

Network Formation Theory and Experiments

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Keynote Talk
EMNET 2013
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Prologue

How behaviour and institutions are affected by social relations is one of the classic questions of social theory. The utilitarian tradition, including classical and neoclassical economics, assumes rational, self-interested behaviour is affected minimally by social relations...

Mark Granovetter (1985)

Economic action and Social Structure

Introduction

Traditionally, economists explain economic phenomena using an approach in which individuals are anonymous and interaction is centralized.

The cornerstone of economic theory

- General equilibrium
- Imperfect competition
- Contracts and transaction costs
- Game theory

reflect these assumptions.

Introduction

This approach has its shortcomings even if we are to restrict attention to traditional questions. The work of [Veblen \(1899\)](#), [Dussenbery \(1949\)](#) and [Rees \(1966\)](#) and [Granovetter \(1974\)](#), highlights this.

But there has been a parallel development in economics, that is probably as important. The scope of the subject is now seen to be much broader than before.

[Michael Sandel \(2012\)](#), *The Moral Limits of Markets*.

Introduction

- **Paul Samuelson (1958)** edition: economics is about the world of *'prices, wages, interest rates, stocks and bonds, banks and credit, taxes and expenditure'*.
- **Greg Mankiw (2004)** : *'there is no mystery about what an 'economy' is. An economy is just a group of people interacting with one another as they go about their lives'*.

But we must be careful here ... for, at the start, we can read:

- **Marshall (1890)**, *'Economics is the study of people in the ordinary business of life'*.

Introduction

The two developments come up against empirical phenomena.

- patterns of diffusion of ideas and products
- contagion/resilience in society, economy, politics
- structure of WWW, Facebook, Twitter
- variations in crime and school performance
- patterns of collaboration among firms
- local clustering and spatial patterns of inequality

Traditional approach is inadequate to address them.

Choice and Structure

The key conceptual innovation has been the idea that

social networks are an outcome of individual actions

This idea, taken in tandem with a number of concepts from across the social and information sciences, creates a powerful new research methodology that has significantly expanded the scope of economics.

Choice and Structure

Over the last two decades, a broad research programme on networks has emerged in economics.

In this lecture my aim is to convey the flavour of this work by taking two examples

- Start with empirics,
- Build a theory and develop predictions
- Test the theory in experiments
- Open issues

Choice and Structure: approaches

Formation of networks is complicated process and subject to a variety of technological, economic and social forces.

- Mathematics: [Erdos-Renyi \(1950's\)](#)
- Sociology: [Doreian and Stokman \(2001\)](#), [Snijders \(1996\)](#)
- Computer science: [Papadimitrou et al \(1999\)](#)
- Physics: [Barabasi \(2002\)](#), [Watts \(1999\)](#)

Network formation: economic approach

- The distinctive feature of an economic approach is human agency: preferences, costs/benefits and externalities.
- Early work on economic approach: [Boorman \(1975\)](#), [Aumann and Myerson \(1988\)](#) and [Myerson \(1991\)](#).

General Framework:

- [Goyal \(1993\)](#), [Bala and Goyal \(2000, Econometrica\)](#)
- [Jackson and Wolinsky \(1996, Journal of Economic Theory\)](#)

The structure of networks

- A network describes a collection of nodes and the links between them.
- Once you begin to study networks it is difficult not to see them everywhere.
- Examples include: Internet, World wide web, airline networks, friendships, research alliances, co-authorships, trade and exchange.

The Law of the Few: empirics

The classical early work of Lazarsfeld, Berelson, and Gaudet (1948) and Katz and Lazarsfeld (1955) investigates the impact of personal contacts and mass media on voting and consumer choice. They found

- *Personal contacts a dominant role in sharing information.*
- *20% of sample of 4,000 source of information for the rest.*
- *Minor differences between influencers and others.*

Adar and Huberman (2001): *similar patterns in online networks.*

Law of the Few: empirics

- Zhang, Ackerman and Adamic (2007) study the Java Forum, an online community of users who ask and respond to queries concerning Java.
- They identify 14,000 users
- 55% users only ask questions,
- 12% both ask and answer queries,
- 13% only provide answers.

The Law of the Few

- A summary of these empirical findings: in social groups, a majority of individuals get most of their information from a very small subset of the group, viz., *the influencers*.
- There are minor differences between the observable economic and demographic characteristics of the influencers and the others.
- **Key question:** *can the law of the few be understood as a consequence of strategic interaction among identical individuals?*

The Law of the Few: theory

Galeotti and Goyal (2010, AER): Individuals acquire information and form links with others to access their information.

- Information is valuable. It can be bought at cost $c > 0$.
- Individuals can form bilateral links with others to access their information. A link costs $k > 0$.
- Information bought by different individuals is a substitute.
- Payoff function for person:

$$f(a_i + \sum a_j) - ca_i - k(\# \text{ links})$$

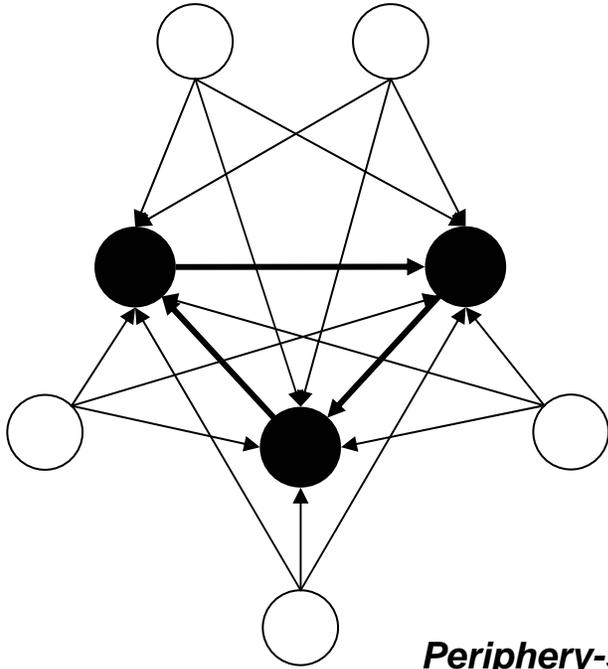
- Function f is increasing and concave. Define $f'(x) = c$.

Law of the Few: theory

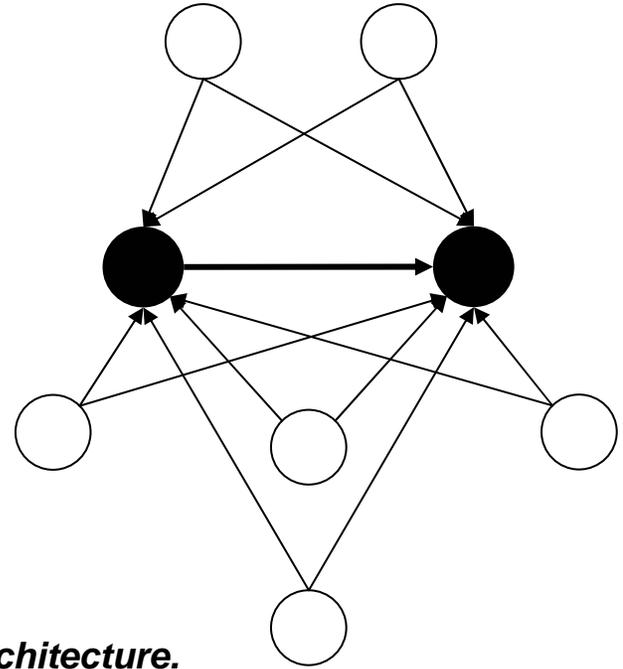
THEOREM (Galeotti and Goyal, 2010)

- *Every equilibrium exhibits law of the few.*
- *The network has a core-periphery architecture*
- *The players in the core acquire information personally*
- *Peripheral players buy no information but form links and get information from core players.*
- *Fraction of core players is small in large society.*

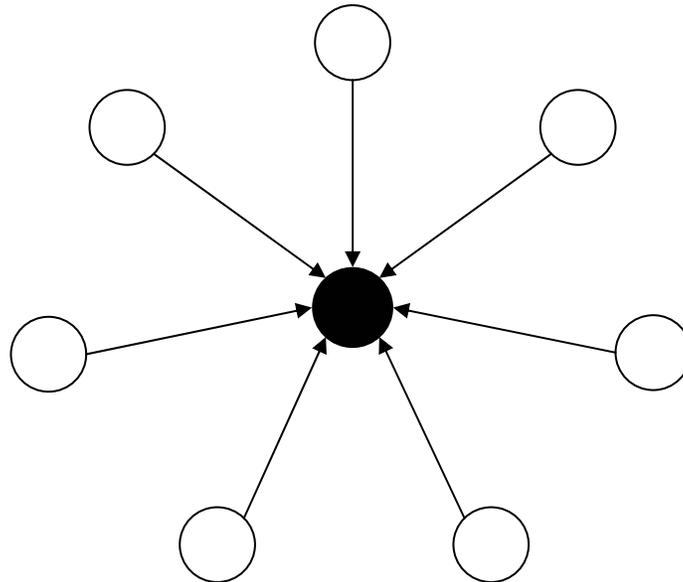
Core-periphery architecture with 3 hubs.



Core-periphery architecture with 2 hubs.



Periphery-sponsored star architecture.



Law of the Few: intuitions

Intuition:

1. Value of information increasing but concave: marginal cost=marginal return at 1.
2. Information acquired by individuals is substitutable. If Mr. A acquires information on his own and from Mr. B then must access 1.
3. Links are costly: Mr. A links with Mr. B then so must everyone else. Information acquirers fully linked. Aggregate information is 1.
4. Upper bound: Mr. A forms a link with Mr. B only if there is minimum information. Upper bound to number of information acquirers.
5. Core-periphery network: aggregate information is 1, so everyone who does not buy information must be linked to everyone who does.

Law of the Few: theory

Implications for welfare?

- Links are costly: for any fixed total information available it is best to minimize links. **Star with hub acquiring all information is efficient network.**
- In equilibrium, the hub sets marginal cost=marginal benefits: **systematic under-provision of efforts.**

Law of the Few: experiment

- *Number of recent experiments:*
 - Goyal, Rosenkranz, Weitzel and Buskens (2013)*
 - Van Leeuwen, Offerman and Schram (2013)*
 - Rong and Houser (2012)*
- Van Leeuwen et al (2013): Design has a 2x2 format. The first set of experiments considers effects of group size: 4 vs. 8
- The main finding: *equilibrium is played rarely: 20% of cases.*
- *No large group size effects*

Law of the Few: experiment

- Suppose that a fraction of linking costs are transferred to receiving agent: costs are 20, 12 transferred to link receiver
- In repeated game, a player who invests a lot in the earlier stages is rewarded with links/transfers, in later rounds.

Finding:

- *Subjects play stage equilibrium in 75% cases with group 4, 20% in group 8. Star network arises in 75% cases.*
- *Core agent chooses in line with stage game prediction in the group 4, but chooses close to the first best level, in group 8.*
- In group 8, agents jockey for core position by making large investments. One agent emerges as core player.
- Consistent with equilibrium play in repeated game.

Law of Few: experiment

General Message:

- *In basic game, hub player earns less than spokes.*
- *Subjects do not play star network. Inequity aversion?*
- *In new game with transfers, hub player earns more than spokes.*
- *Transfers facilitate the emergence of stable star and induce large investments, which approximate first best outcomes.*

Networks of Collaboration

- Leading firms in hi-tech industries rely on a combination of in-house and collaborations. Biotech, pharmaceuticals, IT.
- Hagedoorn (2004) shows
 1. Firms in non-exclusive & extensive relations.
 2. Research alliances have grown over time
 3. Especially prominent in high technology sectors.
 4. Core-periphery network architecture.

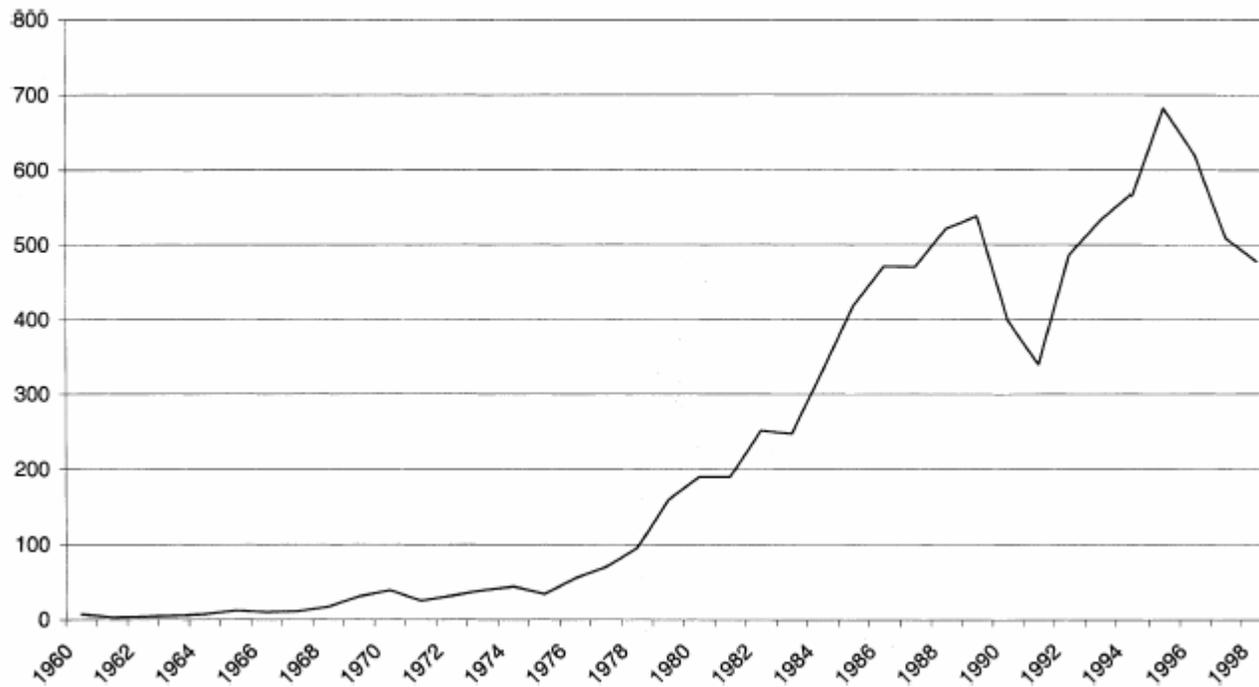


Fig. 1. The growth of newly established R&D partnerships (1960–1998).



Fig. 2. The share (%) of joint ventures in all newly-established R&D partnerships (1960–1998).

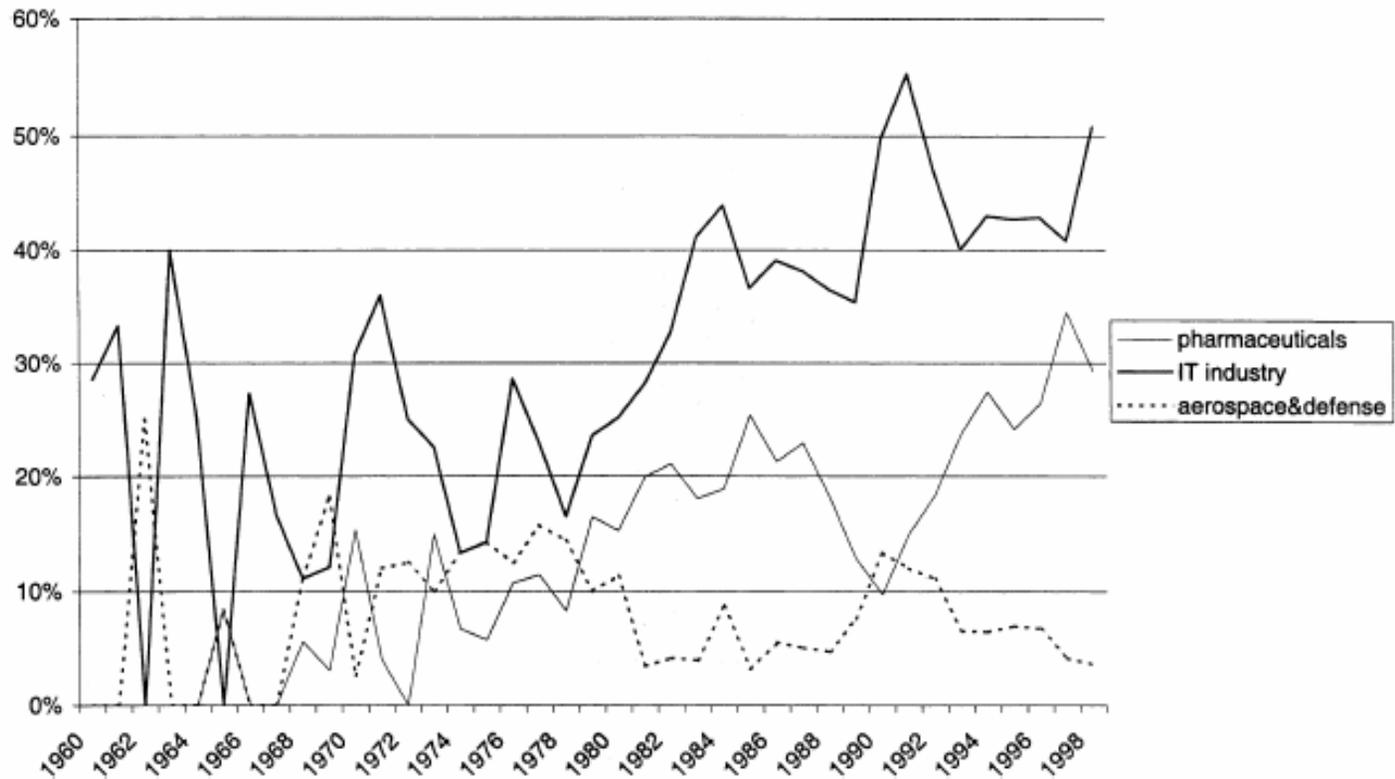


Fig. 4. The share (%) of high-tech industries in all newly established R&D partnerships (1960–1998).

What is the shape of the R&D network? Consider the pharma/biotech industry (Recombinant Data base).

1. *Core-periphery*: Dense network between top 12 pharma. and 12 biotech firms, each firm has a tie with over 15 out of the 23 other firms!

2. *Small world*: Top 24 firms have ties with 1308 other firms, and these firms have 11,303 ties (90% of all ties). Ties involve over 3420 firms (80% of all firms).

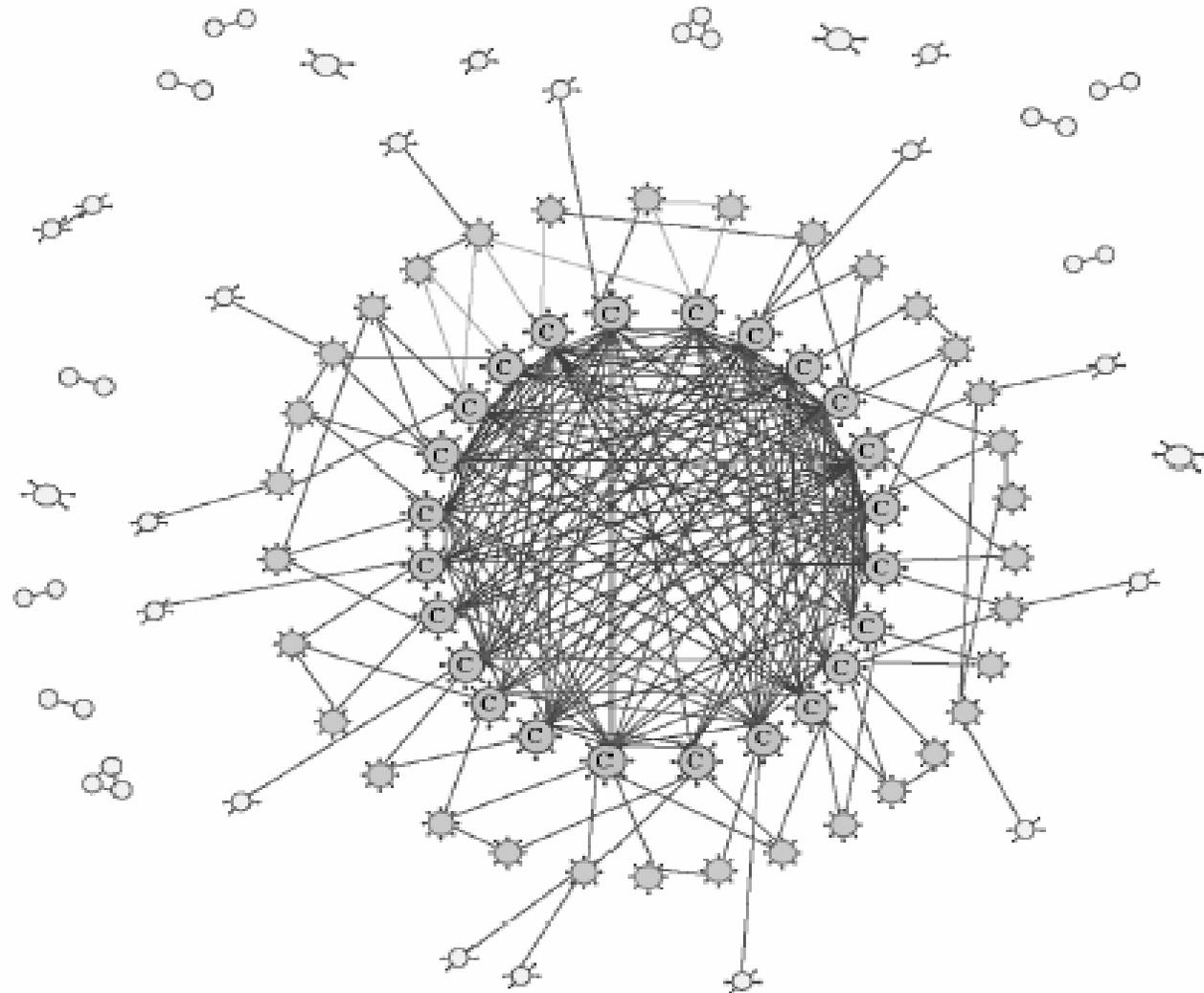
Similar patterns observed in internet and automobile sector.

Table 1**Pharmaceutical and Biotech Firms Most Active in Strategic Alliances, 1973-2001**

<i>Panel A</i> <i>Top 12 Pharmaceutical Firms</i>	Number of Contracts	Number of Partners	Pharma Partners	Biotech Partners	Partners in Top 24
1. GlaxoSmithKline (GSK)	373	248	11.7%	58.5%	20
2. Pharmacia (PHA)	370	271	12.2%	44.1%	21
3. Pfizer (PFE)	287	194	14.4%	57.7%	19
4. Novartis (NVS)	230	167	16.2%	54.5%	18
5. Elan (ELN)	228	153	22.2%	38.6%	14
6. Hoffmann-La Roche (HLR) ^a	224	164	11.7%	62.0%	17
7. Johnson & Johnson (JNJ)	212	170	16.5%	37.6%	16
8. Abbott (ABT)	201	174	13.3%	49.7%	14
9. American Home Products (AHP)	175	124	21.0%	56.5%	19
10. Lilly (LLY)	164	132	13.6%	62.9%	16
11. Merck (MRK)	164	118	16.1%	58.5%	16
12. Bristol-Myers Squibb (BMY)	150	128	10.9%	57.8%	15

Figure 2

Networks in Recombinant Capital Database of Pharmaceutical-Biotech Alliances



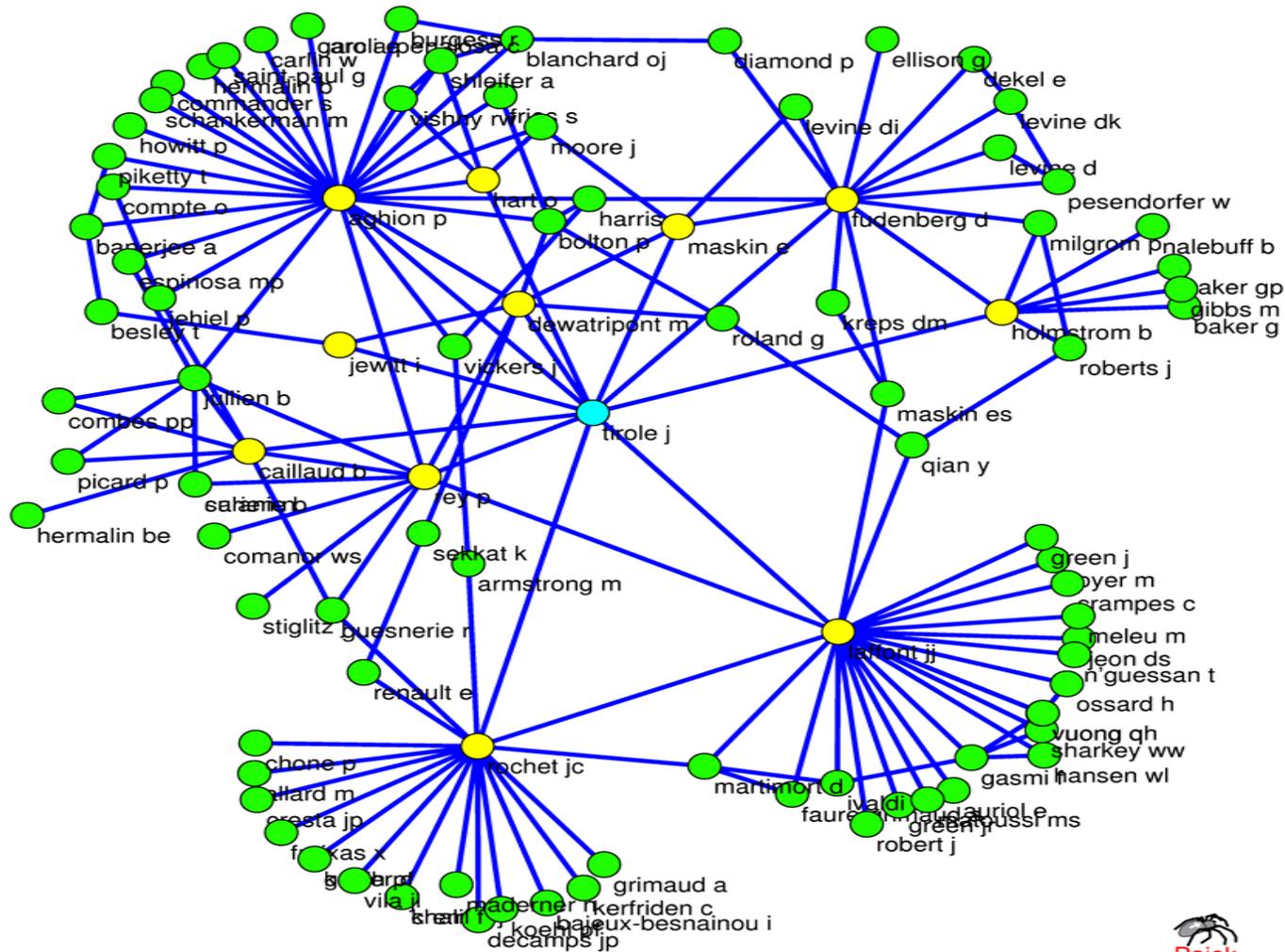
1. The architecture of collaboration

- **ECONOMICS CO-AUTHORSHIP:** *Goyal, van der Leij and Moraga* (2006) found that in 1970-2000 period:

1. Number of economists doubled: 33K to over 80K.
2. The average network distance declined from 12 to 9.
3. The key to the short average distances: economics is spanned by a collection of ***inter-linked stars***.

A star is an economist who writes with many other economists, most of whom have few co-authors and generally do not write with each other.

Local network of J. Tirole in 1990's



Note: Some economists might appear twice or are missing due to the use of different initials or misspellings in EconLit.

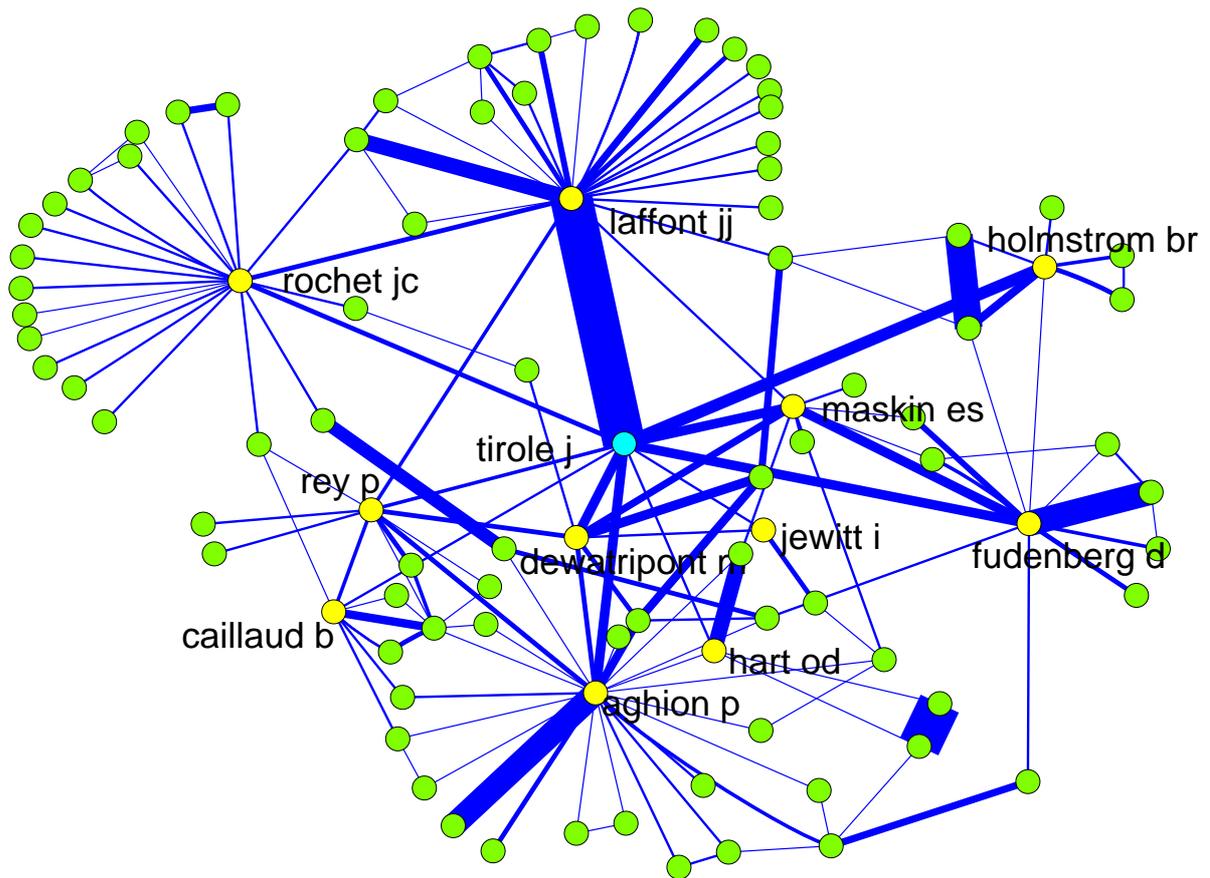
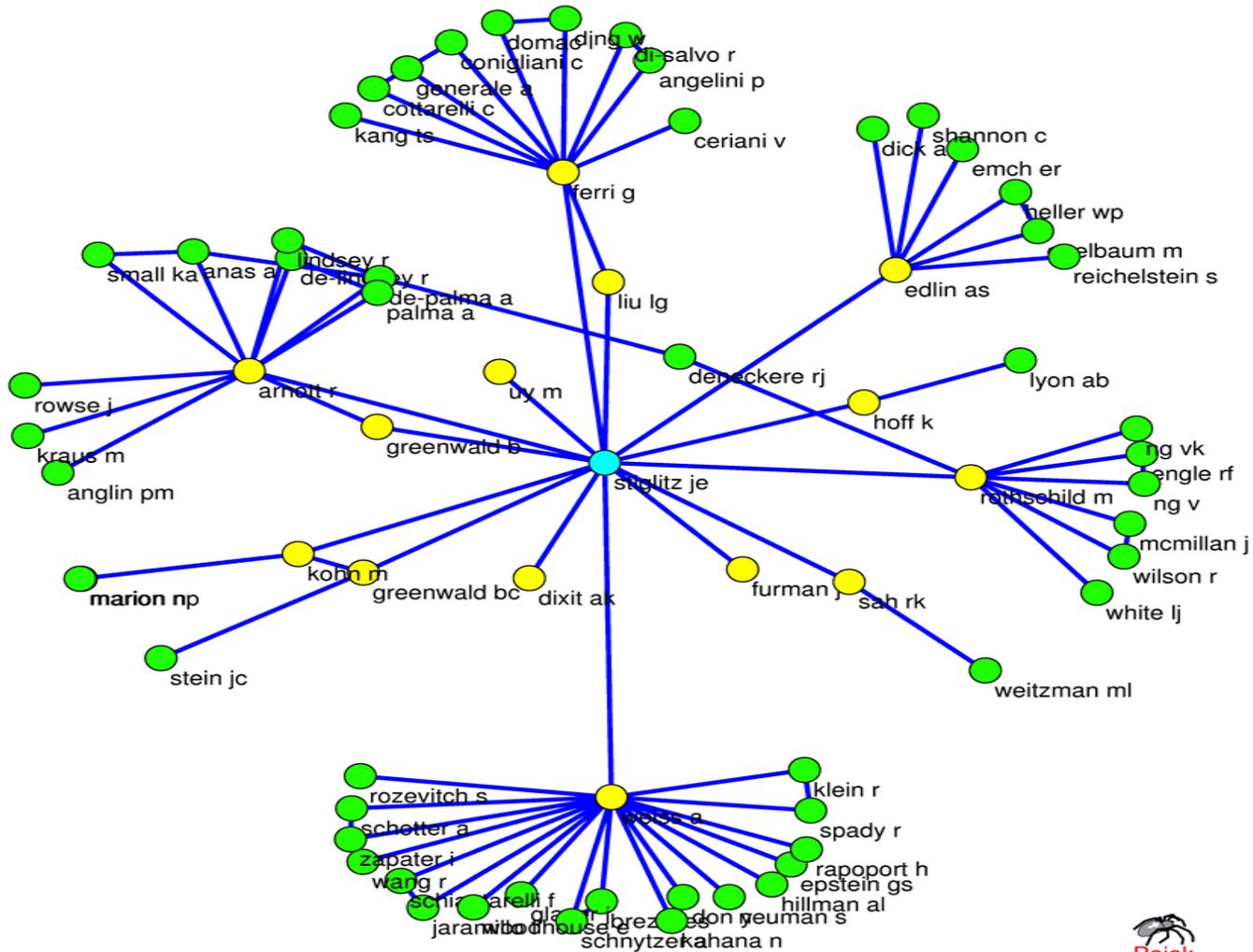


Figure 2: Local network of collaboration of Jean Tirole in the 1990s.

Note: The figure shows all authors within distance 2 of J. Tirole as well as the links between them. The width denotes the strength of a tie. Some economists might appear twice or are missing due to the use of different initials or misspellings in EconLit. The figure was created by software program *Pajek*.

Local network of J. Stiglitz in 1990's



Note: Some economists might appear twice or are missing due to the use of different initials or misspellings in EconLit.

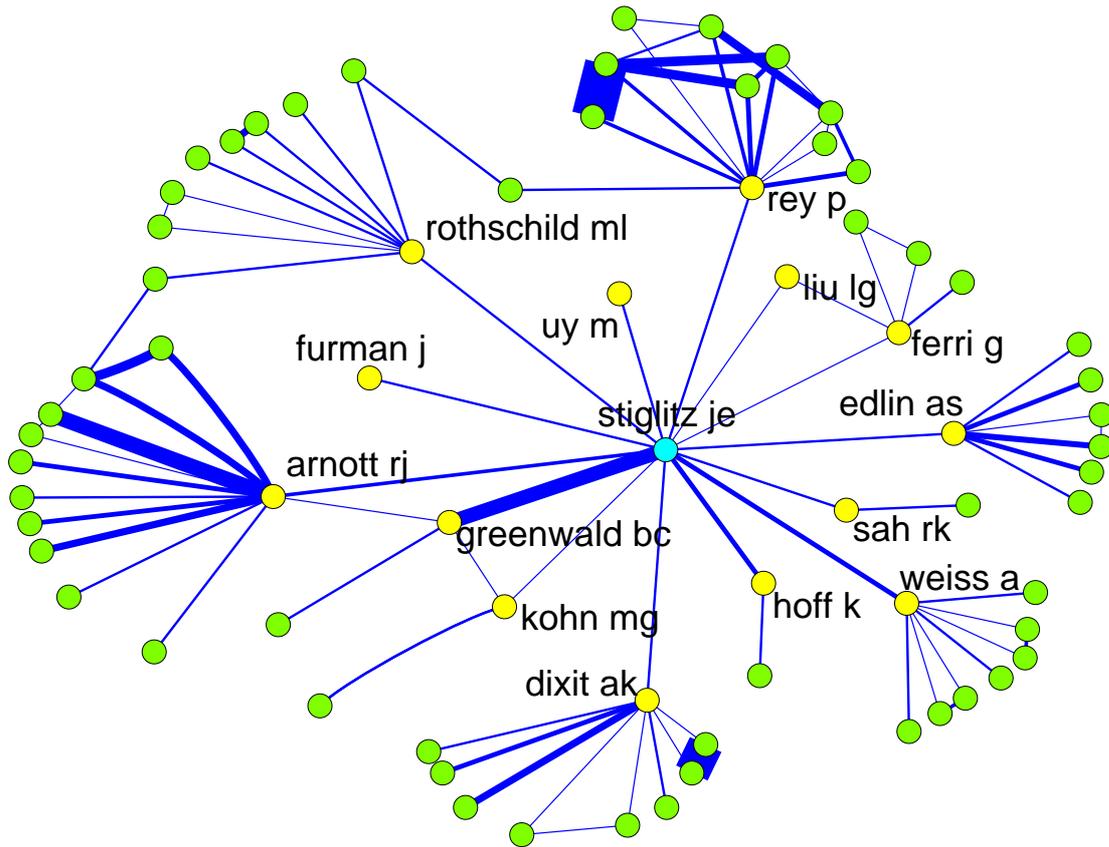


Figure 1: Local network of collaboration of Joseph E. Stiglitz in the 1990s.

Note: The figure shows all authors within distance 2 of J.E. Stiglitz as well as the links between them. The width denotes the strength of a tie. Some economists might appear twice or are missing due to the use of different initials or misspellings in EconLit. The figure was created by software program *Pajek*.

Firms, networks and markets

Networks of firm collaboration

- Firms bilaterally choose research links.
- Partners share technological information which lower costs of production. More links firms lead to lower costs, which leads to larger market share.
- However each link involves a fixed cost C .
- Key feature:
 1. link decided bilaterally.
 2. Networks and markets

Firms, networks and markets

- How do we solve such games? Nash equilibrium is too weak as there is a coordination problem in bilateral link formation, firm A offers no link since it expects no one else to form any links.
- To avoid this problem: refine Nash equilibrium with the requirement that no two players should have an incentive to form an additional link.
- Call this solution concept ***Pairwise Nash Equilibrium***

Firms, networks and markets

- Key incentive issues:
 1. starting from a network, should a firm form an additional link? This depends on a comparison of additional profits and costs of a link: whether returns are concave or convex in own links?
 2. How does others linking alter incentives of A and B: whether links are strategic complements or substitutes?
- In the classical Cournot model of oligopoly payoffs are convex in own links and links are strategic substitutes.
- What are the Pairwise Nash Equilibrium networks?

Model of Network Formation

- *Players*: $N=(1,2,3,\dots,n)$ firms
- *Strategies*: Each firm announces intention to form 0-1 links with others. A link is formed if both firms want it.
- *Payoffs*: A link costs $F>0$ to each firm and lower their costs of production by c .
- Links formed define a network, which defines a vector of firm costs.

The gains from a link depend on market competition.

Strong competition: unique lowest cost firm makes profits

Moderate competition: lower costs imply higher profits.

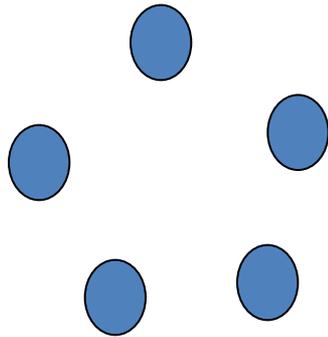
Networks of collaboration: theory

THEOREM (Goyal and Joshi 2003)

- *Suppose $F > 0$ and small.
With strong competition, empty network is unique pair-wise equilibrium.
With moderate competition, complete network is unique pair-wise equilibrium.*

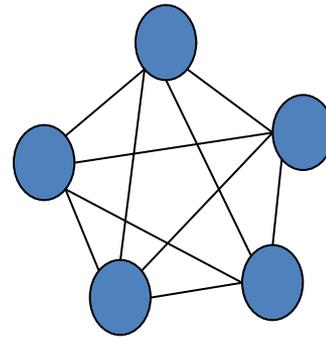
Intuition: in non-empty network, there is always a firm which forms link but makes no profits. Better to delete all links!
If two firms form links, gain at expense of other firms.
Always form links.

General Message: *Two-way influence... markets shape networks and networks define market performance.*



Empty network

Strong competition



Complete network

Moderate competition

Pair-wise equilibrium: low costs

Networks of collaboration: theory

Goyal and Joshi (2003), Deorian (2006)

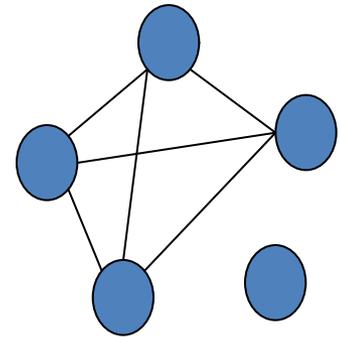
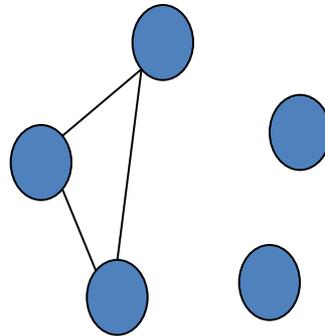
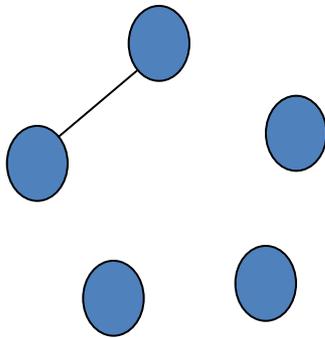
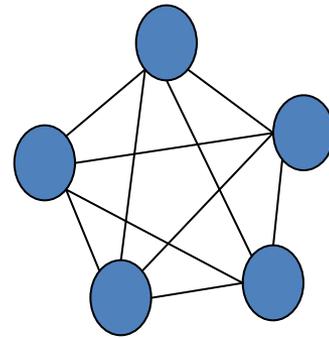
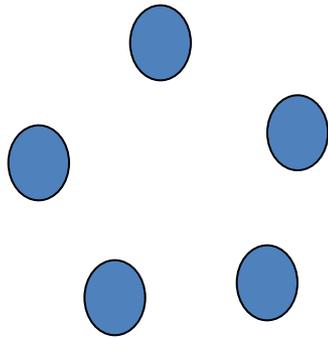
THEOREM

With F large, a pairwise equilibrium network has the dominant group architecture.

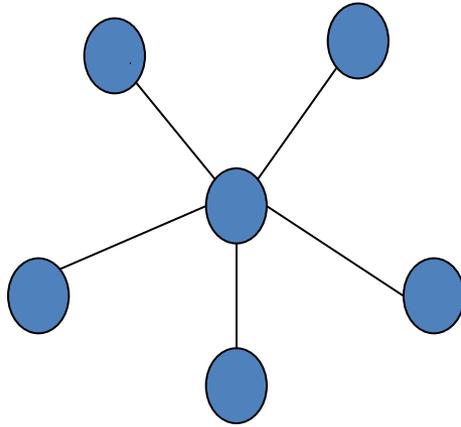
THEOREM

With F large, if firms can make transfers for link formation then the star network and variants of the star are pairwise equilibrium networks.

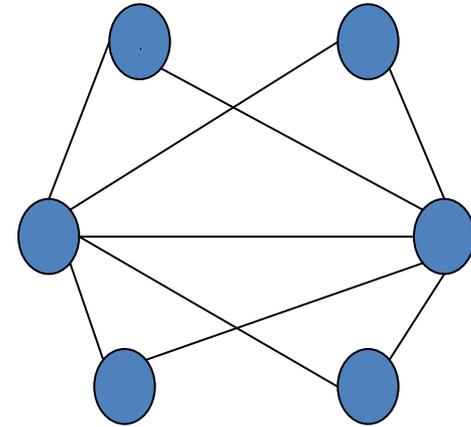
General Message: *In a classical oligopoly model, strategic linking leads to unequal connections, small average distance, high clustering in firm alliance networks.*



Dominant group networks
Moderate competition, high link costs



A. Star Network



B. Inter-linked star (2 centres)

**Equilibrium networks: moderate competition,
high links costs with transfers**

Network advantages

- Does network degree and location confer advantages?

Firm networks: unequal degrees arise in equilibrium and more links translate into higher net profits.

General message: *strategic networking can create large inequalities across players who were ex-ante identical.*

Goyal and Joshi (2003).

Good and Bad networks

- Key idea: links are motivated by individual incentives. Individual linking generates externalities and spill-overs. Tension between equilibrium and socially optimal networks.

General message: *linking creates **negative** profit effects for other firms, there may be too many links in equilibrium.*

Goyal and Joshi (2003), Yi (1998), Westbrook (2012)

Collaboration networks: summary

- Generates sharp predictions on equilibrium networks: unequal degrees, small average distance, arise naturally. Good match with empirics.
- Strategic networking has powerful effects on payoff inequality as well as aggregate social welfare.
- Suggests role of policy – taxes and subsidies – to reorient network formation.

Collaboration Networks: experiment

Zieglmeyer and Pantz (2008):

- This paper experimentally tests the network formation model.

First experiment: designed as a straight test of theory.

1. The data almost perfectly match the predictions when link formation costs are extreme. *Subjects choose empty or complete networks.*
2. Intermediate link formation costs: the prediction is asymmetric networks. *But subjects rarely form asymmetric networks. When they do, observed and predicted quantities are not in accordance with predicted outcome.*

Collaboration Networks: experiment

Second experiment: reduce the complexity of the setting by transforming the original two-stage game into a one-stage game. Formation of inter-firm networks directly determines firms' payoffs.

- *Observed networks coincide with the predicted ones:*

indicating that experimental subjects' limited capacity to foresee the outcomes of the market stage may be driving the earlier discrepancies.

Choice and Structure: Themes

Great success is an extensive set of applications.

- Firm networks: Goyal and Moraga (2001) Goyal and Joshi (2003), Westbrook (2012)
- Co-authorship: Jackson and Wolinsky (1996), Goyal, Moraga and van der Leij (2006).
- Viral marketing: Galeotti and Goyal (2010), Campbell (2013).
- Peer effects: Cabrales, Calvo-Armengol and Zenou (2013) .
- Labour: Calvo-Armengol (2004), Galeotti and Merlino (2013).

Choice and Structure: Themes

- Buyer-seller: Kranton and Minehart (2001), Manea (2011)
- Risk-sharing: Bramouille and Kranton (2008), Ambrus et al (2013)
- International trade: Goyal and Joshi (2006), Furasawa and Konishi (2007)
- Homophily and friendship: Currarini, Jackson and Pin (2006).
- Cybersecurity/crime: Baccara and Bar-Issac (2008), Goyal and Vigier (2011)
- Financial Contagion: Cabrales, Gottardi, Vega-Redondo (2013), Elliott, Golub and Jackson (2013), Acemoglu et al (2012)

Closing the Circle

Presented two standard models of network formation.

- Start with empirical phenomena.
- Develop models of linking: costs/benefits and externalities.
- Sharp predictions ... on architecture, distribution and welfare.

Test the theory in an ideal environment: in laboratory

- Experiments point to successes
 - emergence of stars, symmetric/asymmetric firm networks
- Highlight bounded rationality and concerns about fairness.

Networks arise at the intersection of individual incentives and social norms.