Economic Networks

Theory and Applications

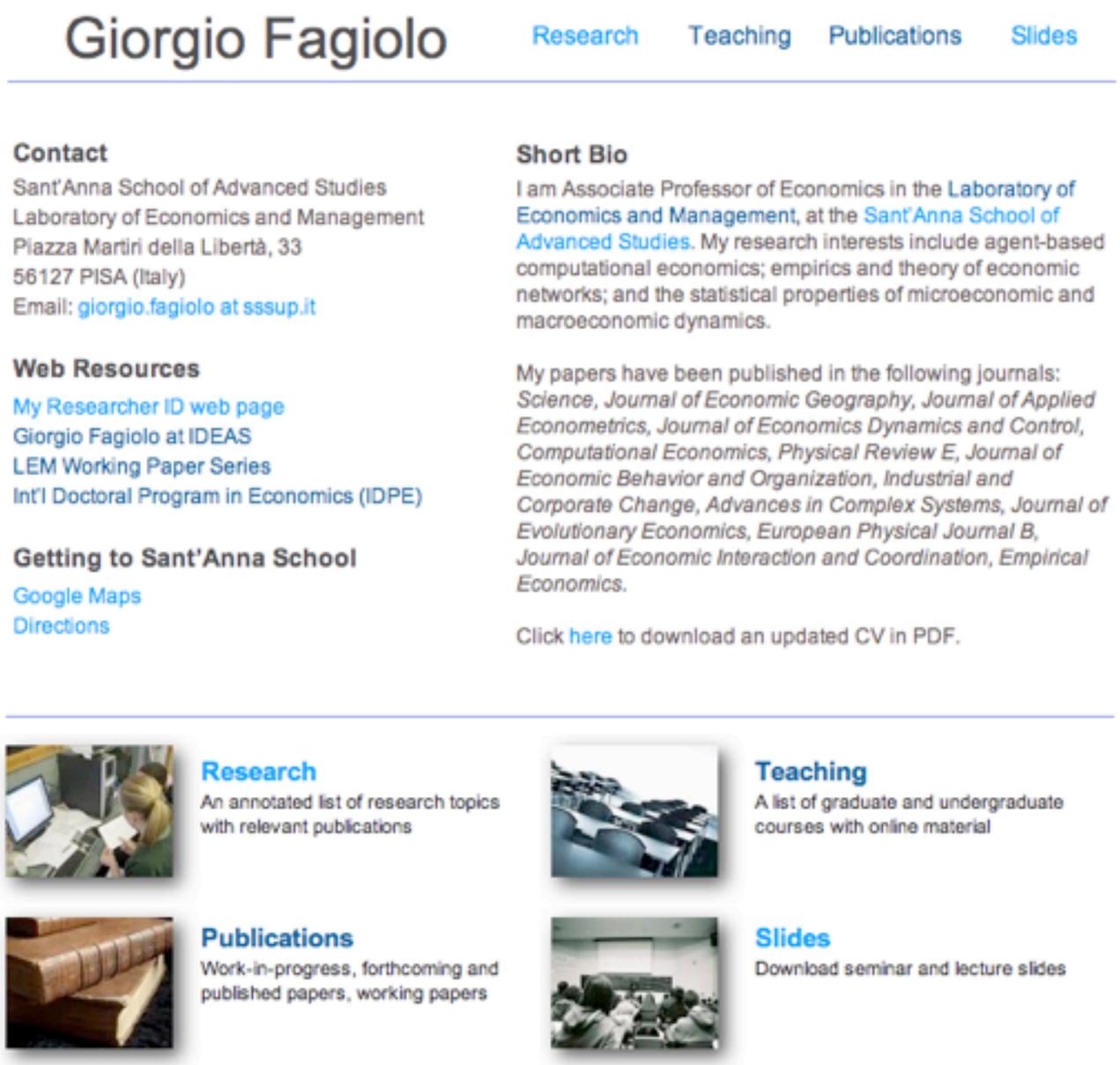
Giorgio Fagiolo

Laboratory of Economics and Management (LEM)
Sant'Anna School of Advanced Studies, Pisa, Italy

http://www.lem.sssup.it/fagiolo/
giorgio.fagiolo@sssup.it

Introduction

My Web Page



http://www.lem.sssup.it/fagiolo/Welcome.html

Main Research Interests

- Economic Networks
  - Applied work: Trade, finance, migration
- Micro-to-Macro Agent-Based Models
  - Business cycle and growth
  - Links between financial and real sectors
- Statistical Properties of Macro Time-Series
  - Fat-tails in macro time-series
  - DSGE models and fat-tailed shocks

Outline of the course

- What is a network? Examples of networks
- Why networks are important for economists?
- Networks and Graphs
- Measures and metrics on networks
- Distributions of metrics and measures in large networks
- Modeling Networks
- Economic applications

Logistics

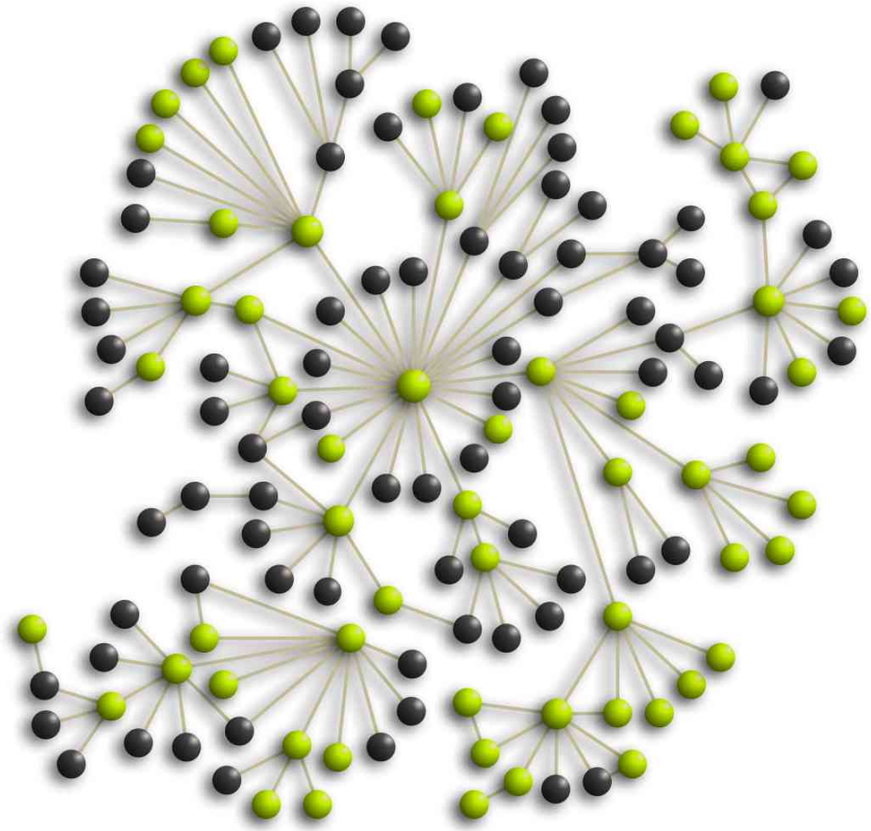
- 6 Meetings, approx 30 hours
- Theory and applications
- Running examples: ITN (+ IFN, IMN)
- Software: Matlab, Gephi (viz), Python/NetworkX
- Economic applications
- Course website: http://www.lem.sssup.it/fagiolo/Teaching
- Ref book: Newman, M.E.J.: Networks. An Introduction, Oxford University Press, 2010

What's Next

- What is a network? Examples of networks
- Why networks are important for economists?
- Networks and Graphs
- Measures and metrics on networks
- Distributions of metrics and measures in large networks
- Modeling Networks
- Economic applications

What is a network?

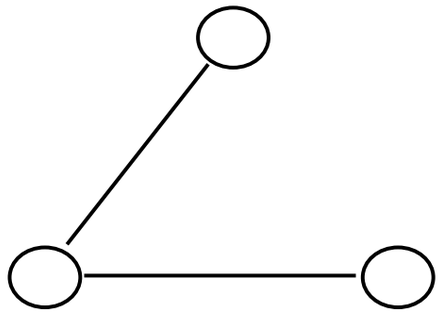
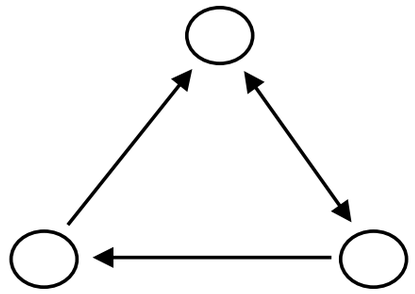
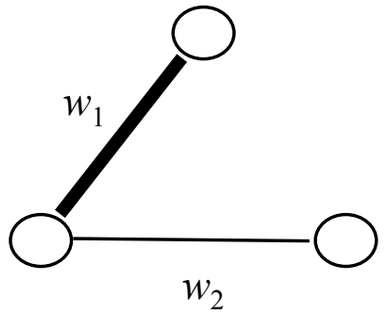
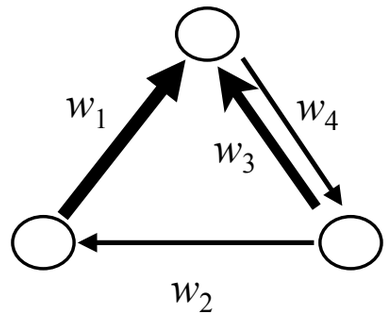
- A graph-theoretic representation of relationships (links) between units (nodes) of a system in a given point in time (or time interval)



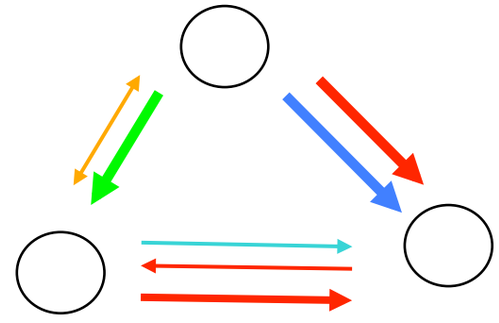
- Nodes: entities, units, agents, possibly heterogeneous
- Links: existence of relation between nodes

Different Types of Network Representations

Simple Graphs

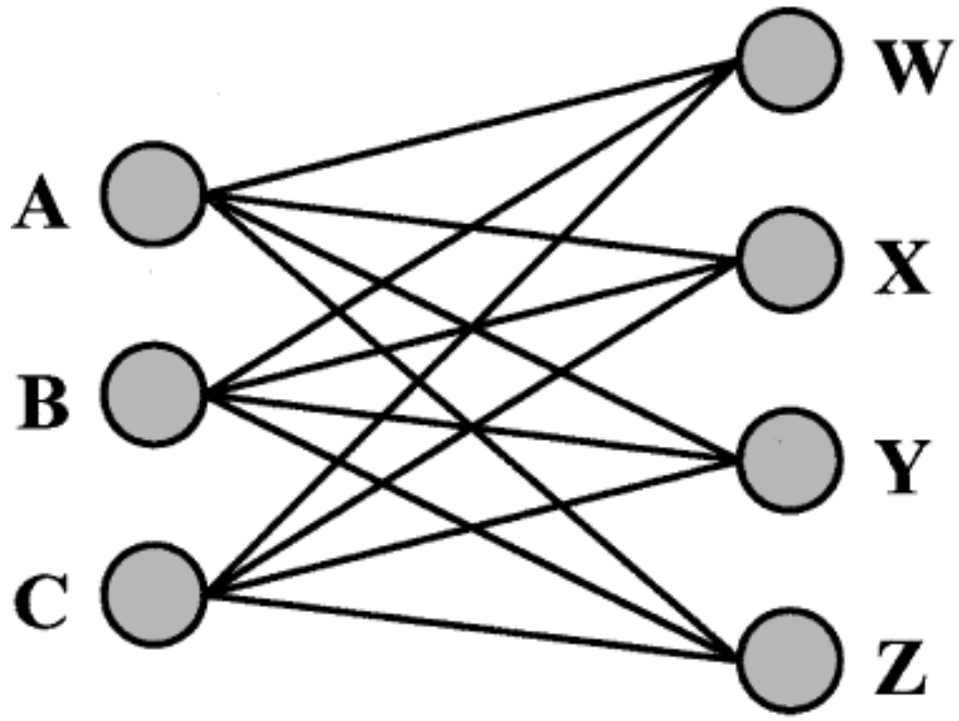
	Undirected	Directed
Binary		
Weighted		

Multi Graphs

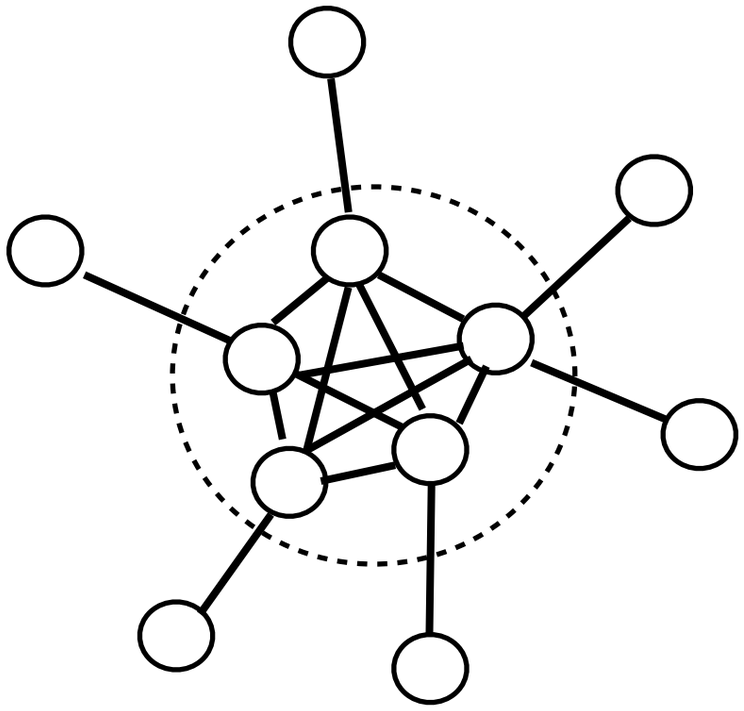


Bi-Partite Networks

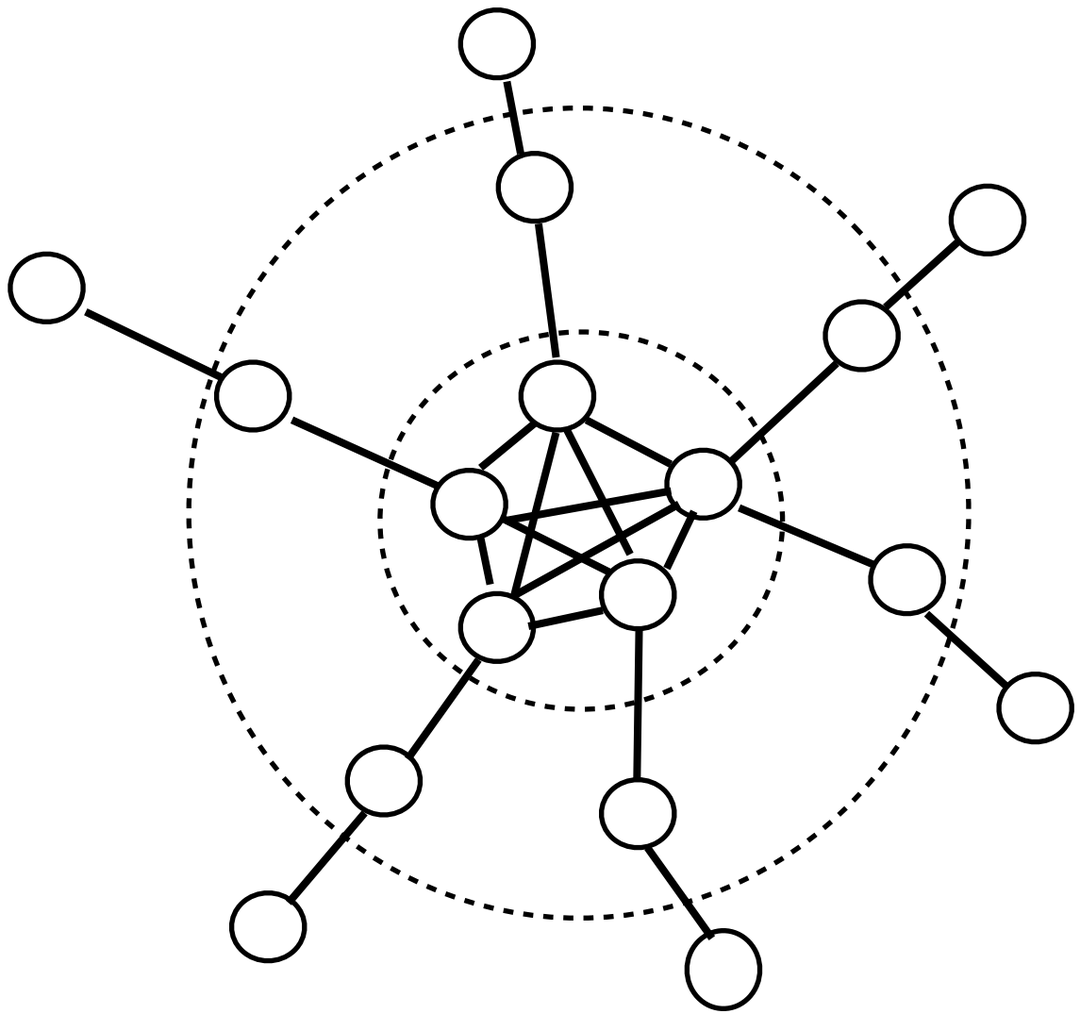
- Nodes are divided in 2 (or more generally K distinct sets)
- Links between nodes of the same set are not allowed
- Simple Bipartite networks: vertices of first set may be connected to vertices of second set
- Complete Bipartite networks: every vertex of the first set must be connected to every vertex of second set



Core-Periphery and Tiered Networks

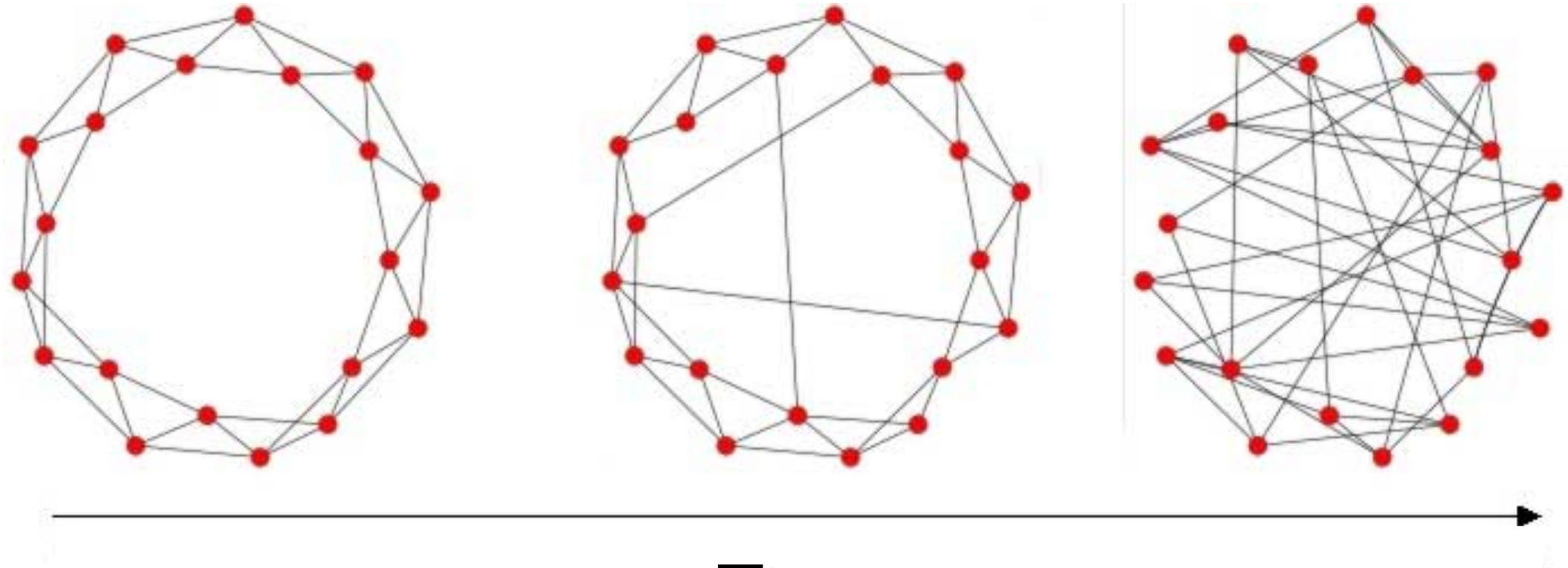


Core-Peryphery: Dense core with periphery layers



Tiered: Core, intermediate layer, periphery layer

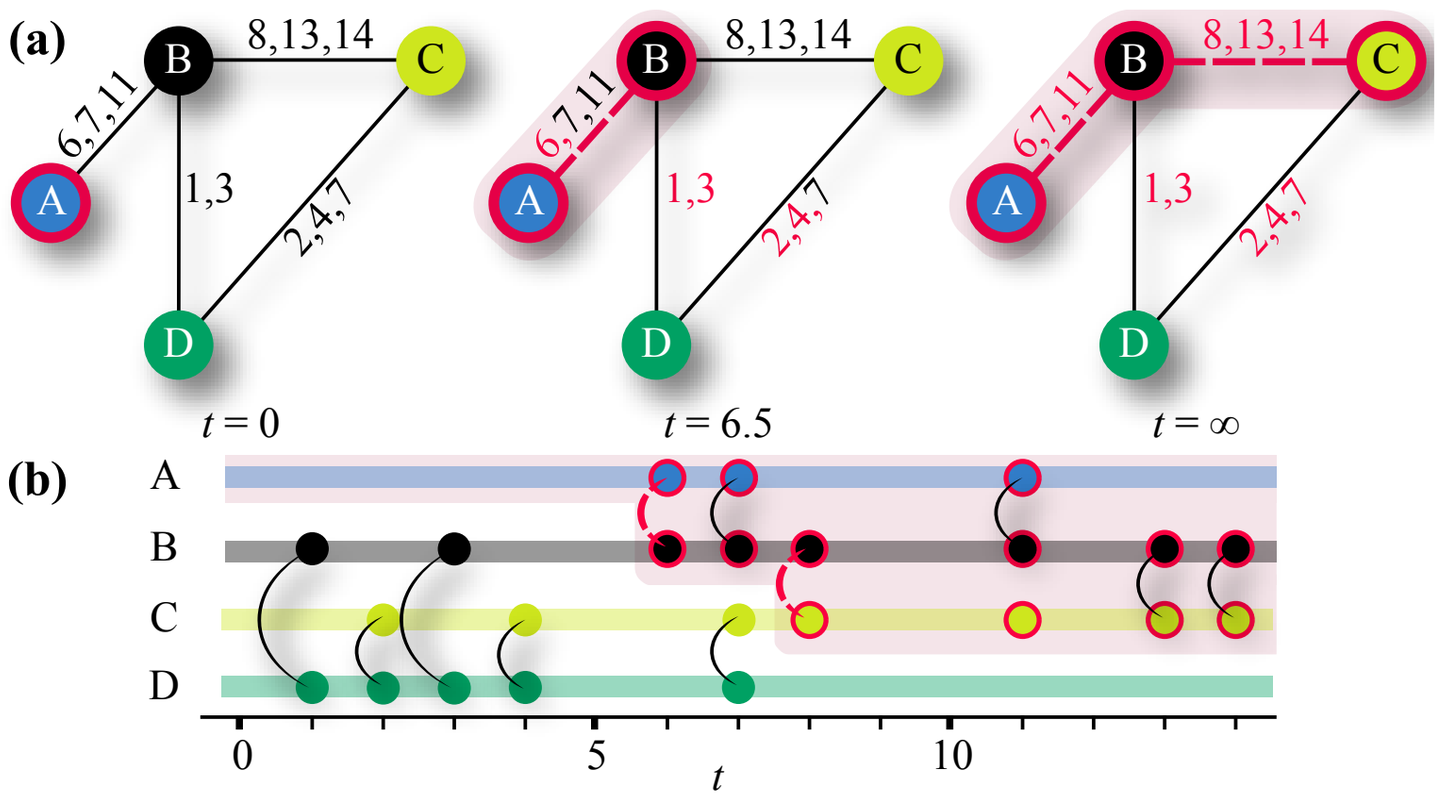
Network Dynamics



Time

- More generally: time sequence of weighted directed multi graphs...

Temporal Networks



- In many cases, the edges are not continuously active (sequences of instantaneous contacts)
- Temporal structure of edge activations can affect dynamics of systems interacting through the network
- See Holme and Saramaki, 2001, arXiv:1108.1780v2

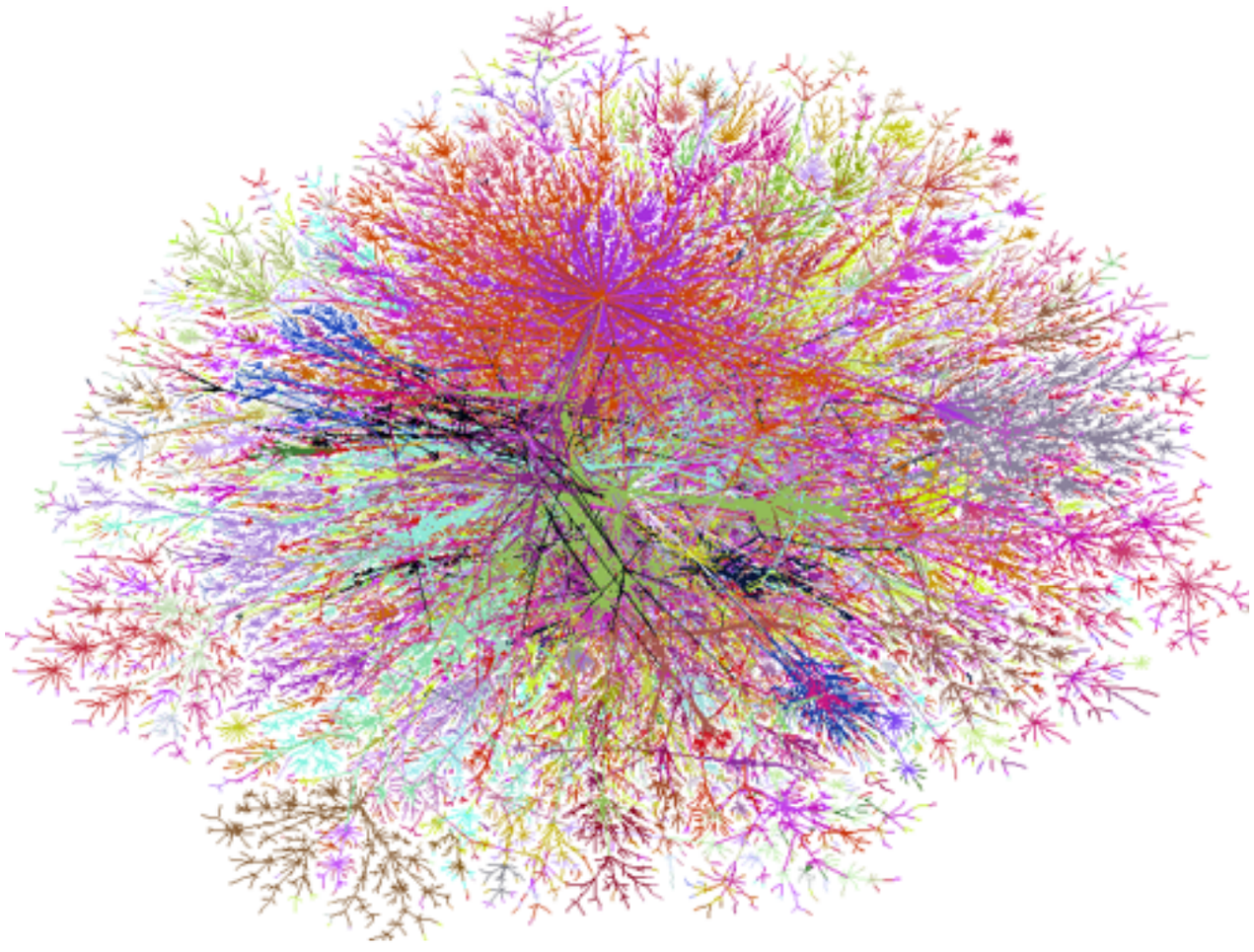
Real-World Networks: Some Examples

- Technological networks
- Biological and ecological networks
- Information networks
- Linguistic and cognitive networks
- Social networks
- Economic networks

... interdisciplinary approach to the study of networked systems...

Technological Networks (I)

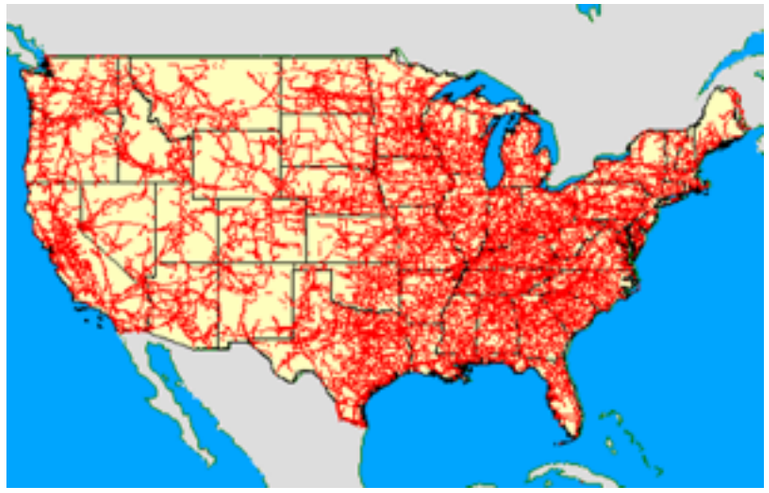
- The Internet: physical connections between physical devices (main routers, switching centers, ISP, end-user computers)
- Impossible to probe Internet network structure directly, data gathered via routing tables of autonomous systems (i.e., domains)
- See Pastor-Satorras and Vespignani: Evolution and structure of the Internet, 2004

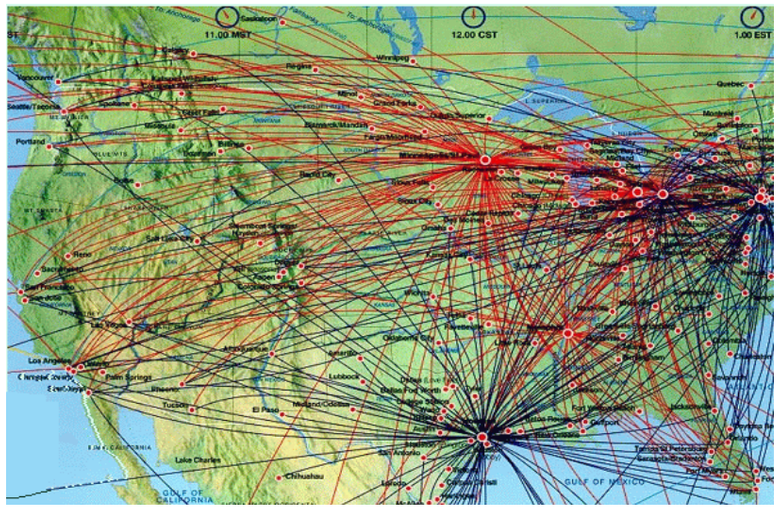


AS-level Structure: Nodes are AS and links represent routes taken by data traveling between them

Technological Networks (II)

- Telephone networks (landlines, wireless)
- Power grids
- Transportation networks (road, rail, and airlines)
- Delivery and distribution networks (cargos)



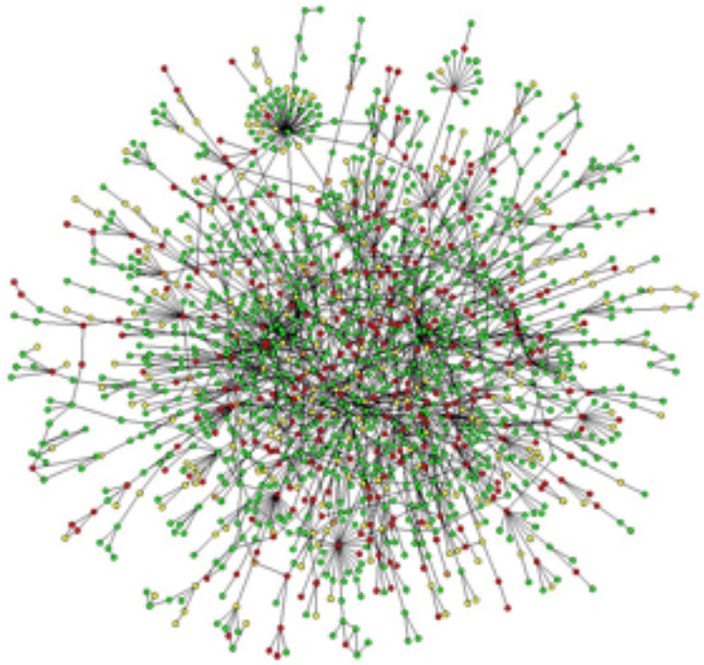


Biological and Ecological Networks

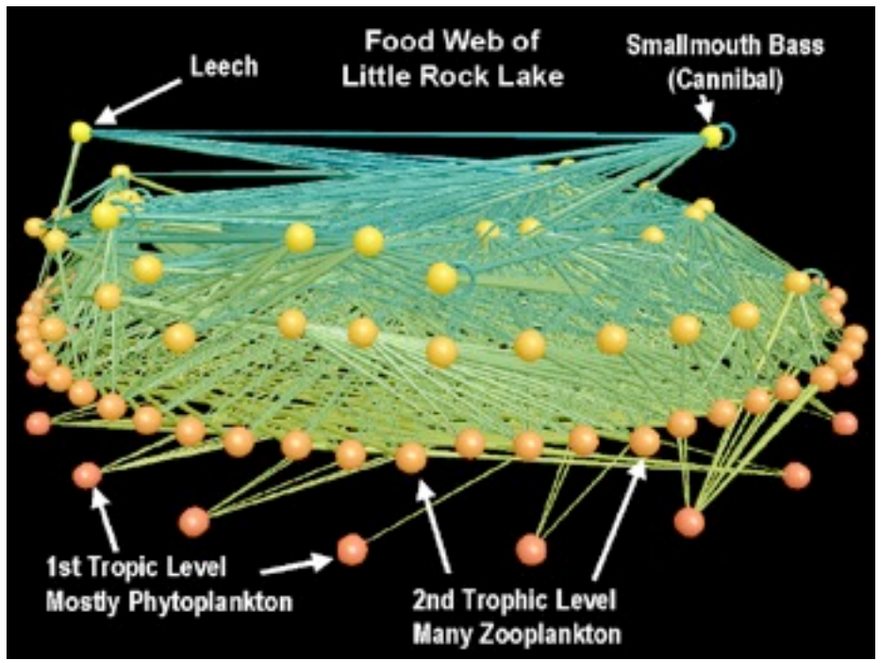
- Protein-protein interaction networks: physical interactions between proteins; nodes=proteins; bilateral link: two proteins interact

- Metabolic networks: nodes are chemicals produced and consumed in metabolic reactions within the cell (amino acids, carbohydrates, lipids, etc.)

- Food webs: directed network representing which species prey which other in a given ecosystem



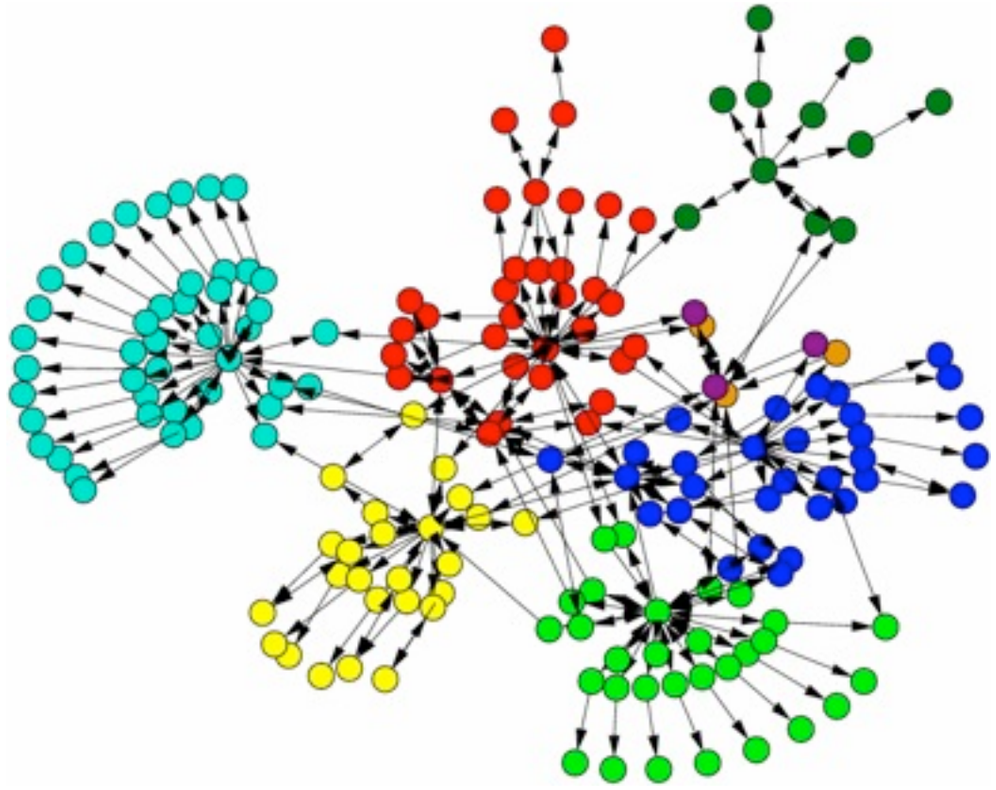
Protein-protein network for yeast



Predatory interactions in Little Rock Lake, WI, USA

Information Networks (I)

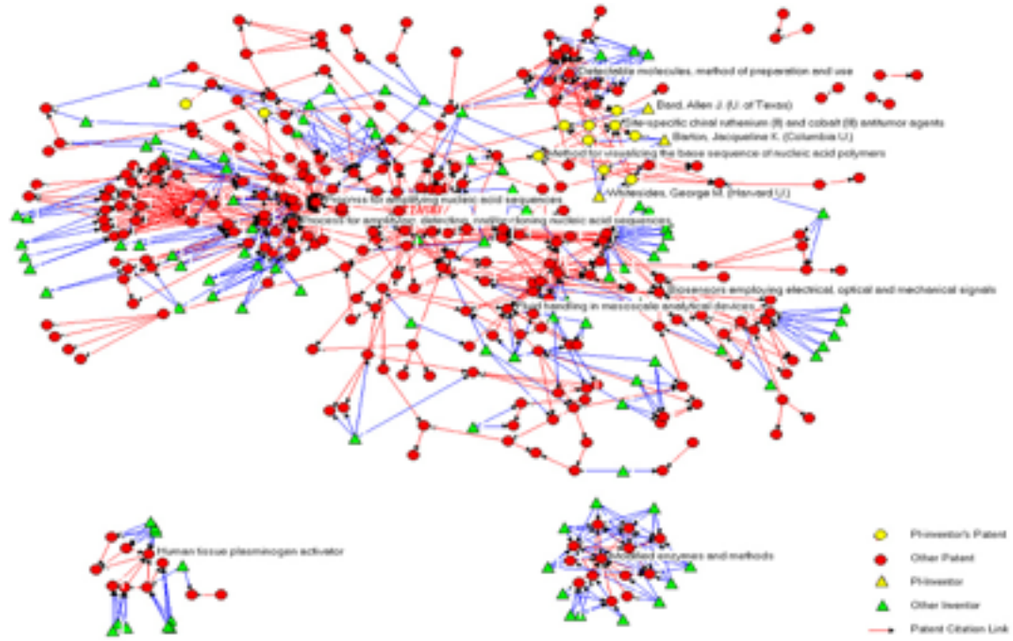
- The WWW: nodes are webpages and directed links represent hyperlinks
- Data gathered through crawlers (breadth-first search)
- Problems: Access to crawlers is denied by some websites, dynamically-generated pages; directionality of the network prevents pages to be reached; extremely dynamic evolution
- Only snapshots available
- Other WWW-based networks: Wikipedia



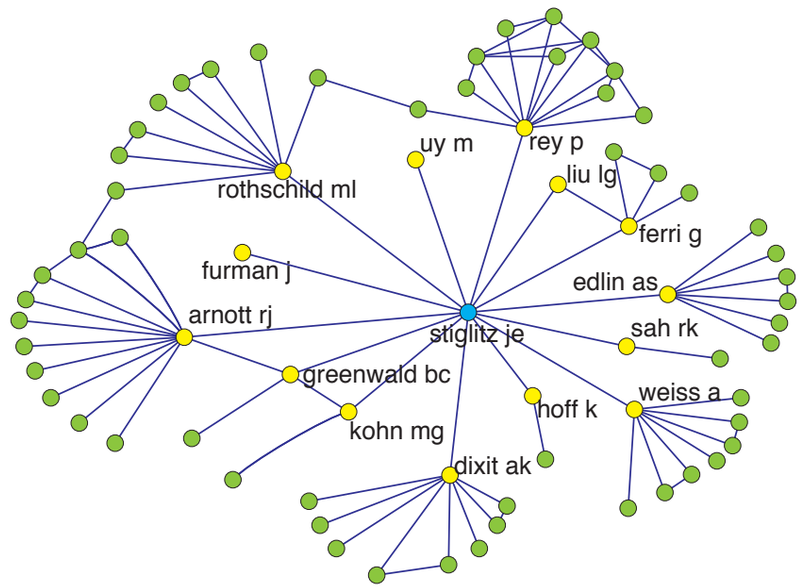
Webpages on a corporate website:

Information Networks (II)

- Citation networks: nodes are academic papers/researchers or patents; directed links represent citations
- Reasons for citing: usefulness, credits, influence, disagreeing
- Data gathered through software (Citeseer, Google Scholar, etc.)
- Citation networks do not typically contain cycles (the WWW can): all directed edges point backward in time, as papers can be cited only if they have been written
- Other citation networks: political blogs, web social networks, legal citations, etc.



Chemistry: molecular biology and microbiology

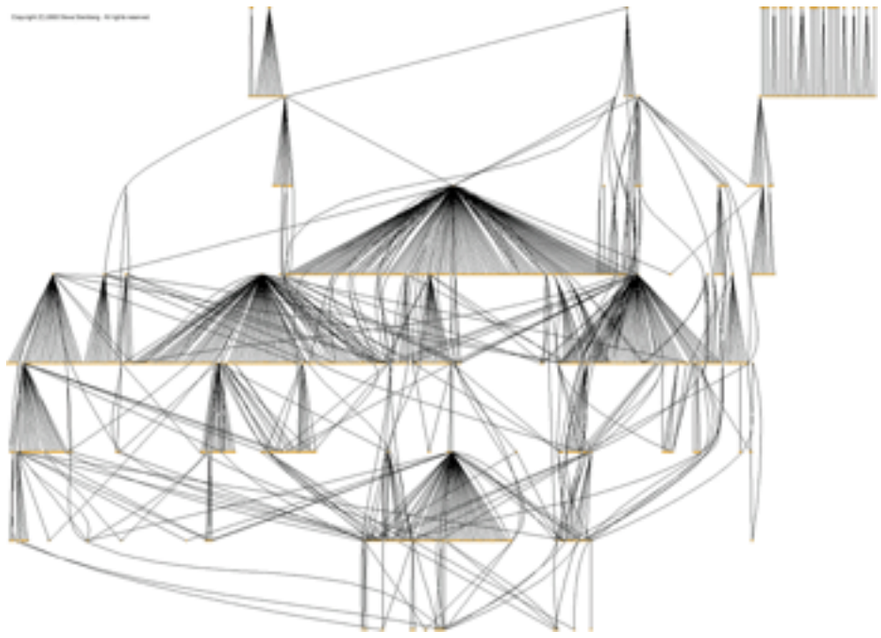


Local network of collaboration of Joseph E. Stiglitz in the 1990s.

Other Information Networks

- P2P Networks: nodes are computers and links represent sharing relationships. Very difficult to get data about network structure (only example: Gnutella)

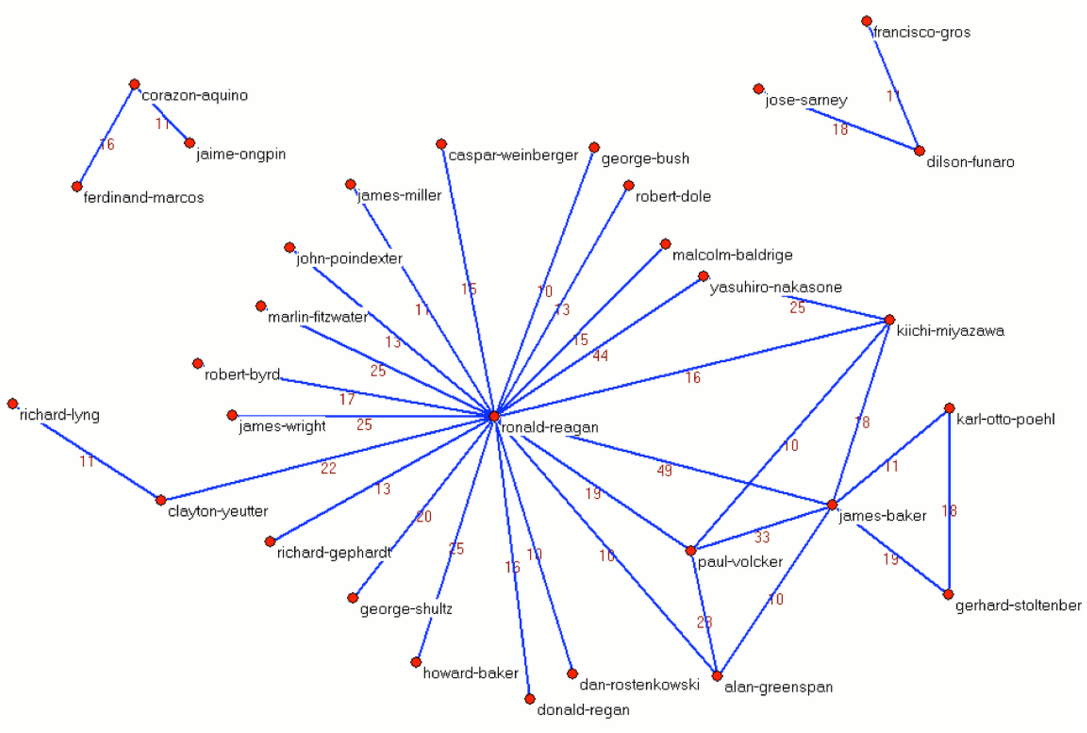
- Recommender networks: two types of nodes (bipartite graph), products and people, with edges connecting people with products they buy or like; very useful in designing recommender systems (amazon.com)



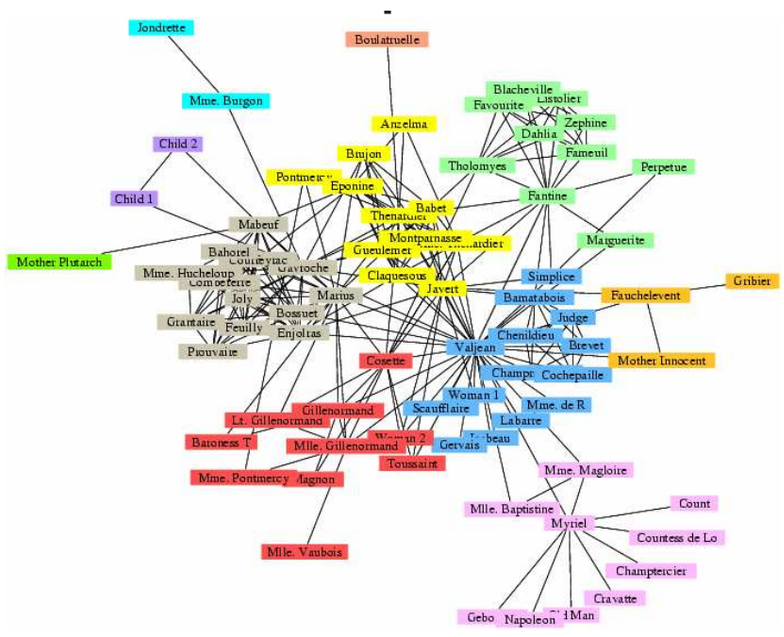
The Gnutella network

Linguistic and Cognitive Networks

- Networks that can be established by studying the feature of one (or more) languages
- Nodes: words. Links: relationship between words due to position, syntax, or grammar
- Co-occurrence networks: link is present if words are neighbours in a given text (or a little far apart)
- Word association networks: experiments were people are asked to say the first word that comes in their mind after a stimulus, i.e. another word
- Thesaurus networks: words are connected if they are synonymous



Co-occurrence network between person names in Reuters news

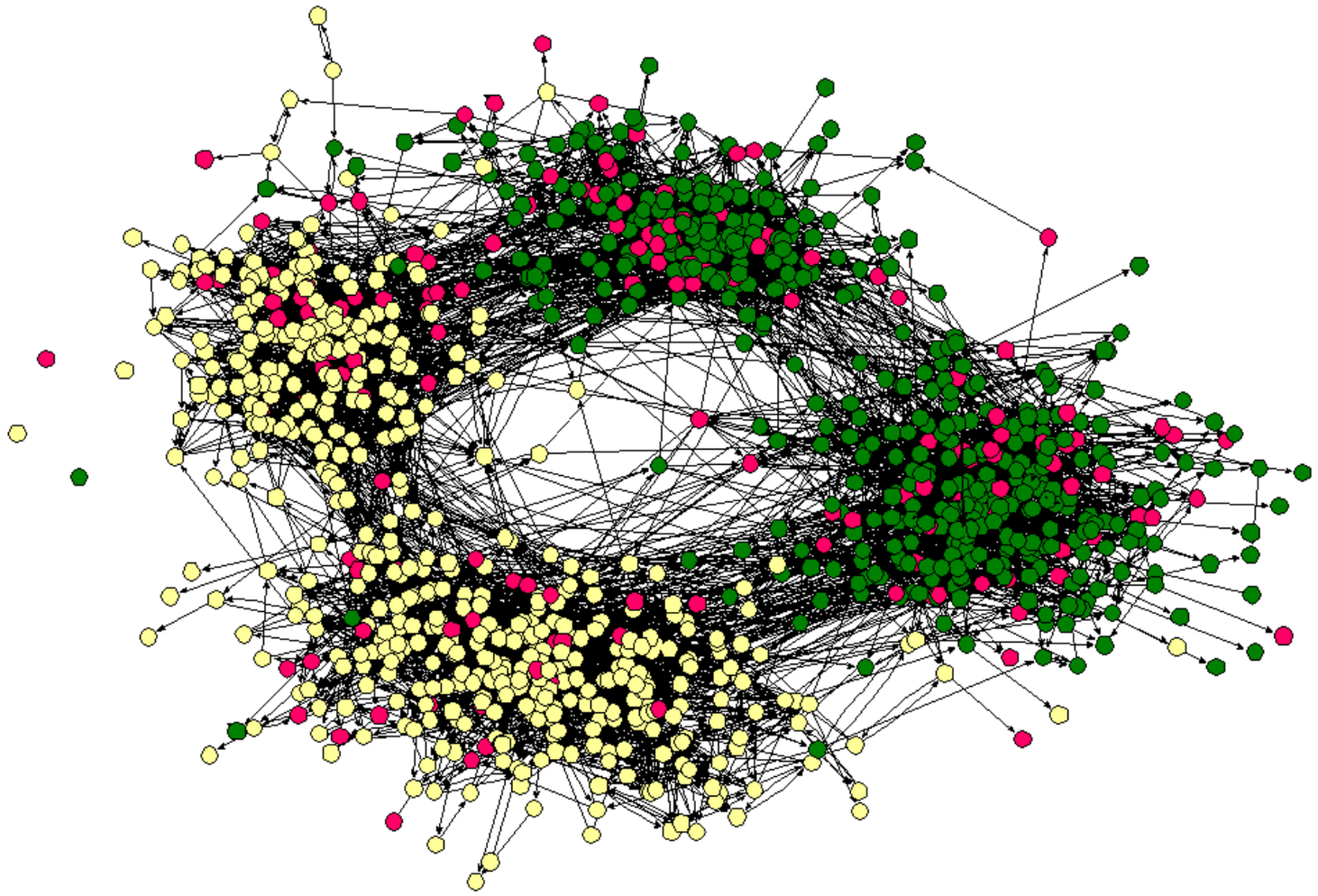


Character network in Hugo's Les Miserables

Social Networks

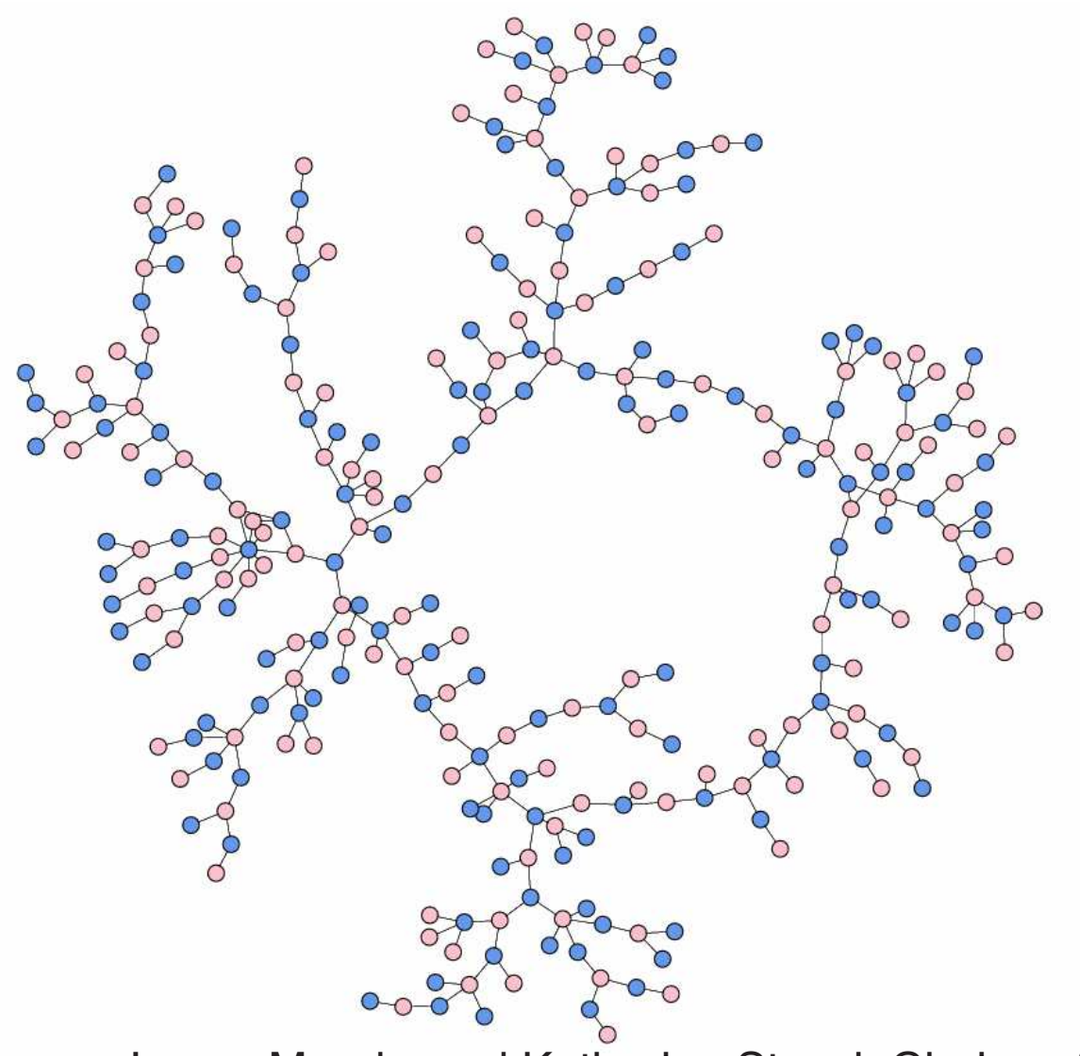
- Networks where nodes are people and links represent social relationships: a huge class of networks (sometimes overlapping with economic networks)
  - Friendship and acquantainships
  - Dating and sexual contacts
  - Collaboration and affiliation: scientists, movie actors, musicians
  - Criminal networks
  - Historical networks: marriage and power (Padgett)
  - Online communities (what today is known as a "Social Network")
  - Overlapping between board of directors of companies
  - Contacts between business people
  - ... and many more

SNs: High School Friendships



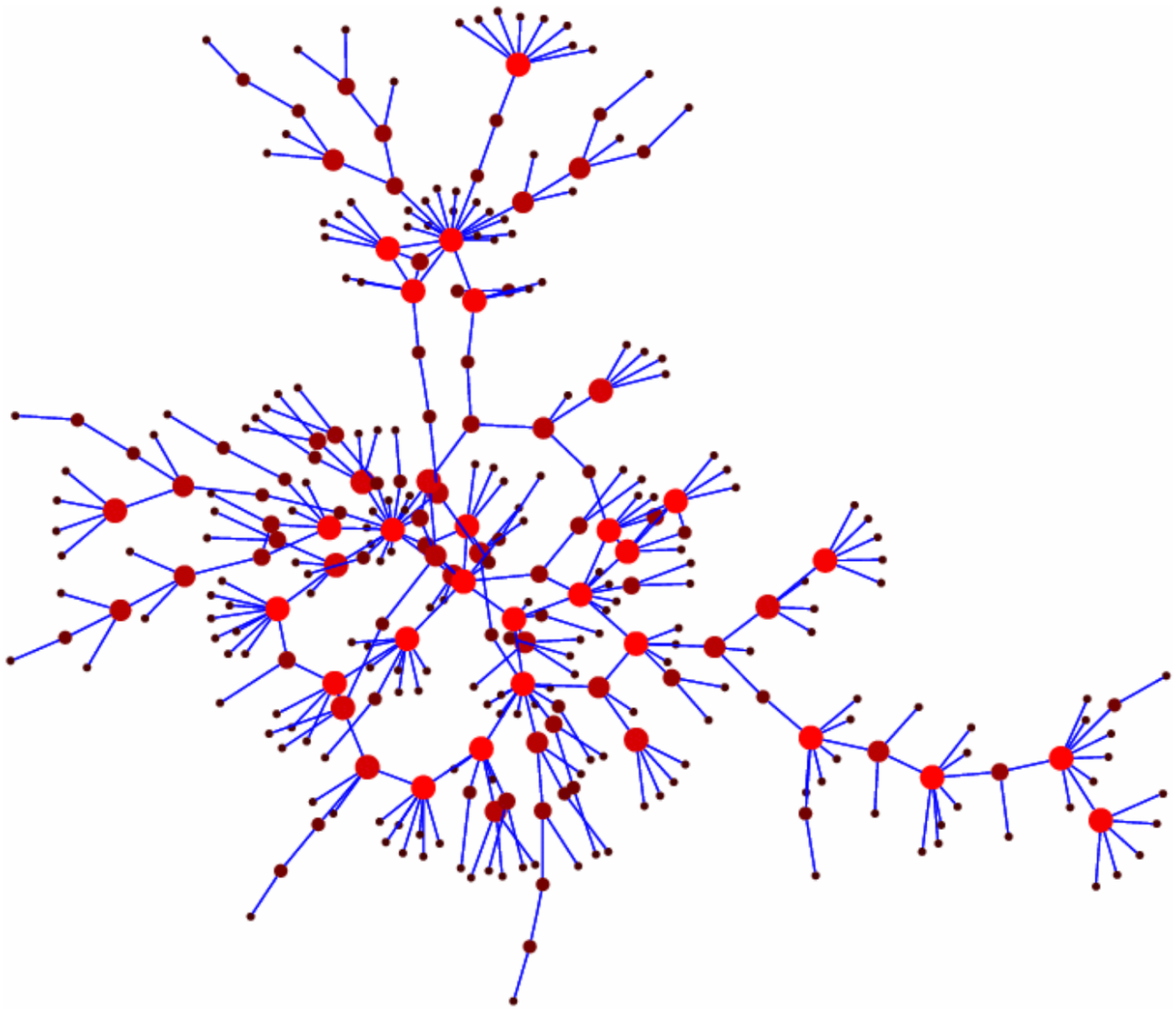
- Nodes = Students, Links = Friendships, Color = Ethnic group
- Data: J. Moody, Race, school integration, and friendship segregation in America, *American Journal of Sociology* 107, 679-716 (2001).
- Figure: M.E.J. Newman, The structure and function of complex networks, *SIAM Review* 45, 167-256 (2003). `www-personal.umich.edu/~mejn/networks/`

SNs: Dating Networks



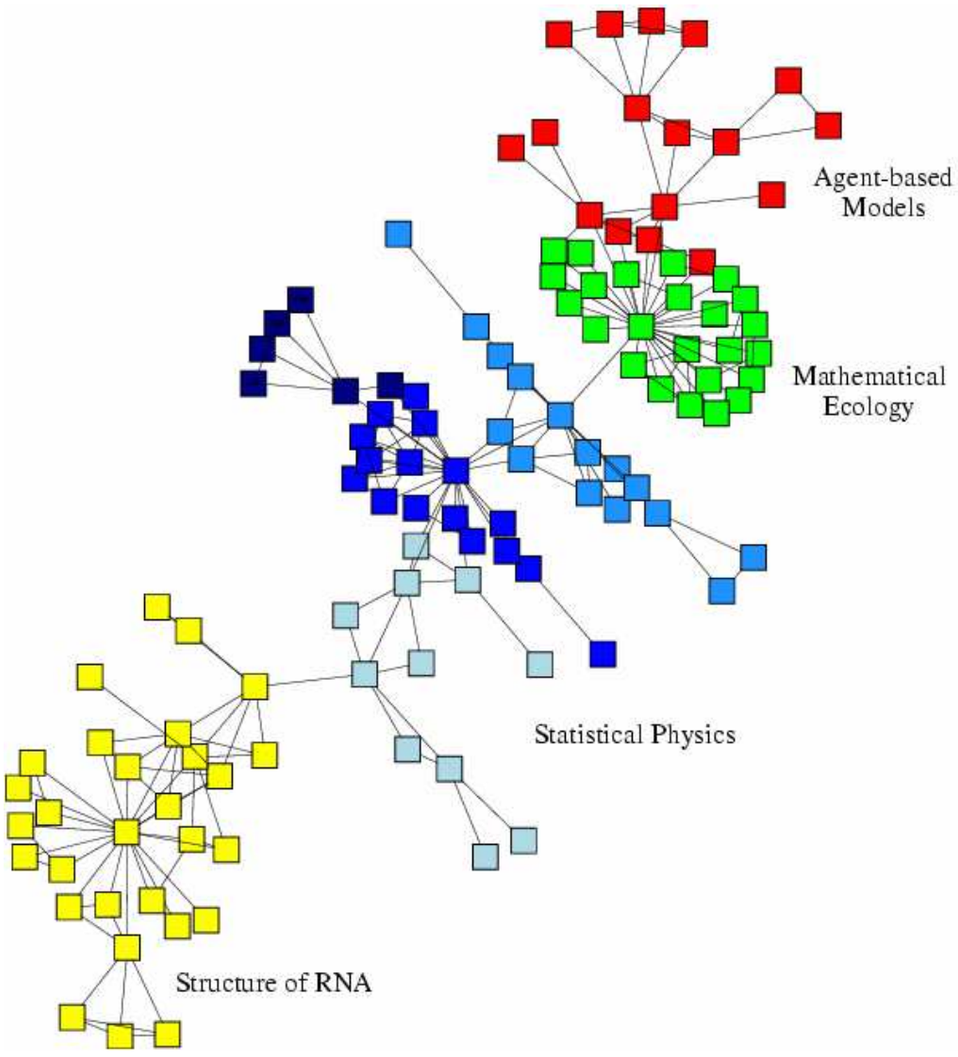
- Data: Peter S. Bearman, James Moody, and Katherine Stovel, Chains of affection: The structure of adolescent romantic and sexual networks, American Journal of Sociology 110, 44-91 (2004).
- Figure: M.E.J. Newman, The structure and function of complex networks, *SIAM Review* 45, 167-256 (2003). `www-personal.umich.edu/~mejn/networks/`

SNs: Sexual Networks



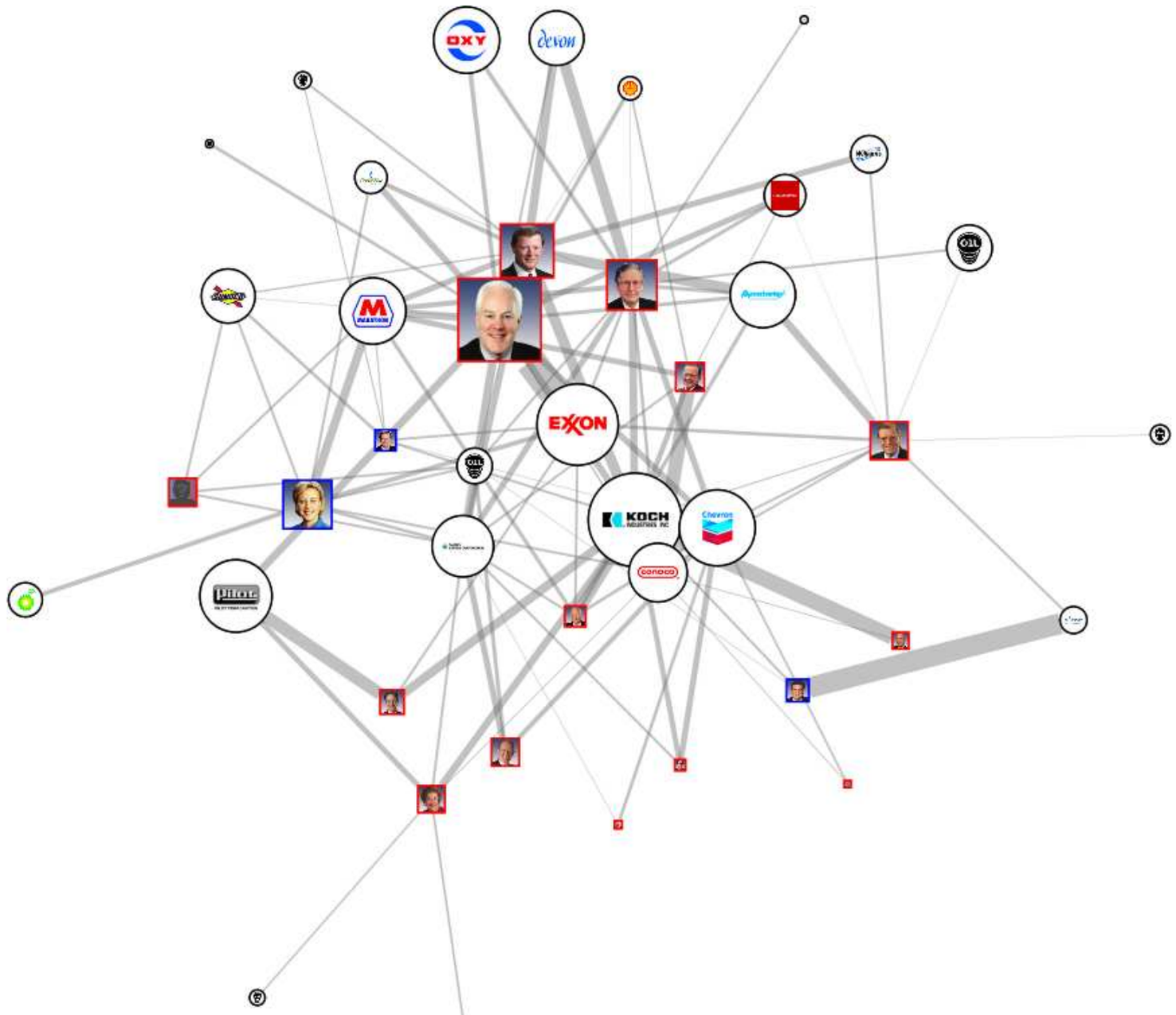
- Figure source: M.E.J. Newman, The structure and function of complex networks, SIAM Review 45, 167-256 (2003).
- Data from: Potterat et al,, Risk network structure in the early epidemic phase of HIV transmission in Colorado Springs, Sexually Transmitted Infections 78, i159-i163 (2002).

SNs: Interdisciplinary Collaborations



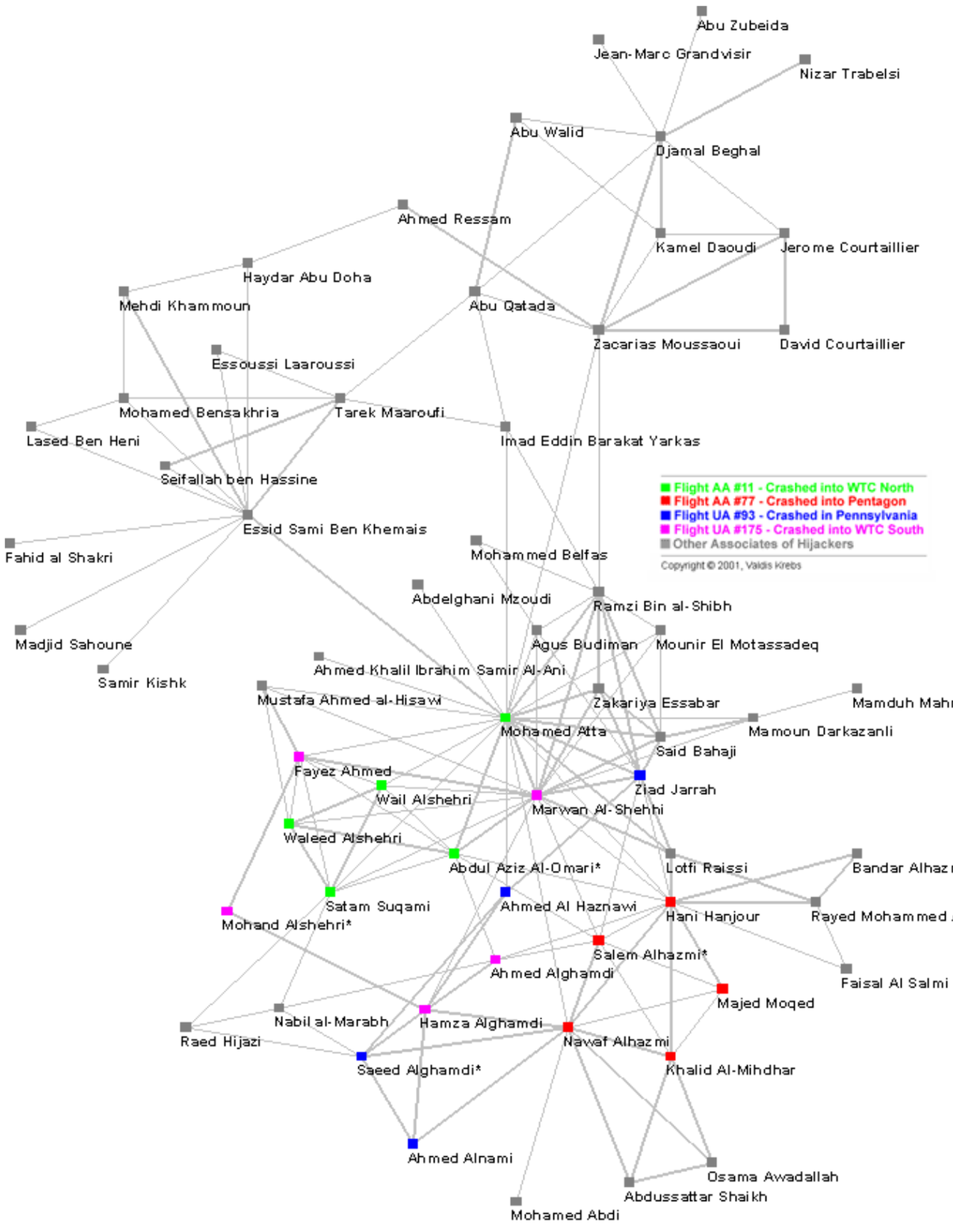
- Nodes = Researchers, Links indicate that the researchers have co-authored one or more papers.
- Figure: M. Girvan and M. E. J. Newman, Community structure in social and biological networks, Proc. Natl. Acad. Sci. USA 99, 8271-8276 (2002).

SNs: Politics and Sustainability



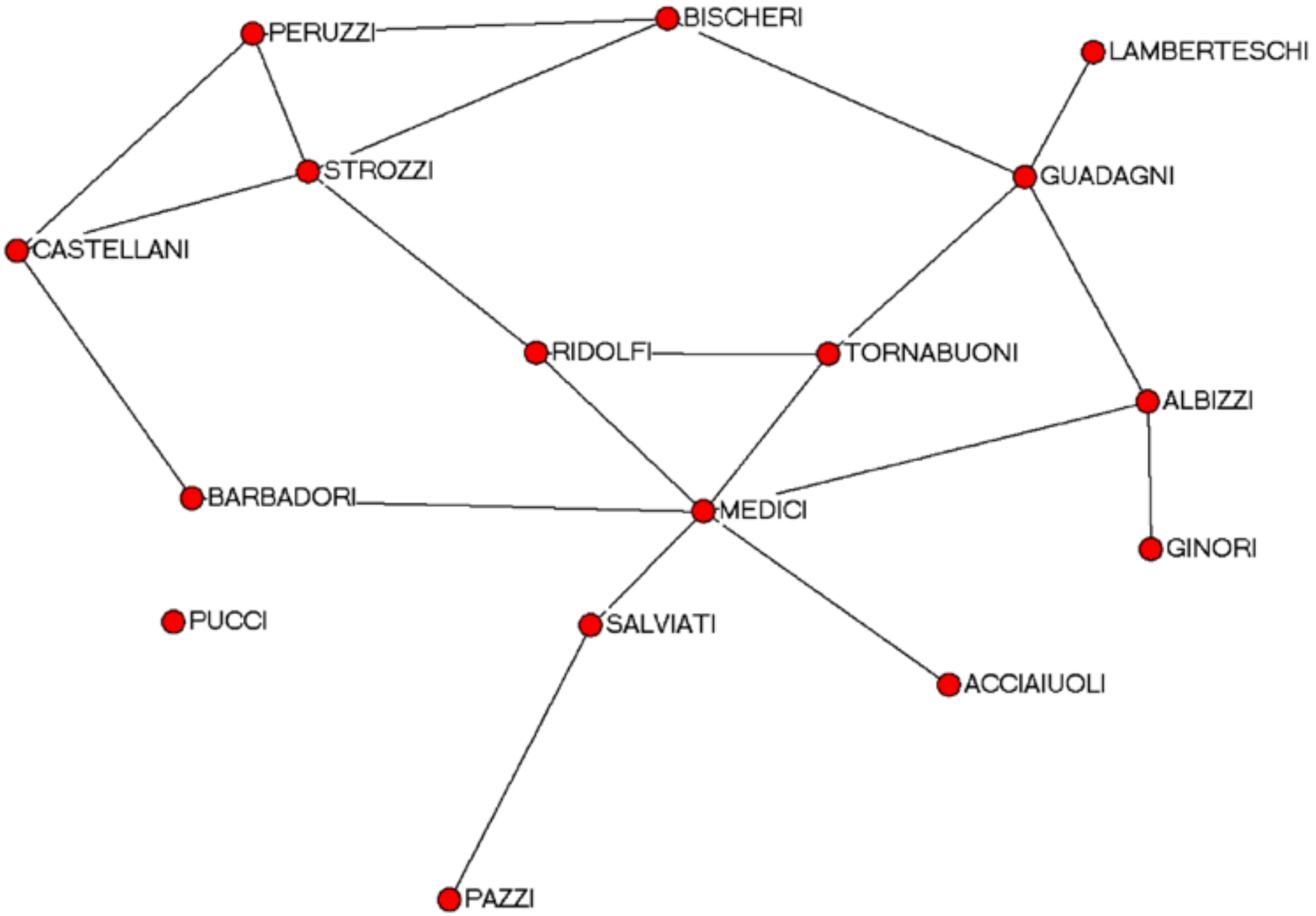
- Links are senators or corporations. `http://oilmoney.priceofoil.org/`.

SNs: Terrorist Networks



Network of terrorists involved in 9/11 attack (Source: http://www.orgnet.com/hijackers.html)

SNs: Historical Networks

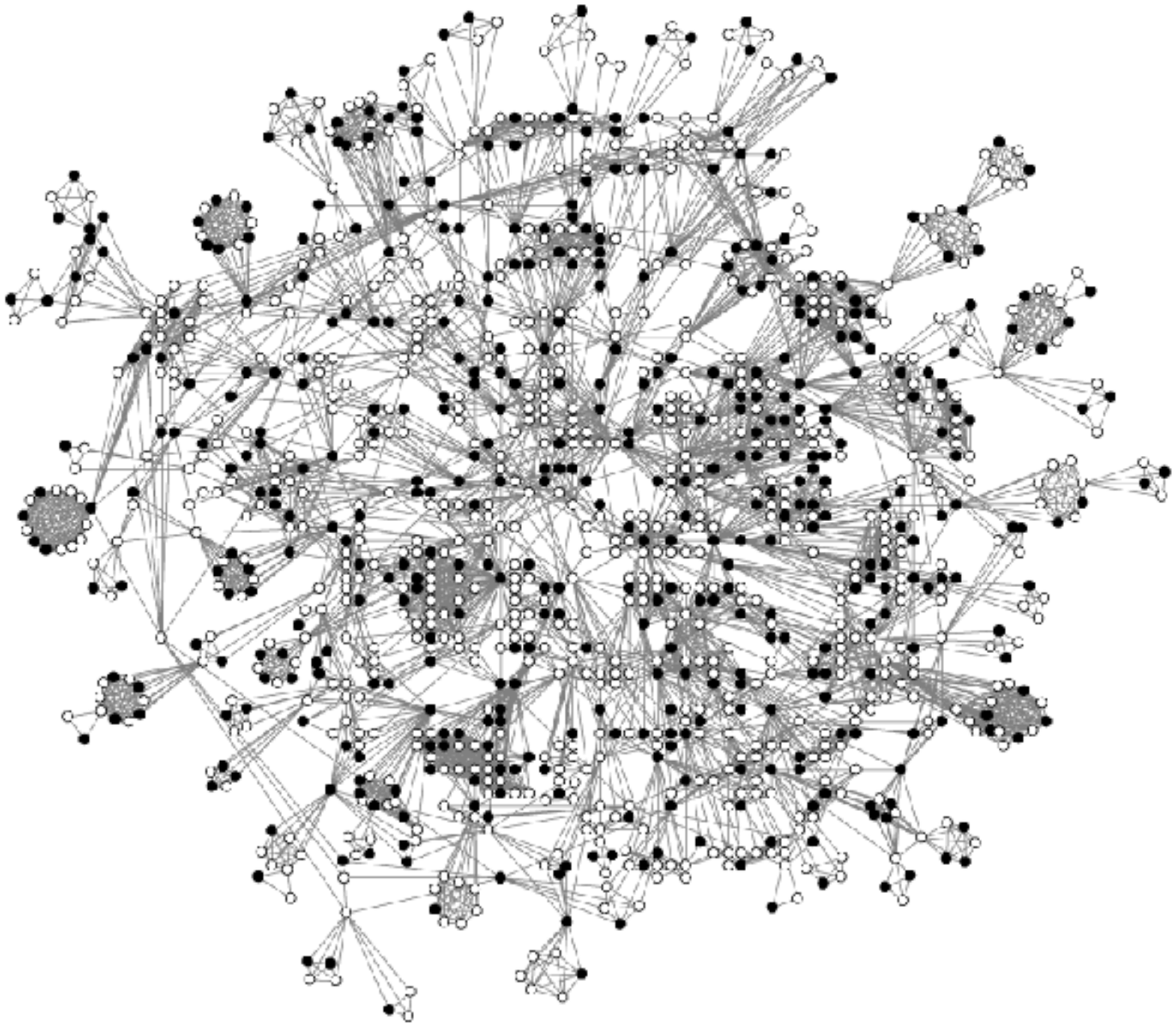


Padgett: Family relationships in Renaissance Florence (1300-1500). Padgett's data contains information on about 60,000 persons: 10,000+ marriages, 14,000+ loans, 3,000+ business partnerships/firms, 40,000+ tax records, 12,000+ political-office elections.

Online Social Networks: FB

- Characterizing the entire social network of active members of Facebook in May 2011, a network then comprised of 721 million active users
- Given that the world's population was around 6.9 billion people in May 2011, this means that this network includes roughly 10 percent of the world's population
- There are 68.7 billion friendship edges, so the average Facebook user in these studies had around 190 Facebook friends
- The degrees of separation between any two Facebook users is smaller than the commonly cited six degrees, and has been shrinking over the past three years as Facebook has grown.
- While the entire world is only a few degrees away, a user's friends are most likely to be of a similar age and come from the same country
- Only 10% of people have less than 10 friends, 20% have less than 25 friends, while 50% (the median) have over 100 friends
- See http://arxiv.org/abs/1111.4503 and http://arxiv.org/abs/1111.4570

SNs: Interlocking Directorates



The network structure among directors (circles) who form part of the largest group of interconnected directors. Two directors are connected if they are members of the same board. The solid circles refer to women, whereas the hollow circles refer to men. Source: interpersonal network among Norwegian directors (Opsahl and Seierstad, 2009)

Economic Networks

- Networks where nodes are economic agents (individuals, firms, consumers, organizations, industries, countries, etc.) and links **mostly** represent market interactions
- Main economic-network (somewhat overlapping) classes:
  - Trade (goods and services) networks
  - Investment Networks (FDI, i.e. M&A, Green Field)
  - Migration and Travel Networks
  - Financial networks
  - Firm networks
  - Labor-market networks

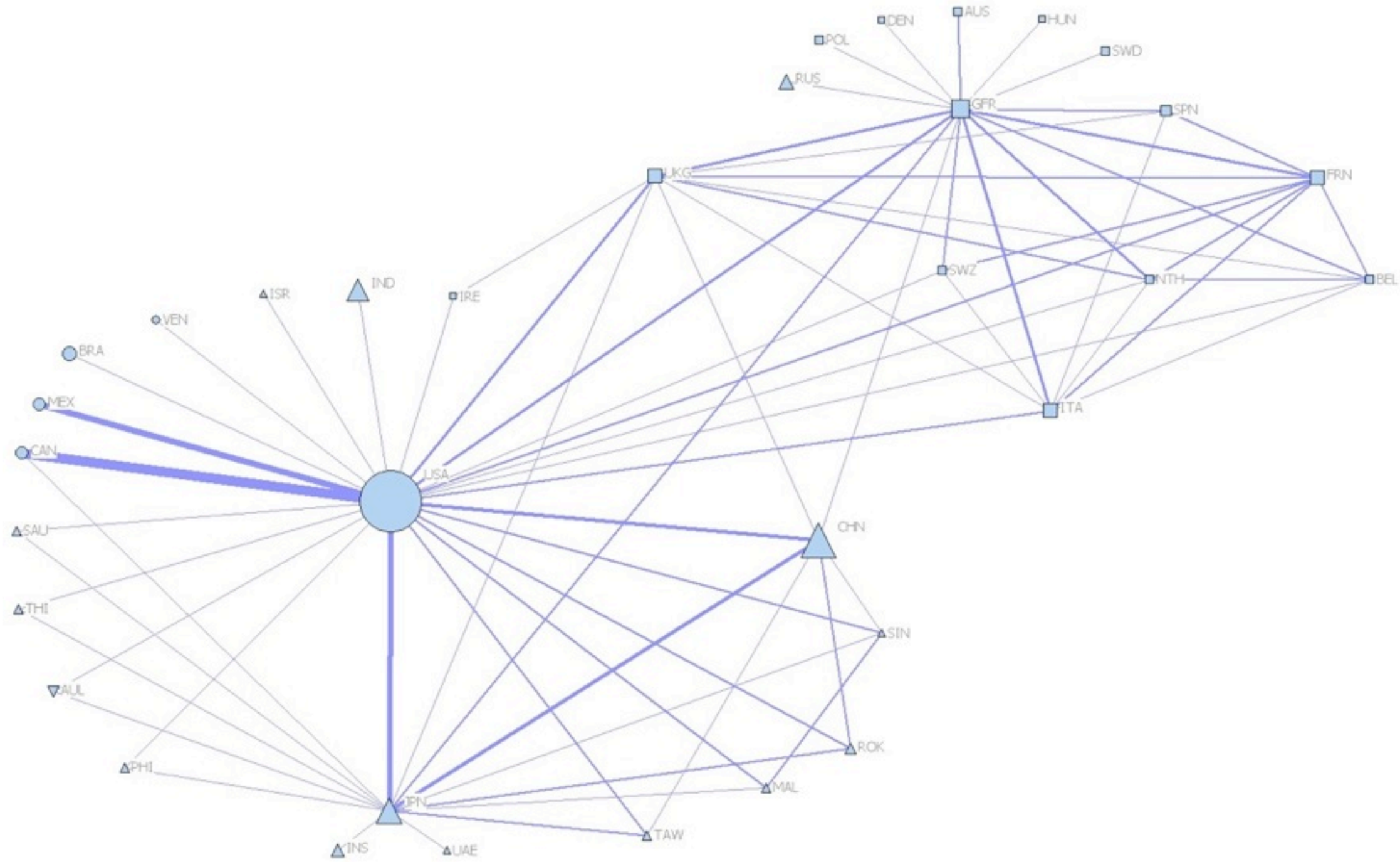
Trade Networks

- International Trade Network (aka World Trade Web): nodes are countries and links represent (product specific) import/export relationships

- Product-Space Network: Nodes are products. Node size is the size of the market for a given product. Links represent similarity between products: similar products are more likely to be exported in tandem.

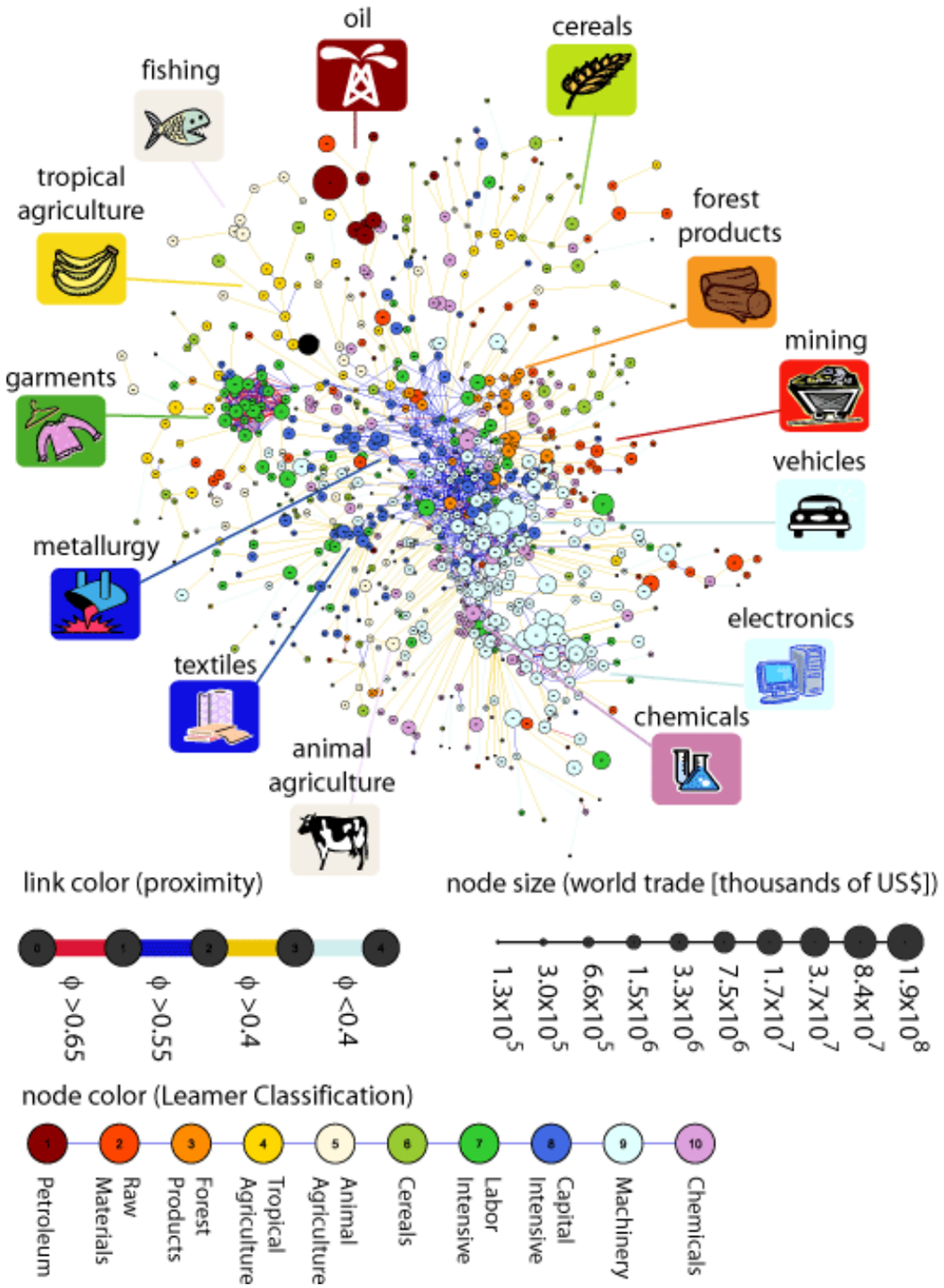
- Trade Agreement Network: Nodes are countries and links represent RTAs (bilateral, multilateral) in force between them at a given point in time.

The International-Trade Network (Year: 2000)



Source: Fagiolo (2010).
Notes: Only largest 1% link weights reported. Node size proportional to country GDP. Node Shape: Continent

The Product-Space Network



- Source: Hidalgo et al. (2007)
- More-sophisticated products are located in a densely connected core whereas less-sophisticated products occupy a less-connected periphery.
- Countries tend to move over time through the product space by developing goods close to those they currently produce.
- Most countries can reach the core only by traversing empirically infrequent distances, which may help explain why poor countries have trouble developing more competitive exports and fail to converge to the income levels of rich countries.

Investment Networks

- Foreign Direct Investment (FDI): Investment of foreign assets into domestic structures, equipment and organizations.
- Main classes: M&A or green-field investment
- FDI: Nodes are countries. Node size is the size of the country. Links represent the value of FDI (M&A or GF, or both) that firms of the origing country do into the target country

Migration and Travel Networks

- Migration data record stock of people born in a given country that are present at a given point of time in another country, disaggregated by nationality, age, gender, etc.

- Data record stocks, not flows... they measure the cumulative effect of migrations, not their actual unfolding process

- Migration network: Nodes are countries. Links are weighted by the number of people born in the origin country and present at a given point in time in the target country

- Travel data: Gathered by World Tourism organizations, measure the flows of people traveling for leisure or business and leaving from any origin country and arriving in any destination country in a given time interval (year)

- Employed to proxy human capital flows in growth exercises

- Travel network: Nodes are countries. Links are weighted by the number of people traveling from originating country and arriving in destination country in a given year.

Financial Networks (I)

- Networks where nodes may be banks, financial institutions, countries, private companies, but also stocks, bonds, and other financial products; and links represent financial relations or correlation between market-behavior indicators

- Interbank network: nodes are banks operating in a certain market and an edge from bank X to bank Y is there if bank X borrows liquidity from bank Y

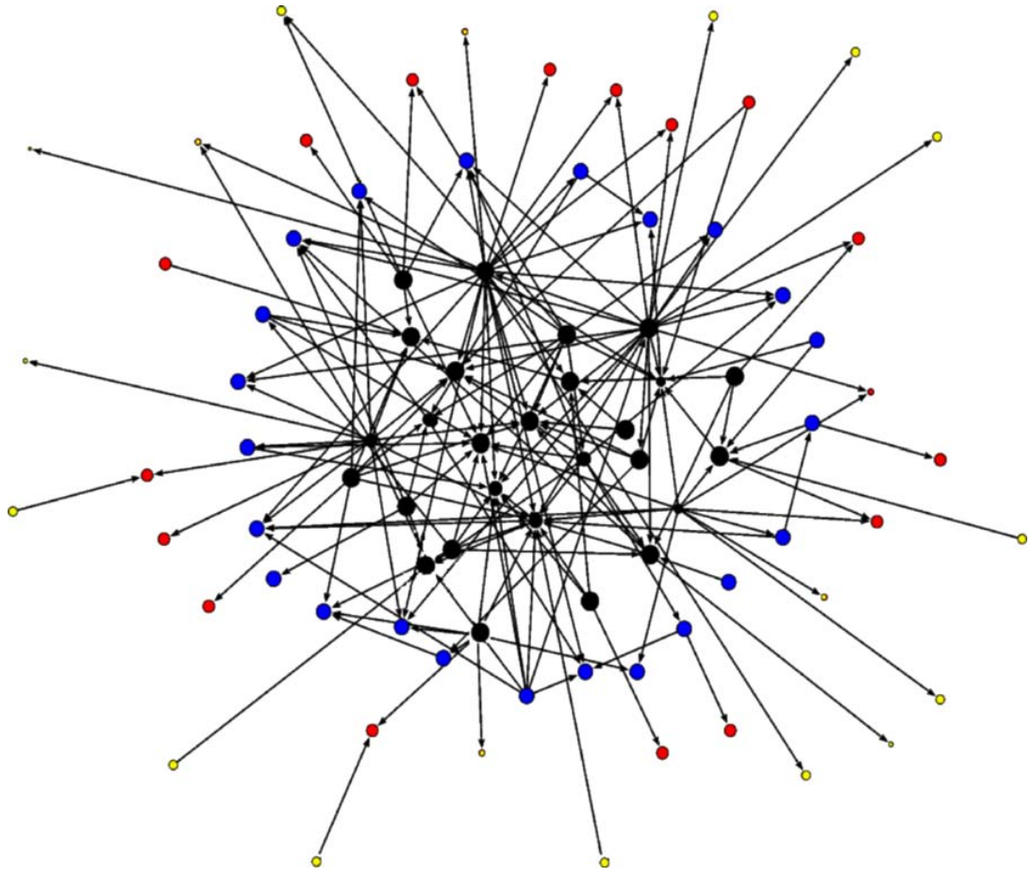


FIG. 1. (Color online) A plot of the interbank network. The group of the vertices (banks) goes from light (group of small banks) to dark (large banks) (the color codes for the various groups are the following: 1=yellow, 2=red, 3=blue, 4=black). Note that the darkest vertices (bank of group 4) form the core of the system.

Source: De Masi, Iori, Caldarelli (2006)

Financial Networks (II)

- Stock ownership networks: nodes are companies or financial institutions traded on a stock market and directed, weighted links indicate that a company owns a portion of the other

- Board of directors and interlocking directorates

- The macro IFN: nodes are countries and links represent debt held by a given country and issued by another country (see Schiavo, Fagiolo, Reyes, 2010, QF)

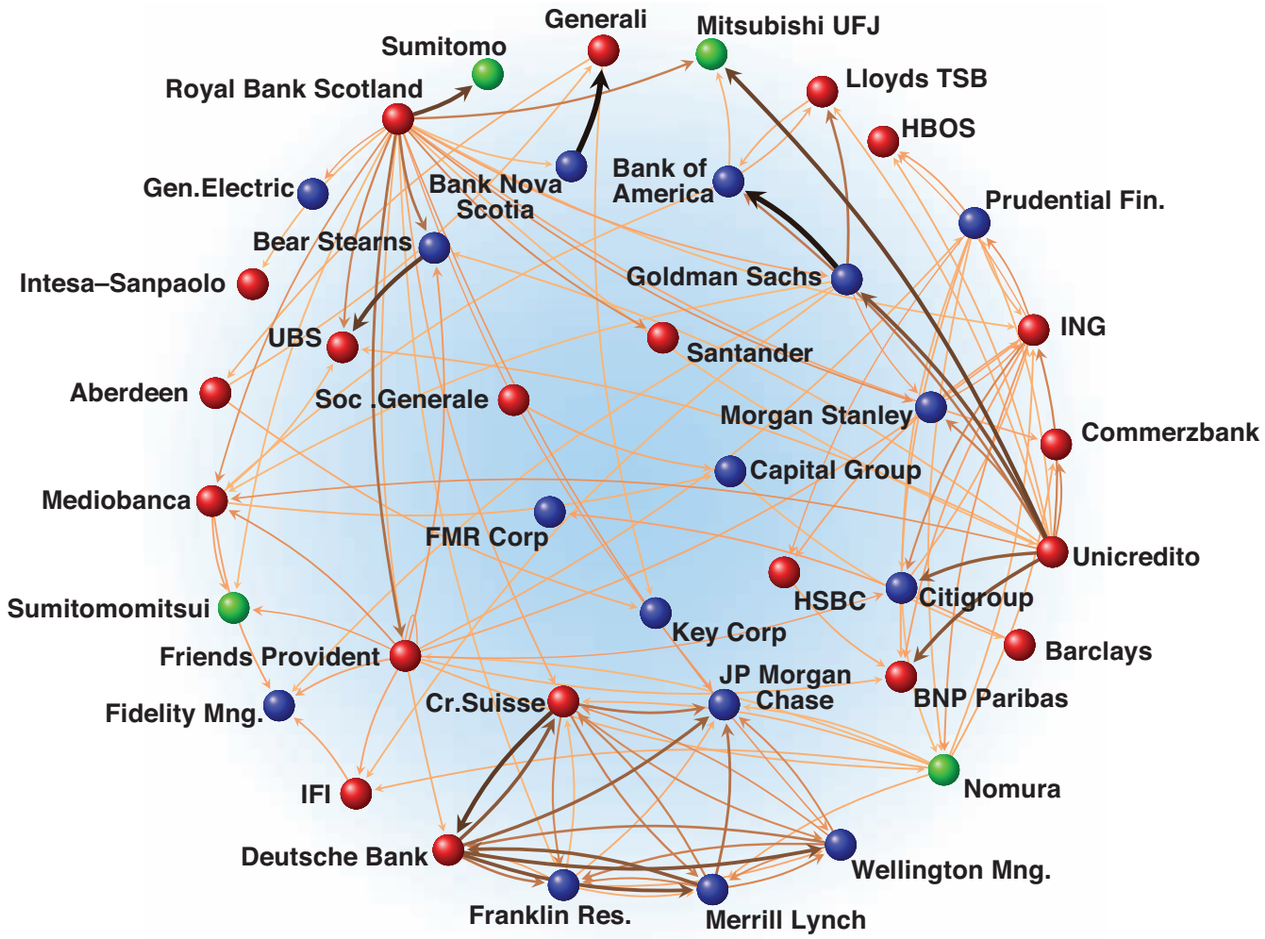


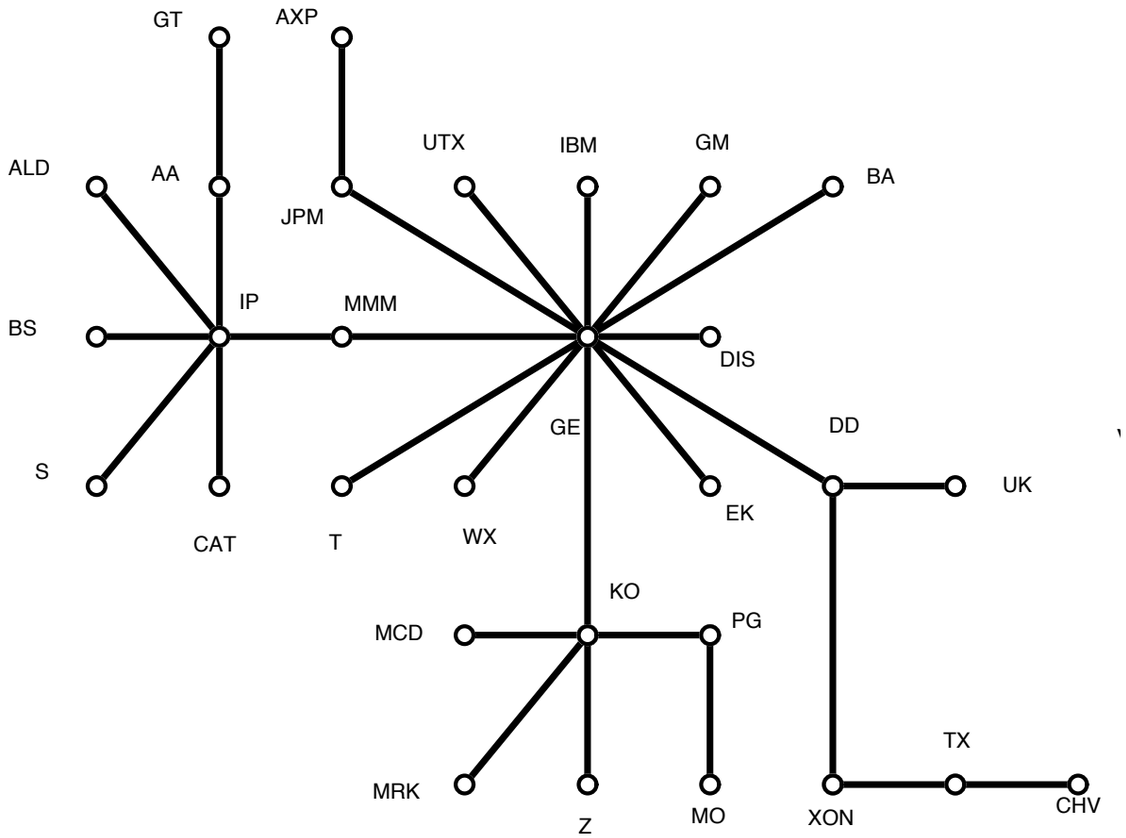
Fig. 2. A sample of the international financial network, where the nodes represent major financial institutions and the links are both directed and weighted and represent the strongest existing relations among them. Node colors express different geographical areas: European Union members (red), North America (blue), other countries (green). Even with the reduced number of links displayed in the figure, relative to the true world economy, the network shows a high connectivity among the financial institutions that have mutual share-holdings and closed loops involving several nodes. This indicates that the financial sector is strongly interdependent, which may affect market competition and systemic risk and make the network vulnerable to instability.

Source: Schweitzer et al. (Science, 2009)

Financial Networks (III)

- Stock-price correlation networks: nodes are stocks quoted e.g. in NYSE or Nasdaq, weighted undirected links represent correlation between logarithmic stock price returns (i.e. variation of log of stock price) over time

- Build a MST: start from max correlation; connect two nodes involved; proceed along the list of correlation values, ranked from highest to lowest until we connect all nodes (no cycles allowed)



Source: Mantegna (1996)

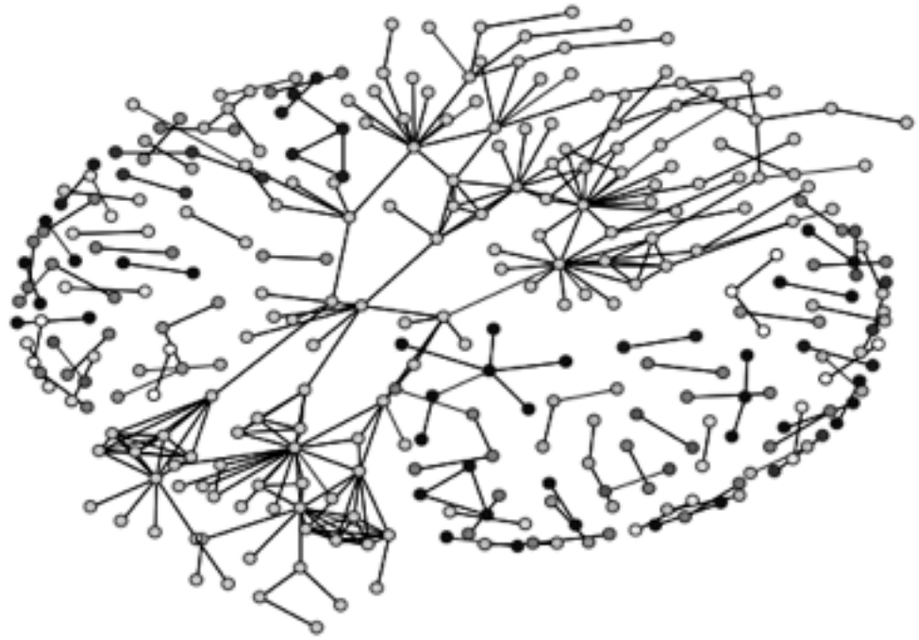
Firm Networks (I)

- Firm strategic-alliance networks: links represent official firm strategic alliances in different industries. The structure of network alliances may affect their potential for knowledge creation

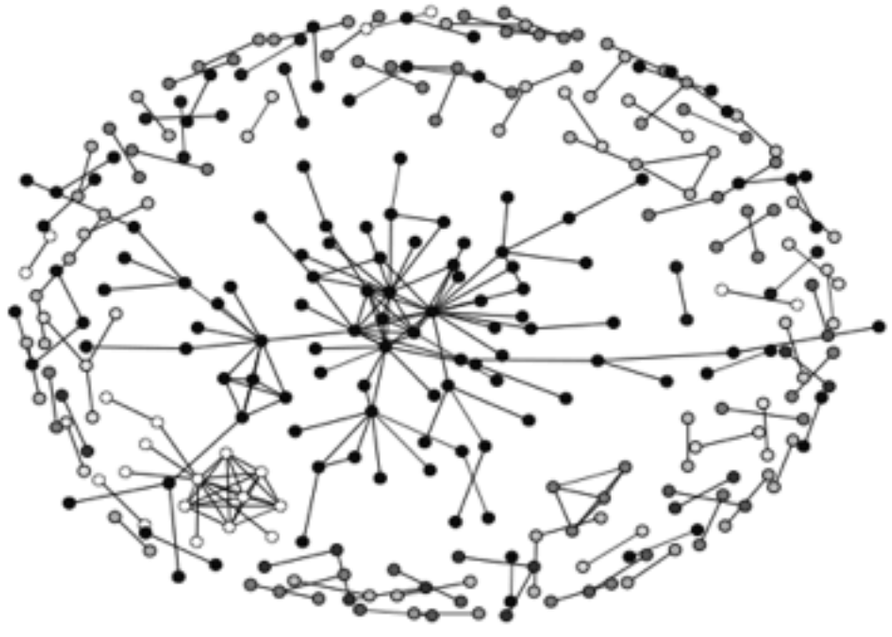
- Other firm networks: ownership and control, who owns who, etc.

Figure 1 **Network Size and Component Structure (Common Shade of Gray Indicates Firms in Same Component)**

Computers, 1996



Computers, 1997



Source: Schilling and Phelps (2007)

Firm Networks (II)

- Knowledge diffusion networks: Nodes are firms in a certain area (e.g. industrial cluster) and links proxies (tacit) knowledge and information exchanged between firms.

- Example: Giuliani (several papers) and the wine industry in Colchagua Valley (Chile)

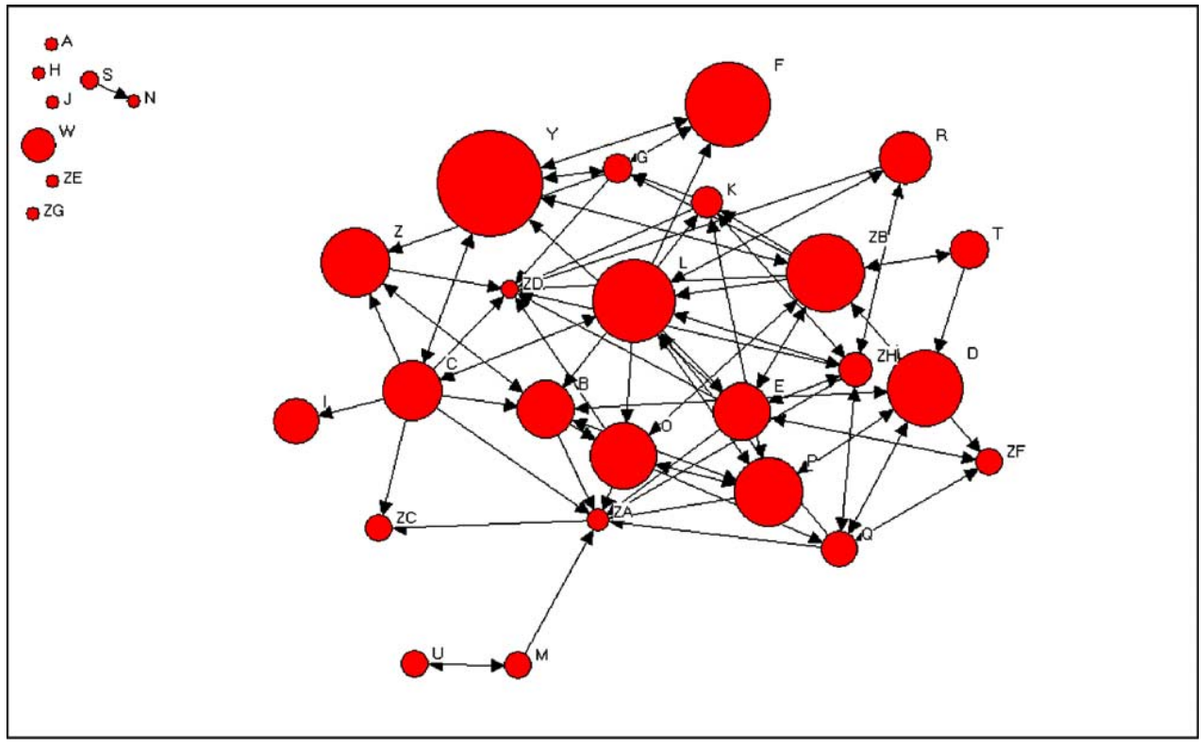


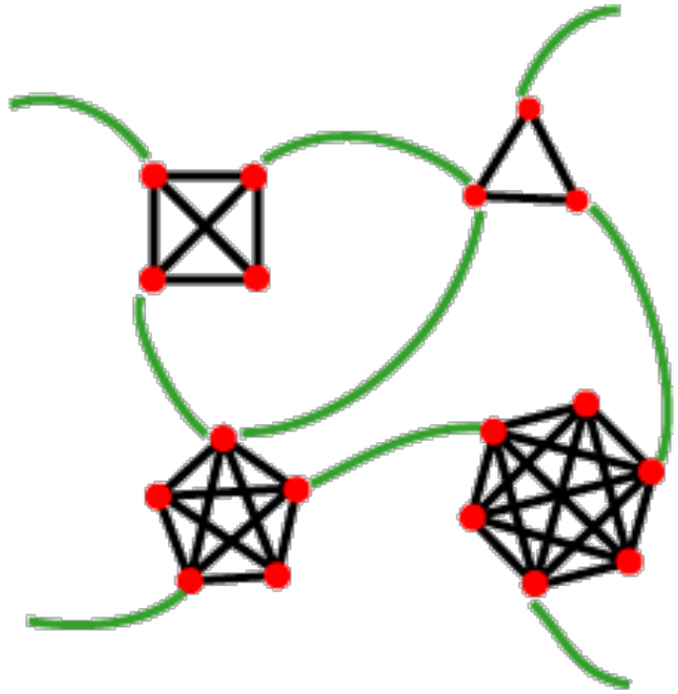
Fig. 1. The local knowledge system in the Colchagua Valley: a graphical representation source: UCINET 6 on author's own data. Note: An arrow from i to j indicates that i transfers knowledge to j. The diameter of the nodes is proportional to firms' absorptive capacity.

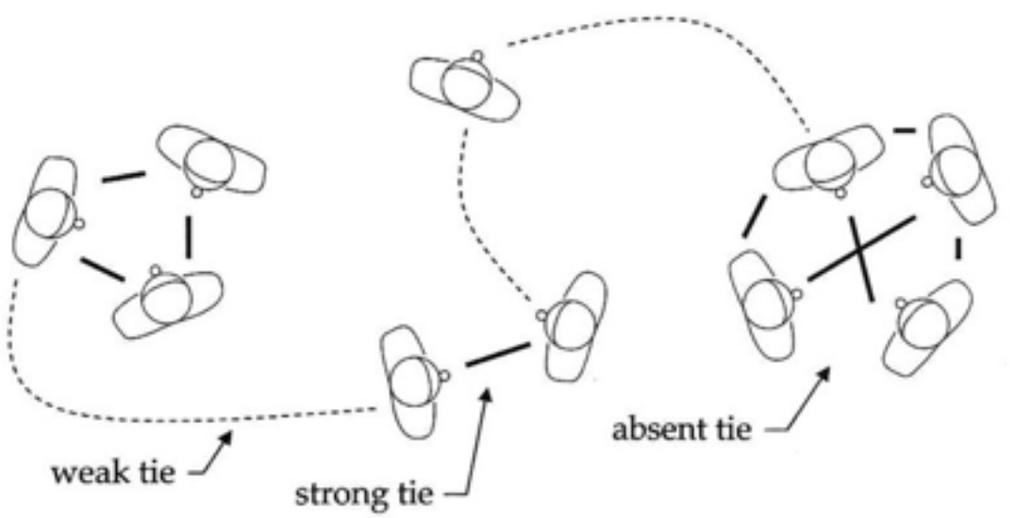
- Inter-firm transaction networks: nodes are firms and directed links represent transactions for goods and services (excluding financial transactions, sales to customers, government and foreign market). Data very difficult to get. Example: Ohnishi et al. for Tokyo, Japan

Labor Market Networks

- Granovetter (1973): the strength of weak ties and the importance of informal contacts in finding employment

- Labor mobility networks: Building (bi-partite) networks using data on establishments at which people work and how do they change in time (data on employer-employee matching data at the establishment level)





Why Networks in Economics

- **Level 1. Data description**: Characterize in a new way economic data, so as to ehnance interaction structure between economic agents

- **Level 2. Explanation**: Write models to explain why the structure of networks looks like it is

- **Level 3. Implications**: Understand empirically or theoretically how the structure of networks may influence what happens over the networks (node behavior)

Level I: Data Description (I)

- Using data about socio-economic relations to build a representation of the system and its dynamics in terms of a time-sequence of networks
- Use graphical tools to visualize the sequence of networks
- Visualization almost always not enough: Compute a set of *ad hoc* network statistics to provide an empirical characterization of the network sequence
- Identify "structural (topological) properties" of the network sequence, i.e. stable and robust statistical properties of network statistics (stylized facts?)

Level I: Data Description (II)

- Can we provide a characterization of network structure and topological properties through a set of network statistics? Which statistics?
- Do different networks exhibit different or similar structural properties? How can we tell if two networks are "different"?
- Are there useful ways to characterize or categorizing networks?
- Are there network "universal" properties characterizing biological, technological, social and economic networks? What if they exist?
- A phenomenological approach...

Level I: Data Description (III)

- How many connections does a node have? Are some nodes more connected than others? Is the entire network connected?
- Are the partners of my partners likely to be very connected on average? Are they connected themselves?
- How much central a node is in the network? Are there nodes more central than others?
- How do networks change through time?
- Are there clusters or groupings within which the connections are particularly strong?

Level 2. Explanation

- Data can help us to understand how real-world networks evolve and how they look like.
- Can we write models of network evolution that are able to reproduce and explain observed network properties?
- Three perspectives:
  - Null models
  - Stochastic network evolution
  - Incentive-based (game-theoretic) models

Level 3: Implications

- Dynamics **of** networks: Do networks properties change over time? What are the long-run properties of such an evolving process? Can we write models to explain how networks evolve and how they got like they are?
- Dynamics **over** networks: Assume to hold fixed the properties of a network. Do different network structures affect the way in which processes going on over networked systems evolve?
- Are the two dynamics coupled?
- **Examples:** Trade and growth, finance and crises spreading, migration and trade, etc.

So...Why Networks in Economics ?

- Networks are about direct interactions: an often-neglected issue in economics: from general equilibrium to game theory
- Network theory: bringing back the focus on interactions
- Hint to economic systems as complex evolving systems
- Consequences for macro models:
  - interactions (and their very structure) do matter...
  - some assumptions (representative-individual, "vacuous" spaces) may be over simplifying ones
  - simple linear representations of economic systems might not always work!

Networks and Econometrics

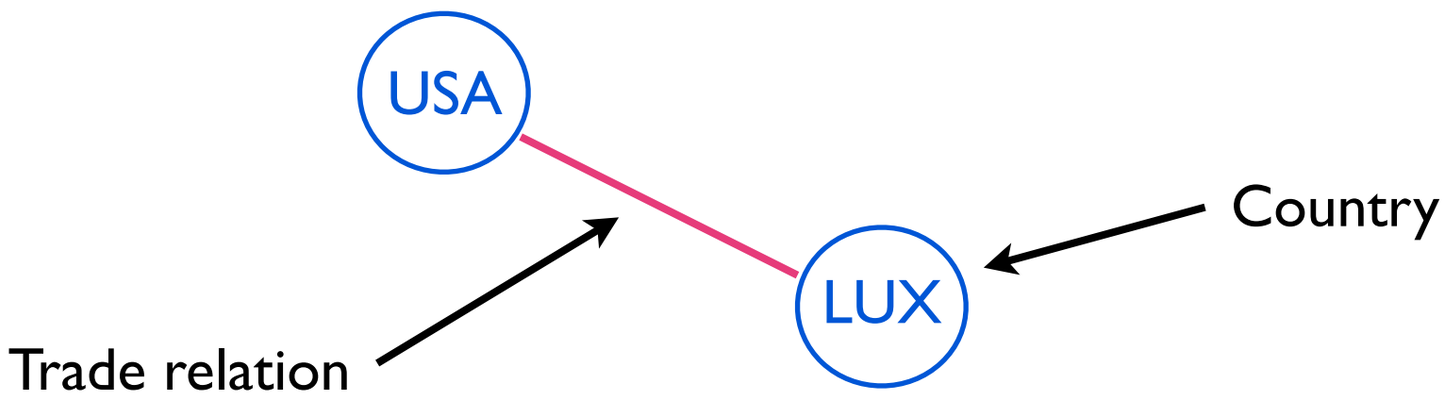
- Does econometrics have any role in network studies? YES
- Detecting the determinants of network properties: fitting econometric models using information on node-specific (non network) properties to explain network properties
- Detecting the implications of network properties: fitting econometric models to predict and understand what is the effect of network properties on node-specific variables
- Endogeneity problem: network structure may influence what is going on at the level of nodes, but the latter may in turn shape network properties. Example: trade and growth.

Running Examples

- International Trade Network (ITN)
- Also:
    - International Financial Network (IFN)
    - International Migration Network (IMN)

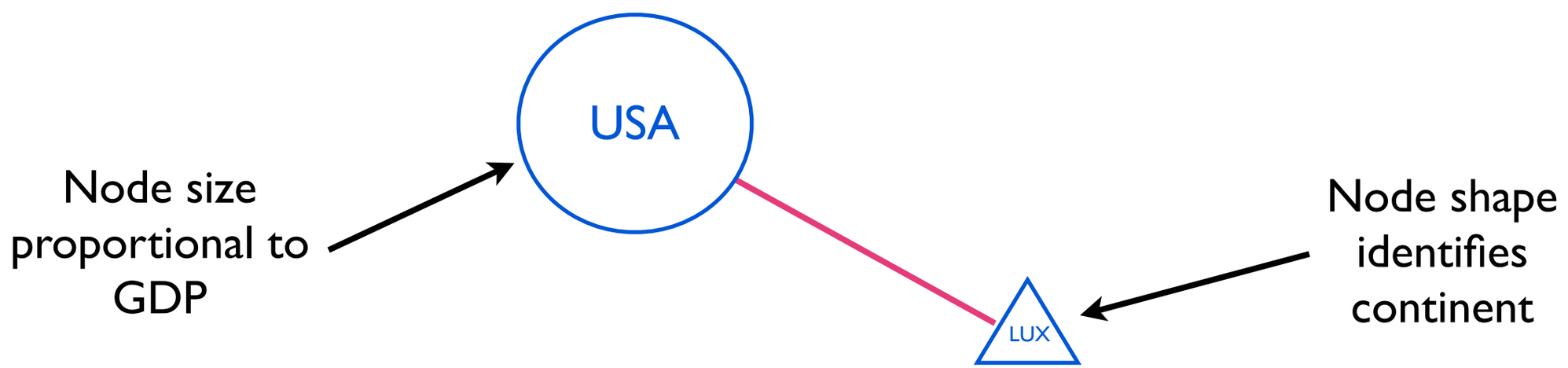
The World-Trade Web (WTW)

- World-Trade Web (WTW) aka Int'l Trade Network (ITN)
- Network representation of international-trade flows among world countries in a given year
- Many years available (1950-2007)
- Countries = nodes
- Links = trade (import/export) relationships



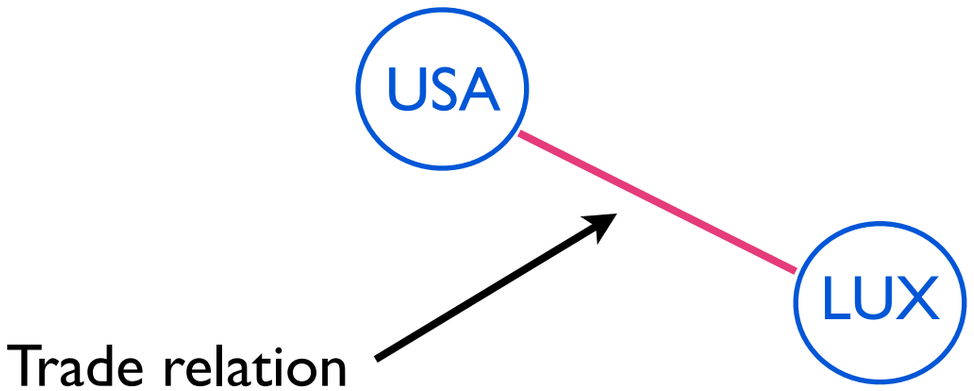
The World-Trade Web (WTW)

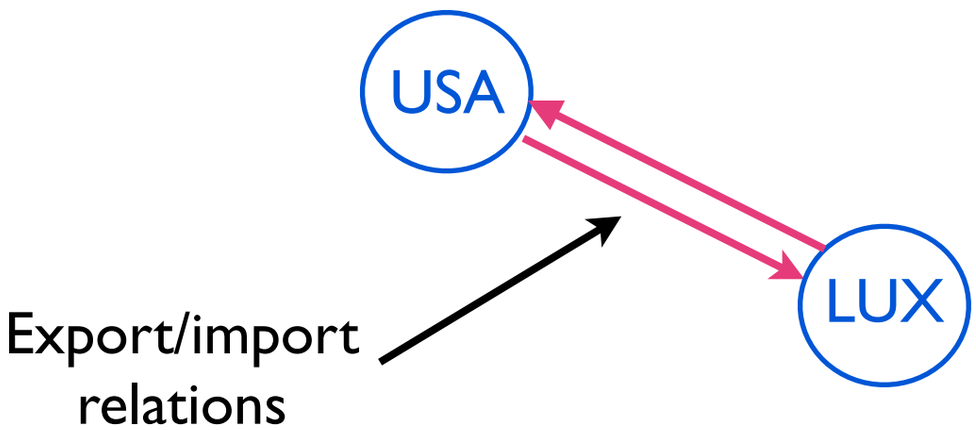
- Main Source: COMTRADE. Many "cleaned" sources available online (Feenstra, Gleditsch, Subramanian & Wei, Rose, baci@cepii, etc.)
- Data: Imports of country i from country j in year t for commodity-class h (HS, SITC)
- Nodes: heterogeneous in their country-specific characteristics (GDP, population, geo position, …)



The World-Trade Web (WTW)

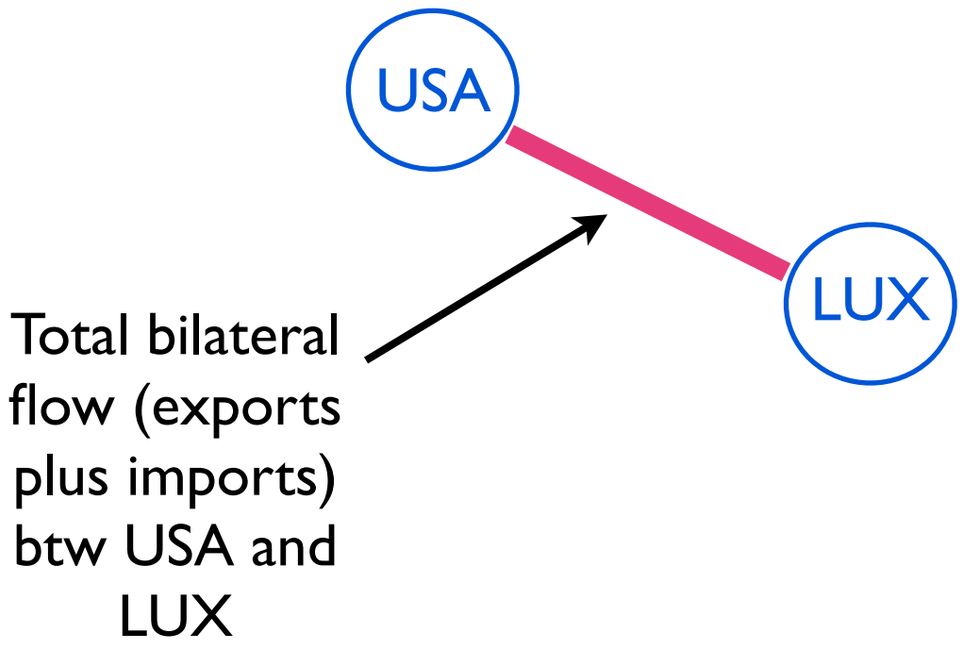
- Links defined as binary trade relationships: existence of non-zero trade flows

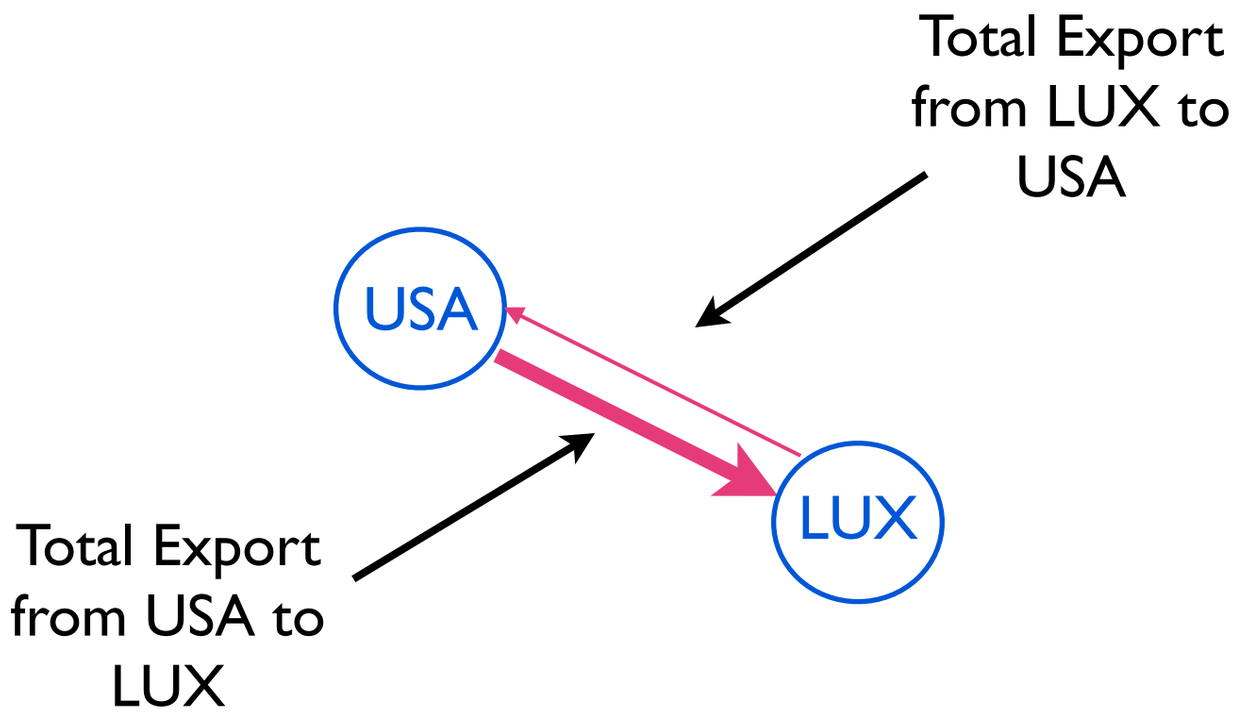




The World-Trade Web (WTW)

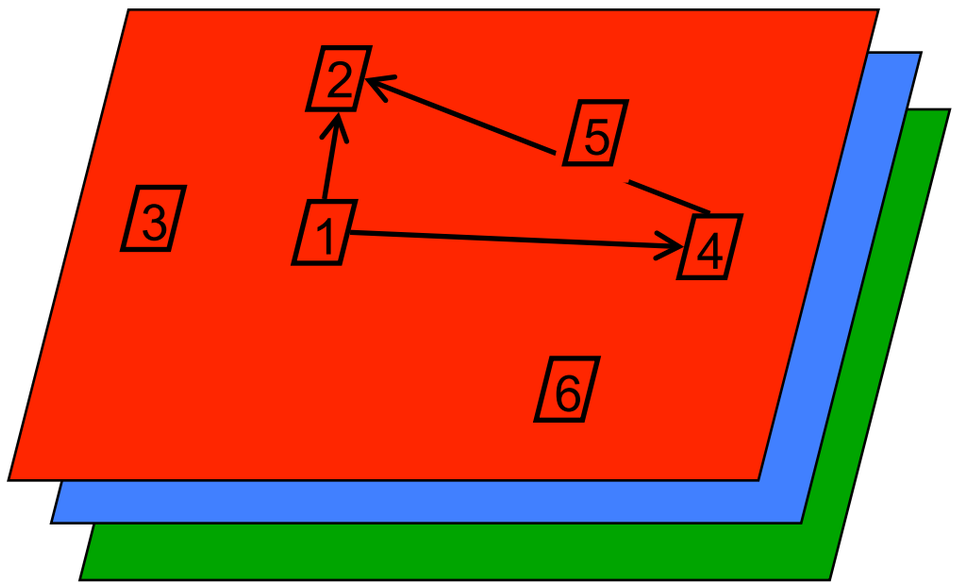
- Link weights defined by total bilateral flows (undirected) or directed import flows (always deflated)



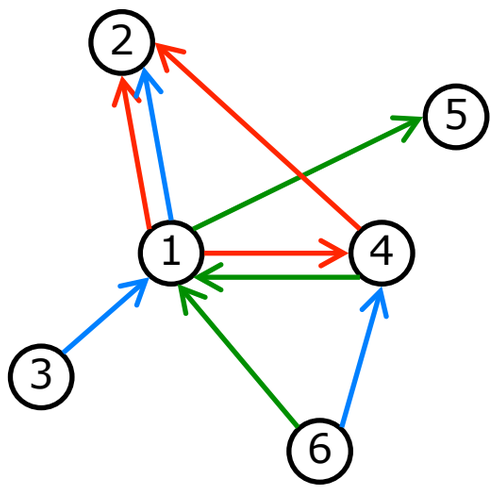


The World-Trade Web (WTW)

- Aggregate vs commodity-specific multi-network



Colors: Commodity-specific networks



Multi-WTW: Union of colored slices

The World-Trade Web (WTW)

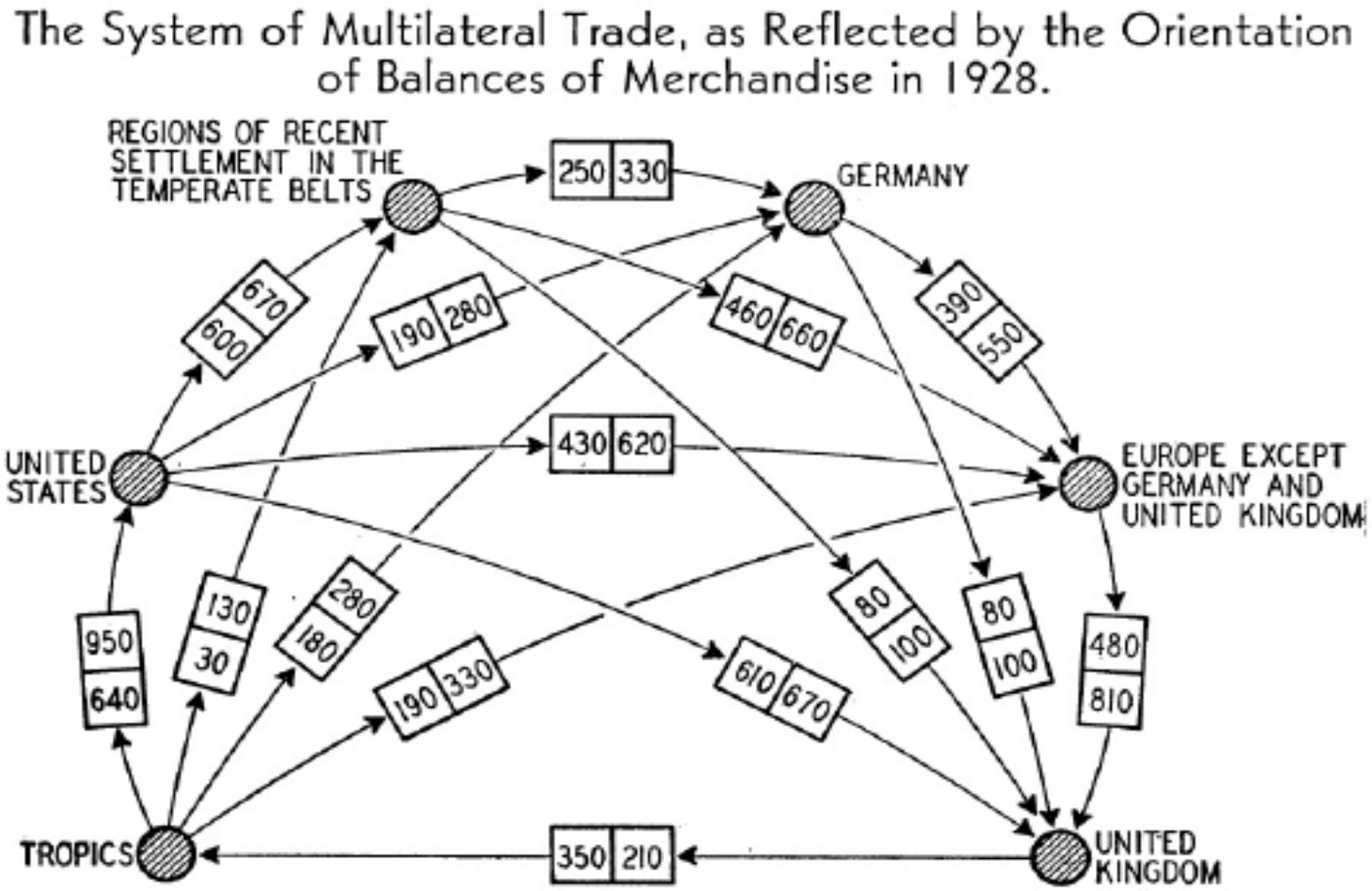


Figure: A natural way of representing international trade is through a network. The figure is from Folke Hilgerdt (1943), "The Case for Multilateral Trade", *American Economic Review*

Source: De Benedictis & Tajoli (2008)

The World-Trade Web (WTW)

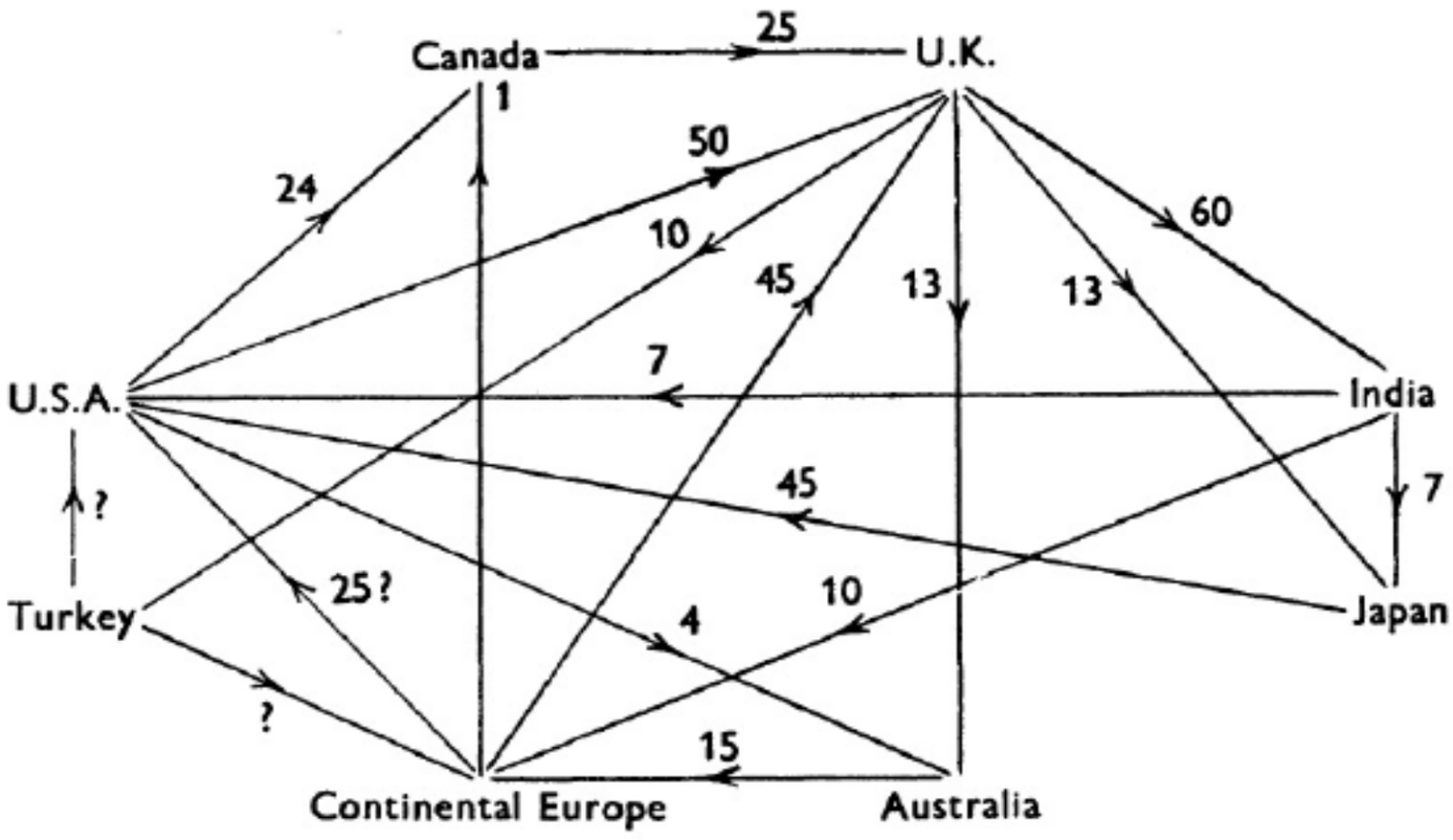
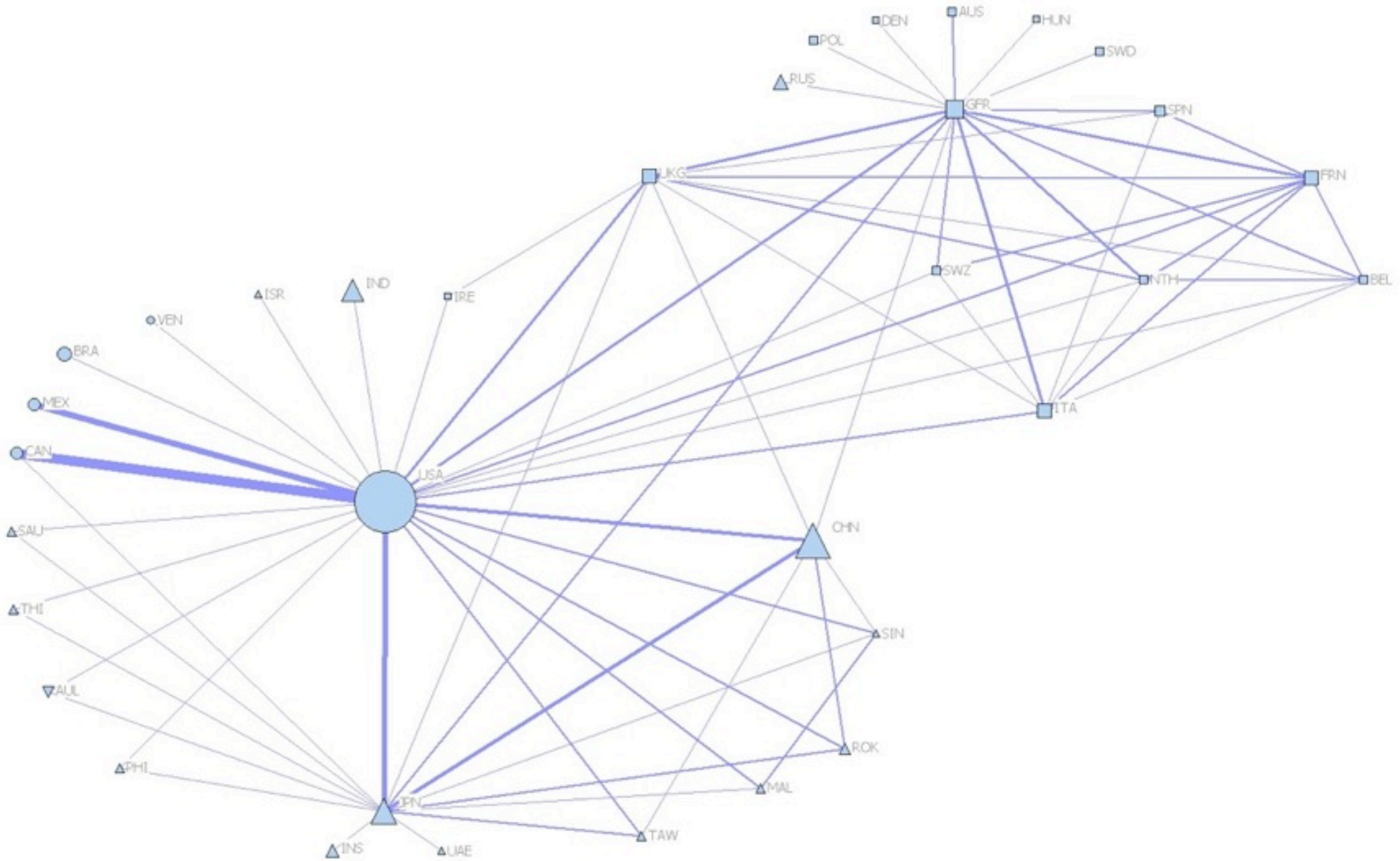


Figure: A natural way of representing international trade is through a network. The figure is from S.B. Saul (1954), "Britain and World Trade: 1870-1914", *The Economic History Review*

Source: De Benedictis & Tajoli (2008)

The weighted-undirected WTW in 2000



Source: Fagiolo (2010).

Notes: Only largest 1% link weights reported. Node size proportional to country GDP. Node Shape: Continent

Why a complex-network approach to int'l trade?

- A different statistical characterization of trade flows emphasizing relations, structure, holistic representation, ... can it add any "fresh" insights on what we already know about int'l trade stylized facts?
- Studying weighted trade paths in the WTW is important as they may proxy interaction channels between world countries (Abeysinghe & Forbes, 2005)
- Topological properties of WTW explain spreading of crises, overall impact of economic shocks; and country-growth dynamics (Kali and Reyes, 2009a,b)

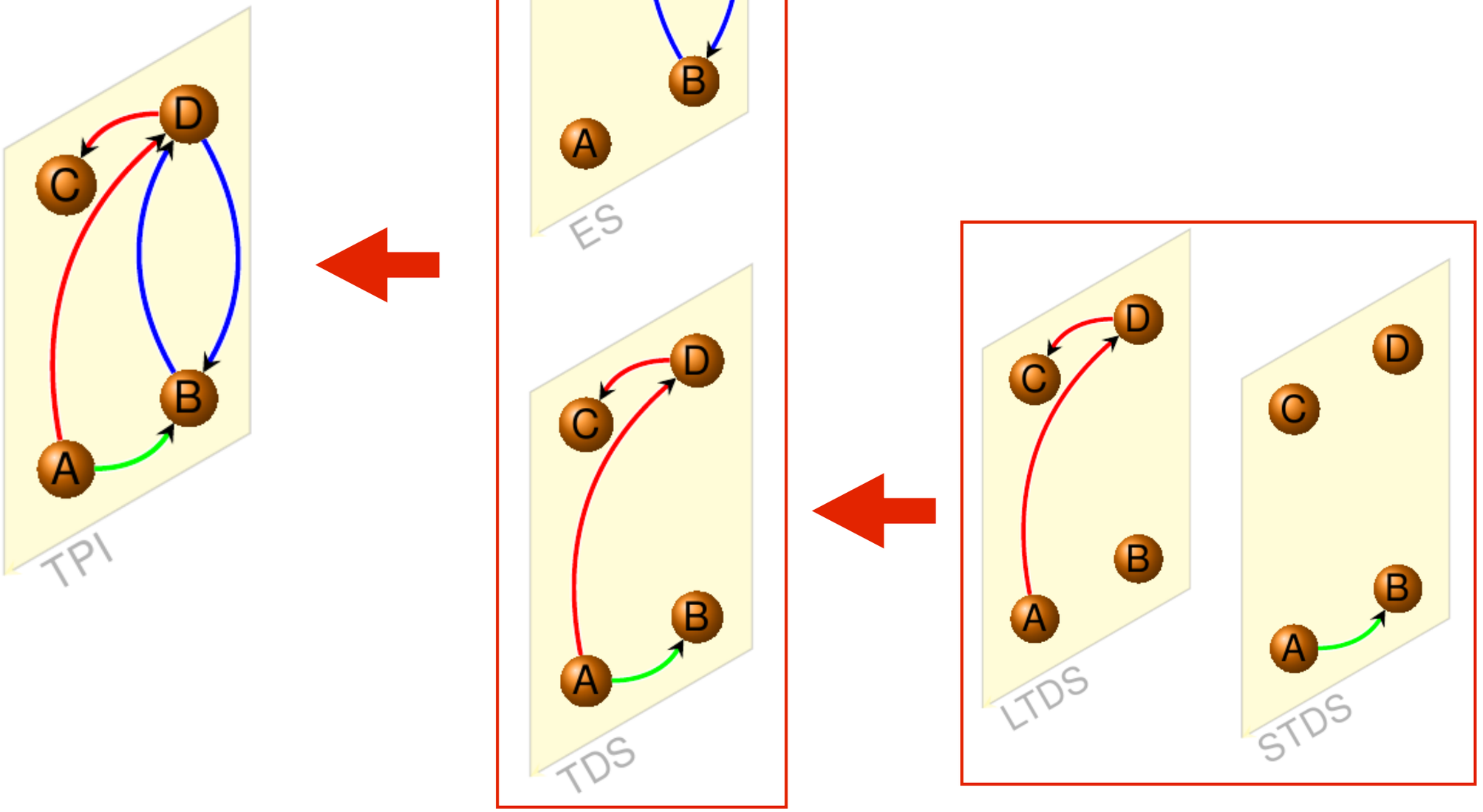
The International-Financial Network (IFN)

- Main source of data: Coordinated Portfolio Investment Survey (CPIS), collected by the International Monetary Found (IMF)
- Data include cross-border portfolio investment holdings of equity securities, long-term debt securities and short-term debt securities listed by country of residence of issuer
- We build a 5-layer weighted-directed multigraph, where each directed link is weighted by the value of security issued by the origin node and held by the target
- We have complete bilateral data for roughly 70 countries for the period 2001–201

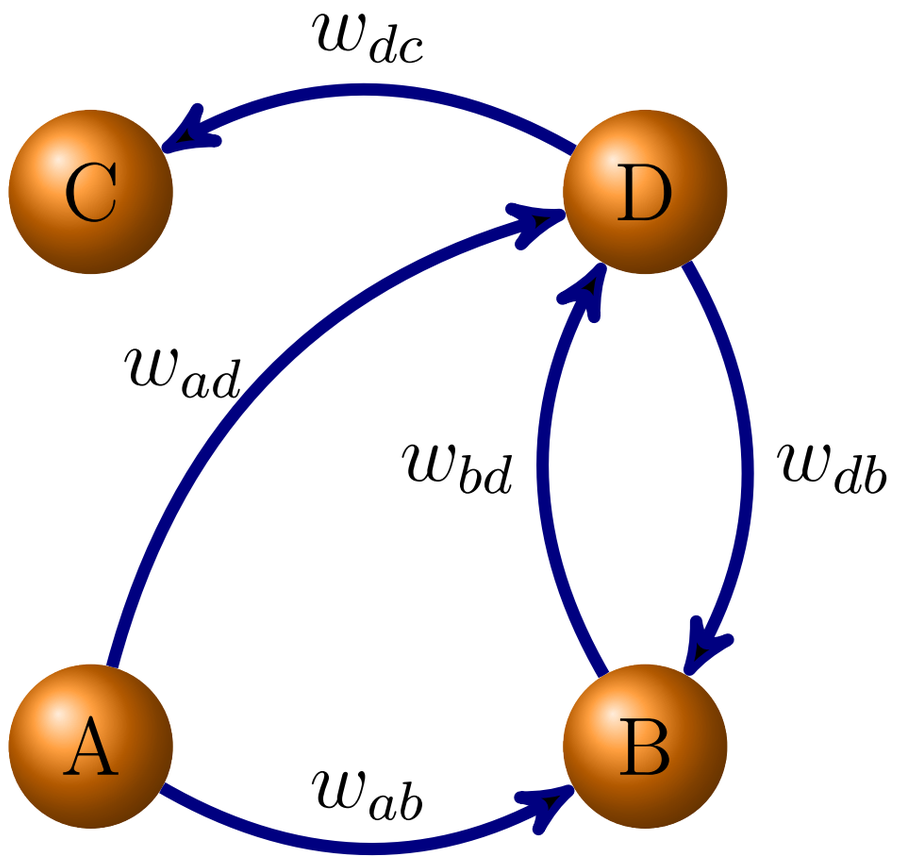
The IFN: What's in the data

- Year's end holdings of securities reported at the economy level, from the asset side (more reliable than liability side)
- Equity, long-term and short-term debt instruments
- Securities held as reserve assets
- Securities held by international organizations
- What's NOT in the data
    - FDIs, Loans, Holdings of domestic securities (issued and held by residents of the same country), Securities acquired under reverse repurchase agreements

The IFN



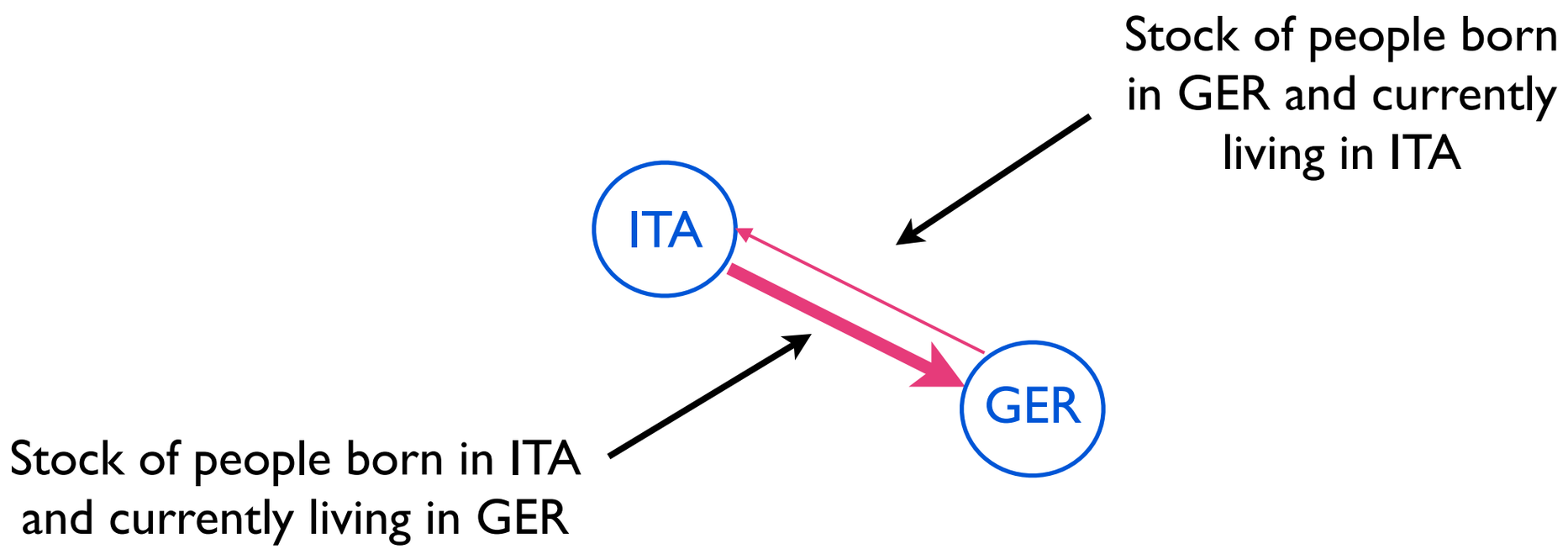
The IFN



Links connect issuing country to security holder. For example, A issues securities held by B and D (i.e. A is a debtor of B and D) where w_{ab} and w_{ad} are the values of such securities in (millions of) current dollars.

The International Migration Network (IMN)

- Nodes are world countries (N=226)
- Link weights represent stock of emigrants (1960-2000)



What's Next

- What is a network? Examples of networks
- Why networks are important for economists?
- Networks and Graphs
- Measures and metrics on networks
- Distributions of metrics and measures in large networks
- Modeling Networks
- Economic applications