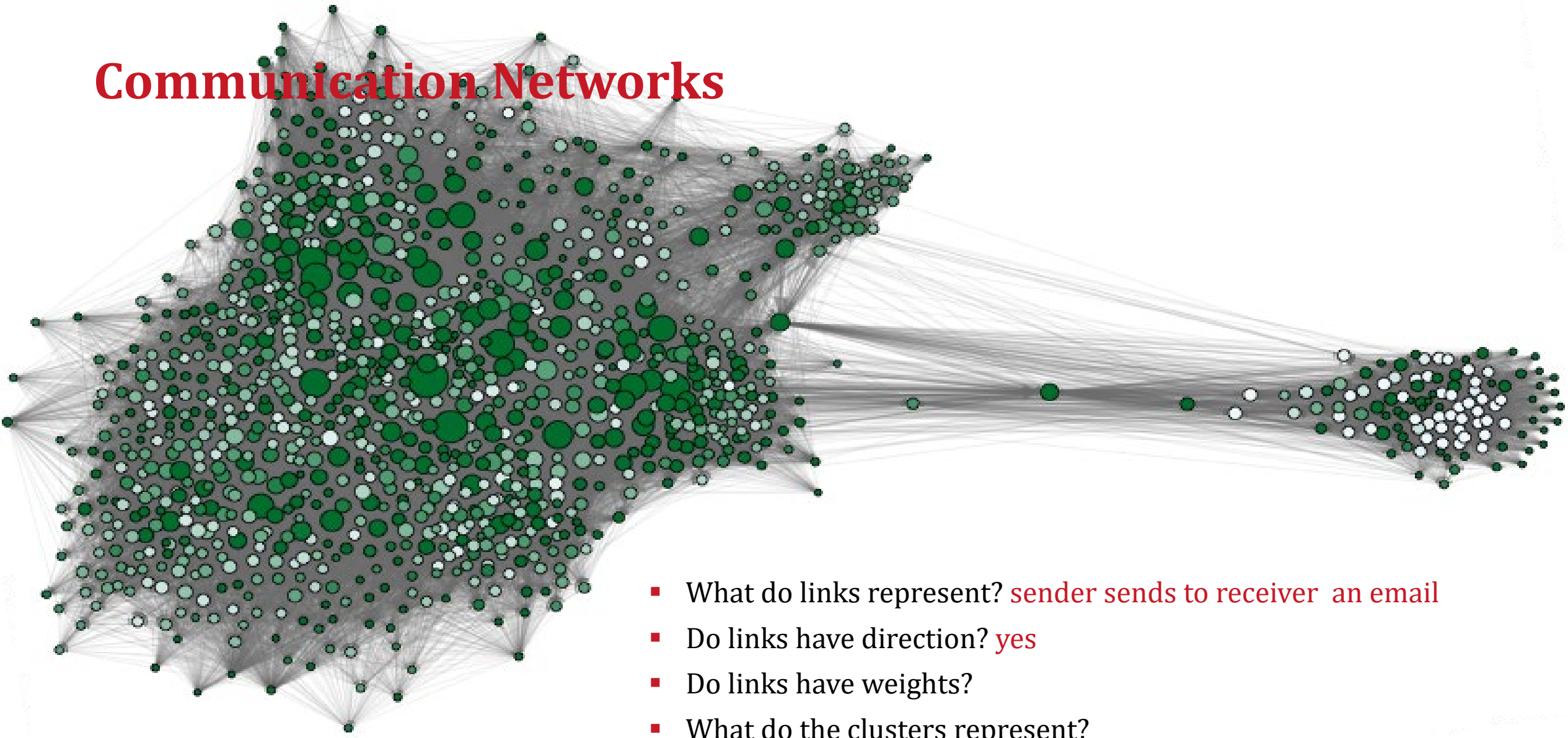
- Email network based on a sample of Enron emails
- What do nodes represent?
- Node size/color represent number of incoming/outgoing links; what do you notice?
- What do links represent?
- Do links have direction?
- Do links have weights?
- What do the clusters represent?

Communication Networks



- What do nodes represent? People exchange emails
- Node size/color represent number of incoming/outgoing links; what do you notice? A larger node receives emails from more people, and a darker node sends emails to more people. The fact that larger nodes tend to be darker and vice versa tells us that there is a correlation between sending and receiving emails

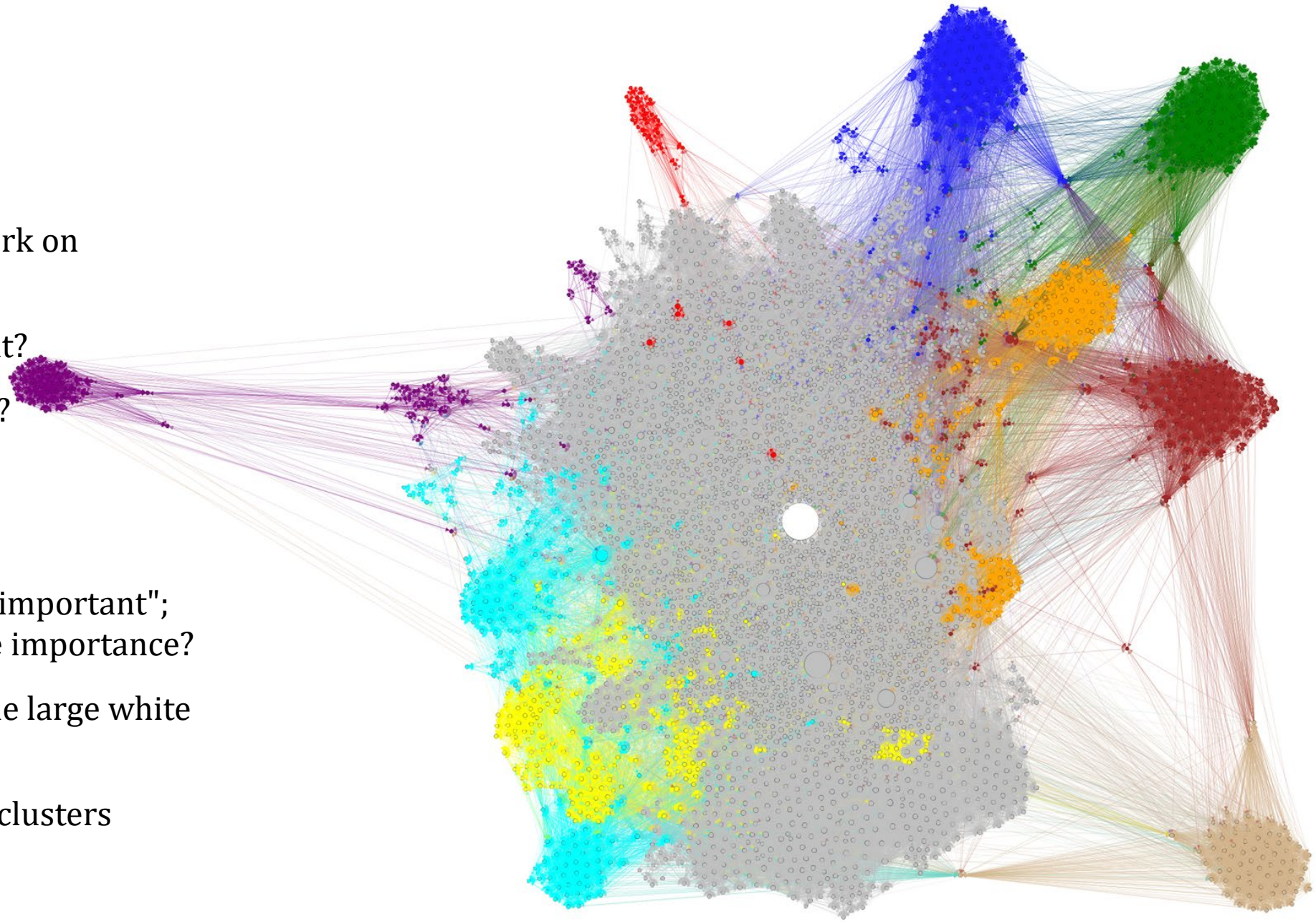
Communication Networks



- What do links represent? sender sends to receiver an email
- Do links have direction? yes
- Do links have weights?
- What do the clusters represent?

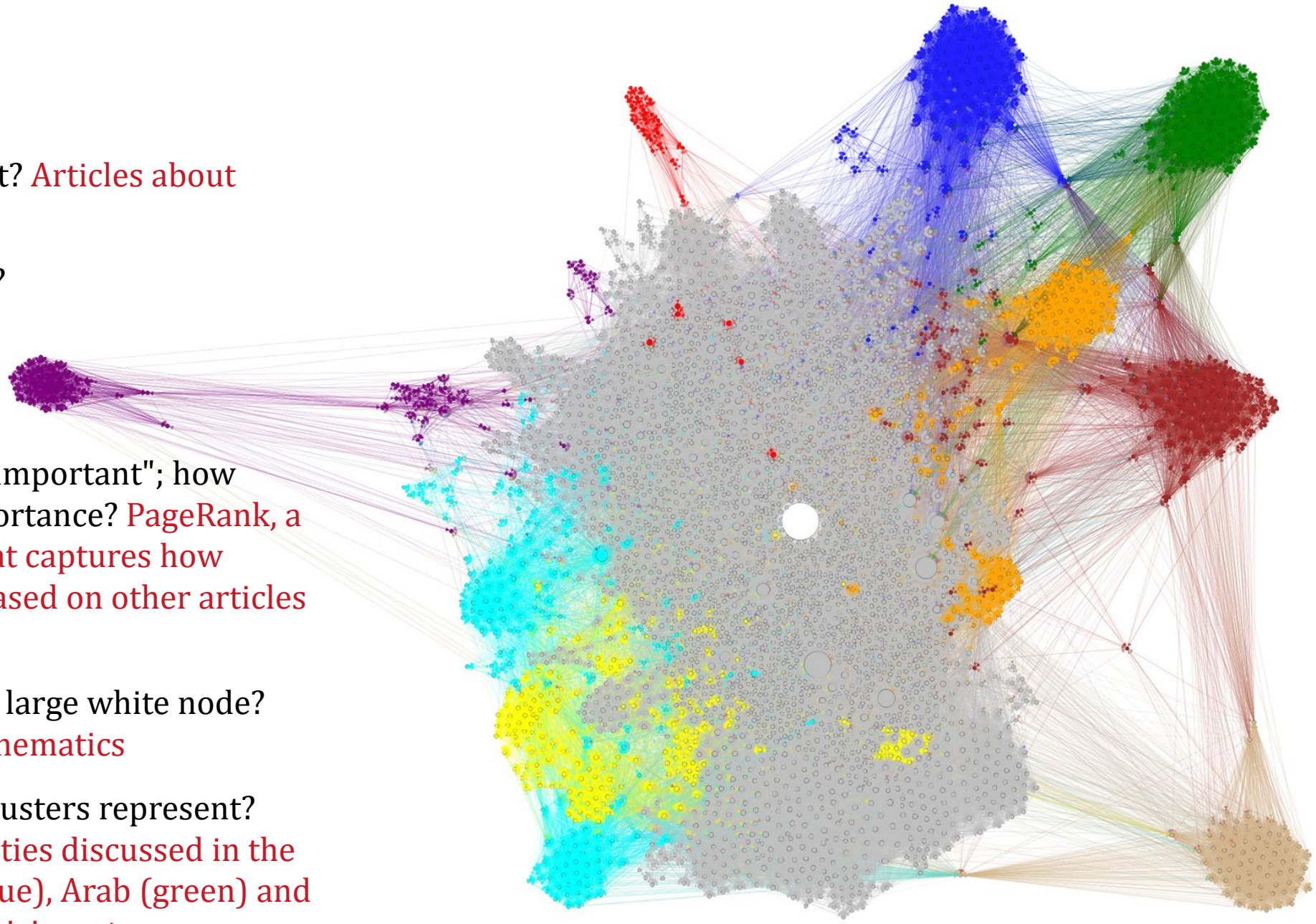
Wikipedia

- Math information network on Wikipedia
- What do nodes represent?
- What do links represent?
- Do links have direction?
- Do links have weights?
- Larger nodes are more "important"; how would you measure importance?
- Can you guess what is the large white node?
- What might the colored clusters represent?



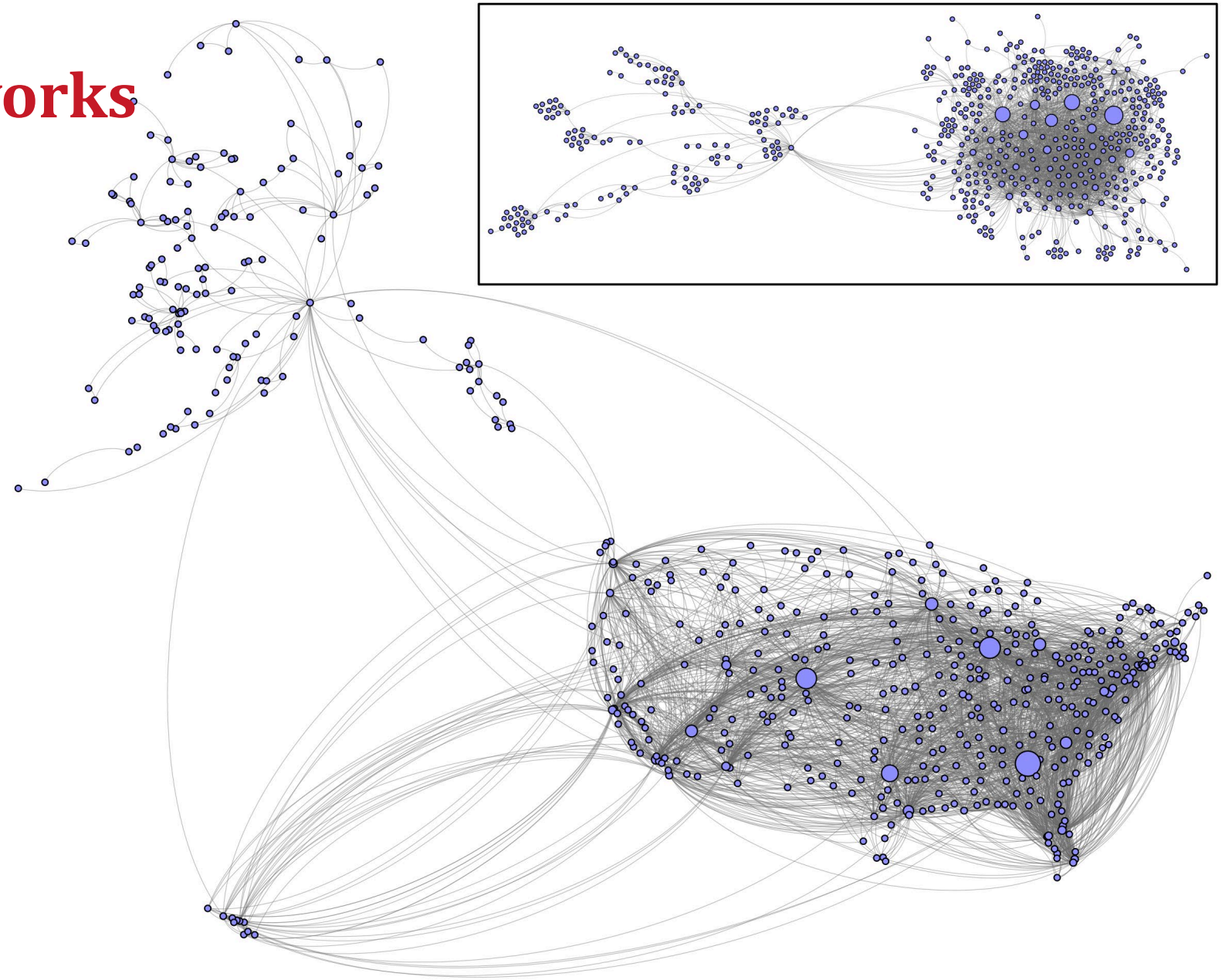
Wikipedia

- What do nodes represent? Articles about maths
- What do links represent?
- Do links have direction?
- Do links have weights?
- Larger nodes are more "important"; how would you measure importance? PageRank, a measure of centrality that captures how important an article is based on other articles that link to it
- Can you guess what is the large white node? General article about Mathematics
- What might the colored clusters represent? Colors highlight communities discussed in the text: theoretical Greek (blue), Arab (green) and Indian (brown) mathematician, etc.



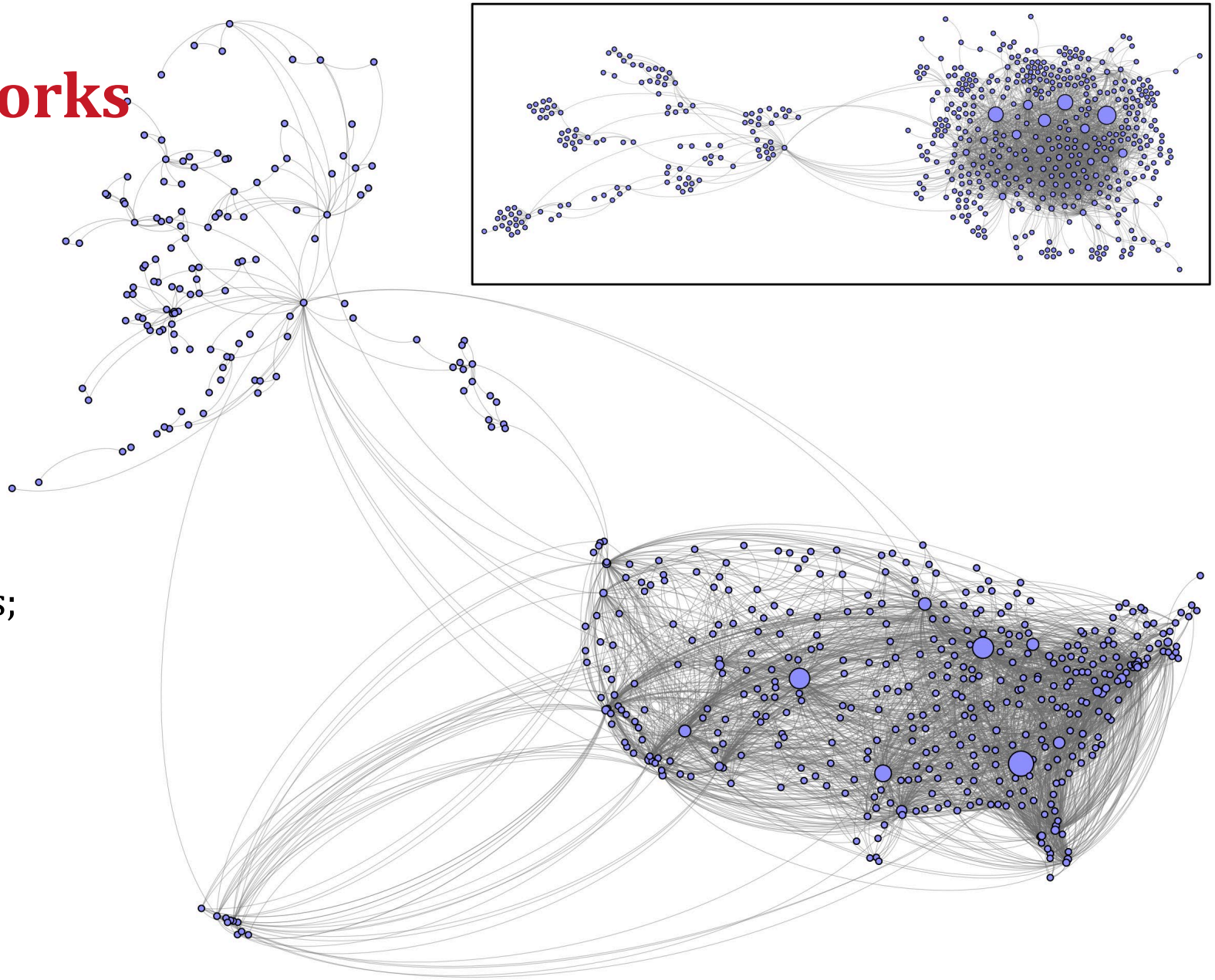
Transportation Networks

- US air transportation network
- What do nodes represent?
- What do links represent?
- Do links have direction?
- Do links have weights?
- Larger nodes have more connections; what do they represent?
- What do the layouts represent?



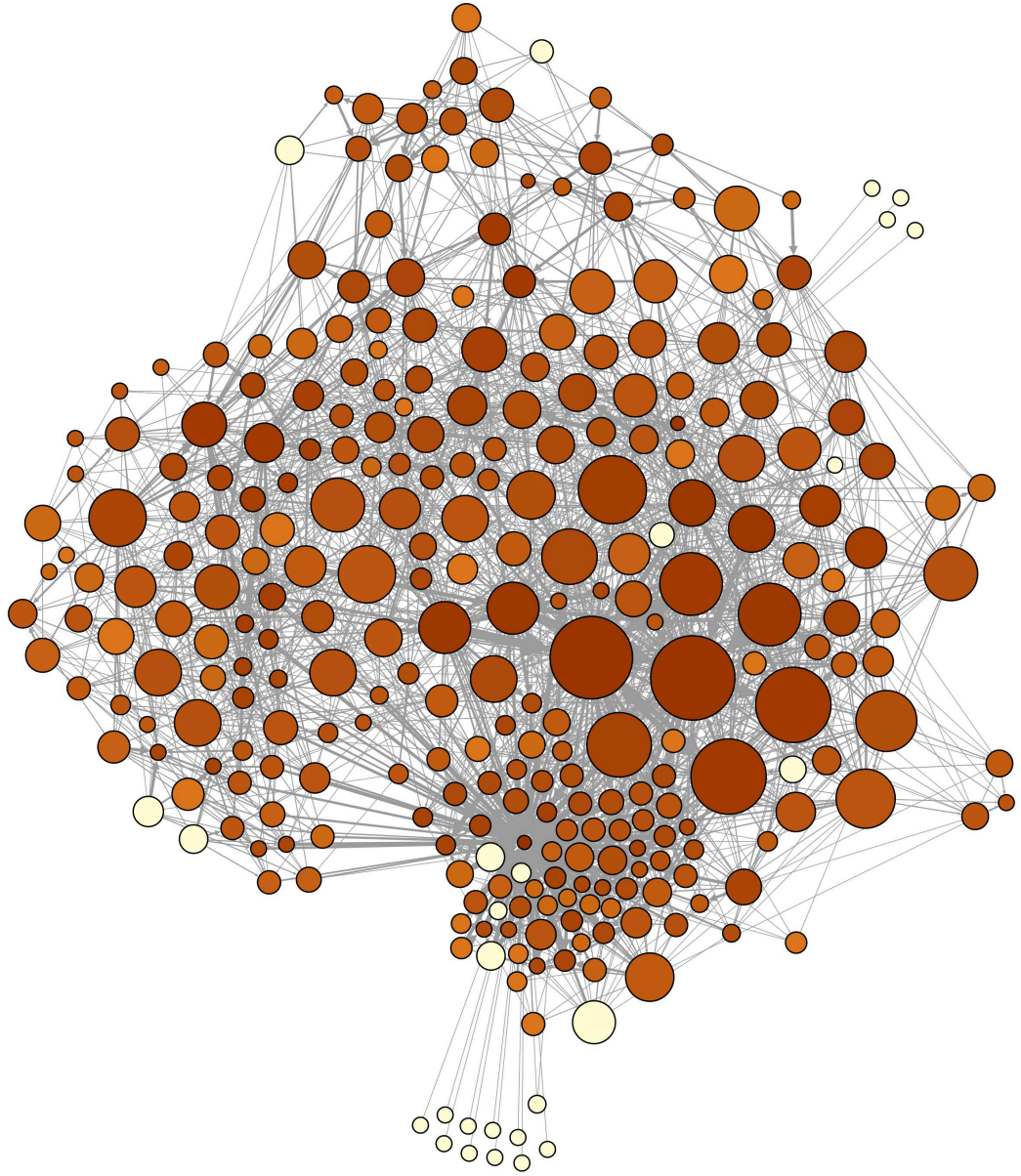
Transportation Networks

- What do nodes represent? Airports/cities
- What do links represent?
- Do links have direction?
- Do links have weights?
- Larger nodes have more connections; what do they represent?
- What do the layouts represent? Air flight networks display a “hub and spoke” structure: a few hubs have huge numbers of links, while the majority of nodes have very few connections



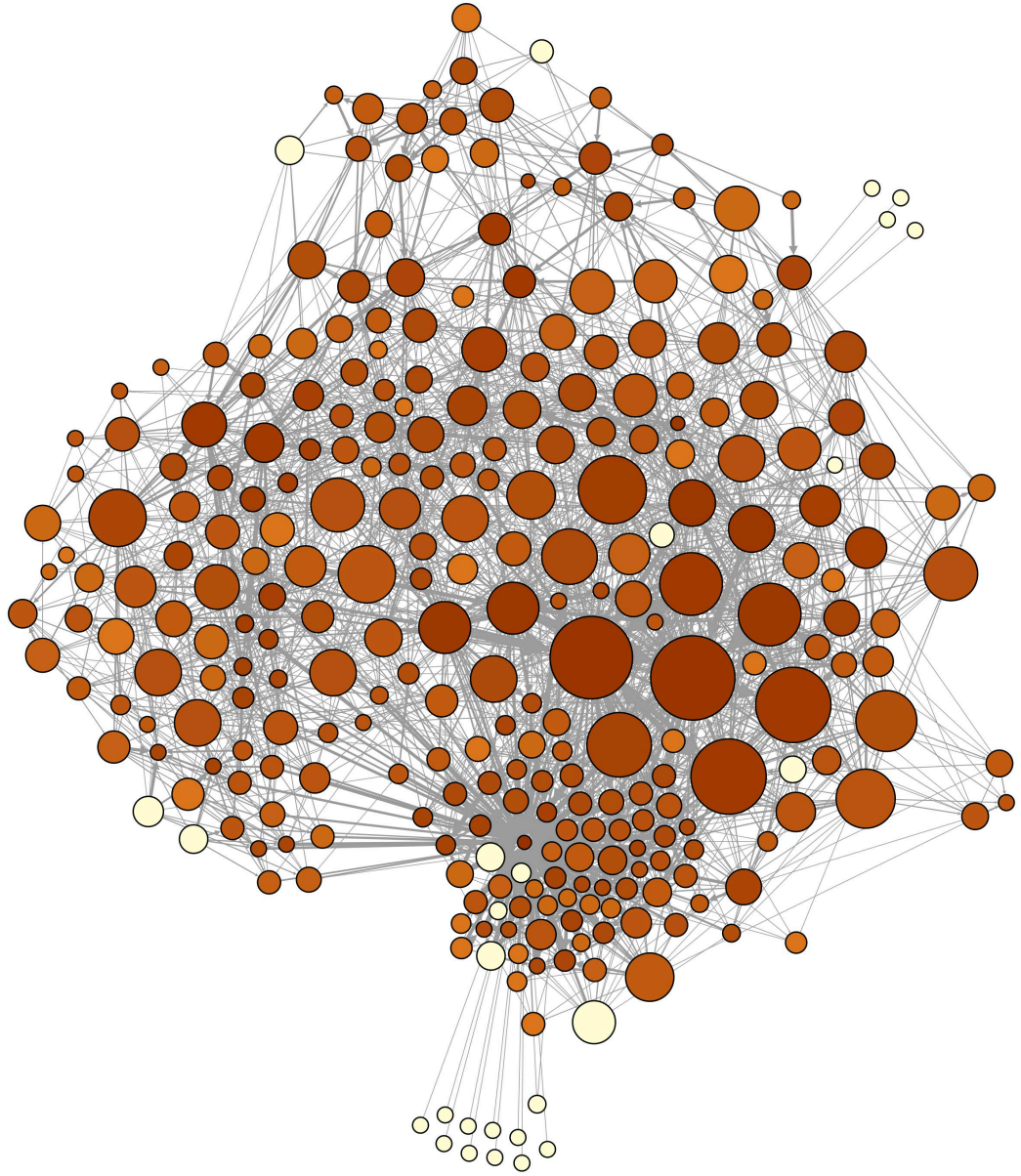
Biological Networks

- Neural network of the roundworm c. elegans
- What do nodes represent?
- What do links represent?
- Larger/darker nodes have more outgoing/incoming connections; what does that mean?

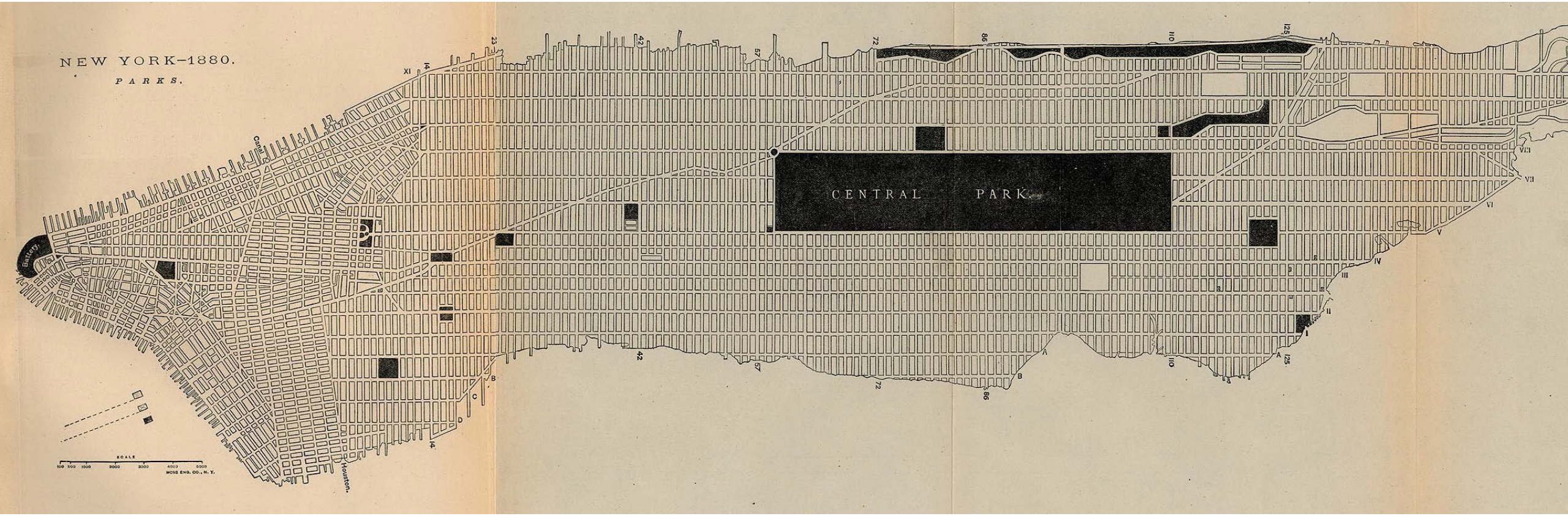


Biological Networks

- What do nodes represent? Neurons
- What do links represent? Synapses
- Larger/darker nodes have more outgoing/incoming connections; what does that mean?



Road Maps



Map of New York in 1880. From Report on the Social Statistics of Cities, Compiled by George E. Waring, Jr., United States Census Office, 1886. Image courtesy of University of Texas Libraries

- What are the nodes and links of the network represented in this street map?

4. Summary

Summary

- Networks are a powerful way to model complex systems with many parts that interact
- Nodes can be anything — people, websites, proteins, animals, machines, or even airports
- Nodes aren't just dots — they can have extra info like location, wealth, activity level, or number of connections
- Links show different kinds of connections — like friendships, messages, travel routes, or data flow
- Some links have a direction (one-way), like sending an email. Others are two-way, like being friends
- Links can also have extra details — such as distance, strength, traffic, or similarity — that affect how the network behaves

References

[1] Menczer, F., Fortunato, S., & Davis, C. A. (2020). A First Course in Network Science Cambridge: Cambridge University Press.

- Chapter 0 Introduction

[2] OLAT course page: https://olat.vcrp.de/url/RepositoryEntry/4669112833

Further Readings

- Baggio, R., Scott, N. and Cooper, C., 2010. Network science: A review focused on tourism. *Annals of Tourism Research*, *37*(3), pp.802-827.
- Siew, C.S., 2020. Applications of network science to education research: Quantifying knowledge and the development of expertise through network analysis. *Education Sciences*, *10*(4), p.101.