Network Structure, Industrial Policy, and Innovation

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Introduction

- Industrial policy: *selective* intervention into key economic sectors
  - widely adopted: Japan, South Korea, China, currently also in the US/Europe
  - takes many forms: SOE, directed credit, R&D subsidies, CHIPS, Inflation Reduction Act
  - historically focus on correcting market failures & externalities; infant industry; learning by doing
  - modern revival: geopolitics, international power, technology competition, supply chain resilience

- How to conduct industrial policy?
  - cross-sector linkages important in identifying "strategic", "pillar", "key" sectors, technologies
  - political economy considerations

- Main critiques: information requirement; hard to implement effectively

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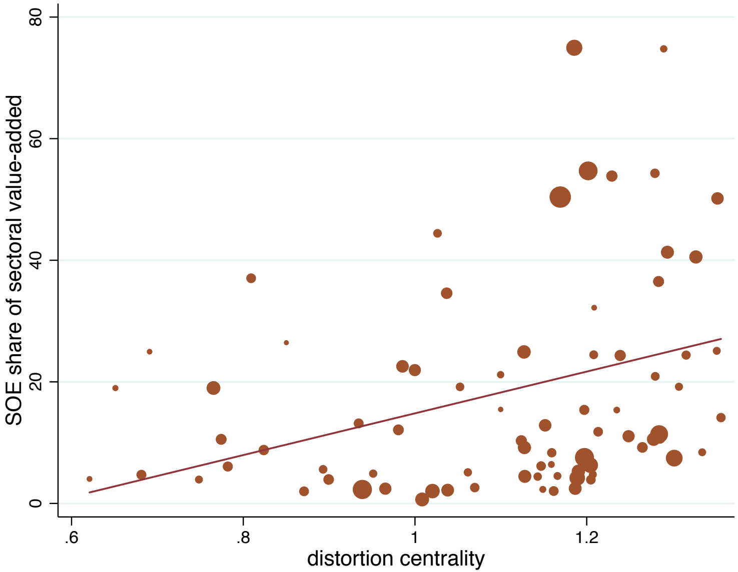
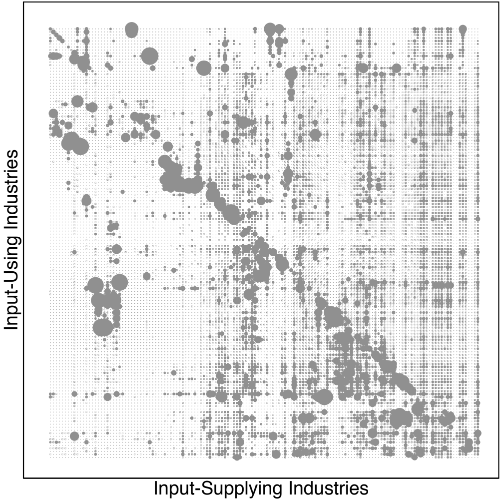
- Main critiques: information requirement; hard to implement effectively
- Liu (2019): industrial policies in production networks
- Liu and Ma (2025): innovation networks and R&D allocation
- Common theme: network sufficient statistics for policy evaluation / counterfactual

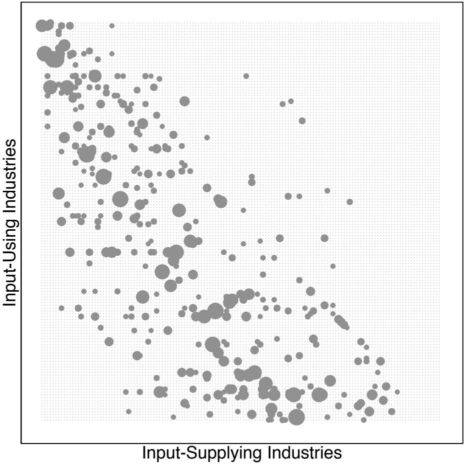
Liu (2019): motivation



Korea's input-output table in 1970



Korea's input-output table in 1970 — sectors ordered by $\xi^{10\%}$

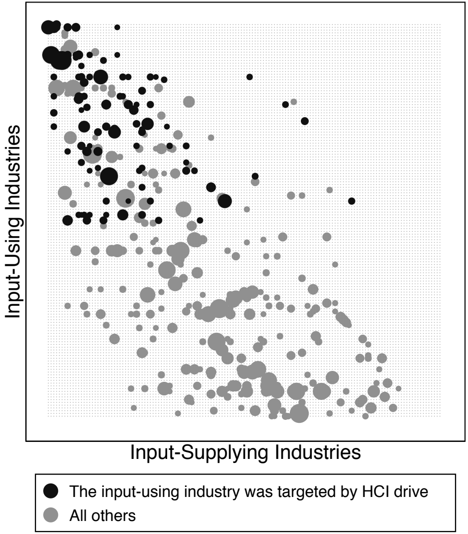


- Testing for hierarchical property: among >1 million unique inequalities,
  - 84% holds true (90% if small violations <0.01 are tolerated)

South Korea in the 1970s promoted sectors with high distortion centrality

“Heavy-Chemical Industry Drive” (1973-1979): promoted six broad “strategic” sectors:

- steel, non-ferrous metals, shipbuilding, machinery, electronics, petrochemicals



Model

- Representative consumer, exogenous factor supply L, one final consumption good

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- Market imperfections $\{\chi_{ij}\}$:
  - financial constraints, contracting frictions, market power, externalities...
  - distort expenditure shares away from production elasticities:

$$(1+\chi_{ij}) \underbrace{\frac{P_j M_{ij}}{P_i Q_i}}_{\text{input expenditure share}} = \underbrace{\frac{\partial \ln F_i\left(L_i, M_{ij}\right)}{\partial \ln M_{ij}}}_{\text{production elasticity}}$$

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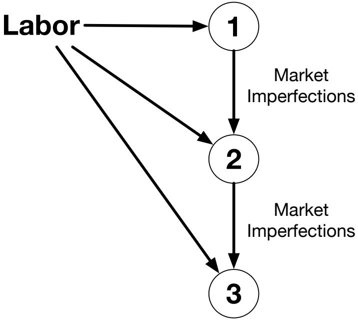
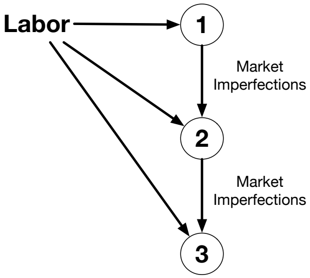


Example

- Example network: three intermediate sectors:
  - upstream (sector 1, iron & steel): $Q_1 = z_1 L_1$
  - midstream (sector 2, machine): $Q_2 = z_2 L_2^{1-\sigma_2} M_{21}^{\sigma_2}$
  - downstream (sector 3, textile): $Q_3 = z_3 L_3^{1-\sigma_3} M_{32}^{\sigma_3}$
  - final good is produced linearly from good 3



- Example market imperfection: intermediate inputs are subject to *credit constraint*s

$$P_i = \min_{\ell_i, m_{i,i-1}, k_i} \left(P_{i-1} m_{i,i-1} + W\ell_i + r k_i \right)$$

$$\text{s.t. } z_i F_i(\ell_i, m_{i,i-1}) \geq 1, \qquad \delta_i P_{i-1} m_{i,i-1} \leq k_i.$$

- Input expenditure

$$P_i M_{i,i-1} = \frac{\sigma_i}{1+\chi_i} P_i Q_i, \qquad \chi_i = r\delta_i$$

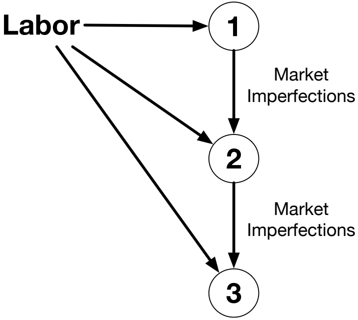
Distortion centrality: the ratio between two standard centrality measures

Standard centrality measures

- "Influence" $\mu_i \equiv \frac{d \ln GDP}{d \ln TFP_i}$: the importance of sectoral TFP
- "Sales share" $\gamma_i \equiv \frac{Sales_i}{GDP}$: sectoral size
- Vertical network: downstream is largest / most influential

$$\mu' \propto \left(\underbrace{\sigma_2\sigma_3}_{\substack{\textbf{upstream} \\ \text{sector 1}}}, \underbrace{\sigma_3}_{\substack{\textbf{midstream} \\ \text{sector 2}}}, \underbrace{1}_{\substack{\textbf{downstream} \\ \text{sector 3}}} \right)$$

$$\gamma' \propto \left(\underbrace{\frac{\sigma_2}{1+r\delta_2} \cdot \frac{\sigma_3}{1+r\delta_3}}_{\substack{\textbf{upstream} \\ \text{sector 1}}}, \underbrace{\frac{\sigma_3}{1+r\delta_3}}_{\substack{\textbf{midstream} \\ \text{sector 2}}}, \underbrace{1}_{\substack{\textbf{downstream} \\ \text{sector 3}}} \right)$$



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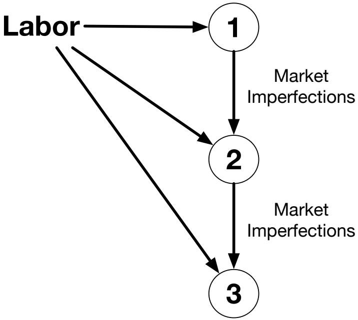

Definition. ***Distortion centrality*** is influence over sales $\xi_i \equiv \mu_i / \gamma_i$.

- In a frictionless economy, $\xi_i = 1$ in all sectors (Hulten 1978)
- In a vertical network, upstream has the highest distortion centrality

$$\xi' \propto \left(\underbrace{(1+\chi_2)(1+\chi_3)}_{\substack{\textbf{upstream} \\ \text{sector 1}}}, \quad \underbrace{1+\chi_3}_{\substack{\textbf{midstream} \\ \text{sector 2}}}, \quad \underbrace{1}_{\substack{\textbf{downstream} \\ \text{sector 3}}} \right)$$

Distortion centrality: captures the value of government subsidies

- Consider sector-specific input subsidies $\{\tau_{ij}\}$

$$(1 - \tau_{ij} + \chi_{ij}) \frac{P_j M_{ij}}{P_i Q_i} = \frac{\partial \ln F_i (L_i, M_{ij})}{\partial \ln M_{ij}}$$

- Subsidies expand sectoral expenditures, but cost government resources
  - balanced subsidies by lump-sum taxes $T \equiv \sum_{i=1}^{N} \left(\sum_{j=1}^{N} \tau_{ij} P_j M_{ij} + \tau_i^L W L_i \right)$

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Theorem

Distortion centrality ξ_i is a sufficient statistic for the social value of policy spending:

$$\left. \frac{dGDP/d\tau_{ij}}{dT/d\tau_{ij}} \right|_{\tau=\mathbf{0}} = \xi_i - 1 \quad \textit{for all } j = 1, ..., S, L.$$

- A general equilibrium spending multiplier; "bang for the buck"

Distortion centrality: quantitatively useful for policy evaluation & counterfactual

- ξ_i: the *social value* of government intervention, incorporating general equilibrium effects
  - $\xi_i > 1 \iff$ subsidizing sector i raises aggregate output

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Proposition

Distortion centrality averages to one across sectors ($\mathbb{E}[\xi] = 1$).

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Proposition

The aggregate gain from sectoral subsidies is

$$\frac{\Delta GDP}{GDP} = Cov(\xi_i, s_i) + O\left(\max_{i,j}\{\tau_{ij}^2\}\right);$$

where s_i is the total subsidy spending per value-added in sector i ($s_i = \frac{\sum_{j=1}^{N} \tau_{ij} P_j M_{ij} + \tau_i^L W L_i}{W L_i}$).

- Useful for policy evaluation & counterfactual

Distortion centrality: importance of upstreamness

- *Should not* promote the most distorted / influential / large sectors
  - In a vertical network, promoting upstream brings the most "bang-for-the-buck"
  - even though upstream is the smallest, least influential, and least distorted

Distortion centrality: importance of upstreamness

- *Should not* promote the most distorted / influential / large sectors
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  - even though upstream is the smallest, least influential, and least distorted
- Result applies to other policy instruments, e.g. subsidized credit
  - cross-sector dispersion in interest rate $\neq$ misallocation

Measuring distortion centrality

Distortion centrality in arbitrary networks:

$$\xi_j = \delta \times \underbrace{\theta_j^F}_{\substack{\text{fraction of good } j \\ \text{sold to consumer}}} + \underbrace{\sum_{i=1}^{N}}_{\substack{\text{sum across} \\ \text{all buyers}}} \left\{ \xi_i \times (1+\chi_{ij}) \times \underbrace{\Theta_{ij}}_{\substack{\text{fraction of good } j \\ \text{sold to buyer } i}} \right\}$$

- High ξ sectors supply disproportionately to distorted sectors, direct or indirectly

matrix notation: $\boldsymbol{\xi}' \propto \boldsymbol{\theta}^{F\prime} \left(\boldsymbol{I} - \mathbf{D} \circ \boldsymbol{\Theta} \right)^{-1}$

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  matrix notation: $\boldsymbol{\xi}' \propto \boldsymbol{\theta}^{F\prime} (\boldsymbol{I} - \mathbf{D} \circ \boldsymbol{\Theta})^{-1}$

- $\boldsymbol{\Theta}$ and $\boldsymbol{\theta}^F$ can be derived from input-output tables, but...

- Empirical challenge: how to measure market imperfections $\mathbf{D} \equiv [1 + \chi_{ij}]$?

$\xi_i^{10\%}$: distortion centrality with constant distortion $\chi_{ij} = 0.1$

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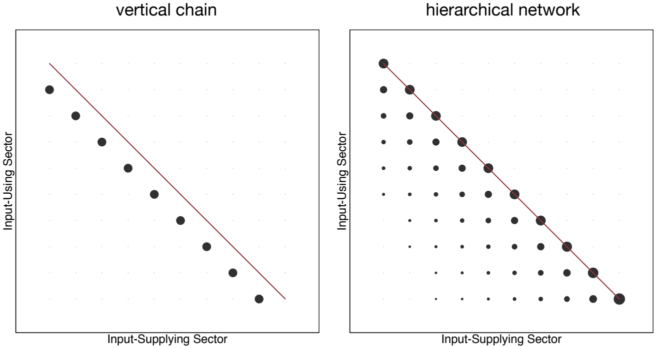
	Average correlation with benchmark $\xi_i^{10\%}$			
	South Korea in 1970		China in 2007	
Panel A: Simulated χ_{ij}'s	**Pearson's r**	**Spearman's ρ**	**Pearson's r**	**Spearman's ρ**
$N(0.1, 0.1)$	0.95	0.93	0.99	0.99
$U[0, 0.1]$	0.98	0.97	1	1
$Exp(0.1)$	0.95	0.94	0.98	0.99
Panel B: Estimated χ_{ij}'s				
De Loecker and Warzynski	-	-	0.99	0.99
Foreign firms as controls	-	-	0.98	0.98
Rajan and Zingales	0.98	0.97	0.98	0.98
Self-reported financial costs	-	-	0.92	0.92
Sectoral profit share	0.91	0.91	0.99	0.98
"Upstreamness" by Antras et al. (2012)	0.96	0.96	0.98	0.97

Measuring distortion centrality

- **Hierarchical networks**: extensions of vertical networks
  - relatively upstream sectors supply disproportionately to other relatively upstream sectors
  - formal definition: IO matrix exhibits decreasing partial column sums



- ξ tends to align with upstreamness (Antras et al. 2012) in hierarchical networks

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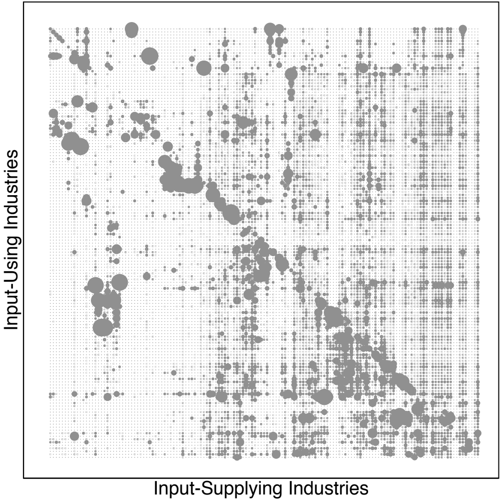

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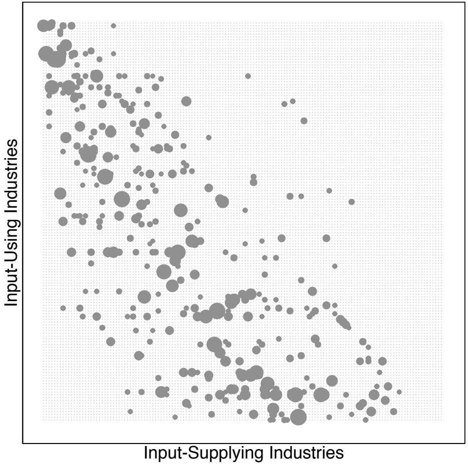

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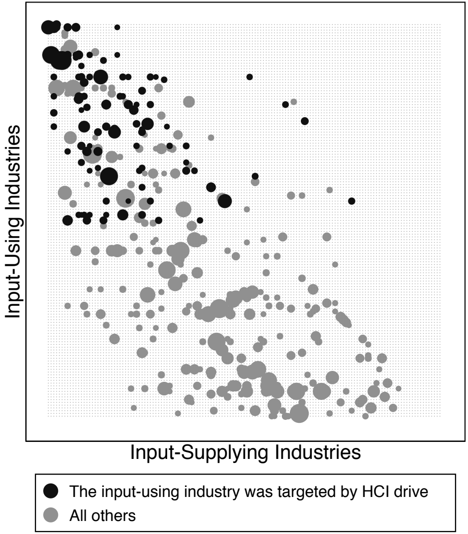
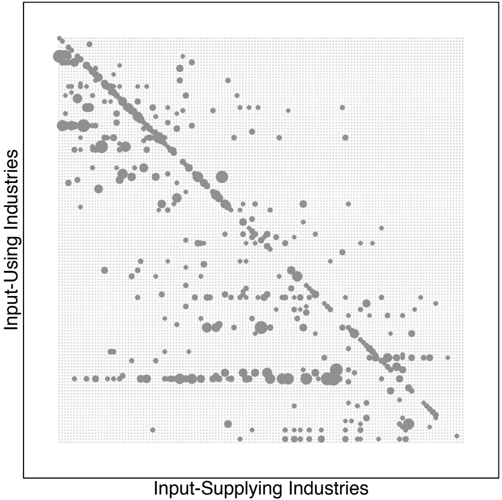


Input-output table of China in 2007 — sectors ordered by $\xi^{10\%}$



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  - 85% holds true (90% if small violations <0.01 are tolerated)

Which Chinese industries have high / low distortion centralities?

Top 10	Bottom 10
Coke making	Canned food products
Nonferrous metals and alloys	Dairy products
Ironmaking	Other miscellaneous food products
Ferrous alloy	Condiments
Steelmaking	Drugs
Metal cutting machinery	Meat products
Chemical fibers	Grain mill products
Electronic components	Liquor and alcoholic drinks
Specialized industrial equipments	Vegetable oil products
Basic chemicals	Tobacco

In China, ξ_i predicts sectoral credit, taxes, and SOE subsidies

	Int. Rate	Debt Ratio	Tax Break	Tax Rate	SOE Share
	(1)	(2)	(3)	(4)	(5)
ξ_i	-0.987^{***}	2.726^{***}	2.911^{**}	-1.589^{***}	7.577^{**}
	(0.223)	(0.622)	(1.412)	(0.431)	(2.963)
adj. R^2	0.301	0.231	0.097	0.176	0.066
Controls	Yes	Yes	Yes	Yes	Yes
# Obs.	79	79	79	79	79

- In sectors with high distortion centrality,
  - firms pay lower interest rates and have more external debt
  - firms pay lower taxes
  - more state-owned enterprises
- Pattern survives after controlling for other potential reasons for intervention
  - capital intensity, profit share, scale of industry, export intensity

To first-order, industrial policies in China account for 6.7% gain in GDP

- Chinese sectoral policies in credit, taxes, and government subsidies to SOEs have all contributed to aggregate efficiency gains

		% GDP gains			
Distortion centrality specification	$sd(\xi)$	Credit	Taxes	SOEs	Total
Benchmark ($\xi^{10\%}$)	0.22	1.69	0.64	1.27	3.60
De Loecker and Warzynski	0.42	3.07	1.19	2.39	6.65
Foreign firms as controls	0.25	1.69	0.67	1.16	3.51
Rajan and Zingales	0.11	1.01	0.36	0.65	2.02
Sectoral profit share	0.17	1.20	0.47	0.95	2.62

Counterfactuals

- Targeting sectors by capital intensity, size, or value-added is unlikely to be effective

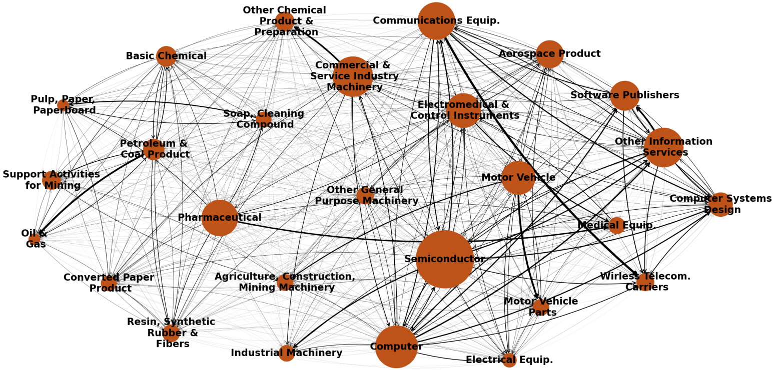
	% GDP gains				
Specification for ξ	$\xi^{10\%}$	**DLW**	Foreign	RZ	ProfitShr
Real-world interventions	3.60	6.65	3.51	2.02	2.62
Counterfactual policy target					
Sales γ	-1.42	-2.57	-1.18	-0.83	-1.14
Consumption share	-2.56	-4.62	-2.43	-1.44	-1.90
Export intensity	1.13	1.98	0.99	0.79	0.80
Sectoral value-added	-1.30	-2.41	-1.11	-0.75	-0.95
Interm. exp. share	1.34	2.39	1.11	0.83	0.87
Optimal Assignment	5.33	10.18	5.85	2.97	3.97

Conclusion

- The covariance formula ($\Delta \ln GDP \approx Cov(\xi_i, GovtSpending_i)$) reveals:
  - Chinese sectoral policies in credit, taxes, and government subsidies to SOEs have all contributed to aggregate efficiency gains
  - altogether account for about 6.7% gains
- Counterfactuals analysis: targeting sectors by capital intensity, size, or value-added is unlikely to be effective
- Many arguments against industrial policies:
  - my theory abstracts away from political economy factors
- Yet, evidence suggests that certain aspects of Korean and Chinese industrial strategy might be motivated by a desire to subsidize sectors that create positive network effects

Liu and Ma (2023) "Innovation Networks and R&D Allocation"

- Innovation is the source of long-run growth
- How to optimally allocate R&D resources to stimulate technological innovation?
  - many economies have dedicated government agencies for innovation policy
  - existing literature focuses on *over-time* or *within-sector* allocation of R&D resources
- **This paper: *cross-sector* allocation of R&D resources in the presence of innovation network**



Baseline model: closed-economy, multi-sector, endogenous growth, knowledge spillovers

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$$\text{Preferences:} \quad \int_0^\infty e^{-\rho t} \ln c_t \, \mathrm{d}t, \quad c_t = \prod_{i=1}^{K} c_{it}^{\beta_i} \qquad \text{Technology:} \quad c_{it} = q_{it}^{\psi} \ell_{it}$$

- q_{it}: a sector's knowledge stock (state variable); can be improved through R&D

$$\text{Flow innovation output:} \quad n_{it} = s_{it}\chi_{it}, \qquad \chi_{it} \equiv \eta_i \prod_{j=1}^{K} q_{jt}^{\omega_{ij}}$$

  - s_{it}: amount of R&D resources used in sector i
  - χ_{it}: R&D productivity; an aggregator of prior knowledge that is useful for R&D in sector i
  - $\mathbf{\Omega} \equiv [\omega_{ij}]$ defines the innovation network; row-sum normalized to one

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- Flow innovation n_{it} improves knowledge stock q_{it} according to the law of motion

$$\dot{q}_{it}/q_{it} = \lambda \ln \left(n_{it}/q_{it} \right)$$

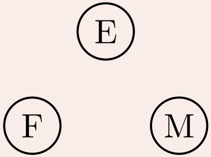
  - without cross-sector spillover ($\boldsymbol{\Omega} = \boldsymbol{I}$), law of motion collapses to $\dot{q}_{it}/q_{it} = \lambda \ln \left(\eta_i s_{it} \right)$

- Given total production and R&D resources ($\bar{\ell}$, $\bar{s}$), how to allocate across sectors (ℓ_{it}, s_{it})?

Example

- Imagine we like **F**ood, **E**lectronics, and **M**edical Devices
- $\beta' = (\beta_F, \beta_E, \beta_M) = (.4, .4, .2)$ capturing "how much" we like them
- R&D can help improve quality or productivity of goods, q_F, q_E, q_M

Intuition & Example



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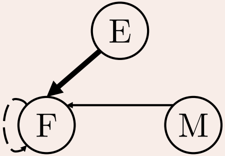

$$\Omega = \begin{array}{c} F \\ E \\ M \end{array} \overset{\begin{array}{ccc} F & E & M \end{array}}{\begin{bmatrix} .40 & .50 & .10 \\ & & \\ & & \end{bmatrix}}, \begin{bmatrix} \chi_F = q_F^{0.40} \cdot q_E^{0.50} \cdot q_M^{0.10} \\ \\ \\ \end{bmatrix},$$

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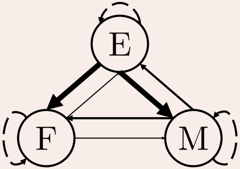

$$\Omega = \begin{array}{c} \\ F \\ E \\ M \end{array} \begin{array}{c} \begin{array}{ccc} F & E & M \end{array} \\ \left[\begin{array}{ccc} .40 & .50 & .10 \\ .05 & .85 & .10 \\ .05 & .75 & .20 \end{array}\right] \end{array}, \left[\begin{array}{l} \chi_F = q_F^{0.40} \cdot q_E^{0.50} \cdot q_M^{0.10} \\ \chi_E = q_F^{0.05} \cdot q_E^{0.85} \cdot q_M^{0.10} \\ \chi_M = q_F^{0.05} \cdot q_E^{0.75} \cdot q_M^{0.20} \end{array}\right],$$

Optimal R&D allocation: planner's optimal control problem

$$V(\{q_{i0}\}) \equiv \max_{\{s_{it}, \ell_{it}\}} \int_0^\infty e^{-\rho t} \sum_i \beta_i (\ln q_{it} + \ln \ell_{it})\, dt$$

$$\text{s.t.} \;\; \dot{q}_{it}/q_{it} = \lambda \left(\ln \eta_i + \ln s_{it} + \sum_j \omega_{ij} (\ln q_{jt} - \ln q_{it}) \right), \quad \sum_i s_{it} = \bar{s}, \quad \sum_i \ell_{it} = \bar{\ell}.$$

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Proposition. For any $\boldsymbol{q}_0$, the optimal allocation of resources is time-invariant: $\ell_{it} = \beta_i \bar{\ell}$ for all t, and

$s_{it} = \gamma_i \bar{s}$ for all t, where $\boldsymbol{\gamma}' \propto \boldsymbol{\beta}' \left(\boldsymbol{I} - \frac{\boldsymbol{\Omega}}{1+\rho/\lambda} \right)^{-1} \equiv \boldsymbol{\beta}' \left(\boldsymbol{I} + \frac{\boldsymbol{\Omega}}{1+\rho/\lambda} + \left(\frac{\boldsymbol{\Omega}}{1+\rho/\lambda} \right)^2 + \cdots \right).$

- Planner incorporates (and discounts) future network spillover effects
  - more patience (low ρ/λ) $\Rightarrow$ network effects matter more

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- Planner incorporates (and discounts) future network spillover effects
  - more patience (low ρ/λ) $\Rightarrow$ network effects matter more
- Extensions: (1) production network; (2) general function forms (endogenous $\boldsymbol{\Omega}$); (3) time-varying, exogenous $\boldsymbol{\Omega}_t$; (4) semi-endogenous growth; (5) factor mobility (btwn. $\bar{\ell}$ and $\bar{s}$); (6) open economy

Innovation centrality and economic growth

- Let $\boldsymbol{a}$ denote the eigenvector centrality of $\boldsymbol{\Omega}$ (i.e., $\boldsymbol{a}' = \boldsymbol{a}'\boldsymbol{\Omega}$, normalized to sum to one)

Lemma. Given time-invariant R&D allocation $\boldsymbol{b}$, the consumption growth rate in a balanced growth path is

$$g(\boldsymbol{b}) = \text{const} + \psi\lambda \times \boldsymbol{a}' \ln \boldsymbol{b}.$$

Proposition. $\boldsymbol{a}$ is the allocation vector (i.e., $s_i/\overline{s} = a_i$) that maximizes the BGP growth rate.

- Optimal R&D $\boldsymbol{\gamma}$ is a weighted average between preferences ($\boldsymbol{\beta}$) and growth-maximizing R&D ($\boldsymbol{a}$)

$$\gamma' (\boldsymbol{I} - \boldsymbol{\Omega}) + \frac{\rho}{\lambda} (\gamma' - \beta') = \mathbf{0}'$$

  - myopic planner: $\lim_{\rho\to\infty} \boldsymbol{\gamma} = \boldsymbol{\beta}$; very patient planner: $\lim_{\rho\to 0} \boldsymbol{\gamma} = \boldsymbol{a}$

Example

Intuition & Example

- Set $\rho = 0.05$, $\lambda = 0.17$:

$$\text{Recall:} \quad \beta = \begin{bmatrix} .4 \\ .4 \\ .2 \end{bmatrix}, \quad \mathbf{\Omega} = \begin{bmatrix} .4 & .5 & .1 \\ .05 & .85 & .1 \\ .05 & .75 & .2 \end{bmatrix}, \quad \boldsymbol{a} = \begin{bmatrix} .08 \\ .81 \\ .11 \end{bmatrix}$$

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Welfare gains from R&D reallocation

Proposition. Consumption-equivalent welfare gain of reallocating R&D from $\boldsymbol{b}$ to $\boldsymbol{\gamma}$ is

$$\mathcal{L}(\boldsymbol{b}) = \exp\left(\frac{\psi\lambda}{\rho} \times \boldsymbol{\gamma}'(\ln \boldsymbol{\gamma} - \ln \boldsymbol{b})\right)$$

- Consumer just as well off under $\boldsymbol{b}$ as under $\boldsymbol{\gamma}$ if consumption multiplied by $\mathcal{L}(\boldsymbol{b})$ at all times

Intuition & Example

- Recall $\boldsymbol{\gamma} = (.18, .69, .13)$, say $\boldsymbol{b} = (1/3, 1/3, 1/3)$, set $\psi = 0.06$:

$$\ln \mathcal{L}(\boldsymbol{b}) = 5.4\%$$

Model extension: general functional forms (endogenous Ω)

	Baseline model	General functional form
preferences	$\int_0^\infty e^{-\rho t} \sum_i \beta_i \ln y_{it}\,\mathrm{d}t$	$\int_0^\infty e^{-\rho t} \ln \mathcal{Y}(y_{it})\,\mathrm{d}t$, $\mathcal{Y}$ CRTS
law of motion	$\dot{q}_{it}/q_{it} = \lambda \ln \left(s_{it}\eta_i \prod_j q_{jt}^{\omega_{ij}} / q_{it} \right)$	$\dot{q}_{it}/q_{it} = \lambda \ln \left(s_{it}\mathcal{X}_i(\{q_{jt}\}) \right)$

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law of motion	$\dot{q}_{it}/q_{it} = \lambda \ln \left(s_{it}\eta_i \prod_j q_{jt}^{\omega_{ij}} / q_{it} \right)$	$\dot{q}_{it}/q_{it} = \lambda \ln \left(s_{it}\mathcal{X}_i(\{q_{jt}\}) \right)$

- In a BGP with R&D allocation $\boldsymbol{b}$, define local elasticities (in BGP, $\mathcal{X}_i$ is locally homog. of deg 0)

$$\beta_i \equiv \frac{\partial \ln \mathcal{Y}(\{q_{it}\ell_{it}\})}{\partial \ln q_{it}}, \qquad \omega_{ij} \equiv \frac{\partial \ln \mathcal{X}_i(\{q_{jt}\})}{\partial \ln q_{jt}}, \qquad \omega_{ii} = 1 - \frac{\partial \ln \mathcal{X}_i(\{q_{jt}\})}{\partial \ln q_{jt}}$$

- Define $\boldsymbol{\gamma}' = \frac{\rho}{\rho+\lambda}\boldsymbol{\beta}' \left(\boldsymbol{I} - \frac{\boldsymbol{\Omega}}{1+\rho/\lambda} \right)^{-1}$

Proposition. (General Functional Forms) To first-order, around the observed BGP, the consumption-equivalent welfare gain of moving R&D allocation from $\boldsymbol{b}$ to $\widetilde{\boldsymbol{b}}$ is

$$\exp\left(\frac{\psi\lambda}{\rho} \times \boldsymbol{\gamma}' \left(\ln \widetilde{\boldsymbol{b}} - \ln \boldsymbol{b} \right) \right).$$

Model extension: semi-endogenous growth

	Baseline model	Semi-endogenous growth
preferences	$\int_0^\infty e^{-\rho t} \sum_i \beta_i \ln\left(q_{it}\ell_{it}\right) \mathrm{d}t$	$\int_0^\infty e^{-\rho t} \sum_i \beta_i \ln\left(q_{it}\ell_{it}\right) \mathrm{d}t$
innovation flow	$n_{it} = \eta_i s_{it} \prod_j q_{jt}^{\omega_{ij}}$	$n_{it} = \eta_i s_{it} \prod_j q_{jt}^{\omega_{ij}}$
law of motion	$\dot{q}_{it}/q_{it} = \lambda \ln\left(n_{it}/q_{it}\right)$	$\dot{q}_{it}/q_{it} = \lambda \ln\left(n_{it}/q_{it}^{(1+\kappa)}\right)$

- Baseline model: $\kappa = 0$, endogenous growth with fixed population
- $\kappa > 0 \implies$ semi-endogenous growth; optimal R&D and welfare accounting formula:

$$\boldsymbol{\gamma}' \propto \boldsymbol{\beta}'\left(I - \frac{\boldsymbol{\Omega}}{1+\kappa+\rho/\lambda}\right)^{-1}$$

$$\ln \boldsymbol{\mathcal{L}} = \frac{\rho}{\kappa\lambda+\rho}\,\frac{\psi\lambda}{\rho}\boldsymbol{\gamma}'\left(\ln\boldsymbol{\gamma} - \ln\boldsymbol{b}\right)$$

Model extension: unilaterally optimal R&D with foreign spillovers

- Suppose the economy benefits from foreign spillovers: $\chi_{it} \equiv \eta_i \prod_j \left[(q_{jt})^{x_{ij}} \left(q_{jt}^f \right)^{1-x_{ij}} \right]^{\omega_{ij}}$
  - x_{ij}: share of domestic contribution of spillovers from j to i
- **Unilaterally optimal**: maximize domestic welfare, taking the path of foreign knowledge as given

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$$\text{Optimal R\&D allocation:} \quad \boldsymbol{\gamma}' \propto \boldsymbol{\beta}' \left(\boldsymbol{I} - \frac{\boldsymbol{\Omega} \circ \boldsymbol{X}}{1 + \rho/\lambda} \right)^{-1}$$

- An economy reliant on foreign knowledge (lower x) should choose R&D as if impatient (high ρ/λ)
  - countries with self-contained network $\Rightarrow$ invest more in innovation-central sectors

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- An economy reliant on foreign knowledge (lower x) should choose R&D as if impatient (high ρ/λ)
  - countries with self-contained network ⇒ invest more in innovation-central sectors
- Open economy log-welfare gains from optimal R&D reallocation is

$$\ln \mathcal{L}(\boldsymbol{b}, \xi) = \underbrace{\xi}_{\text{R\&D self-sufficiency}} \times \frac{\psi\lambda}{\rho} \underbrace{\boldsymbol{\gamma}' (\ln \boldsymbol{\gamma} - \ln \boldsymbol{b})}_{\text{misallocation}}$$

  - more foreign dependent economies (lower ξ) have less to gain from optimal R&D allocations
  - $\xi \equiv \frac{\rho}{\rho+\lambda} \boldsymbol{\beta}' \left(\boldsymbol{I} - \frac{\boldsymbol{\Omega} \circ \boldsymbol{X}}{1+\rho/\lambda} \right)^{-1} \mathbf{1}$. ξ is decreasing in foreign-reliance; $\xi = 1$ only if $x_{ij} = 1 \ \forall i, j$

Outline

- Theory
- Data and descriptives
- Empirical validation of key knowledge spillover mechanism
- Application: assessing R&D allocations across countries
- Conclusions

Map to Empirical Applications

γ	Optimal Allocation	$\gamma' \propto \beta' \left(\boldsymbol{I} - \frac{\boldsymbol{\Omega} \circ \boldsymbol{X}}{1+\rho/\lambda} \right)^{-1}$
$\ln \mathcal{L}(\boldsymbol{b}, \xi)$	Potential Welfare Gains	$\ln \mathcal{L}(\boldsymbol{b}, \xi) = \xi \times \frac{\psi \lambda}{\rho} \gamma' (\ln \gamma - \ln \boldsymbol{b})$

- Key Data:
  - $\boldsymbol{\beta}$: sectoral value-added
  - $\boldsymbol{\Omega}$: innovation network
  - $\boldsymbol{X}$: self-dependence on innovation production
  - $\boldsymbol{b}$: real-world R&D allocation
- Parametrization: $\rho = 0.05$, $\lambda = 0.17$, $\psi = 0.06$
  - optimal allocation γ is robust to alternative parameter values; so is the relative entropy $\gamma' (\ln \gamma - \ln \boldsymbol{b})$
  - welfare effect sensitive to ψ
  - calibrated so that $\frac{\mathrm{d} g^y}{\mathrm{d} \ln \bar{s}} = 0.01$ (semi-elasticity of BGP consumption growth to R&D stock $\bar{s}$)

Innovation Data: Domestic and International

To construct the innovation network $\boldsymbol{\Omega}$, we rely on patent citations

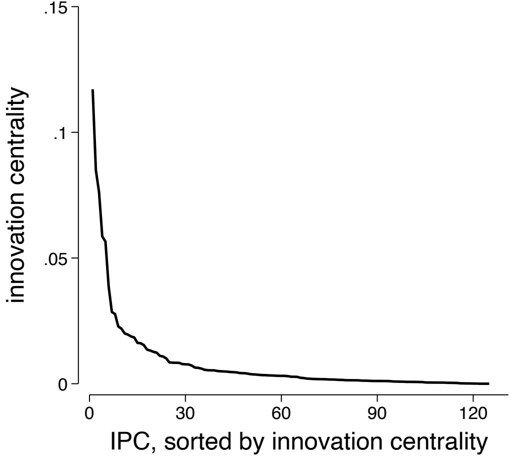
$$\text{(baseline definition)} \qquad \omega_{ij} \equiv \frac{Citations_{ij}}{\sum_k Citations_{ik}}$$

- Domestic U.S. Patent Data from USPTO: 6.9 Million Patents, 1975–2020
  - key information: filing year, assignee, technology class (IPC), citation relations
- International Patent Data from Google Patents: 36 million patents from 42 countries, 1976–2020
  - combines patent data from more than twenty major patent offices (US, Japan, China, EPO, ...)
  - identify unique innovation (origin country and sectors) from multiple patent filings ("patent family")

Production-side information: WIOD

R&D data from firm-level data sets (Compustat, Worldscope, Datastream) and OECD-ANBERD

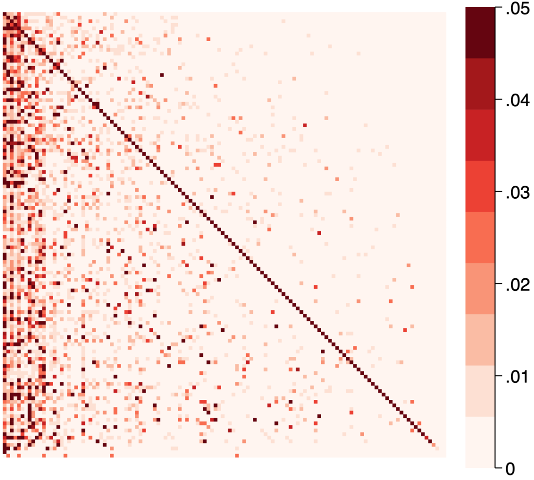
Innovation centrality a is highly heterogeneous



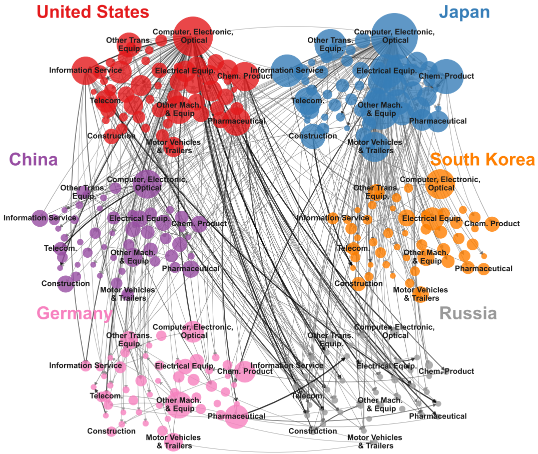
1	A61	medical or veterinary science; hygiene
2	G06	computing; calculating or counting
3	H01	basic electric elements
4	H04	electric communication technique
5	G01	measuring; testing
6	B60	vehicles in general
7	G02	optics
8	B01	physical or chemical processes or apparatus in general
9	C08	organic macromolecular compounds; their preparation or chemical working-up; compositions based thereon
10	F16	engineering elements or units; general measures for producing and maintaining effective functioning of machines or installations; thermal insulation in general

Innovation network Ω visualization, IPC-to-IPC

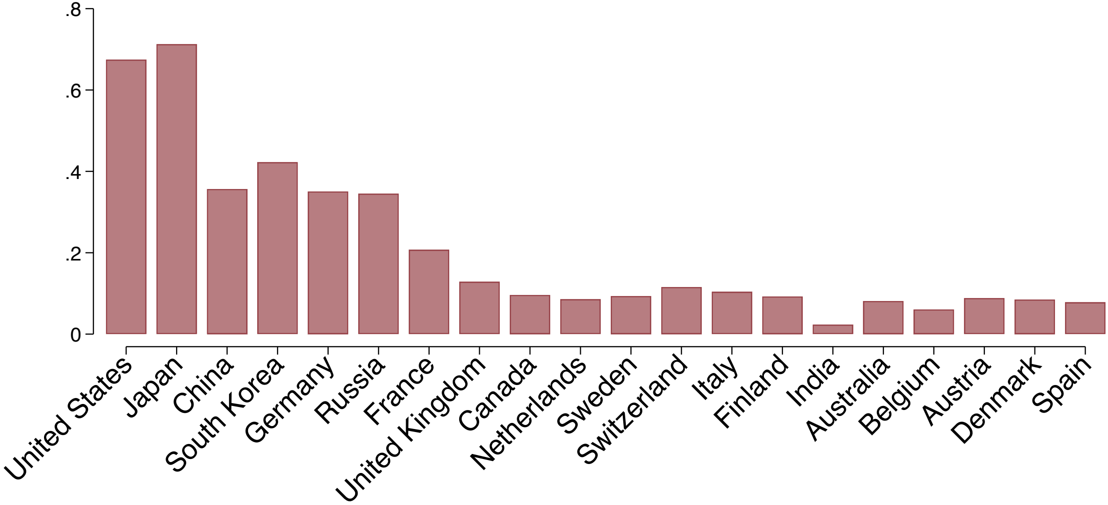
(a) IPC-to-IPC (131×131) network **Ω**



(b) The global innovation network



x_{ij}: Domestic citation shares across 20 countries



- The innovation network $\boldsymbol{\Omega}$ is highly stable across countries and time
  - only weakly correlated with production network

Countries	All	US	Japan	China	South Korea	Germany	Russia	France	UK	Canada	Netherlands
All		0.98	0.87	0.87	0.84	0.89	0.63	0.86	0.92	0.88	0.81
US	0.95		0.84	0.86	0.82	0.88	0.64	0.85	0.92	0.88	0.80
Japan	0.86	0.83		0.88	0.89	0.85	0.63	0.87	0.86	0.84	0.83
China	0.85	0.86	0.87		0.88	0.85	0.66	0.85	0.87	0.86	0.82
South Korea	0.78	0.77	0.83	0.84		0.84	0.64	0.84	0.85	0.82	0.84
Germany	0.85	0.87	0.81	0.80	0.72		0.64	0.83	0.87	0.83	0.81
Russia	0.62	0.63	0.62	0.62	0.55	0.61		0.65	0.64	0.64	0.66
France	0.91	0.86	0.79	0.77	0.72	0.82	0.57		0.86	0.85	0.83
UK	0.87	0.89	0.85	0.85	0.80	0.86	0.64	0.80		0.88	0.82
Canada	0.86	0.88	0.79	0.81	0.71	0.81	0.59	0.80	0.81		0.81
Netherlands	0.84	0.85	0.79	0.82	0.75	0.79	0.58	0.78	0.79	0.81	

Time Period	All years	2020	2010	2000	1990	1980
All years		0.98	0.98	0.97	0.90	0.89
2020	0.95		0.97	0.93	0.86	0.85
2010	0.96	0.97		0.96	0.88	0.87
2000	0.93	0.92	0.96		0.92	0.90
1990	0.90	0.80	0.84	0.90		0.91
1980	0.81	0.77	0.81	0.87	0.89	

- Significant cross-country variation in optimal R&D allocation γ

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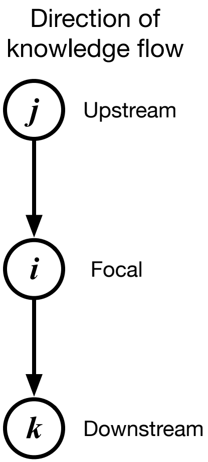
Evidence for knowledge spillover, building on Acemoglu, Akcigit, and Kerr (PNAS 2016)



- Upstream patents foster sector i's future innovation; effect weakens over time

$$\ln n_{it} = \ln \eta_i + \ln s_{it} + \lambda \underbrace{\sum_{j=1}^{K} \omega_{ij} \left(\int_0^\infty e^{-\lambda s} \ln n_{jt-s}\, \mathrm{d}s \right)}_{\text{knowledge from upstream sectors}}$$

- We construct the empirical counterpart to "knowledge from upstream":

$$\text{Knowledge}_{it}^{Up} \equiv \sum_{j=1, j\neq i}^{K} \omega_{ij} \sum_{s=1}^{10} \log Patent_{j,t-s}$$

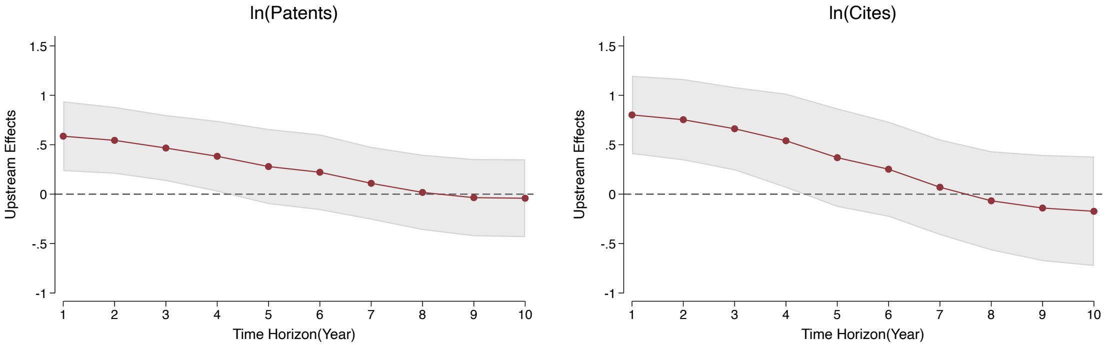
- We show $\text{Knowledge}_{it}^{Up}$ predicts sector i's innovation, effects decay over time
  - holds in both the U.S. domestic & the global innovation networks
- To rule out "common shock", we show:
  1. "knowledge" from downstream doesn't predict sector i's innovation
  2. "knowledge" aggregated through input-output linkages doesn't either
  3. results robust to using tax-induced R&D cost variations as IV (Bloom et al. 2013)

Upstream knowledge fosters new innovation in focal sector

$$Innovation_{it} = \beta \times \text{Knowledge}_{it}^{Up} + \xi_i + \xi_t + \text{control}_{it} + \varepsilon_{it}$$

$Y=$	ln(Patents)				ln(Cites)			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$Knowledge_{it}^{Up}$	0.586***	0.600***	0.508***	0.679**	0.802***	0.830***	0.743***	0.974***
	(0.180)	(0.205)	(0.174)	(0.266)	(0.202)	(0.218)	(0.196)	(0.279)
$ln(R\&D)_{i,t-1}$	0.275***	0.274***	0.279***	0.269***	0.258***	0.256***	0.261***	0.174**
	(0.063)	(0.062)	(0.060)	(0.070)	(0.086)	(0.086)	(0.086)	(0.082)
$Knowledge_{it}^{Down}$		-0.029				-0.058		
		(0.157)				(0.098)		
$Knowledge_{it}^{Up,IO}$			0.363**				0.268	
			(0.173)				(0.205)	
Specification	OLS	OLS	OLS	IV 2nd Stage	OLS	OLS	OLS	IV 2nd Stage
IV 1st Stage F-statistics				465.9				465.9
R^2	0.915	0.915	0.917	0.152	0.901	0.901	0.902	0.099
No. of Sectors	94	94	94	94	94	94	94	94
No. of Obs	1847	1847	1847	1113	1847	1847	1847	1113
Fixed Effects	Sector, Year				Sector, Year			

Impulse response shows upstream spillover effect weakens over longer lags



Global Innovation Network

$$Innovation_{mit} = \beta^{Up} \times \text{Knowledge}^{Up}_{mit} + \beta^{Down} \times \text{Knowledge}^{Down}_{mit} + \xi_{mi} + \xi_{mt} + \xi_{it} + \varepsilon_{mit}$$

$Y=$	ln(Patents)				ln(Cites)			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$Knowledge^{Up}_{mit}$	0.157***	0.199***	0.154***	0.202*	0.348***	0.424***	0.345***	0.405***
	(0.057)	(0.061)	(0.057)	(0.113)	(0.083)	(0.089)	(0.084)	(0.147)
$ln(R\&D)_{mi,t-1}$	0.033***	0.034***	0.032***	0.066***	0.046***	0.046***	0.046***	0.072***
	(0.010)	(0.010)	(0.010)	(0.014)	(0.014)	(0.014)	(0.014)	(0.022)
$Knowledge^{Down}_{mit}$		-0.091**				-0.167***		
		(0.043)				(0.059)		
$Knowledge^{Up,IO}_{mit}$			0.079				-0.038	
			(0.064)				(0.070)	
Specification	OLS	OLS	OLS	IV 2nd Stage	OLS	OLS	OLS	IV 2nd Stage
IV 1st Stage F-statistics				146.2				146.2
R^2	0.969	0.969	0.969	0.040	0.944	0.944	0.945	0.031
No. of Country x Sectors	564	564	550	280	564	564	550	280
No. of Obs	10,552	10,552	10,318	4,467	10,552	10,552	10,318	44,67
Fixed Effects	Country x Sector, Country x Year, Sector x Year				Country x Sector, Country x Year, Sector x Year			

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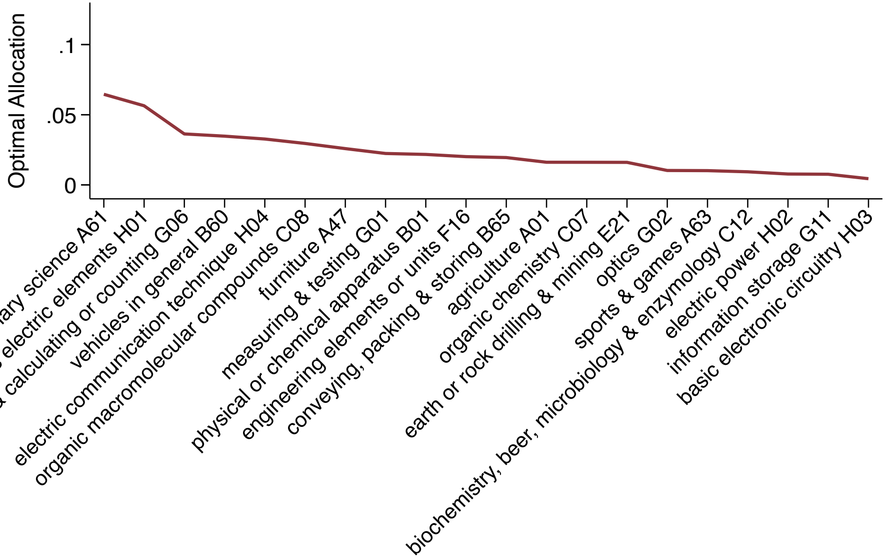
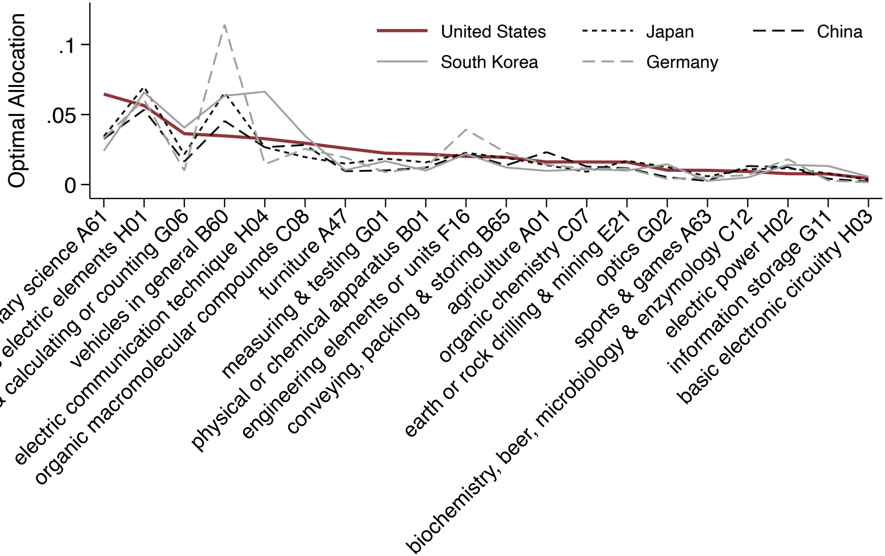
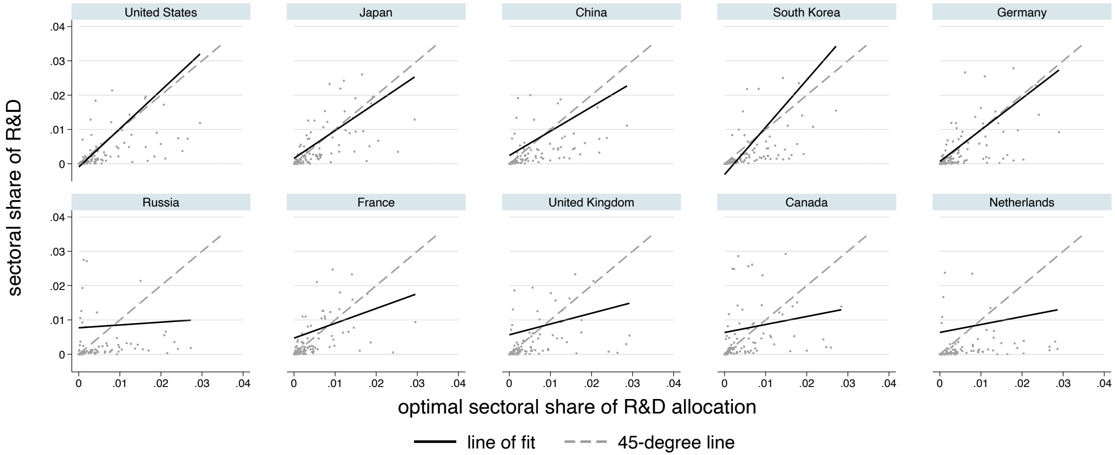
Optimal R&D Allocation in US



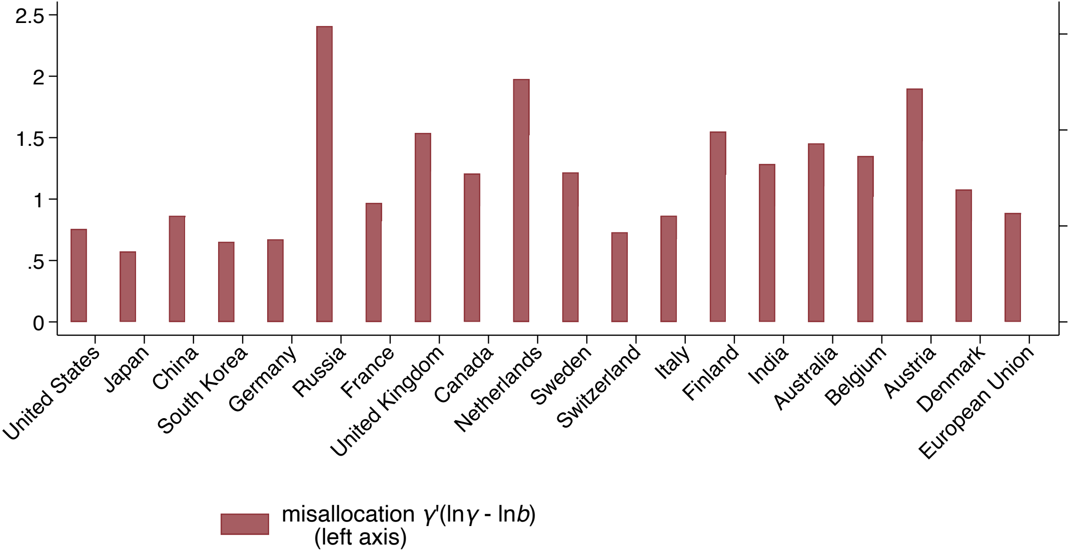
Optimal R&D Allocation in Top Innovative Economies



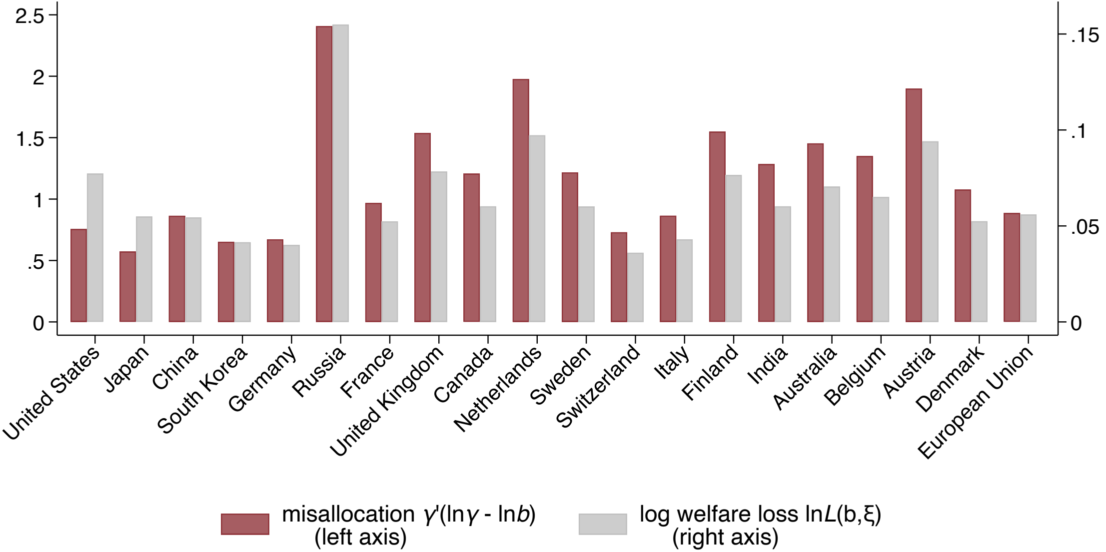
Actual vs optimal R&D allocations across countries (2010–2014)



R&D allocative inefficiency in the data



R&D allocative inefficiency in the data

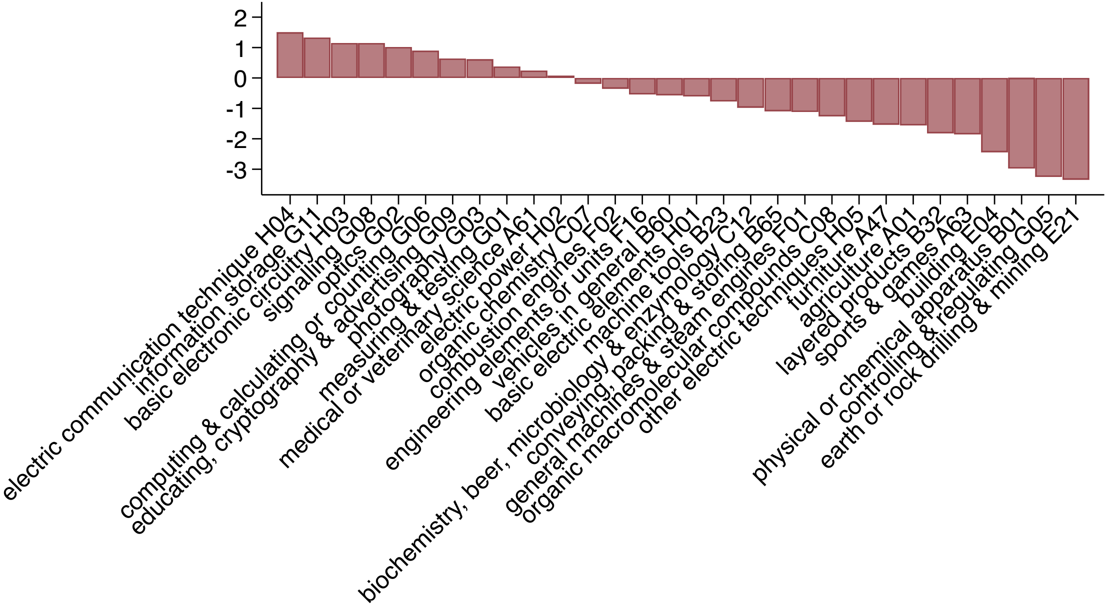


Consumption-equivalent welfare gains

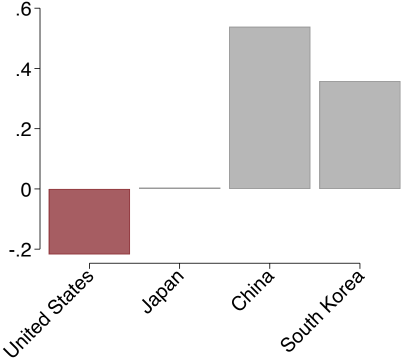
	US	Japan	China	South Korea	Germany	Russia	France	UK	Canada	Netherlands
2000	9.98	4.24	5.78	5.25	4.79	13.70	5.17	7.55	7.22	6.70
2005	8.85	5.04	5.26	3.92	4.11	11.18	5.38	8.17	7.29	5.45
2010	8.04	5.64	5.60	4.24	4.09	16.76	5.38	8.15	6.21	10.22

	Sweden	Switzerland	Italy	Finland	India	Australia	Belgium	Austria	Denmark	European Union
2000	6.65	5.18	5.04	5.39	10.91	5.72	5.72	6.52	5.93	5.91
2005	5.53	4.10	4.57	5.63	8.33	4.19	5.62	8.50	5.30	5.04
2010	6.20	3.67	4.40	7.95	6.21	7.30	6.73	9.87	5.39	5.76

Log-difference between actual and optimal R&D allocation, US, top 30 IPCs

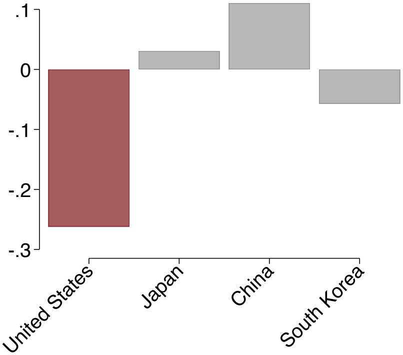


Examples of Misallocation (1): Semiconductors



- US underfunds semi-conductor R&D by about 21%
- South Korea and China invest more aggressively
- Policy Relevance
  - CHIPS for America Act
  - Facilitating American-Built Semiconductors Act

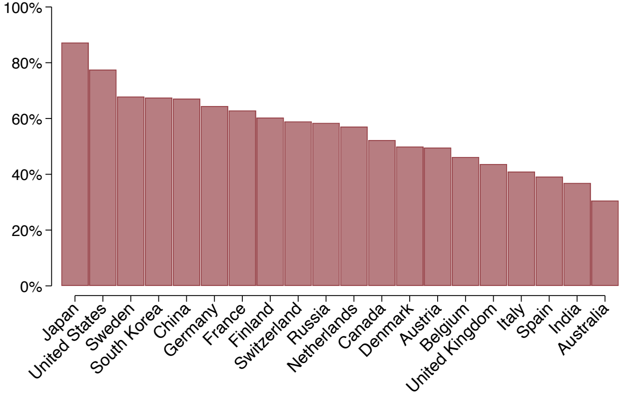
Examples of Misallocation (2): Green Innovation



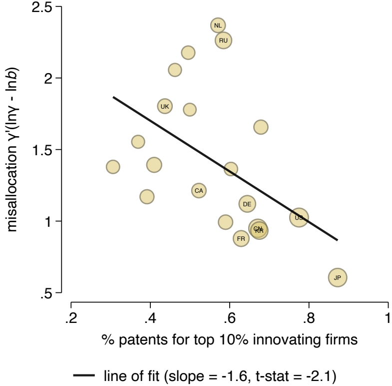
- Policy Relevance
  - Green innovation grants, tax credit, ...
  - Impact investment
- In Our Calculation: US green-innovation R&D
  - Under-funded by about 25%
  - While other countries have milder misallocation

Innovation hubs

(a) Fraction of patents by top 10% firms



(b) ↗ innovation hubs ⇔ ↗ efficiency



Conclusion

- Theory: optimal innovation allocation in innovation networks
  - sufficient statistics for optimal R&D & misallocation accounting in closed & open economies
  - planner should direct R&D towards more fundamental sectors, but incentive muted in open economics
- Construct the global patent citation network; empirical validation of knowledge spillover dynamics
- Japan, US, South Korea, Germany are the most allocatively efficient among advanced economies, but welfare cost of R&D misallocation in other economies mitigated by foreign spillovers
- Moving to efficient allocation $\Longrightarrow$ consumption-equivalent gains of 8% in the US in 2010