CS224w: Social and Information Network Analysis

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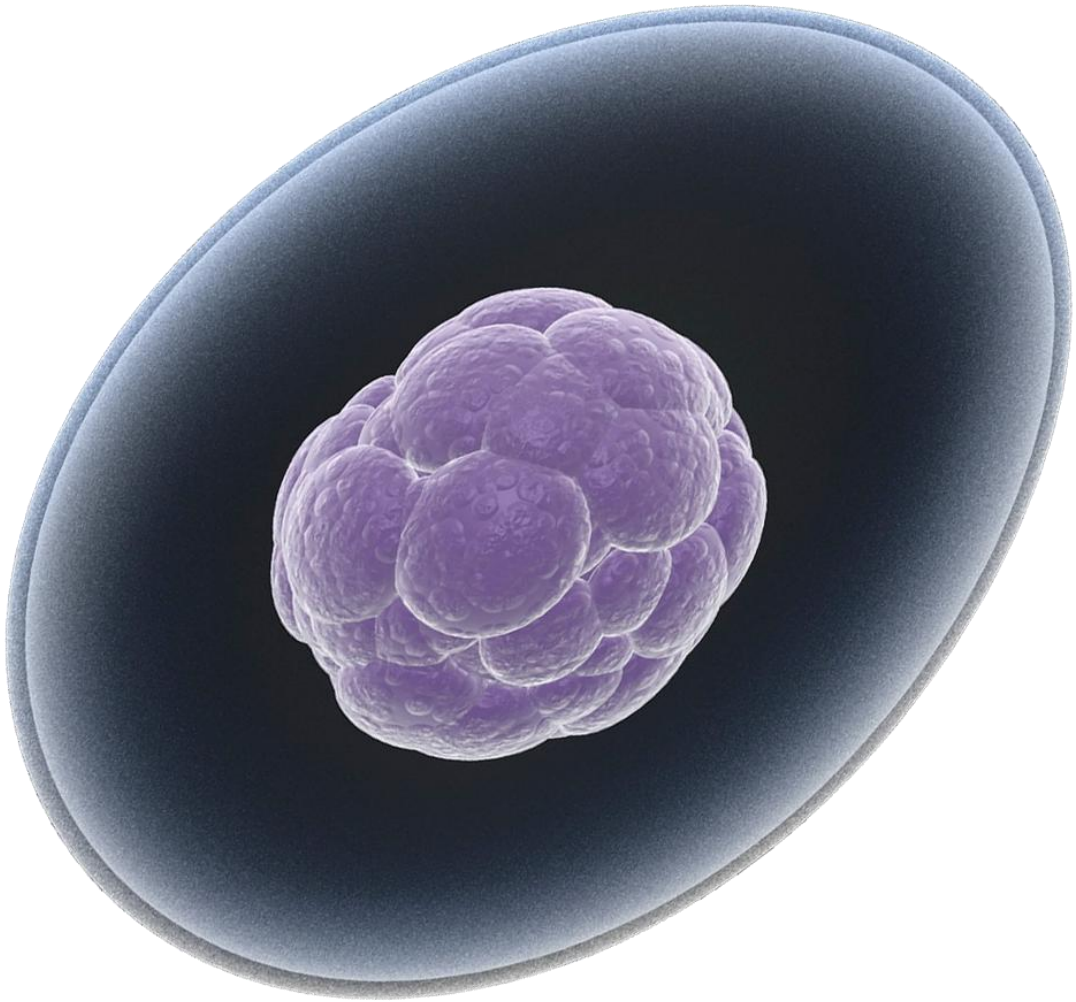
Jure Leskovec, Stanford University
http://cs224w.stanford.edu

What do the following things have in common?

World economy

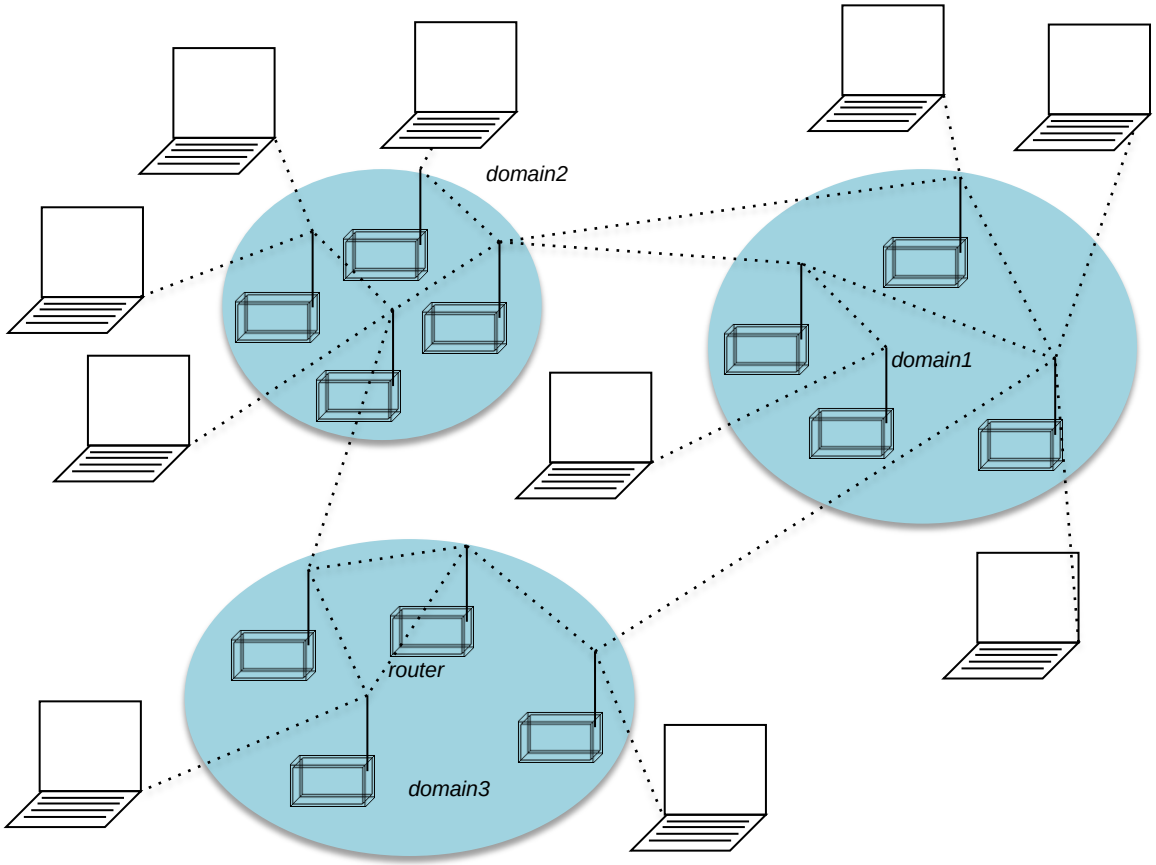


Human cell


Swiss Cottage
St. John's Wood
Mornington Crescent
King's Cross St. Pancras
Road & Barnsbury
Kilburn High Road
South Hampstead
Maida Vale
Paddington
Edgware Road
Baker Street
Great Portland Street
Euston
Angel
Old Street
Warren Street
Euston Square
Farringdon
Marylebone
Regent's Park
Russell Square
Barbican
Bayswater
Holland Park
Notting Hill Gate
Lancaster Gate
Bond Street
Oxford Circus
Goodge Street
Holborn
Chancery Lane
Moorgate
Queensway
Marble Arch
Tottenham Court Road
St. Paul's
Bank
Covent Garden
Cannon Street
High Street Kensington
Hyde Park Corner
Green Park
Piccadilly Circus
Leicester Square
Mansion House
Monument
Knightsbridge
Charing Cross
Gloucester Road
Sloane Square
St. James's Park
Blackfriars
Temple
Earl's Court
South Kensington
Victoria
Westminster
Embankment
London Bridge
Waterloo
Fulham Broadway

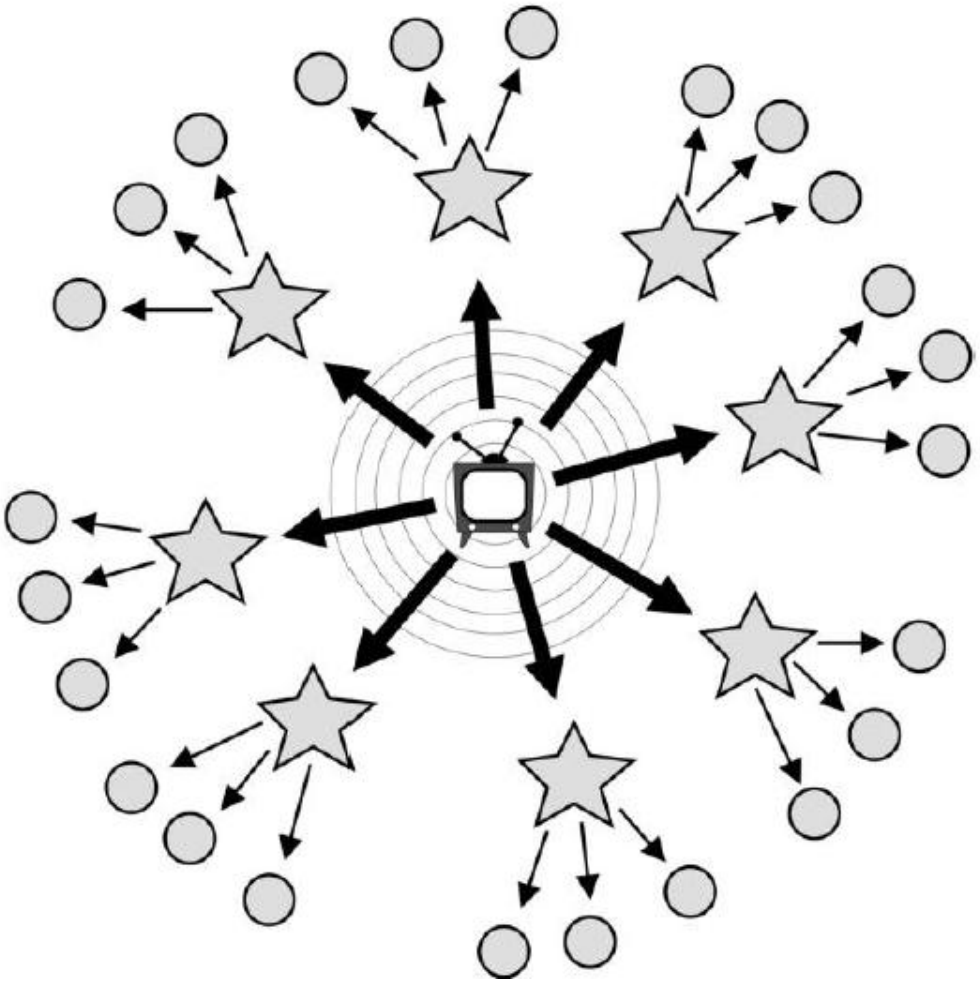
Roads

Brain

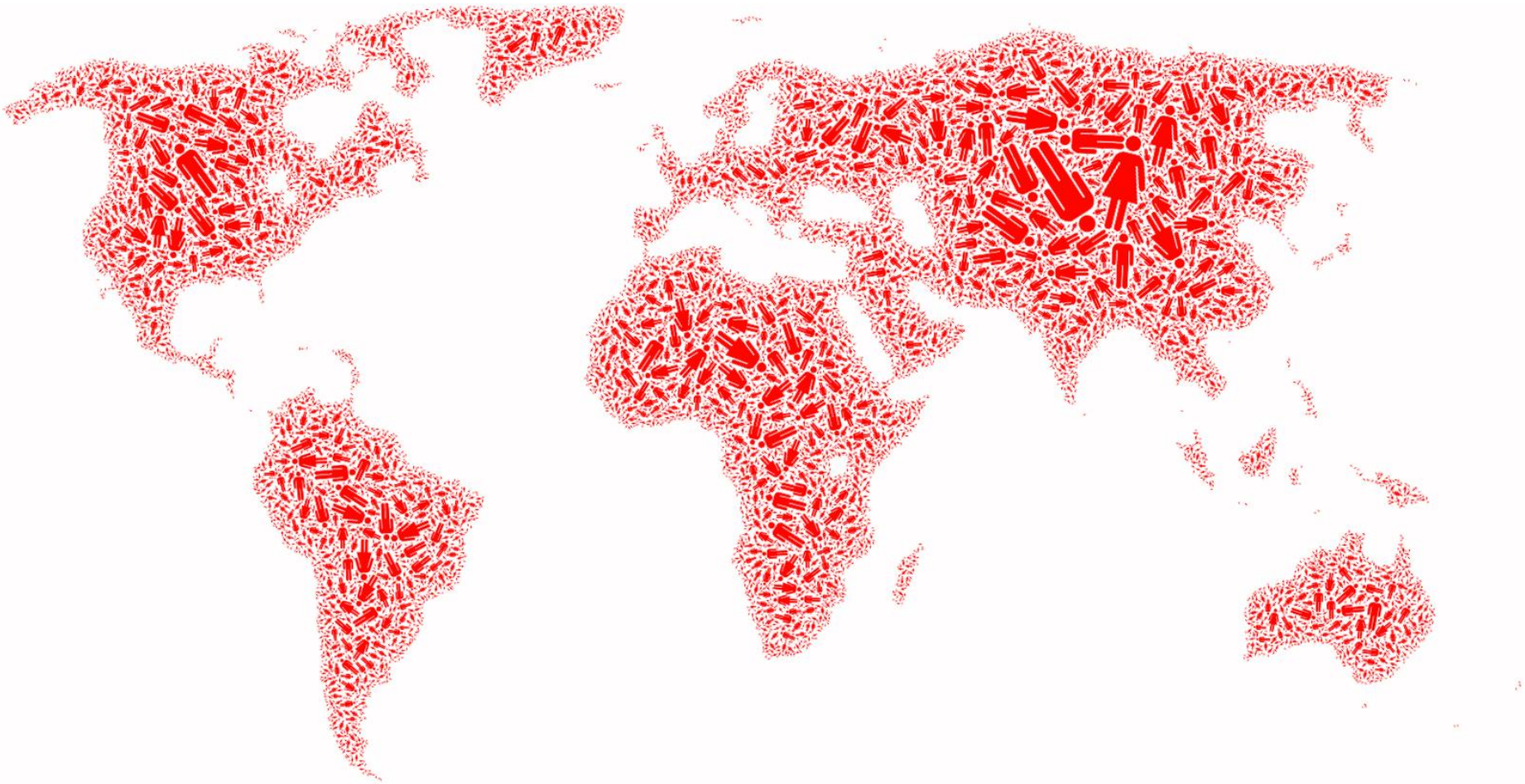


Internet

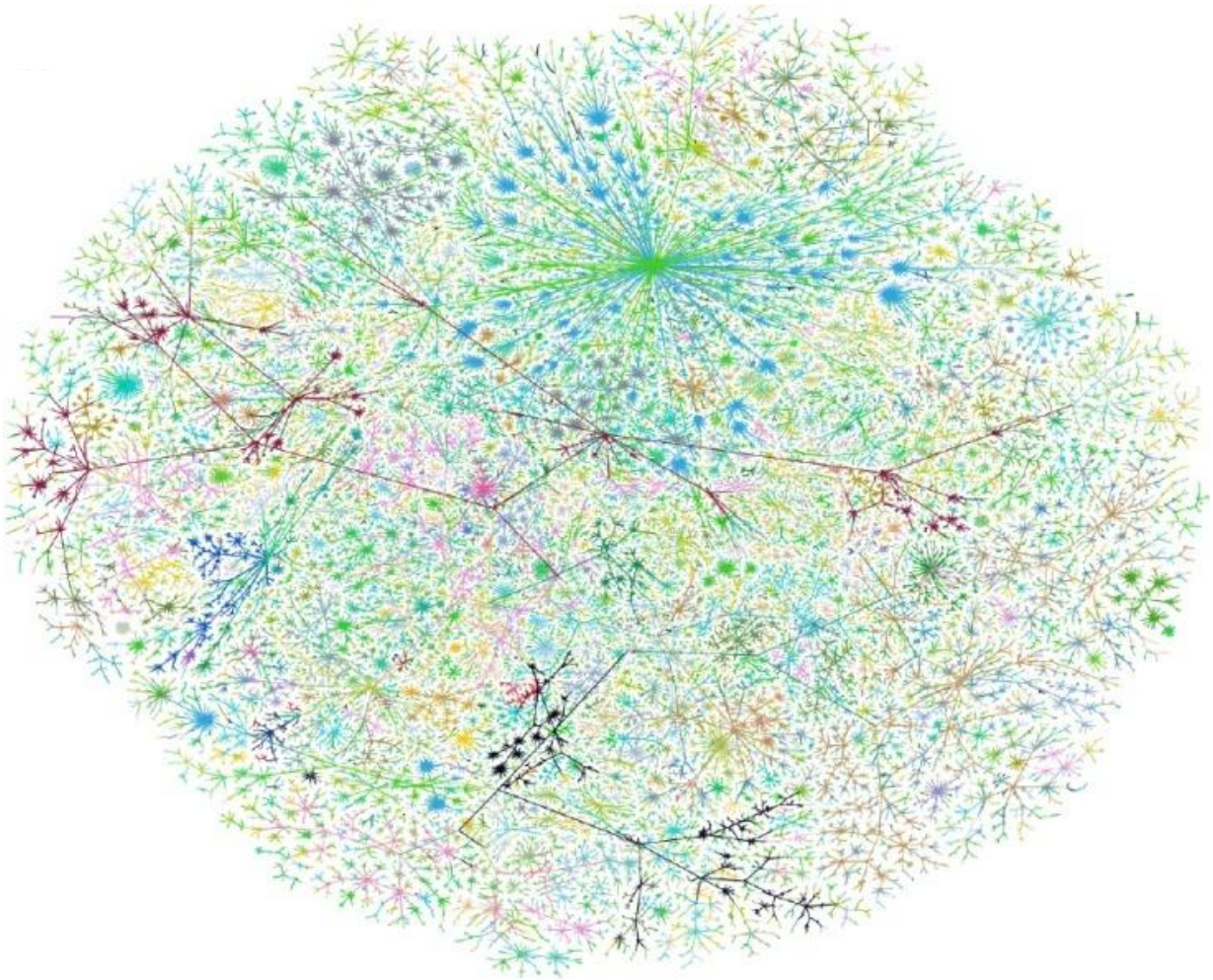
Friends & Family



Media & Information



Society



The Network!

Networks!!

Behind each such system there is an intricate wiring diagram, **a network**, that defines the **interactions** between the components

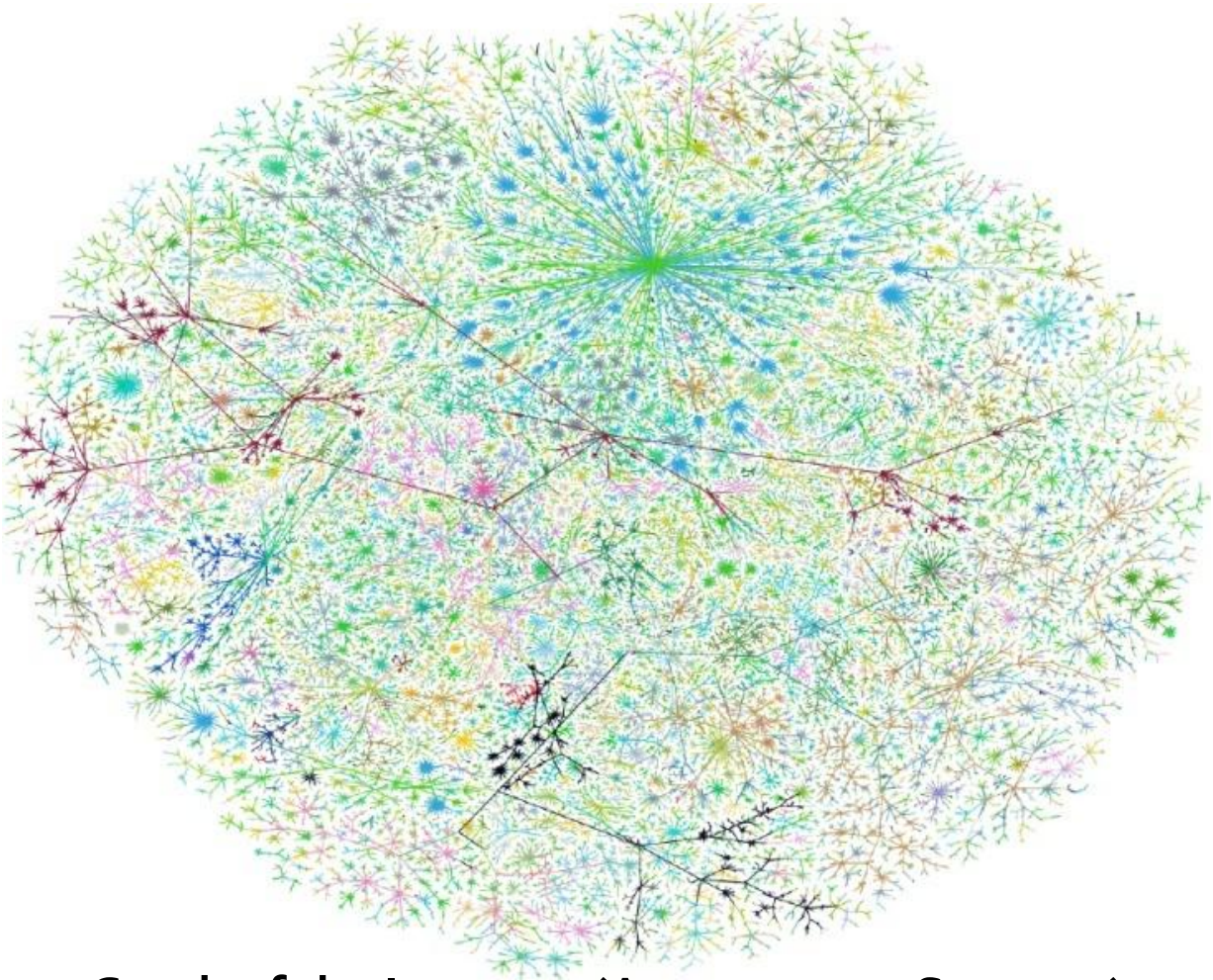
We will never understand these systems unless we understand the networks behind it

Networks: Social

Facebook social graph

4-degrees of separation [Backstrom-Boldi-Rosa-Ugander-Vigna, 2011]

Networks: Communication

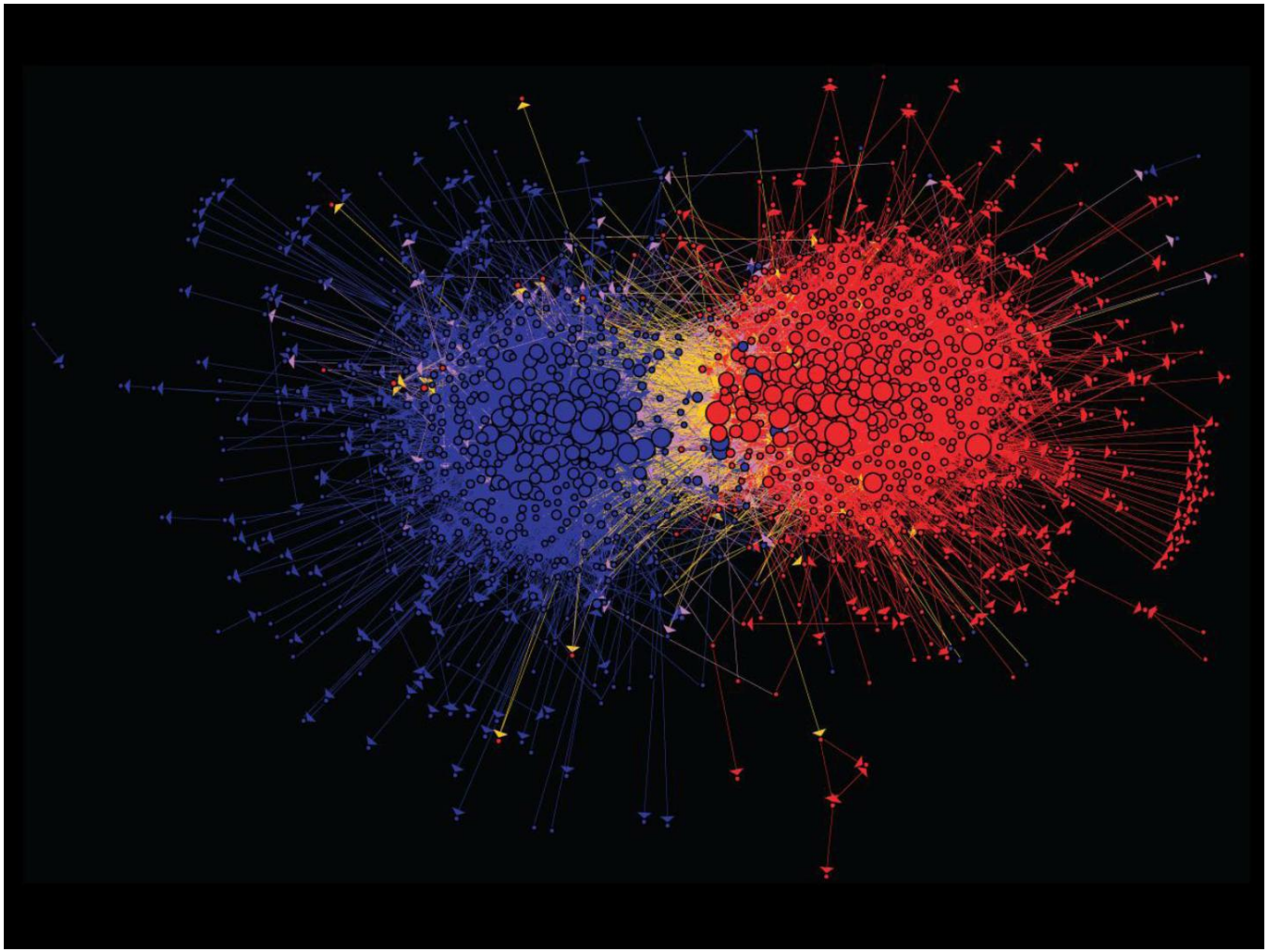


Graph of the Internet (Autonomous Systems)

Power-law degrees [Faloutsos-Faloutsos-Faloutsos, 1999]

Robustness [Doyle-Willinger, 2005]

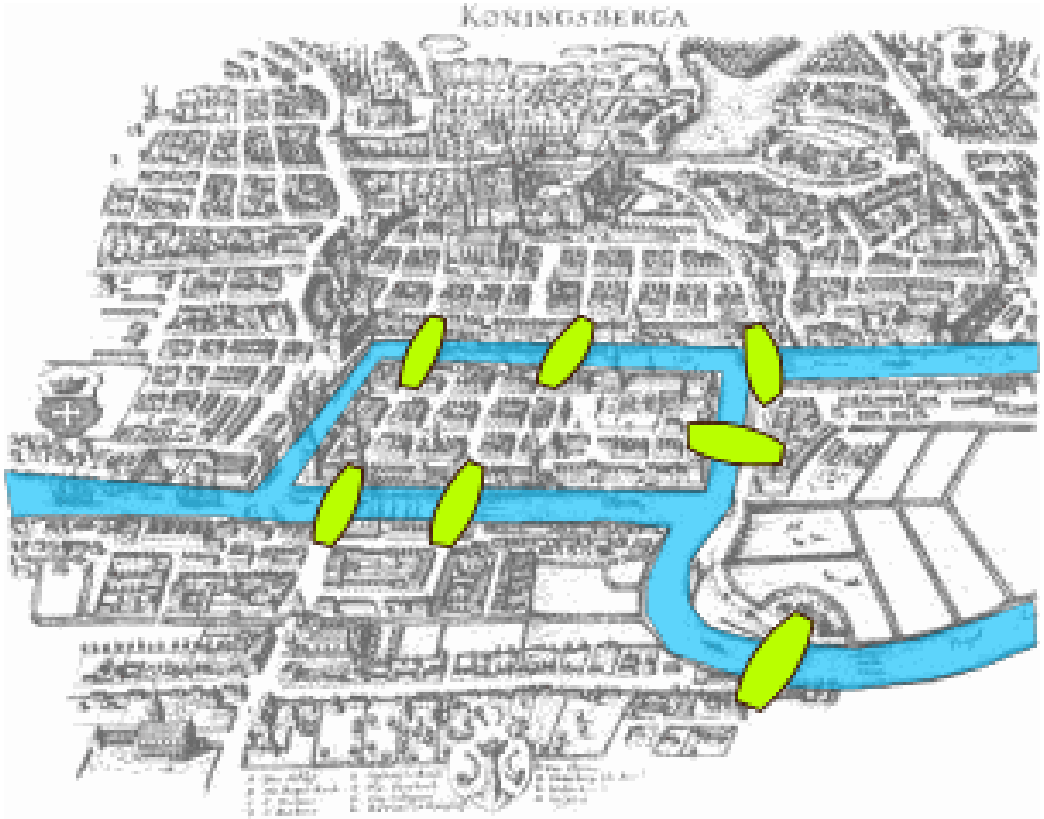
Networks: Media



Connections between political blogs

Polarization of the network [Adamic-Glance, 2005]

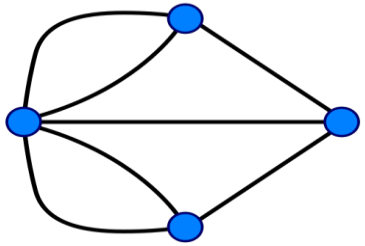
Networks: Technology



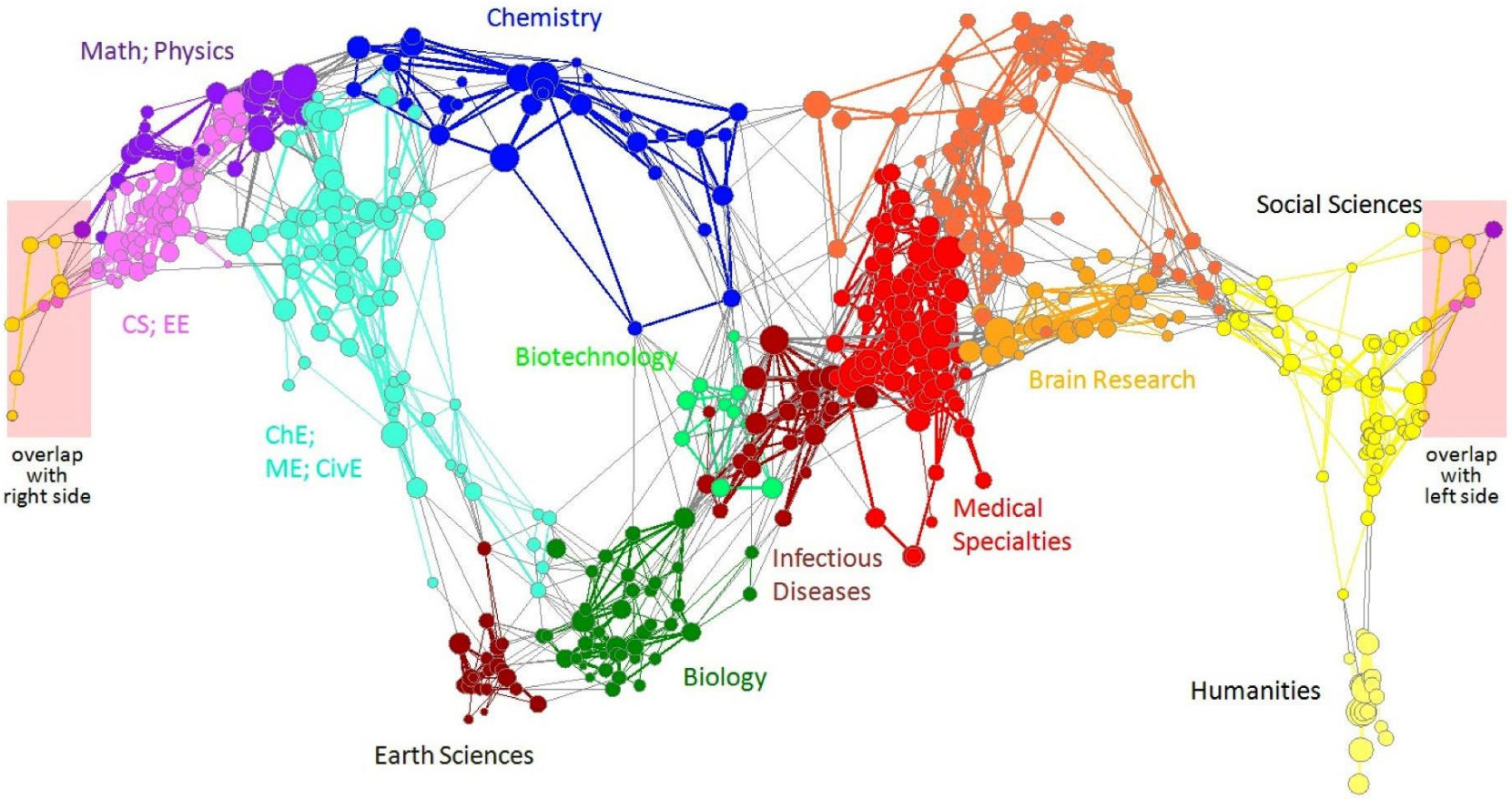
Seven Bridges of Königsberg

[Euler, 1735]

Return to the starting point by traveling each link of the graph once and only once.



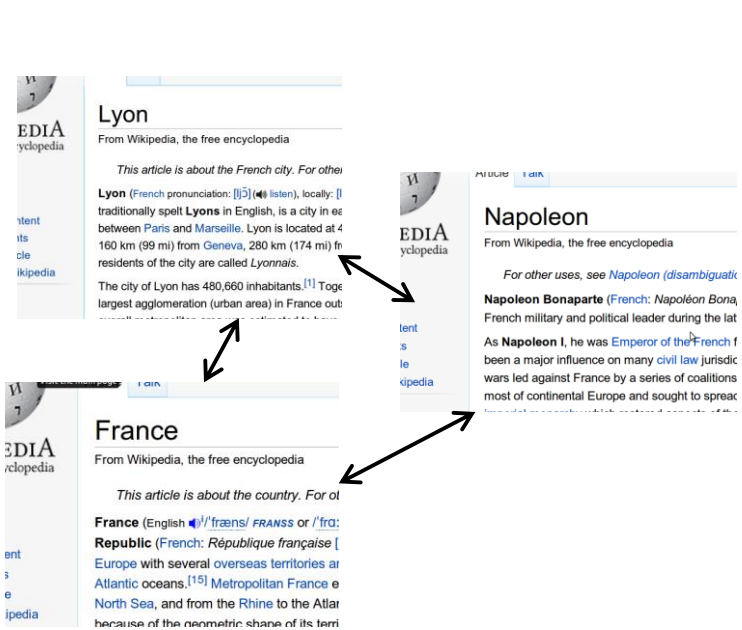
Networks: Information

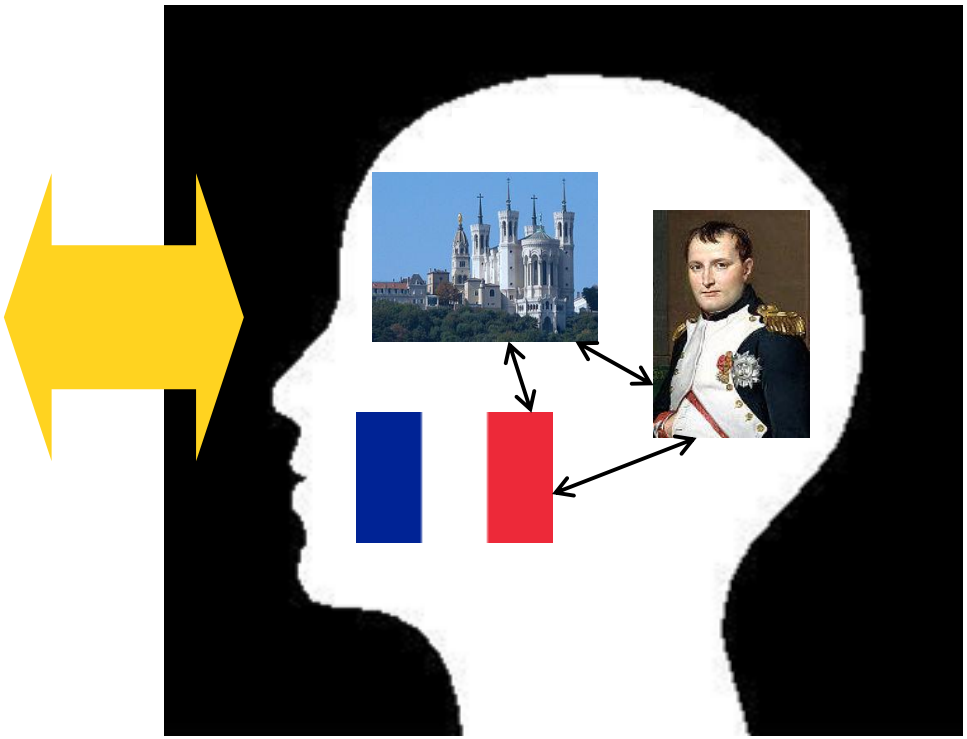


Citation networks and Maps of science

[Börner et al., 2012]

Networks: Knowledge



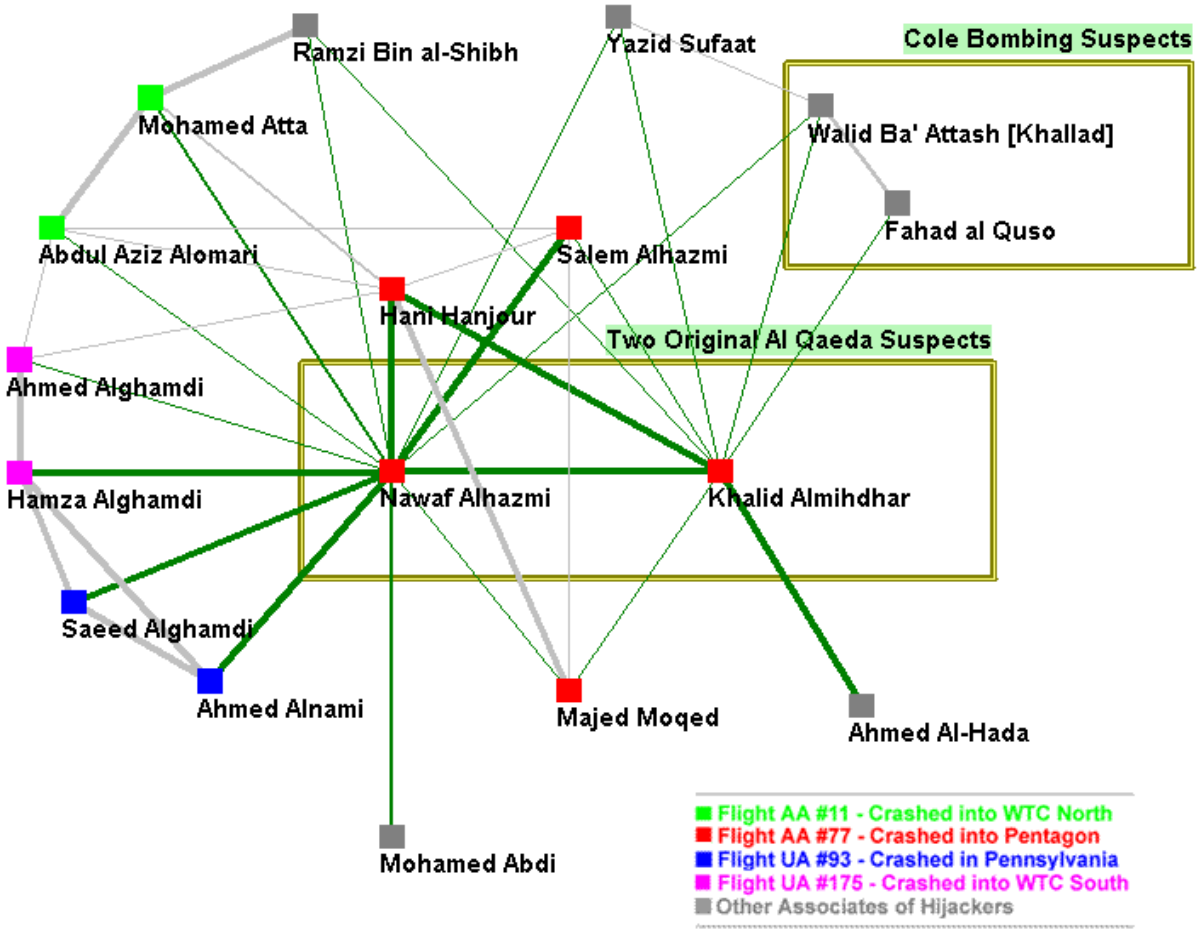


Understand how humans navigate Wikipedia

Get an idea of how people connect concepts

[West-Leskovec, 2012]

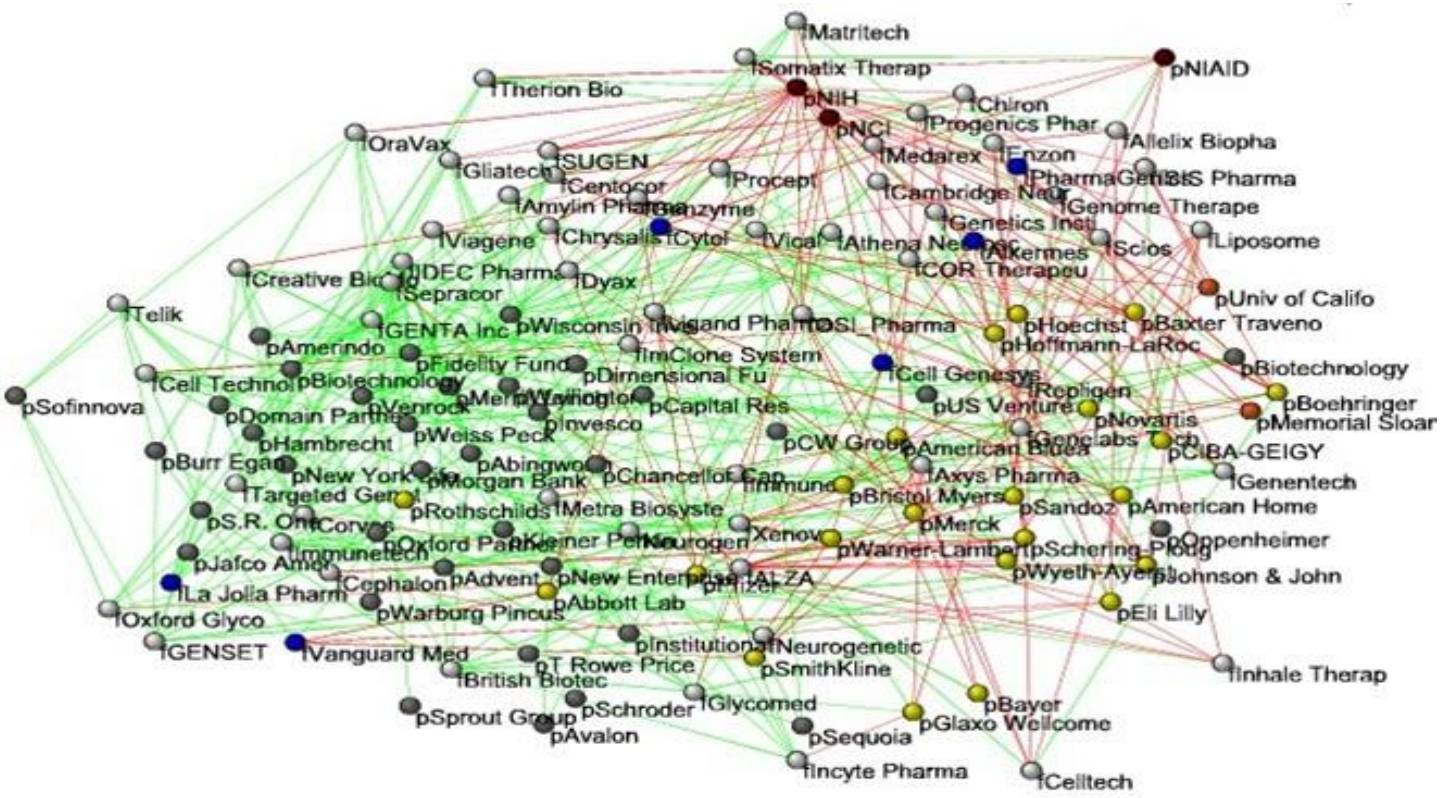
Networks: Organizations



9/11 terrorist network

[Krebs, 2002]

Networks: Economy



Nodes:

- Companies
- Investment
- Pharma
- Research Labs
- Public
- Biotechnology

Links:

- Collaborations
- Financial
- R&D

Bio-tech companies

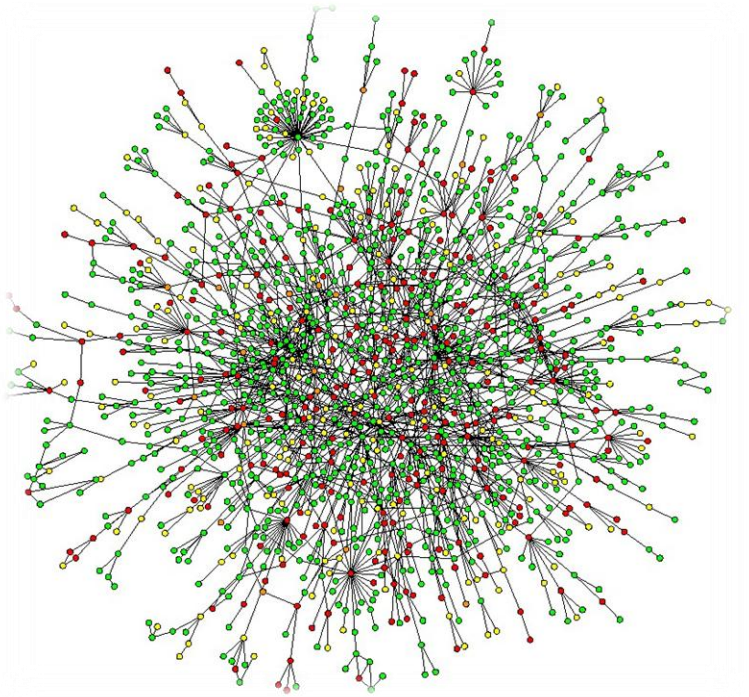
[Powell-White-Koput, 2002]

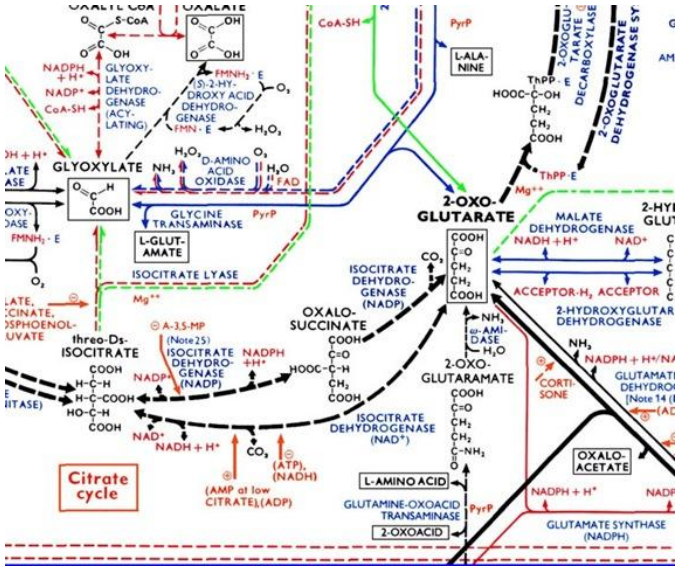
Networks: Brain

Human brain has between 10-100 billion neurons

[Sporns, 2011]

Networks: Biology





Protein-Protein Interaction Networks:

Nodes: Proteins

Edges: 'physical' interactions

Metabolic networks:

Nodes: Metabolites and enzymes

Edges: Chemical reactions

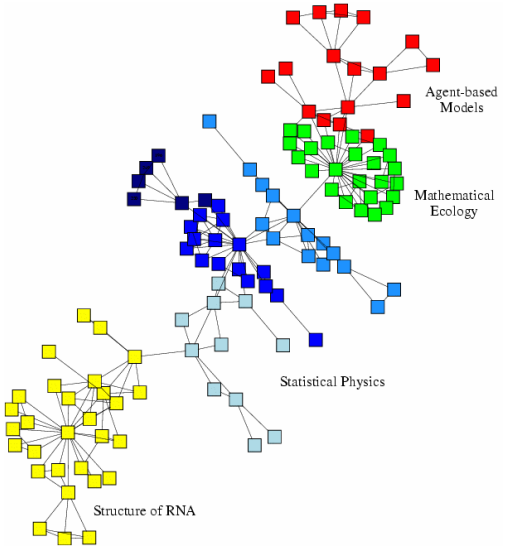
Reasoning about Networks

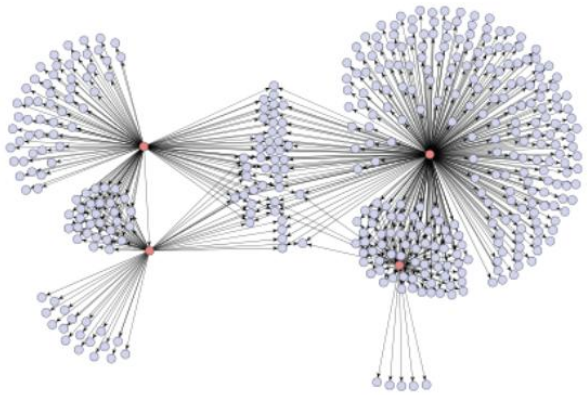
- **How do we reason about networks?**
  - **Empirical:** Study network data to find organizational principles
  - **Mathematical models:** Probabilistic, graph theory
  - **Algorithms** for analyzing graphs
- **What do we hope to achieve from studying networks?**
  - Patterns and statistical **properties** of network data
  - **Design principles** and **models**
  - **Understand** why networks are organized the way they are (Predict behavior of networked systems)

Networks: Structure & Process

What do we study in networks?

- **Structure and evolution:**
  - What is the structure of a network?
  - Why and how did it became to have such structure?
- **Processes and dynamics:**
  - Networks provide "skeleton" for spreading of information, behavior, diseases
  - How do information and diseases spread?



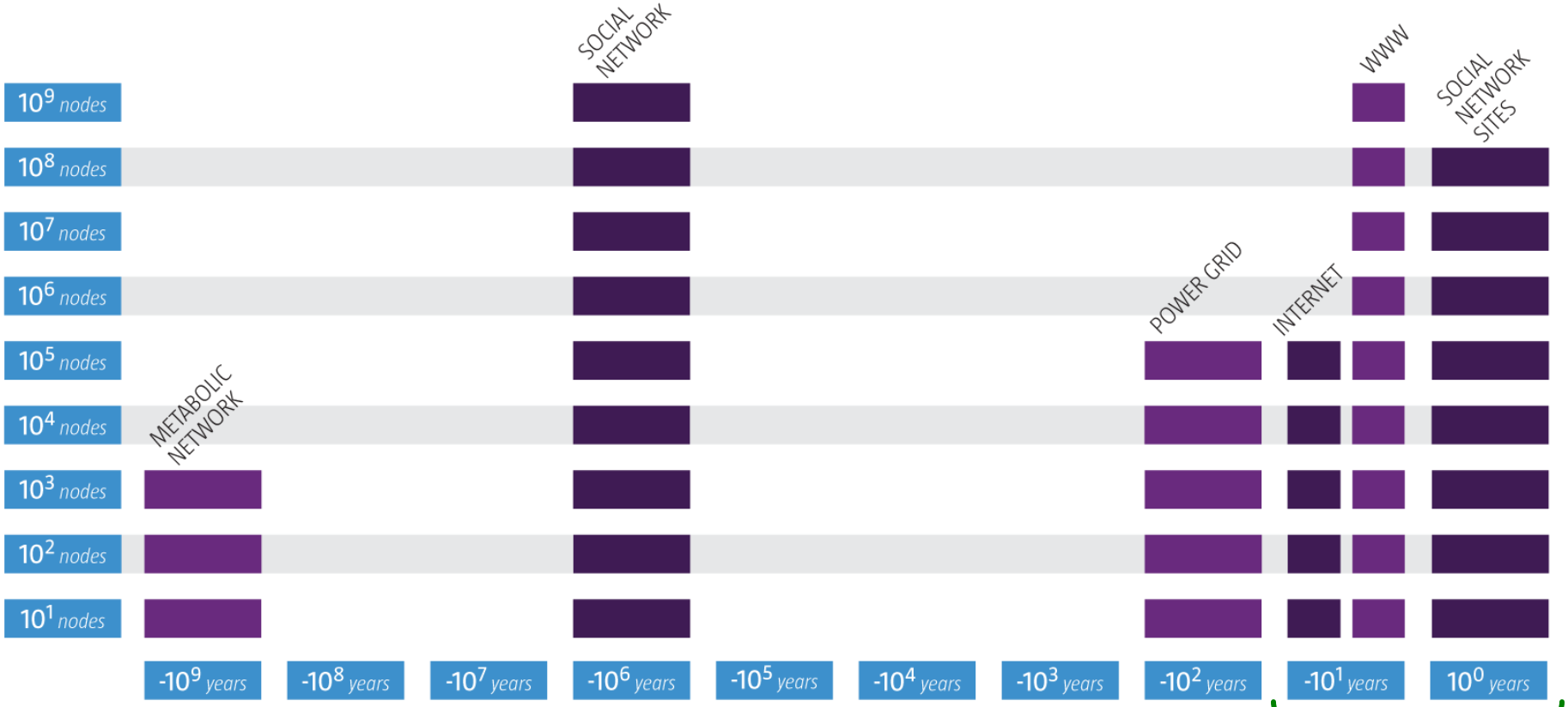


Why Networks? Why Now?

Why is the role of networks expanding?

- **Data availability**
  - Rise of Mobile, Web 2.0 and Social media
- **Universality**
  - Networks from science, nature, and technology are more similar than one would expect
- **Shared vocabulary between fields**
  - Computer Science, Social science, Physics, Economics, Statistics, Biology
- **Impact!**
  - Social networking, Social media, Drug design

Networks: Why Now?



Age and size of networks

Networks: Size Matters

- **Network data: Orders of magnitude**
  - 436-node network of email exchange at a corporate research lab [Adamic-Adar, SocNets '03]
  - 43,553-node network of email exchange at an university [Kossinets-Watts, Science '06]
  - 4.4-million-node network of declared friendships on a blogging community [Liben-Nowell et al., PNAS '05]
  - 240-million-node network of communication on Microsoft Messenger [Leskovec-Horvitz, WWW '08]
  - 800-million-node Facebook network [Backstrom et al. '11]

Web – The Lab for Humanity

The Web is our "laboratory" for understanding the pulse of humanity.

Networks: Impact

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- **Google**
  Market cap: $250 billion
- **Cisco**
  Market cap: $100 billion
- **Facebook**
  Market cap: $50 billion

Networks Really Matter

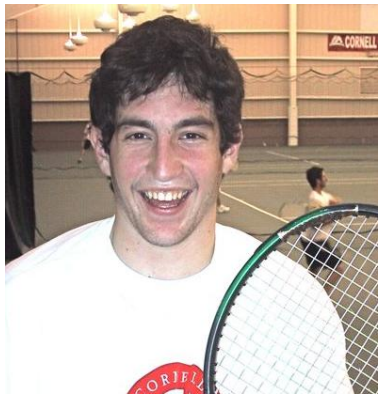
- If you were to understand the spread of diseases, **can you do it without social networks?**
- If you were to understand the WWW structure and information, **hopeless without invoking the Web's topology.**
- If you want to understand dissemination of news or evolution of science, **it is hopeless without considering the information networks**

Course Logistics

Logistics: Course Assistants

Bob West (head TA)

Ashton Anderson



Jacob Bank

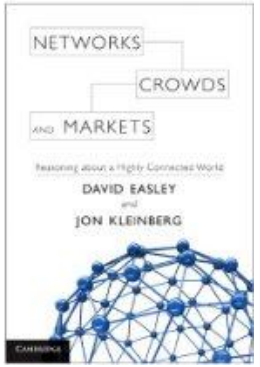
Anshul Mittal

Yu (Wayne) Wu

See course website for office hour schedule!

Logistics: Website

- http://cs224w.stanford.edu
  - Slides posted at least 30 min before the class
- **Readings:**
  - Mostly chapters from Easley&Kleinberg
  - Papers
- **Optional readings:**
  - Papers and pointers to additional literature
  - **This will be very useful for project proposals**



Logistics: Communication

- **Piazza Q&A website:**
  - http://piazza.com/stanford/fall2012/cs224w
    - If you don't have @stanford.edu email address, send us your email and we will manually register you to Piazza
- **For e-mailing course staff, always use:**
  - cs224w-aut1213-staff@lists.stanford.edu
- **We will post course announcements to Piazza (make sure you check it regularly)**

Work for the Course & Grading

- **Final grade will be composed of:**
  - **Homeworks: 50%**
    - Homework 0: 2%
    - Homeworks 1,2,3,4: 12% each
  - **Substantial class project: 50%**
    - Proposal: 20%
    - Project milestone: 15%
    - Final report: 50%
    - Poster presentation: 15%
  - Extra credit for class/Piazza participation

Course Schedule

Week	Assignment	Due on THU
2	Homework 0	October 4
3	Homework 1	October 11
4	Project proposal	October 18
5	Homework 2	October 25
	Work on the project	
7	Homework 3	November 8
8	Project milestone	November 15
	Thanksgiving break	
9	Homework 4	November 29
	Poster session	December 10 12:15-3;15pm
	Final report	December 11 (no late days!)

Homeworks, Write-ups

- **Assignments take time. Start early!**
- **How to submit?**
  - **Paper (**Print code!**):** In class and in cabinet in Gates
  - **SCPD:** Submit via SCPD
  - **In addition,** write-ups (proposal, milestone, final report) have to **also** be submitted electronically
    - Email PDF to stanford.cs224w@gmail.com
- **2 late days for the quarter:**
  - 1 late day expires at the start of next class
  - Max 1 late day per assignment

Course Projects

- **Substantial course project:**
  - **Experimental evaluation** of algorithms and models on an interesting network dataset
  - A **theoretical project** that considers a model, an algorithm and derives a rigorous result about it
  - Develop **scalable algorithms** for massive graphs
    - Can become part of SNAP library
- **Performed in groups of 3 students**
- Project is the **main work** for the class

Prerequisites

- **Good background in:**
  - Algorithms
  - Graph theory
  - Probability and Statistics
  - Linear algebra
- **Programming:**
  - You should be able to write non-trivial programs
- **4 recitation sessions:**
  - 2 to review programming tools (SNAP, NetworkX)
  - 2 to review basic mathematical concepts

Course Syllabus

Introduce properties, models and tools for

- Large real-world networks
- Processes taking place on networks

through real applications and case studies

- **Goal:** find **patterns, rules, clusters, outliers, …**
  - … in large static and evolving graphs
  - … in processes spreading over the networks

Course Syllabus

- Covers a wide range of **network analysis techniques** – from basic to state-of-the-art
- **You will learn about things you heard about:**

  Six degrees of separation, small-world, page rank, network effects, P2P networks, network evolution, spectral graph theory, virus propagation, link prediction, power-laws, scale free networks, core-periphery, network communities, hubs and authorities, bipartite cores, information cascades, influence maximization, …

- **Covers algorithms, theory and applications**
- **It's going to be fun ☺**

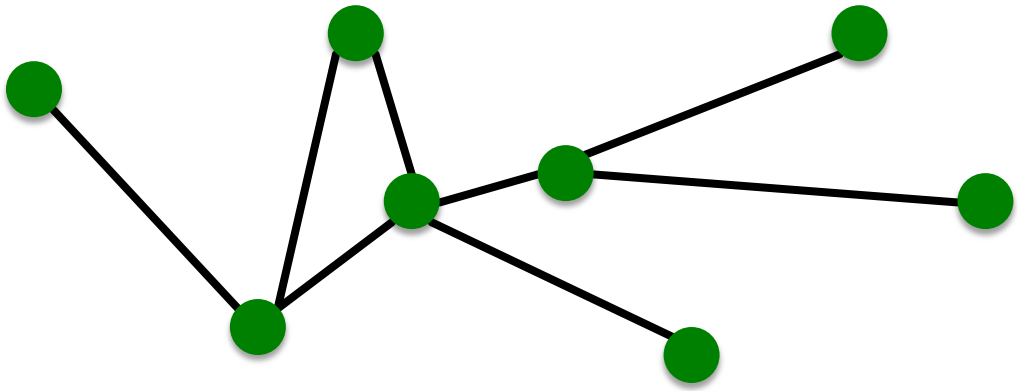
Starter Topic: Structure of the Web Graph

Structure of Networks?

Network is a collection of objects where some pairs of objects are connected by links

What is the structure of the network?

Components of a Network



- **Objects:** nodes, vertices N
- **Interactions:** links, edges E
- **System:** network, graph $G(N,E)$

Networks or Graphs?

- **Network** often refers to real systems
  - Web, Social network, Metabolic network

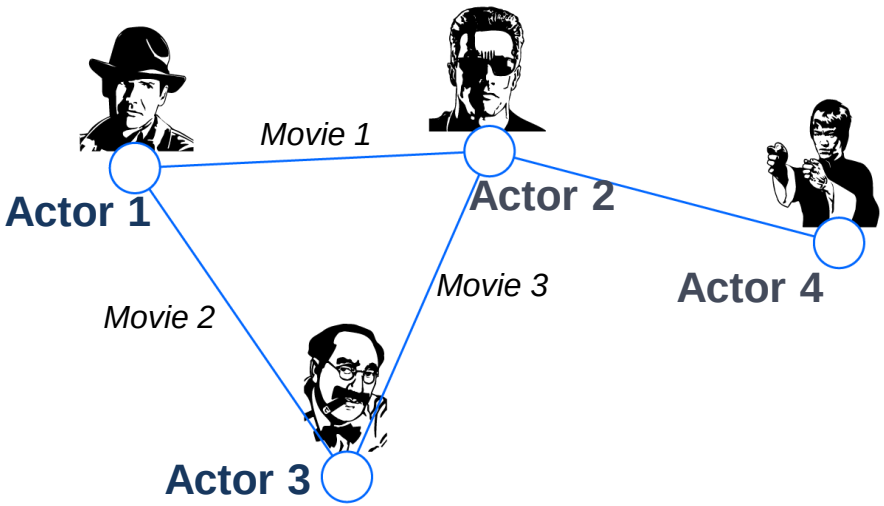
  Language: Network, node, link

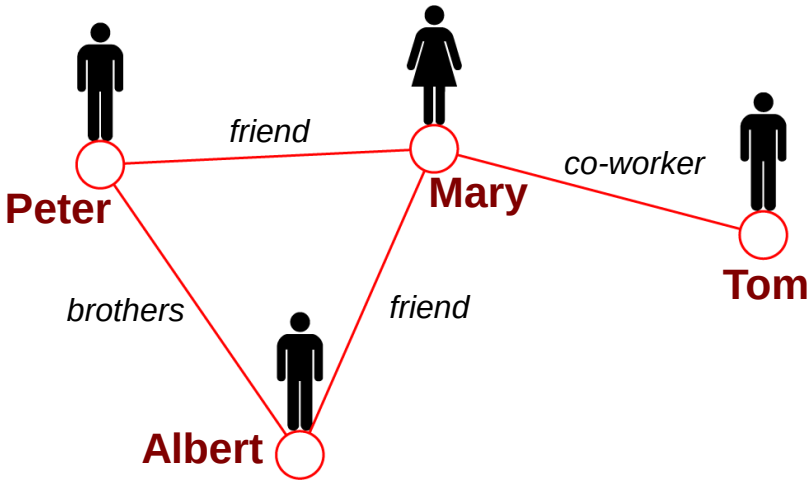
- **Graph:** mathematical representation of a network
  - Web graph, Social graph (a Facebook term)

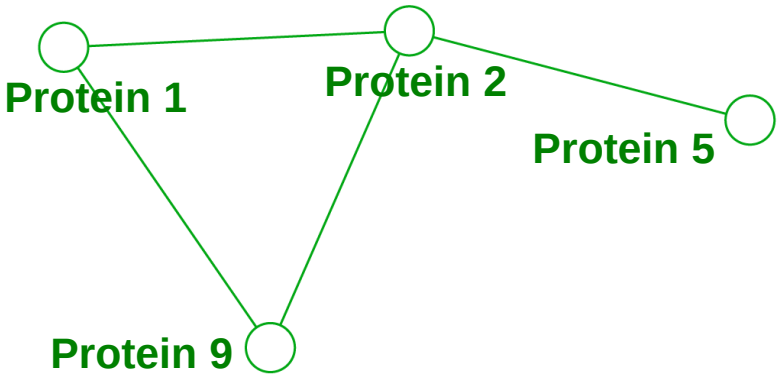
  Language: Graph, vertex, edge

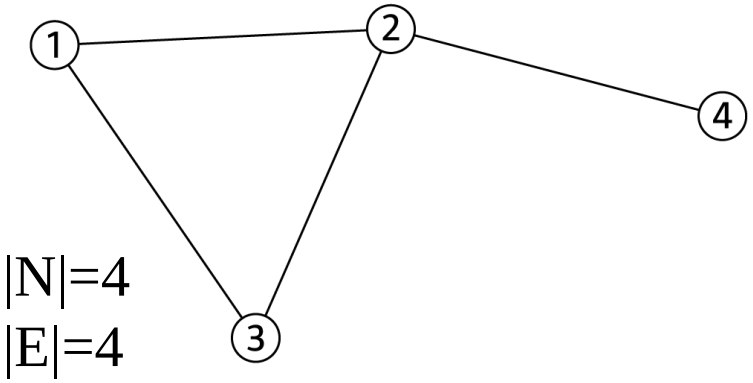
We will try to make this distinction whenever it is appropriate, but in most cases we will use the two terms interchangeably

Networks: Common Language







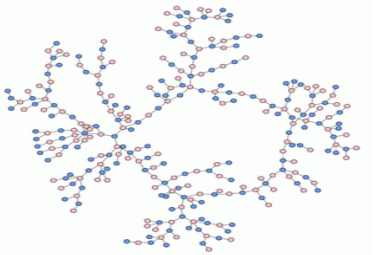


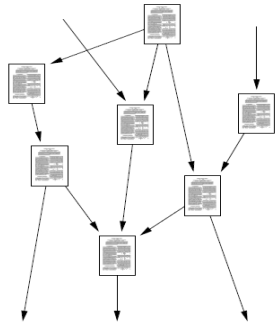
Choosing Proper Representation

- **Choice of the proper network representation determines our ability to use networks successfully:**
  - In some cases there is a unique, unambiguous representation
  - In other cases, the representation is by no means unique
  - The way you assign links will determine the nature of the question you can study

Choosing Proper Representation

- If you connect individuals that work with each other, you will explore a **professional network**
- If you connect those that have a sexual relationship, you will be exploring **sexual networks**
- If you connect scientific papers that cite each other, you will be studying the **citation network**



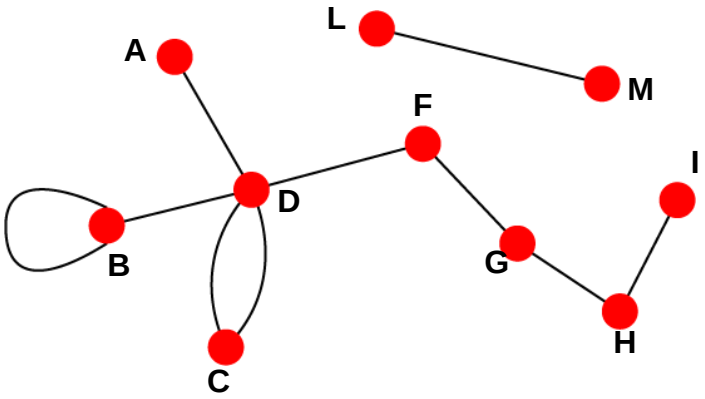


- **If you connect all papers with the same word in the title, you will be exploring what?** It is a network, nevertheless

Undirected vs. Directed Networks

Undirected

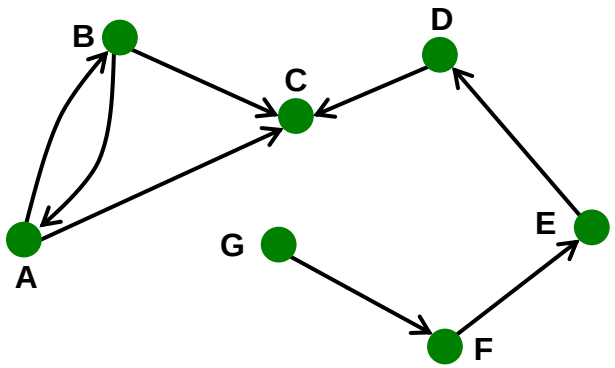
- Links: undirected (symmetrical)



- Examples:
  - Collaborations
  - Friendship on Facebook

Directed

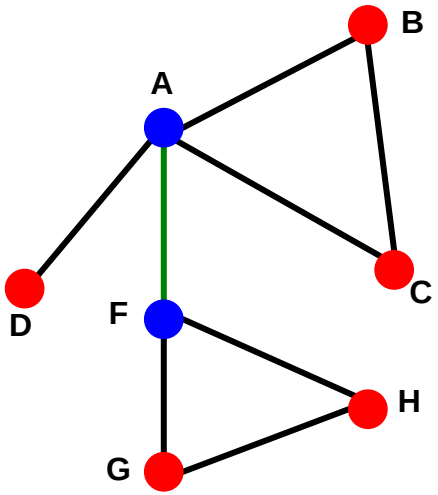
- Links: directed (arcs)

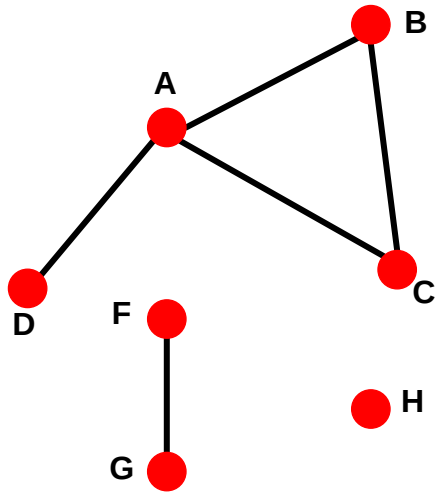


- Examples:
  - Phone calls
  - Following on Twitter

Connectivity of Graphs

- **Connected (undirected) graph:**
  - Any two vertices can be joined by a path.
- A disconnected graph is made up by two or more connected components





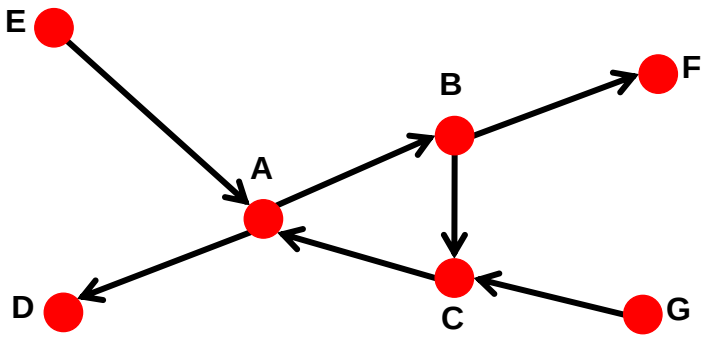
Largest Component:
Giant Component

Isolated node (node F)

Bridge edge: If we erase it, the graph becomes disconnected.
Articulation point: If we erase it, the graph becomes disconnected.

Connectivity of Directed Graphs

- **Strongly connected directed graph**
  - has a path from each node to every other node and vice versa (e.g., A-B path and B-A path)
- **Weakly connected directed graph**
  - is connected if we disregard the edge directions



Graph on the left is connected but not strongly connected (e.g., there is no way to get from F to G by following the edge directions).

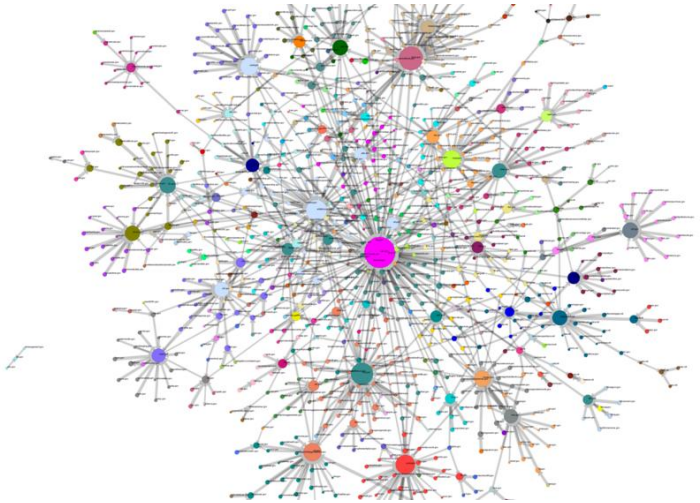
Web as a Graph

- **Q: What does the Web "look like"?**
- **Here is what we will do next:**
  - We will take a real system (i.e., the Web)
  - We will collect lots of Web data
  - We will represent the Web it as a graph
  - We will use language of graph theory to reason about the structure of the graph
  - Do a computational experiment on the Web graph
  - **Learn something about the structure of the Web!**

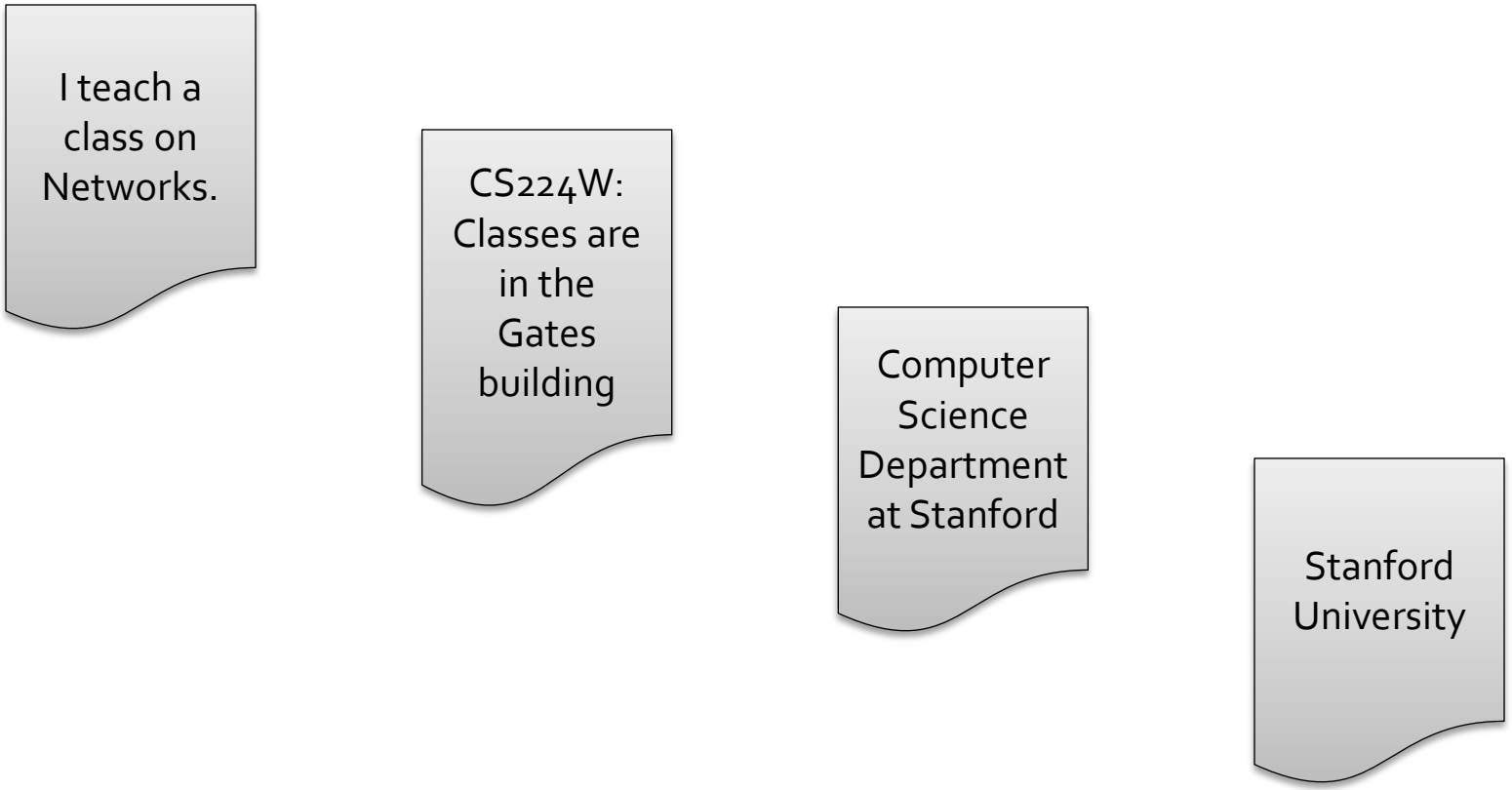
Web as a Graph

Q: What does the Web "look like" at a global level?

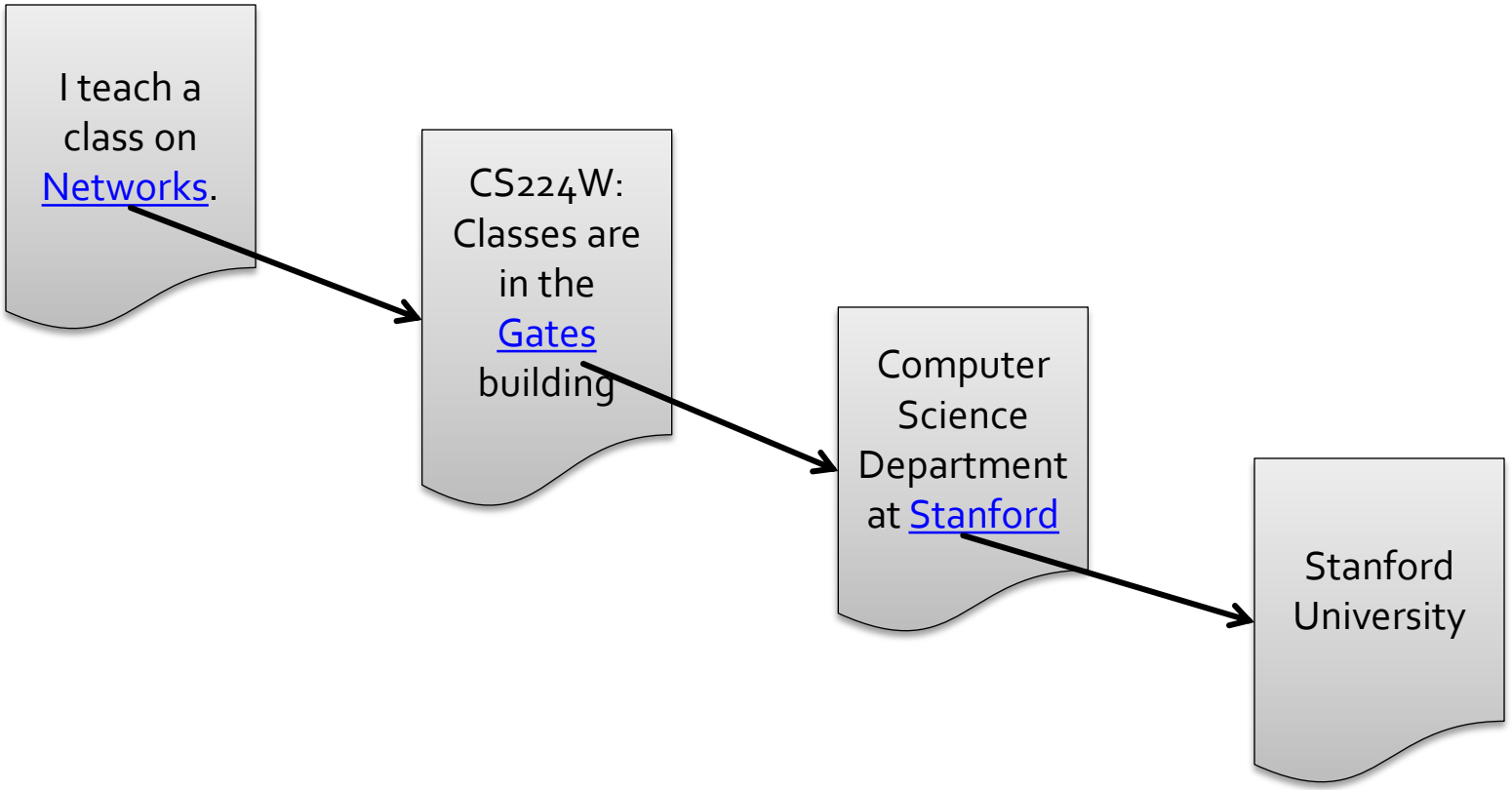
- **Web as a graph:**
  - Nodes = web pages
  - Edges = hyperlinks
  - Side issue: What is a node?
    - Dynamic pages created on the fly
    - "dark matter" – inaccessible database generated pages



The Web as a Graph

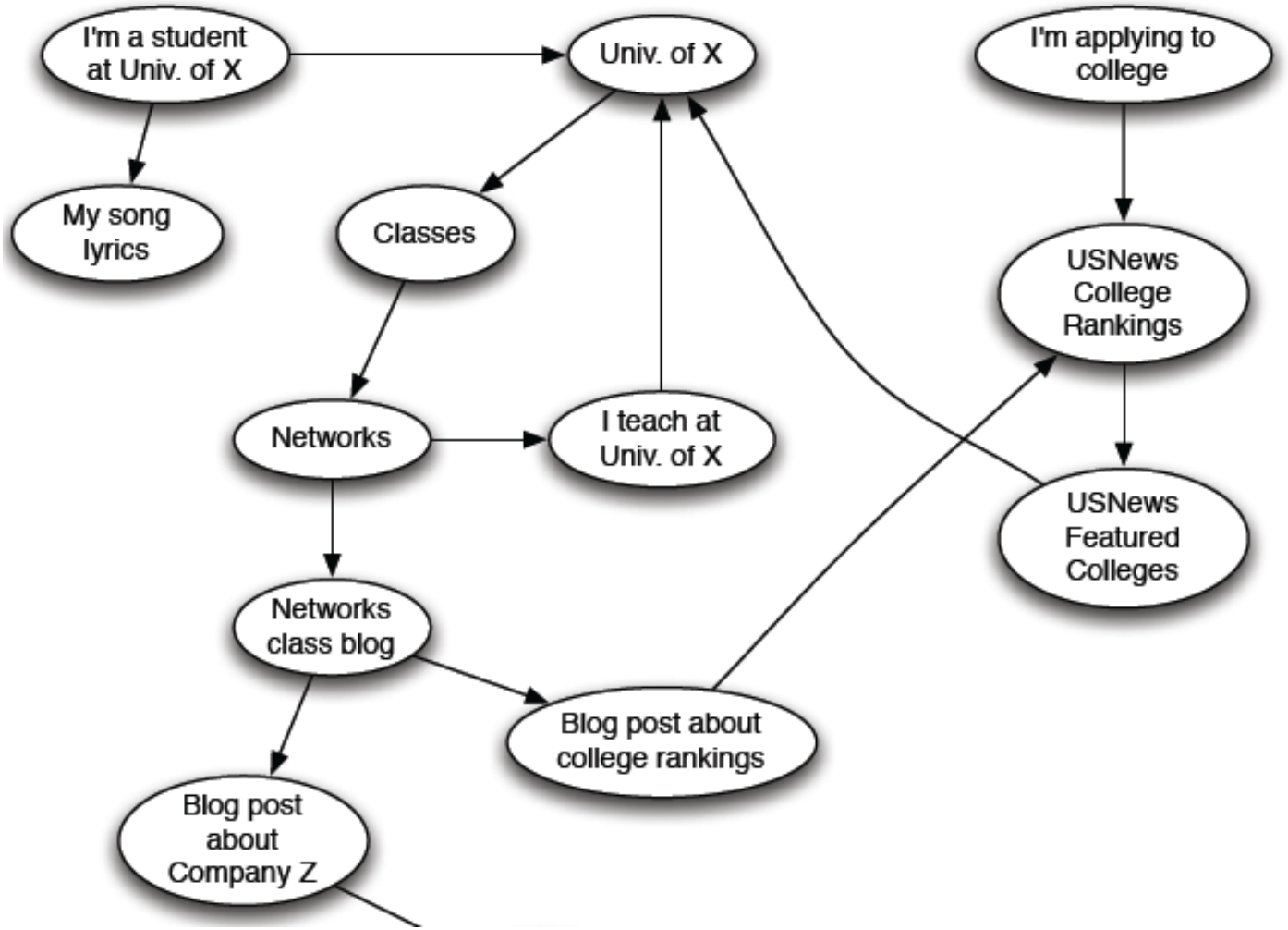


The Web as a Graph

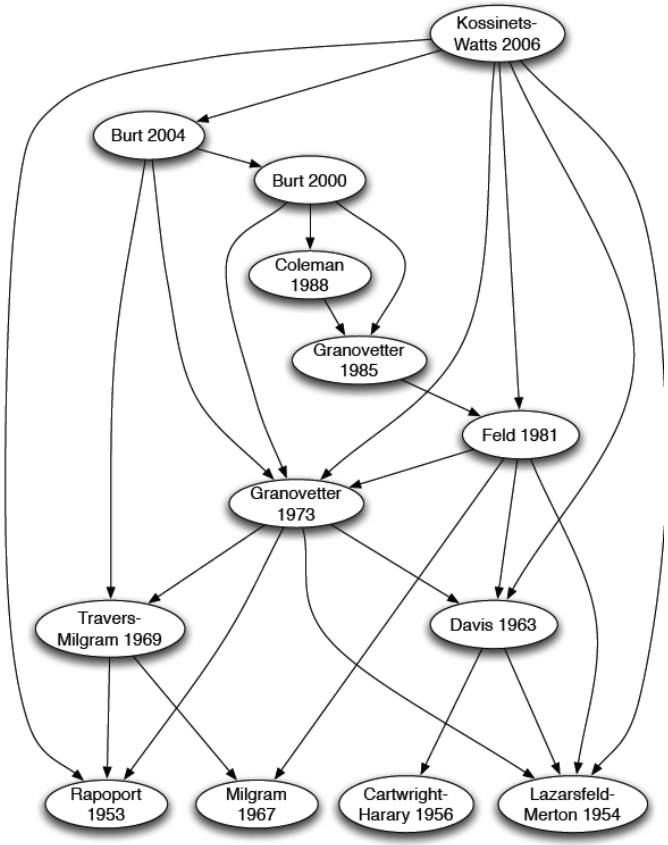


- In early days of the Web links were **navigational**
- Today many links are **transactional**

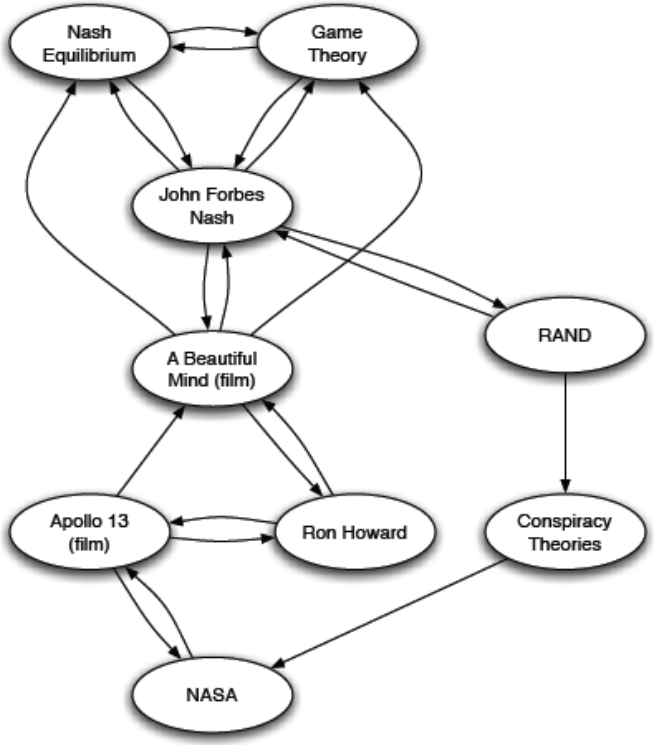
The Web as a Directed Graph



Other Information Networks



Citations



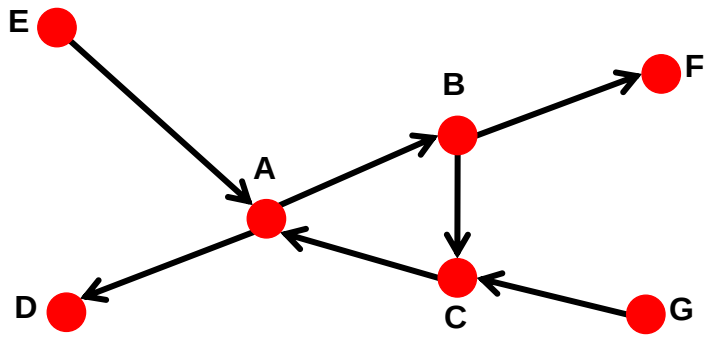
References in an Encyclopedia

What Does the Web Look Like?

- How is the Web linked?
- What is the "map" of the Web?

Web as a directed graph [Broder et al. 2000]:

- Given node v, what can v reach?
- What other nodes can reach v?



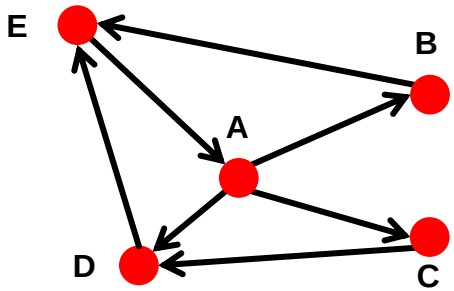
$$In(v) = \{w \mid w \text{ can reach } v\}$$
$$Out(v) = \{w \mid v \text{ can reach } w\}$$

For example:
In(A) = {A,B,C,E,G}
Out(A)={A,B,C,D,F}

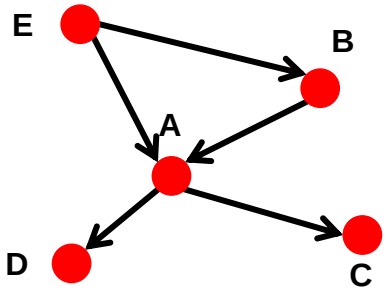
Directed Graphs

- **Two types of directed graphs:**
  - **Strongly connected:**
    - Any node can reach any node via a directed path

      $In(A)=Out(A)=\{A,B,C,D,E\}$



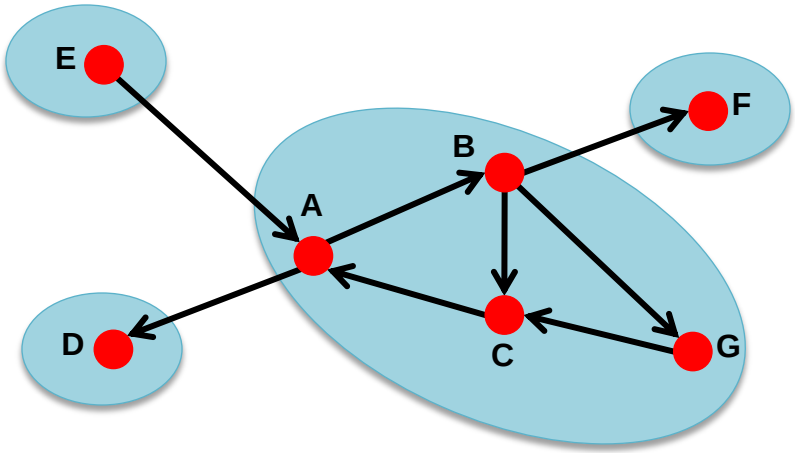
  - **DAG – Directed Acyclic Graph:**
    - Has no cycles: if u can reach v, then v can not reach u



- **Any directed graph can be expressed in terms of these two types!**

Strongly Connected Component

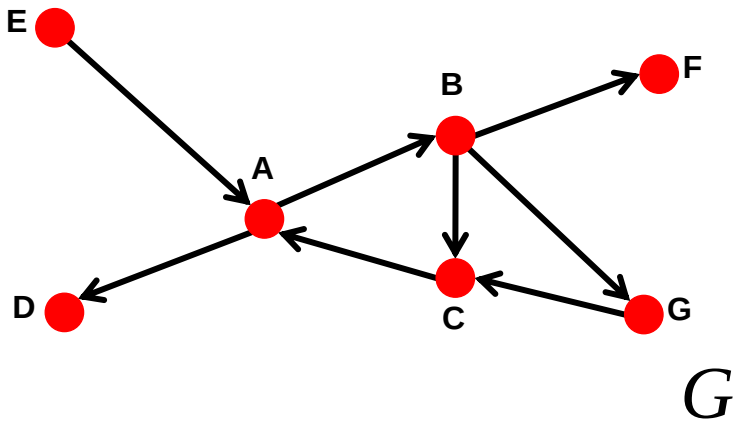
- **Strongly connected component (SCC)** is a set of nodes S so that:
  - Every pair of nodes in S can reach each other
  - There is no larger set containing S with this property



Strongly connected components of the graph: {A,B,C,G}, {D}, {E}, {F}

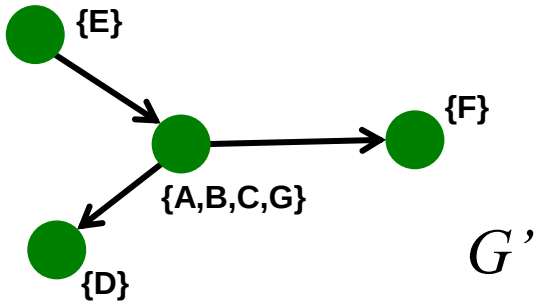
Strongly Connected Component

- **Fact:** Every directed graph is a DAG on its SCCs
  - (1) SCCs partitions the nodes of G
    - Each node is in exactly one SCC
  - (2) If we build a graph G' whose nodes are SCCs, and with an edge between nodes of G' if there is an edge between corresponding SCCs in G, then G' is a DAG



G

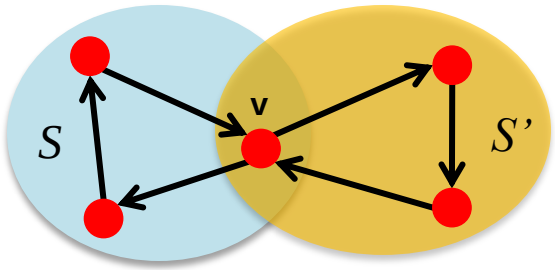
(1) Strongly connected components of graph G: {A,B,C,G}, {D}, {E}, {F}
(2) G' is a DAG:



G'

Proof of (1)

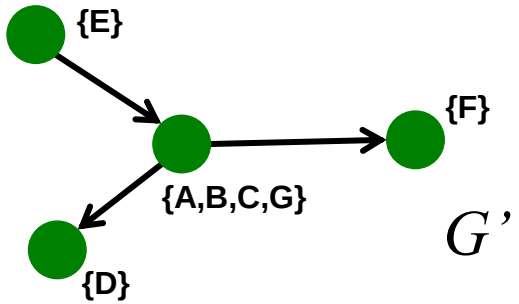
- **Claim: SCCs partitions nodes of G.**
  - This means: Each node is member of exactly 1 SCC.
- Proof by contradiction:
  - Suppose there exists a node v which is a member of 2 SCCs S and S'.

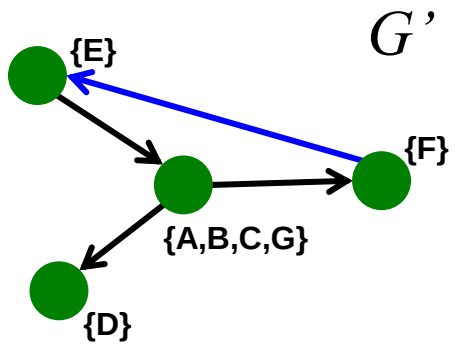


  - But then $S \cup S'$ is one large SCC!
    - Contradiction!

Proof of (2)

- **Claim: G' (graph of SCCs) is a DAG.**
  - This means: G' has no cycles.
- Proof by contradiction:
  - Assume G' is not a DAG
  - Then G' has a directed cycle.
  - Now all nodes on the cycle are mutually reachable, and all are part of the same SCC
  - But then G' is not a graph of connections between SCCs (SCCs are defined as maximal sets)
    - Contradiction!



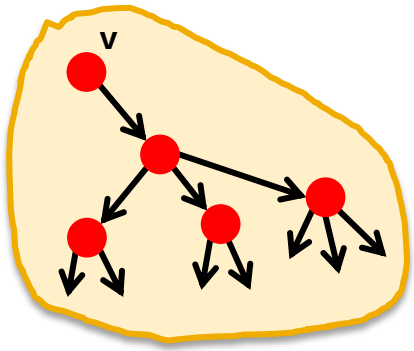


Now {A,B,C,G,E,F} is a SCC!

Graph Structure of the Web

- **Goal:** Take a large snapshot of the Web and try to understand how its SCCs "fit together" as a DAG
- **Computational issue:**
  - Want to find a SCC containing node v?
  - **Observation:**
    - $Out(v)$ … nodes that can be reached from v
    - **SCC containing v is:** $Out(v) \cap In(v)$

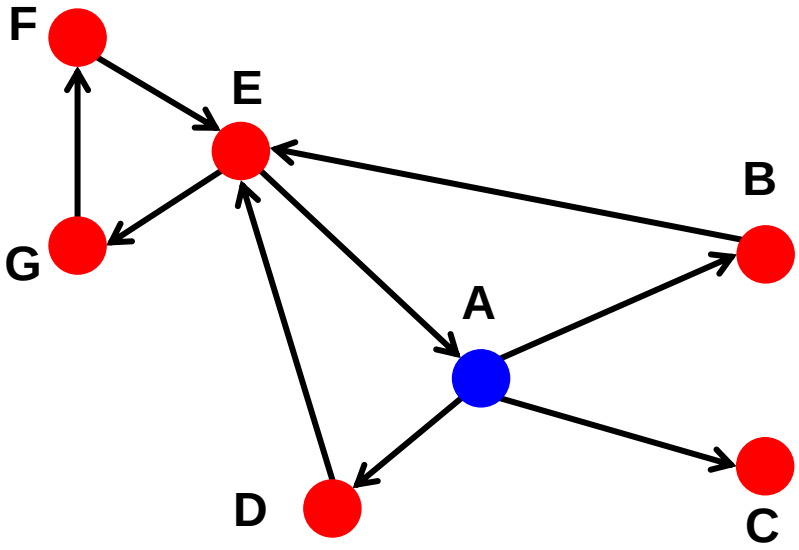
      $= Out(v,G) \cap Out(v,\overline{G})$, where $\overline{G}$ is G with all edge directions flipped



$Out(v)$

Out(A) ∩ In(A) = SCC

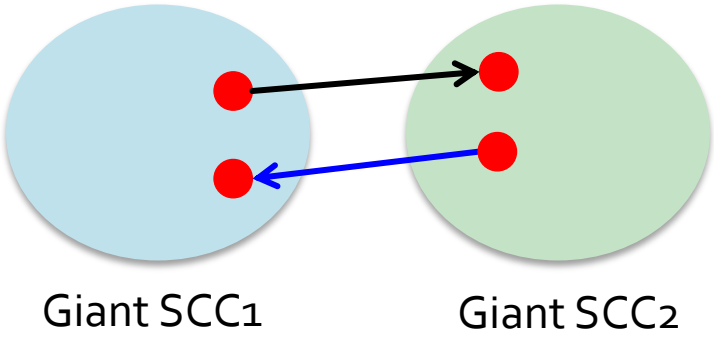
- **For example:**



  - Out(A) = {A, B, C, D, E, F, G}
  - In(A) = {A, B, D, E, F, G}
  - So, SCC(A) = Out(A) ∩ In(A) = {A, B, D, E, F, G}

Graph Structure of the Web

- There is a giant SCC
- There won't be 2 giant SCCs
- Heuristic argument:
  - It just takes 1 page from one SCC to link to the other SCC
  - If the 2 SCCs have millions of pages the likelihood of this not happening is very very small



Structure of the Web

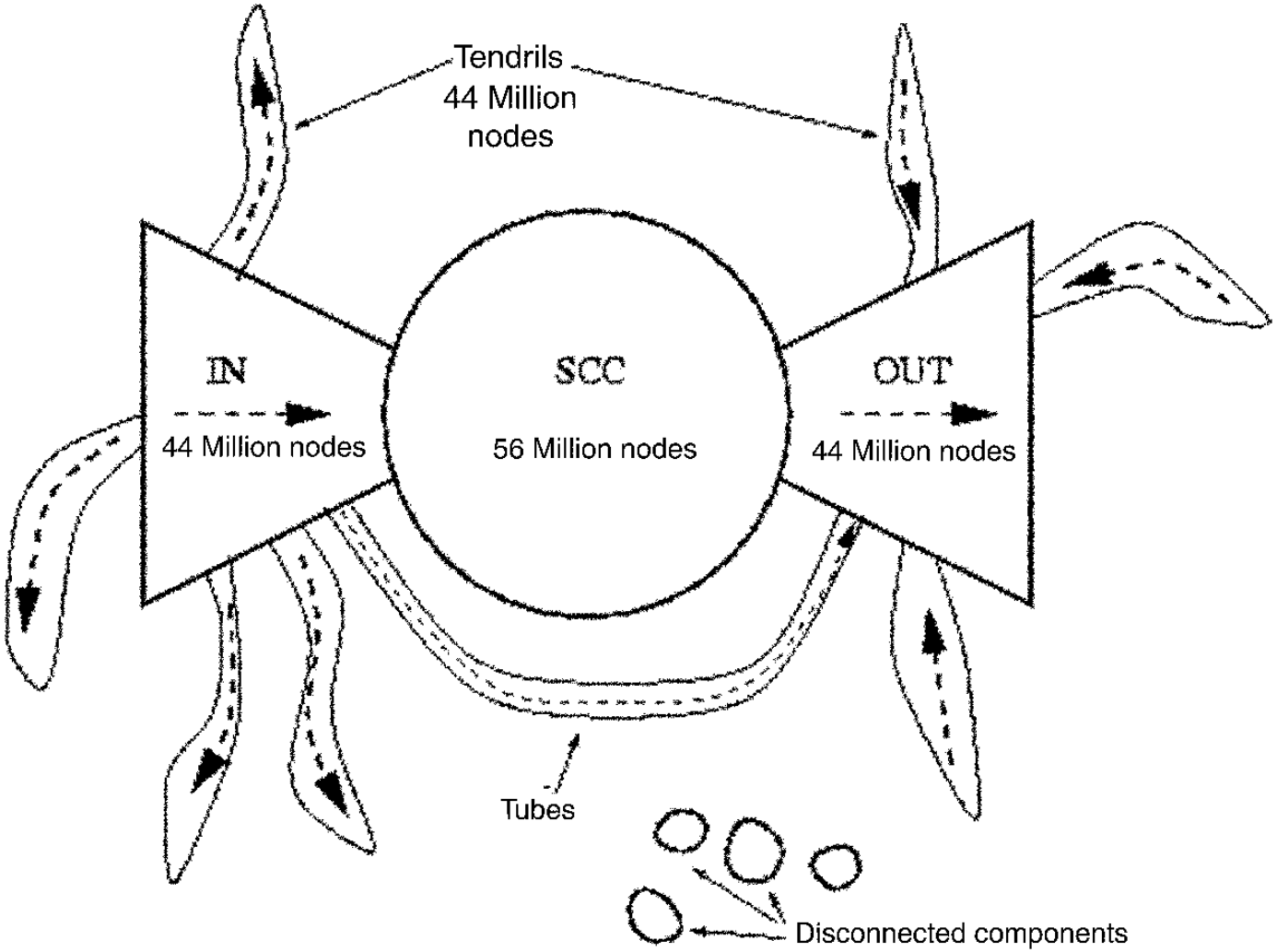
- **Broder et al., 2000:**
  - Altavista crawl from October 1999
    - 203 million URLS
    - 1.5 billion links
  - Computer: Server with 12GB of memory
- **Undirected version of the Web graph:**
  - 91% nodes in the largest weakly conn. component
  - Are hubs making the web graph connected?
    - Even if they deleted links to pages with in-degree >10 WCC was still ≈50% of the graph

Structure of the Web

- **Directed version of the Web graph:**
  - **Largest SCC:** 28% of the nodes (56 million)
  - Taking a random node v
    - Out(v) ≈ 50% (100 million)
    - In(v) ≈ 50% (100 million)

- **What does this tell us about the conceptual picture of the Web graph?**

Bow-tie Structure of the Web



203 million pages, 1.5 billion links [Broder et al. 2000]

What did We Learn/Not Learn ?

- **Learn:**
  - Some conceptual organization of the Web (i.e., the bowtie)
- **Not learn:**
  - **Treats all pages as equal**
    - Google's homepage == my homepage
  - **What are the most important pages**
    - How many pages have k in-links as a function of k?
      The degree distribution: $\sim 1 / k^2$
    - Link analysis ranking -- as done by search engines (PageRank)
  - **Internal structure inside giant SCC**
    - Clusters, implicit communities?
  - **How far apart are nodes in the giant SCC:**
    - Distance = # of edges in shortest path
    - Avg = 16 [Broder et al.]