Network structure and outcomes

Paul Schrimpf

UBC
Vancouver School of Economics

April 6, 2021

References

- Overviews:
  - Jackson (2010), https://class.coursera.org/networksonline-001
  - Goyal (2012)
- Network industries: Economides (1996), Economides and Encaoua (1996)

Section 1

Introduction

Introduction 1

- Network: nodes & links between them
- Questions:
  - How does network structure affect behavior?
  - How are networks formed?
- Focus on networks that are not owned by a single entity
  - i.e. not on network industries where a single firm owns and controls its network (telecom, electricity, airlines, etc)
  - Relatively new area, little empirical work

Networks in IO

- R&D collaboration
- Trade
- Buyer-supplier
- Consumer information & targeting

Section 2

Describing Networks

Basic notation

- Nodes $\in \{1, ..., N\} = \mathcal{N}$
- Adjacency matrix G, $N \times N$ matrix with g_{ij} representing connection between i and j
- Graph $\equiv (\mathcal{N}, G)$
  - Undirected $\equiv$ symmetric G
  - Directed $\equiv$ asymmetric G
  - Unweighted (or discrete) $\equiv g_{ij} \in \{0, 1\}$
  - Weighted $\equiv$ not discrete

Summary statistics 1

- Distance between two nodes = shortest path between them (∞ if no connected path)
- Diameter = largest distance between nodes
- Clustering
  - of graph is portion of j and k connected given j and k both connected to i
  - of node i is the portion of time j and k are connected directly given j and k are connected to i
  - average clustering of graph = average across nodes of node clustering
- Degree of a node = number of links
  - Directed graphs: in-degree & out-degree
  - Degree centrality $= \frac{\text{degree}}{N-1}$
  - Network density = fraction of possible links present $= \frac{\text{average degree}}{N-1}$
  - Degree distribution = CDF of node degree

Summary statistics 2

- Centrality measures:
  - Degree, closeness, betweenness, decay
  - Eigenvector, Katz, Bonacich

Section 3

Network structure & outcomes

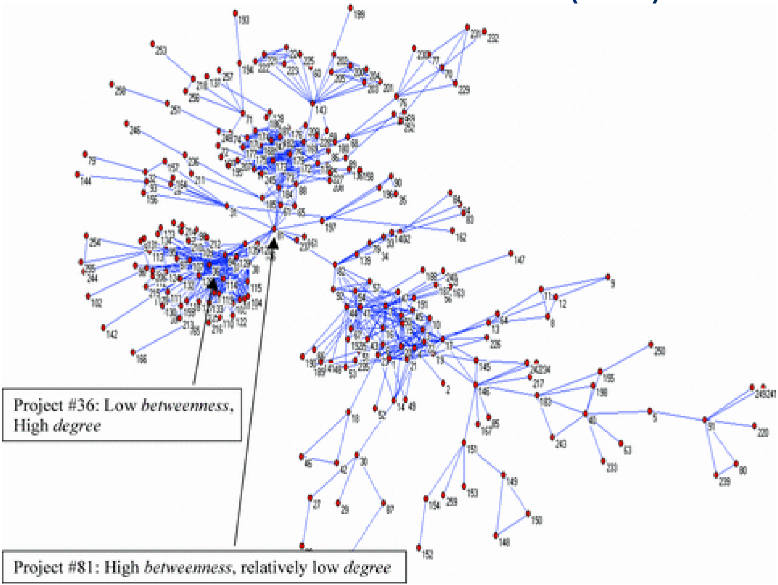
Network structure & outcomes

- Question: how does network structure affect some outcome?
- Reduced form work: regress outcome on node or network summary statistics

Example: Fershtman and Gandal (2011)

- Knowledge spillovers in open-source projects
- Data:
  - Sourceforge
  - Contributor network: linked if participated in same project
  - Project network: linked if have common contributors
- Question: how important are project vs contributor spillovers for project success?
  - Project spillover = developers learn from working on a particular project
  - Contributor spillover = developers learn from working with other developers
- Related paper: Claussen, Falck, and Grohsjean (2012)

Example: Fershtman and Gandal (2011)



Example: Fershtman and Gandal (2011)

Table: The Distribution of Contributors per Project and Projects per Contributor

Project Network		Contributor Network	
Contributors	N Projects	Projects	N Contributo
1	77,571	1	123,562
2	17,576	2	22,690
3–4	11,362	3–4	10,347
5–9	6,136	5–9	3,161
10–19	1,638	10–19	317
20–49	412	20–49	26
≥ 50	56	≥ 50	1
Total projects	114,751	Total contributors	160,104

Example: Fershtman and Gandal (2011)

Table: Distribution of Component Size

Component Size (Contributors)	Components (Subnetworks)
55,087	1
196	1
65–128	2
33–64	27
17–32	152
9–16	657
5–8	2,092
3–4	4,810
2	8,287
1	47,787

Example: Fershtman and Gandal (2011)

Table: Distribution of Degree

Degree	Number of Contributors
0	47,787
1	22,133
2	14,818
3–4	20,271
5–8	20,121
9–16	16,228
17–32	10,004
33–64	5,409
65–128	2,040
129–256	802
257–505	491

Empirical specification

- Degree centrality as measure of direct connections
- Closeness centrality $= C_C(i) = \frac{N-1}{\sum_{j \in \mathcal{N}} d(i,j)}$ – conditional on degree measures indirect connections
- S_i = success = number of downloads

$$S_i = \alpha + \gamma C_c(i)/(N-1) + \beta \text{degree}_i + \text{controls}$$

Results - project network

Table: Regression Results: Dependent Variable: ldownloads

	Regression 1	(All 66,511 Projects)	Regression 2	(Giant Component: 18.697
Independent variables	Coefficient	T-Statistic	Coefficient	T-Statistic
Constant	0.72	17.76	1.45	3.62
lyears_since	1.42	60.66	1.68	31.08
lcount_topics	0.23	9.07	0.18	3.59
lcount_trans	0.35	11.73	0.45	8.15
lcount_aud	0.36	10.44	0.44	5.85
lcount_op_sy	0.11	5.95	0.18	5.00
ds_1	1.96	60.57	2.01	31.90
ds_2	0.60	17.58	0.78	11.50
ds_3	0.89	25.83	0.66	9.95
ds_4	1.86	57.21	1.80	29.27
ds_5	2.72	79.97	2.61	40.96
ds_6	2.12	27.07	2.03	15.35
inactive	0.45	6.11	0.39	2.75
lcpp	0.46	18.71	0.87	29.34
ldegree	0.19	9.45	0.079	2.10
giant_comp	0.21	3.86		
lgiant_cpp	0.44	12. 05		
lgiant_degree	0.05	1.26		
lcloseness			0.69	3.21
Number of observations	66,511		18,697	
Adjusted R^2	0.41		0.40	

Contributor effects

- Regress downloads on average contributor degree and average contributor closeness centrality (and controls)
- Result:
  - Coefficient on log average closeness $= 0.12$, with $t = 1.59$
  - Coefficient on log average degree $= -0.019$, with $t = -0.72$
- Including both contributor and project measures, project ones significant, contributor ones not

Robustness

Dept Variable: Ldownloads Independent variables	$\geq$ 2yr, Coef	$\geq$ 200dl T Stat	$<$ 3.6yr, Coef	$\geq$ 200dl T Stat	$\geq$ 2yr, Coef	$\geq$ 200dl T Stat
Constant	5.75	13.35	6.21	14.55	8.51	16.29
lyears_since	1.08	11.18	0.91	11.40	1.06	10.97
lcount_topics	0.06	1.31	0.06	1.12	0.06	1.23
lcount_trans	0.42	9.61	0.44	8.83	0.41	9.39
lcount_aud	0.21	2.65	0.46	5.62	0.18	2.28
lcount_op_sy	0.26	7.91	0.26	6.62	0.26	7.94
ds_1	0.46	6.83	0.75	6.23	0.46	6.88
ds_2	0.57	7.31	0.52	4.80	0.57	7.68
ds_3	0.27	4.35	0.23	2.72	0.28	4.44
ds_4	0.19	3.45	0.18	2.41	0.18	3.24
ds_5	0.75	12.99	0.54	6.92	0.73	12.80
ds_6	0.73	7.00	0.45	3.06	0.72	6.89
Inactive	0.018	0.12	0.02	0.11	0.041	0.28
lcpp	0.76	22.21	0.63	19.30	0.59	15.38
ldegree	0.19	5.07	0.0038	0.09	0.019	0.43
lcloseness	0.71	3.28	0.54	2.37	0.45	2.08
lbetweenness					0.30	9.21
Number of observations	6,397		4,086		6,397	
Adjusted R^2	0.28		0.25		0.29	

Limitations

- How to interpret results?
    - Network structure affects downloads
    - Downloads affect contributions, which affects network structure
- Why closeness centrality and degree? (they do explore robustness to other measures, but none of them theoretically motivated)

Claussen, Falck, and Grohsjean (2012)

- Developer networks in electronic games
- Panel data 1972-2007 on games & developers
- Construct network of developers 1995-2007
- Developers linked in year t if worked together anytime between 1972 and t
- Look at relationship between revenue (or rating) & degree centrality & closeness centrality

Claussen, Falck, and Grohsjean (2012)

$$S_{igdpt} = \alpha_i + \alpha_d + \alpha_p + \alpha_t + \beta_1 D_{igdpt-1} + \beta_2 C_{igdpt-1} + CV_{igdpt}\gamma + \epsilon_{igdpt}$$

- Developer i
- Game g
- Developing firm d
- Publisher p
- Year t

Claussen, Falck, and Grohsjean (2012)

Table 1
Summary statistics.

Variable	N	Mean	SD	Min	Max
ln(revenue)	151,677	14.958	1.701	4.264	19.440
Critics' score	146,675	0.007	0.781	−3.831	2.223
Degree centrality D_{igdpt}	148,627	0.001	0.002	0.000	0.041
Closeness centrality C_{igdpt}	148,627	0.205	0.038	0.052	0.338
Leading position	151,677	0.213	0.410	0	1
Tenure	151,677	3.871	4.254	0	28
Team size	151,677	65.780	53.234	1	297
Licensed game	151,677	0.362	0.480	0	1

Claussen, Falck, and Grohsjean (2012)

Table 3
Baseline regression results with revenue as success measure.

	(3–1)	(3–2)	(3–3)	(3–4)
	Dependent variable: ln(revenue)			
Degree centrality D_{igdpt}	8.494*	8.029*	7.281**	6.512*
	(4.468)	(4.342)	(3.321)	(3.644)
Closeness centrality C_{igdpt}	−0.137	−0.307	−0.105	−0.223
	(0.201)	(0.217)	(0.155)	(0.174)
Co-worker degree c. $\overline{D}_{-igdpt}$			40.20	56.53
			(60.77)	(45.38)
Co-worker closeness $\overline{C}_{-igdpt}$			−0.548	−3.122
			(3.059)	(2.567)
Tenure	0.0170	0.0612	0.0236	0.0676
	(0.0618)	(0.0886)	(0.0664)	(0.0932)
Team size	0.00447***	0.00396***	0.00446***	0.00394***
	(0.000937)	(0.000990)	(0.000938)	(0.000991)
Licensed game	0.192***	0.172**	0.193***	0.171**
	(0.0720)	(0.0771)	(0.0721)	(0.0774)
Network measures lagged	No	Yes	No	Yes
Observations	151,484	94,597	151,443	94,388
Number developers	56,944	30,993	56,937	30,956
Within-developer R^2	0.635	0.638	0.635	0.638
Between-developer R^2	0.802	0.742	0.798	0.736
Overall R^2	0.736	0.689	0.734	0.684

Notes: Fixed-effect OLS point estimates with standard errors clustered at the project

Gandal and Stettner (2016)

"Network dynamics and knowledge transfer in virtual organisations"

- Panel data of Sourceforge contributions
- Look for direct & indirect spillovers
- Programmers who work on many projects positively impact success beyond their effect on connectivity in the network

Athey and Ellison (2014)

"Dynamics of Open Source Movements"

- Dynamic model of open source contributions and commercial competitors
- Theory paper, not empirical

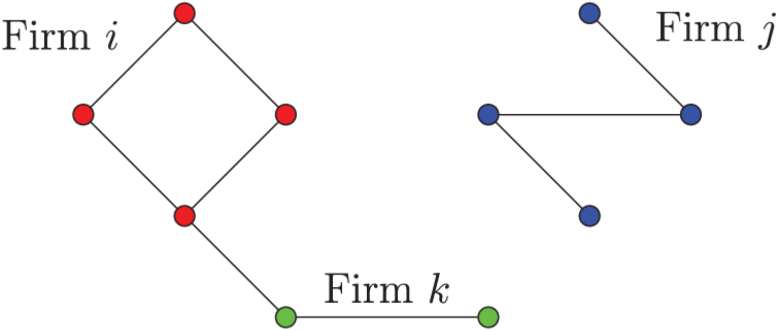
Knowledge Spillovers through Networks of Scientists

Zacchia (2019)

- Weighted network of publicly traded companies
- Links = proportion of firms' inventors that have former patent collaborations
- Main endogeneity concern: common unobservables
- IV motivated by model of firm interaction

Network Among Inventors

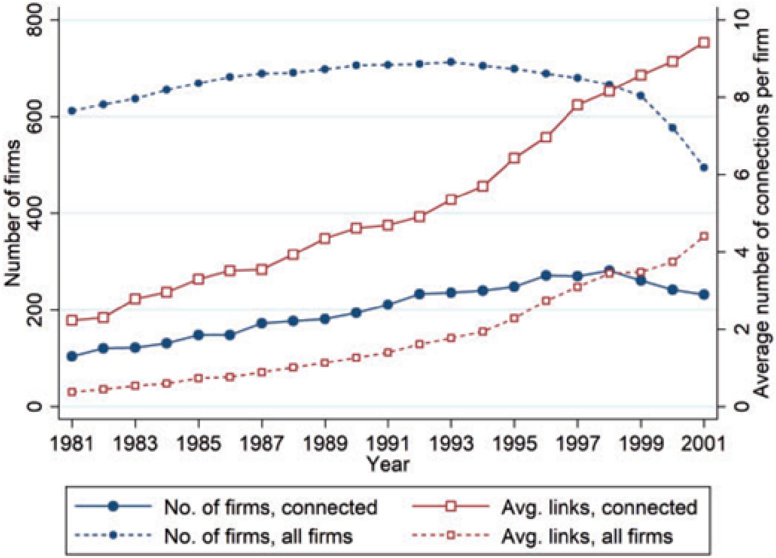
- Inventor m and n linked ($p_{(mn)t} = 1$) if m and n collaborated on any past patent

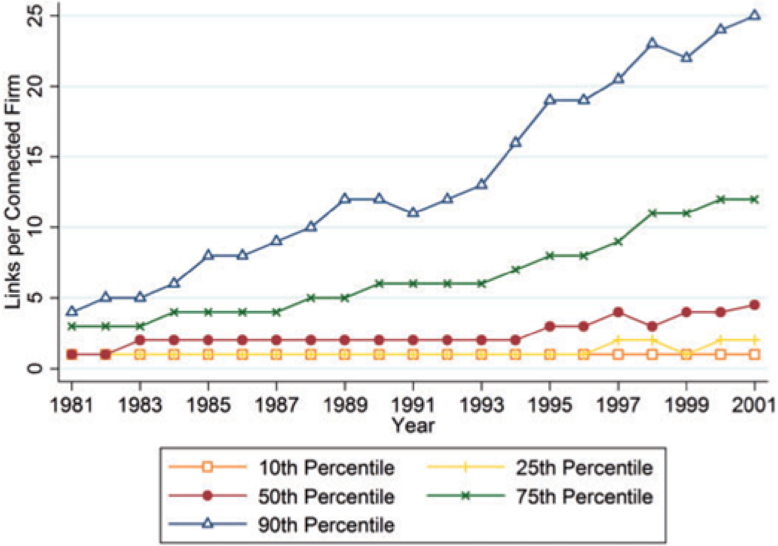


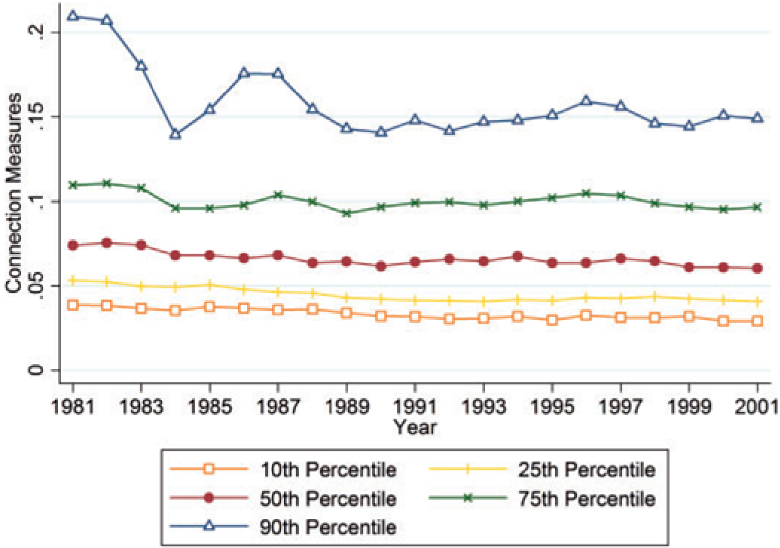
Network Among Firms

$$c^f_{(ij)t} = f\left(\frac{\text{inv. of i connectected to j at t} + \text{inv. of j connectected to i at t}}{\text{inv. of i at t} + \text{inv. of j at t}}\right)$$

- Symmetric
- $0 \leq c^f_{(ij)t} \leq 1$
- In empirical results, $f(\cdot) = \sqrt{\cdot}$ and $g_{(ij)t} = c^{\sqrt{\cdot}}_{(ij)t}$


Number of firms
0
200
400
600
800
Average number of connections per firm
0
2
4
6
8
10
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
Year
No. of firms, connected
No. of firms, all firms
Avg. links, connected
Avg. links, all firms


Links per Connected Firm
0
5
10
15
20
25
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
Year
10th Percentile
25th Percentile
50th Percentile
75th Percentile
90th Percentile


Connection Measures
0
.05
.1
.15
.2
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
Year
10th Percentile
25th Percentile
50th Percentile
75th Percentile
90th Percentile

Network structure and outcomes

Paul Schrimpf

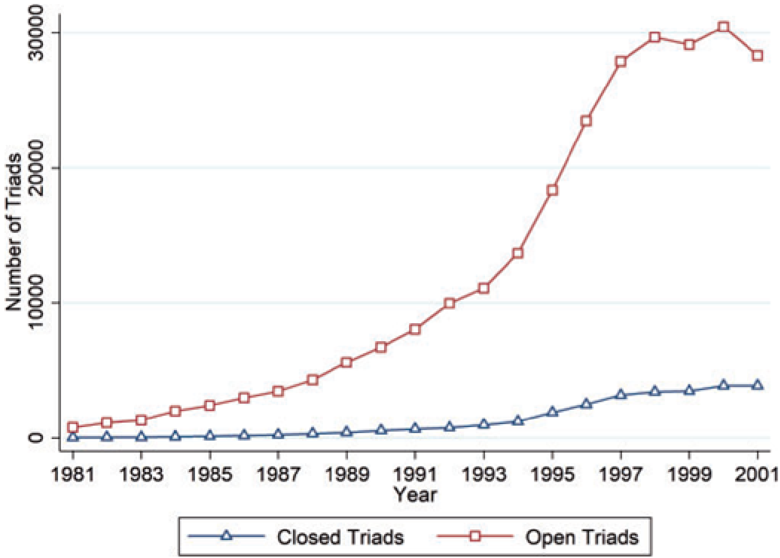
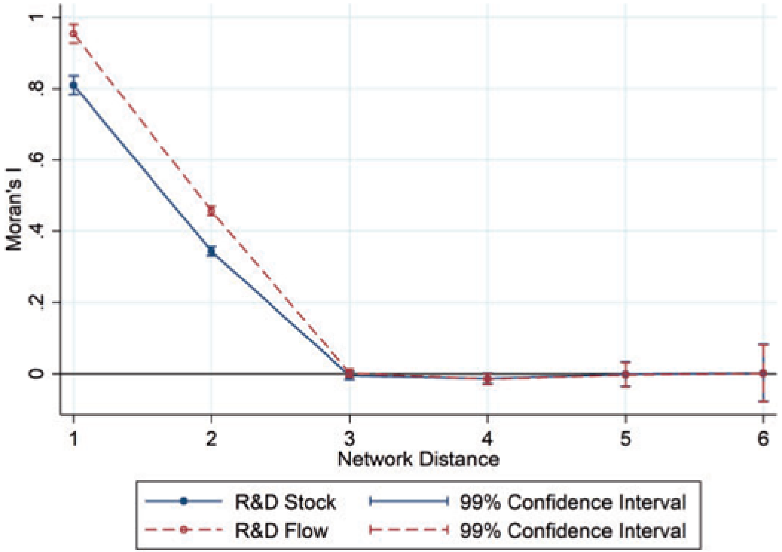


TABLE 1

Summary statistics, 1981–2001

	No network	Quartile of $\sum_t \bar{g}_{it}$			
		1	2	3	4
Y_{it}: real sales (Millions 1996$\$$)	751	1,066	1,383	2,172	10,462
	(3,792)	(2,357)	(2,504)	(4,533)	(20,058)
V_{it}/A_{it}: Tobin's q	1.886	1.885	2.573	2.734	3.410
	(2.031)	(1.839)	(3.080)	(3.306)	(4.118)
P_{it}: patent stock (cit. weighted)	7.453	16.09	24.65	74.03	652.0
	(48.17)	(44.75)	(50.91)	(143.8)	(1322.1)
E_{it}: employees (thousands)	4.068	6.940	9.328	12.40	57.09
	(12.52)	(15.80)	(16.63)	(22.43)	(96.80)
Y_{it}/E_{it}: labour productivity	135.6	134.5	157.1	156.5	192.4
	(80.06)	(106.6)	(95.43)	(117.7)	(153.3)
Y_{it}/K_{it}: capital productivity	6.932	5.308	5.142	4.941	4.184
	(6.083)	(3.167)	(3.992)	(3.292)	(2.883)
Y_{it}/S_{it}: productivity of R&D	39.31	19.71	51.10	11.12	4.342
	(134.1)	(70.47)	(479.9)	(34.46)	(3.932)
$Y_{it}/$ Jaffe measure (i,t)	80.28	107.7	140.0	211.6	962.5
	(407.7)	(238.5)	(264.9)	(435.4)	(1787.8)
$Y_{it}/\prod_j S_{jt}^{g_{(i,j)t}}$: Y to spillover pool		953.9	846.2	577.6	198.9
		(2,224.0)	(1,762.1)	(1,858.7)	(1,339.6)
No. of observations	4,363	1,854	1,819	1,949	2,028


Moran's I
0
.2
.4
.6
.8
1
1
2
3
4
5
6
Network Distance
R&D Stock
R&D Flow
99% Confidence Interval
99% Confidence Interval

Econometric Model

$$\log Y_{it} = \alpha_i + \sum_{q=1}^{Q} \beta_q \log X_{itq} + \gamma \log S_{it} + \delta \sum_{j=1}^{N} g_{(ij)t} \log S_{jt} + \tau_t + \nu_{it}$$

- Output Y_{it}
- Inputs X_{itq}
- R&D stock S_{it} (depreciated past sum of R&D expenditures)
- $\delta =$ strength of R&D spillovers

Endogeneity

- $\mathrm{E}[\log S_{jt} v_{it}] \neq 0$ from e.g. v_{jt} correlated with v_{it}, or S_{jt} chosen with some knowledge of v_{it}
- Endogenous connections $\mathrm{E}[g_{(ij)t} v_{it}] \neq 0$

Analytic Framework

- Firms $\mathcal{I}$ with connection $\mathcal{G}$
- Knowledge capital

$$\tilde{S}_i = S_i^{\gamma} \left(\prod_j S_j^{g_{ij}} \right)^{\delta}$$

- R&D cost $e^{\bar{\omega}_i} S_i$
- Cobb-Douglas Production as above
- Firms maximize profits (output minus linear input costs minus R&D costs)

Equilibrium

- Unique Bayes-Nash equilibrium with

$$\log S_i^* = \frac{\log \gamma + \sum_q \beta_q (\log \beta_q - \log \xi_q - \log \gamma)}{1 - \gamma - \sum_q \beta_q} b_i^*(\mathcal{G}; \vartheta) + s_i^*(\Omega_i; \mathcal{G})$$

where

  - $\vartheta = \frac{\delta}{1-\gamma-\sum_q \beta_q}$
  - $b_i^*(\mathcal{G}; \vartheta)$ is Katz-Bonacich network centrality
  - Ω_i is firm's information set and

$$s_i^*(\Omega_i; \mathcal{G}) = \frac{\omega_i - (1 - \sum_q \beta_q)\bar{\omega}_i + \log \mathrm{E}[\prod_j e^{g_{ij} \delta s_j^*(\Omega_j, \mathcal{G})} | \Omega_i]}{1 - \gamma - \sum_q \beta_q}$$

Identifying Assumptions

- Correlation of $\log S_{jt}$ with unobservables of i happens through $s_i^*(\Omega_i; \mathcal{G})$ due to ω_{it} and ω_{jt} possibly being correlated and Ω_i potentially being informative about ω_{jt}
- Assumption 1: $\exists C > 0$ such that if distance from i to j is greater than C, then $Cov(\omega_i, \omega_j | d_{ij} > C) = 0$ and $Cov(\bar{\omega}_i, \bar{\omega}_j | d_{ij} > C) = 0$
- Assumption 2: $\exists L > 0$ such that $d_{ij} > L$ implies $(\omega_j, \bar{\omega}_j) \notin \Omega_i$
- Implies:

$$Cov(\omega_i, \log S_j | d_{ij} > C + L) = 0$$
$$Cov(\log S_i \log S_j | d_{ij} \leq C + 2L) \lesseqgtr 0$$
$$Cov(\log S_i \log S_j | d_{ij} > C + 2L) = 0$$

- Use $\log S_k$ as instrument for $\log S_j$ when k and j are distance $C + L < D \leq C + 2L$ apart

TABLE 2

Production function, ordinary least squares estimates, 1981–2001

	(1)	(2)	(3)	(4)	(5)
Private R&D (γ)	0.0455***	0.0438***	0.0568***	0.0554***	0.0515***
	(0.0108)	(0.0105)	(0.0118)	(0.0128)	(0.0142)
R&D spillovers (δ)	0.0159***	0.0147***	0.0114***	0.0118***	0.0116***
	(0.0023)	(0.0024)	(0.0024)	(0.0025)	(0.0028)
Geographic spillovers		0.0035	0.0027	0.0023	0.0015
		(0.0021)	(0.0020)	(0.0023)	(0.0019)
Capital	0.2071***	0.2061***	0.2035***	0.2020***	0.2023***
	(0.0143)	(0.0145)	(0.0194)	(0.0213)	(0.0198)
Labour	0.6550***	0.6580***	0.6634***	0.6613***	0.6622***
	(0.0241)	(0.0249)	(0.0351)	(0.0359)	(0.0363)
Jaffe tech. proximity		0.1352**	0.0361	0.0026	0.0179
		(0.0581)	(0.0583)	(0.0766)	(0.0805)
Fixed effects	YES	YES	YES	YES	YES
Only network	NO	NO	YES	YES	YES
No. of communities (Community × Year Effects)	0	0	0	10	20
No. of observations	12,503	12,503	7,607	7,607	7,607

Notes: The table reports OLS estimates of model (4.11). Columns 1 and 2 are estimated over the entire original sample of 736 firms in the time interval 1981–2001. Estimates in columns 3, 4, and 5 restrict the sample to firms with at least one non-zero connection ($g_{(ij)t} \neq 0$) in any year t; all observations of these firms are also included for years with no connections. All estimates include firm and year fixed effects. Columns 4 and 5 include additional community-by-year fixed effects, where communities are obtained via the Louvain algorithm with $\varphi = 0.8$ (10 communities) in column 4 and $\varphi = 0.6$ (20 communities) in column 5. Standard errors are clustered by the 20 “communities” obtained via the Louvain algorithm with $\varphi = 0.6$ (small sample corrections are applied). All observations of the same individual firm in different years enter the same cluster. For estimates not restricted to the network, firms outside the network constitute single clusters. Asterisks denote conventional significance levels of t-tests (**$p < 0.05$; ***$p < 0.01$).

TABLE 3

Production function, first stage estimates, 1981–2001

	(1)	(2)	(3)	(4)	(5)
Distance 2 instrument	0.0043***	0.0044***			
	(0.0002)	(0.0002)			
Distance 3 instrument		-0.0001*	0.0006***	0.0005***	0.0005***
		(0.0001)	(0.0001)	(0.0001)	(0.0001)
Private R&D	0.1598***	0.1774***	0.5022***	0.4612***	0.4357***
	(0.0517)	(0.0488)	(0.1463)	(0.1436)	(0.1504)
Capital	0.1827	0.1895	0.6169**	0.5903**	0.5923**
	(0.1133)	(0.1098)	(0.2622)	(0.2719)	(0.2746)
Labour	−0.0761	−0.0530	−0.6482**	−0.6021**	−0.6541**
	(0.0921)	(0.0913)	(0.2412)	(0.2636)	(0.2631)
Jaffe tech. proximity	1.8439***	1.8224***	3.3663**	3.2740**	3.3672**
	(0.4808)	(0.5123)	(1.5953)	(1.3777)	(1.4690)
Fixed effects	YES	YES	YES	YES	YES
Only network	YES	YES	YES	YES	YES
No. of communities					
(Community × Year Effects)	0	0	0	10	20
F-statistic	255.17	219.47	24.92	32.06	19.18
No. of observations	7,607	7,607	7,607	7,607	7,607

Notes: The table reports OLS "first stage" regressions of the spillover variable $\sum_{j\neq i} g_{(ij)t} \log S_{jt}$ on selected instruments and all other right-hand side variables included in the regressions from Table 2. The sample is restricted to firms with at least one non-zero connection ($g_{(ij)t} \neq 0$) in any year t; all observations of these firms are also included for years with no connections. Columns 1 and 2 include, on the right hand side, the distance 2 instrument; columns 2 through 5 include the distance 3 instrument. All estimates include firm and year fixed effects. Columns 4 and 5 include additional community-by-year fixed effects, where communities are obtained via the Louvain algorithm with $\varphi = 0.8$ (10 communities) in column 4 and $\varphi = 0.6$ (20 communities) in column 5. Standard errors are clustered by the 20 "communities" obtained via the Louvain algorithm with $\varphi = 0.6$ (small sample corrections are applied). All observations of the same individual firm in different years enter the same cluster. Asterisks denote conventional significance levels of t-tests ($^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$).

TABLE 4

Production function, two stages least squares estimates, 1981–2001

	(1)	(2)	(3)	(4)	(5)
Private R&D (γ)	0.0560***	0.0562***	0.0510***	0.0489***	0.0464***
	(0.0117)	(0.0118)	(0.0111)	(0.0127)	(0.0131)
R&D spillovers (δ)	0.0127***	0.0125***	0.0204**	0.0230**	0.0211**
	(0.0029)	(0.0030)	(0.0084)	(0.0088)	(0.0095)
Geographic spillovers	0.0027	0.0027	0.0030	0.0026	0.0018
	(0.0019)	(0.0019)	(0.0018)	(0.0021)	(0.0018)
Capital	0.2025***	0.2027***	0.1969***	0.1944***	0.1956***
	(0.0200)	(0.0199)	(0.0225)	(0.0244)	(0.0234)
Labour	0.6642***	0.6640***	0.6692***	0.6677***	0.6685***
	(0.0357)	(0.0356)	(0.0373)	(0.0382)	(0.0392)
Jaffe tech. proximity	0.0314	0.0324	0.0041	−0.0364	−0.0167
	(0.0549)	(0.0553)	(0.0545)	(0.0669)	(0.0744)
Spillovers IV(s)	$D=2$	$D=2,3$	$D=3$	$D=3$	$D=3$
Fixed effects	YES	YES	YES	YES	YES
Only network	YES	YES	YES	YES	YES
No. of communities (Community × Year Effects)	0	0	0	10	20
No. of observations	7,607	7,607	7,607	7,607	7,607

Notes: The table reports IV-2SLS estimates of model (4.11). All estimates are restricted to firms with at least one non-zero connection ($g_{(ij)t} \neq 0$) in any year t; all observations of these firms are also included for years with no connections. Models in columns 1 and 2 employ the distance 2 instrument; models in columns 2 through 5 employ the distance 3 instrument. All estimates include firm and year fixed effects. Columns 4 and 5 include additional community-by-year fixed effects, where communities are obtained via the Louvain algorithm with $\varphi = 0.8$ (10 communities) in column 4 and $\varphi = 0.6$ (20 communities) in column 5. Standard errors are clustered by the 20 "communities" obtained via the Louvain algorithm with $\varphi = 0.6$ (small sample corrections are applied). All observations of the same individual firm in different years enter the same cluster. Asterisks denote conventional significance levels of t-tests ($^{**}p < 0.05$; $^{***}p < 0.01$).

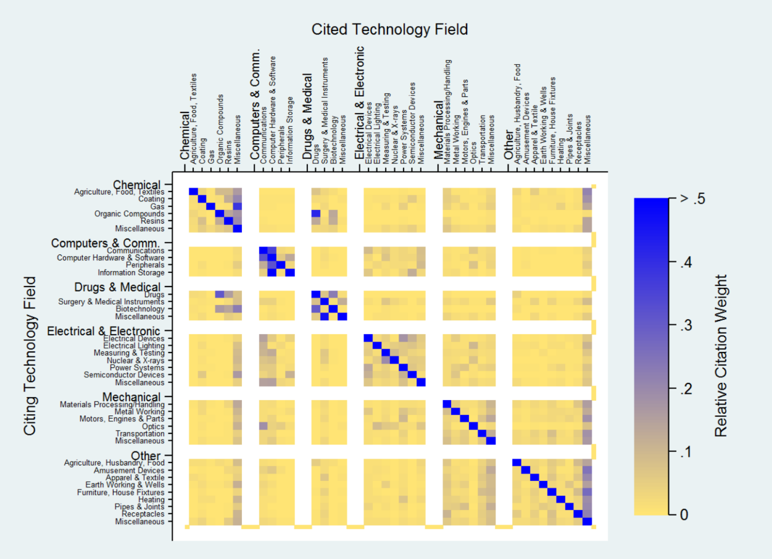
Conclusions

- $D = 2$ IV near OLS implies $D = 2$ might be too small, i.e. $C = 2$
- Marginal social return $= (\gamma + \delta \bar{g}_i)\frac{Y_i}{S_i} = 114\%$ considerably greater than marginal private return $= \gamma \frac{Y_i}{S_i} = 102\%$

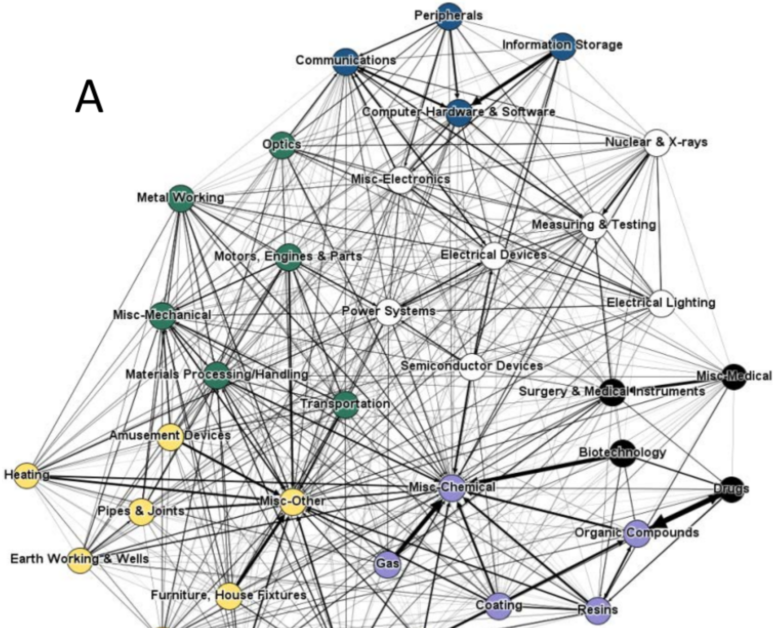
Acemoglu, Akcigit, and Kerr (2016)

"Innovation network"

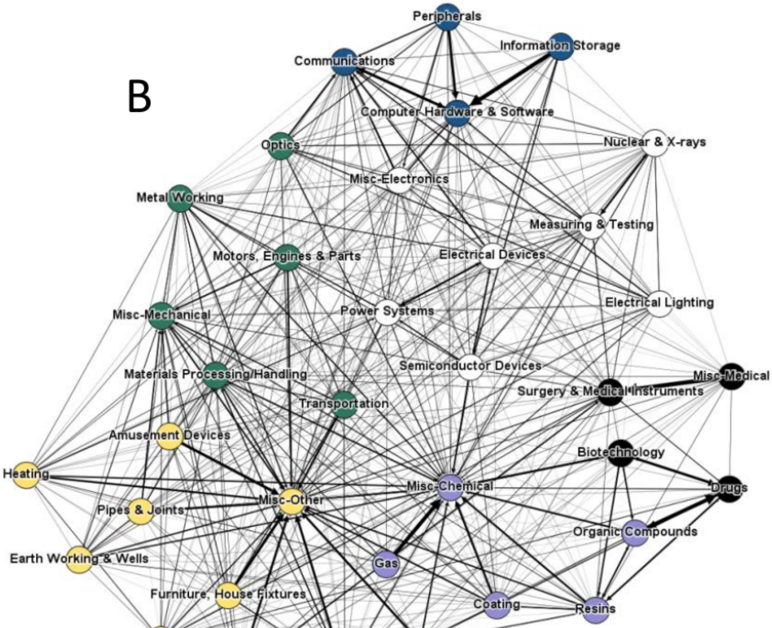
- Directed network of patent citations, 1975-2004
- Results:
  - Network stable over time
  - Past innovations (patents) in connected industries predict current patents
  - Impact of innovations are localized

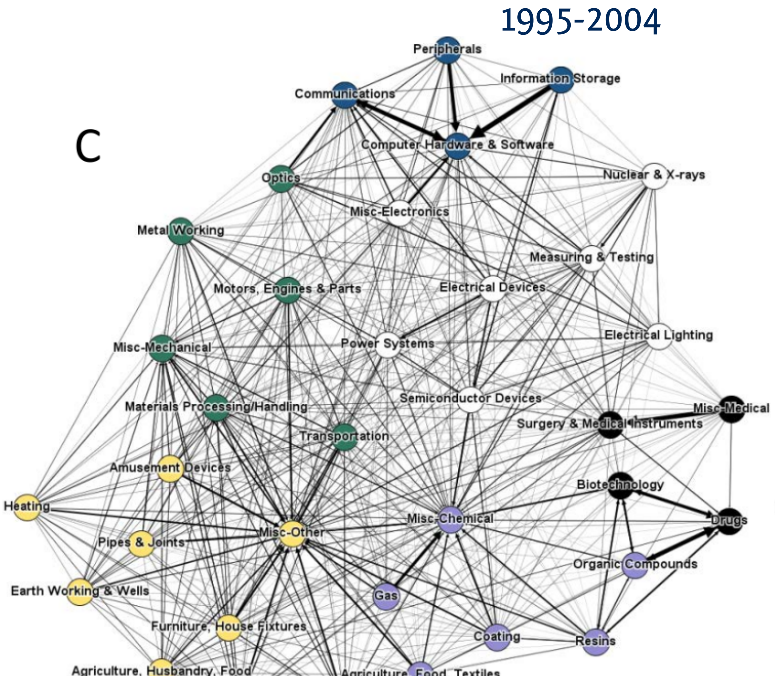

Cited Technology Field
Citing Technology Field
Relative Citation Weight
Chemical
Agriculture, Food, Textiles
Coating
Gas
Organic Compounds
Resins
Miscellaneous
Computers & Comm.
Communications
Computer Hardware & Software
Peripherals
Information Storage
Drugs & Medical
Drugs
Surgery & Medical Instruments
Biotechnology
Miscellaneous
Electrical & Electronic
Electrical Devices
Electrical Lighting
Measuring & Testing
Nuclear & X-rays
Power Systems
Semiconductor Devices
Miscellaneous
Mechanical
Materials Processing/Handling
Metal Working
Motors, Engines & Parts
Optics
Transportation
Miscellaneous
Other
Agriculture, Husbandry, Food
Amusement Devices
Apparel & Textile
Earth Working & Wells
Furniture, House Fixtures
Heating
Pipes & Joints
Receptacles
Miscellaneous
> .5
.4
.3
.2
.1
0

1975-1984


A
Peripherals
Information Storage
Communications
Computer Hardware & Software
Nuclear & X-rays
Optics
Misc-Electronics
Metal Working
Measuring & Testing
Motors, Engines & Parts
Electrical Devices
Electrical Lighting
Misc-Mechanical
Power Systems
Semiconductor Devices
Materials Processing/Handling
Misc-Medical
Surgery & Medical Instruments
Transportation
Amusement Devices
Biotechnology
Heating
Misc-Chemical
Drugs
Misc-Other
Pipes & Joints
Organic Compounds
Earth Working & Wells
Gas
Furniture, House Fixtures
Coating
Resins

1985-1994


B
Peripherals
Information Storage
Communications
Computer Hardware & Software
Nuclear & X-rays
Optics
Misc-Electronics
Metal Working
Measuring & Testing
Motors, Engines & Parts
Electrical Devices
Electrical Lighting
Misc-Mechanical
Power Systems
Semiconductor Devices
Materials Processing/Handling
Misc-Medical
Surgery & Medical Instruments
Transportation
Amusement Devices
Biotechnology
Heating
Misc-Chemical
Drugs
Misc-Other
Pipes & Joints
Organic Compounds
Earth Working & Wells
Gas
Furniture, House Fixtures
Coating
Resins


1995-2004
C
Peripherals
Information Storage
Communications
Computer Hardware & Software
Nuclear & X-rays
Optics
Misc-Electronics
Metal Working
Measuring & Testing
Motors, Engines & Parts
Electrical Devices
Electrical Lighting
Misc-Mechanical
Power Systems
Semiconductor Devices
Materials Processing/Handling
Misc-Medical
Surgery & Medical Instruments
Transportation
Amusement Devices
Biotechnology
Heating
Misc-Chemical
Drugs
Misc-Other
Pipes & Joints
Organic Compounds
Earth Working & Wells
Gas
Furniture, House Fixtures
Coating
Resins
Agriculture, Husbandry, Food
Agriculture, Food, Textiles

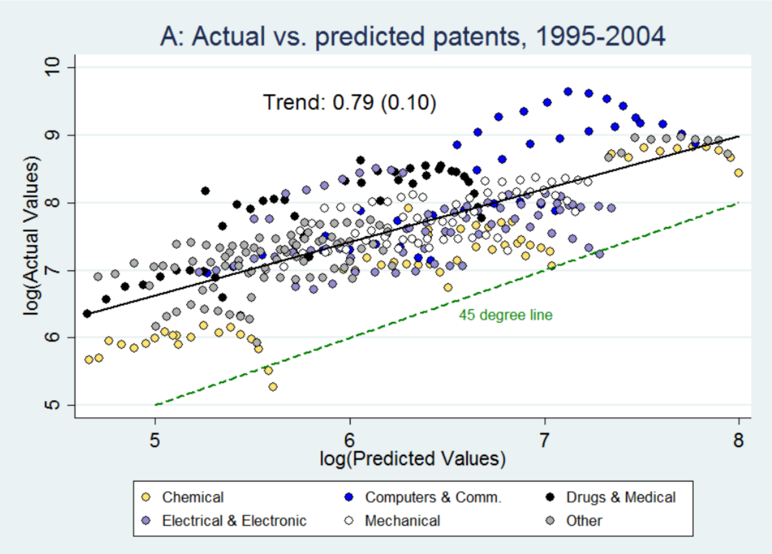
Predicting patents

- Predicted patents in industry j from past citations:

$$\hat{P}_{j,t} = \sum_{k \neq j} \sum_{a=1}^{10} \frac{Citations_{j \to k,a}}{Patents_k} P_{k,t-a}$$

where

- $Citations_{j \to k,a}$ = citations of a patent in industry k that is a years old from j
- $Patents_k$ = total patents in k
- Both estimated using 1975-1994 data
- Predictions for 1995-2004


A: Actual vs. predicted patents, 1995-2004
Trend: 0.79 (0.10)
45 degree line
log(Actual Values)
log(Predicted Values)
5
6
7
8
9
10
5
6
7
8
Chemical
Computers & Comm.
Drugs & Medical
Electrical & Electronic
Mechanical
Other

Appendix Table 2: Disaggregated analysis of innovation network

	Full sample with >5 per annum			Restricted sample with >50 per annum		
	(1)	(2)	(3)	(4)	(5)	(6)
	Dependent variable is log cumulative patent counts in patent class 1995-2004					
Log cumulative patents 1985-1994	0.678	0.732	0.840	0.785	0.806	0.905
	(0.061)	(0.055)	(0.066)	(0.083)	(0.069)	(0.079)
Log expected patenting from network stimulus	0.345			0.265		
	(0.052)			(0.066)		
Log expected patenting from network stimulus due to top 10 upstream classes		0.298			0.294	
		(0.056)			(0.066)	
Log expected patenting from network stimulus due to next 10 upstream classes		0.067			-0.041	
		(0.074)			(0.091)	
Log expected patenting from network stimulus outside of top 20 upstream classes		-0.061			-0.032	
		(0.054)			(0.068)	
Log expected patenting from network stimulus within subcategory			0.077			0.043
			(0.029)			(0.037)
Log expected patenting from network stimulus within rest of category			0.105			0.097
			(0.037)			(0.047)
Log expected patenting from network stimulus outside of category			-0.004			0.012
			(0.048)			(0.054)

Notes: See Appendix Table 1. In Columns 2 and 5, we separate the upstream stimulus provided by the ten most-important upstream classes, the next ten upstream classes, and those beyond. These upstream classes are defined by citation shares made by the focal class during the pre-1995 period. In two cases, the patent class cites fewer than ten upstream categories and is excluded. Columns 3 and 6 alternatively rely on the USPTO classification system of subcategories and categories, which is naturally cruder since it is less-tailored to an individual technology's citation patterns. The disaggregated results do not add up to the total network effect due to the log transformations.

Acemoglu, Daron, Ufuk Akcigit, and William R Kerr. 2016. "Innovation network." *Proceedings of the National Academy of Sciences* :201613559URL http://www.pnas.org/content/113/41/11483.abstract.

Athey, Susan and Glenn Ellison. 2014. "Dynamics of Open Source Movements." *Journal of Economics & Management Strategy* 23 (2):294–316. URL https://onlinelibrary.wiley.com/doi/abs/10.1111/jems.12053.

Claussen, Jörg, Oliver Falck, and Thorsten Grohsjean. 2012. "The strength of direct ties: Evidence from the electronic game industry." *International Journal of Industrial Organization* 30 (2):223 – 230. URL http://www.sciencedirect.com/science/article/pii/S016771871100083X.

Economides, Nicholas. 1996. "The economics of networks." *International Journal of Industrial Organization* 14 (6):673 – 699. URL http://www.sciencedirect.com/science/article/pii/0167718796010156.

Economides, Nicholas and David Encaoua. 1996. “Special issue on network economics: Business conduct and market structure.” *International Journal of Industrial Organization* 14 (6):669 – 671. URL http://www.sciencedirect.com/science/article/pii/0167718796010193.

Fershtman, Chaim and Neil Gandal. 2011. “Direct and indirect knowledge spillovers: the “social network” of open-source projects.” *The RAND Journal of Economics* 42 (1):70–91. URL http://dx.doi.org/10.1111/j.1756-2171.2010.00126.x.

Gandal, Neil and Uriel Stettner. 2016. “Network dynamics and knowledge transfer in virtual organisations.” *International Journal of Industrial Organization* 48:270–290. URL https://www.sciencedirect.com/science/article/pii/S0167718716301278.

Goyal, Sanjeev. 2012. *Connections: an introduction to the economics of networks*. Princeton University Press. URL http://site.ebrary.com/lib/ubc/docDetail.action?docID=10364776.

Jackson, Matthew O. 2010. *Social and economic networks*. Princeton University Press.

Zacchia, Paolo. 2019. "Knowledge Spillovers through Networks of Scientists." *The Review of Economic Studies* 87 (4):1989–2018. URL https://doi.org/10.1093/restud/rdz033.