Supply Chain Disruptions, the Structure of Production Networks, and the Impact of Globalization

Matthew Elliott
Cambridge

Matthew O. Jackson
Stanford & SFI

BUSINESS

Tesla to Halt Production in Germany as Red Sea Conflict Hits Supply Chains

Disruption related to attacks on ships by Houthi rebels raise risk of supply-chain crisis in Europe

By William Boston Follow *, Costas Paris* Follow *and Benoit Faucon* Follow

Updated Jan. 12, 2024 1:45 pm ET

BERLIN—Tesla TSLA -3.67% ▼ plans to halt production at its only large factory in Europe for two weeks because of a lack of parts, a sign of how the fallout from recent attacks on ships in the Red Sea is starting to ripple through the global economy.

Yemen-based, Iran-backed Houthi fighters have launched successive attacks on commercial ships navigating the crucial trade route in recent months,

This Paper

Tractable model of (global, complex) supply chains to:

- characterize short-run impact of a shock,
- contrast with long-run impact,
- investigate how impacts depend on network/complexity,
- examine impact of globalization on fragility.

Some Related Literature

- **Foundational work:** Leontief (1936), Long Jr and Plosser (1983), Acemoglu, Carvalho, Ozdaglar, and Tahbaz-Salehi (2012)
- **Surveys:** Bernard (2018), Carvalho and Tahbaz-Salehi (2019), Baqaee and Rubbo (2022), Antràs and Chor (2022), Elliott and Golub (2022), Baldwin and Freeman (2022).
- **Production networks:** e.g., Dhyne et al. (2015); Magerman et al. (2016); Brummitt et al. (2017); Baqaee (2018); Oberfield (2018); Acemoglu and Tahbaz-Salehi (2020), Acemoglu and Azar (2020), Baqaee and Farhi (2021), Carvalho et al. (2021),Kopytov et al. (2021), Di Giovanni et al. (2022); Bernard et al. (2022), Elliott et al. (2022), Bui et al. (2022), König et al. (2022), Pellet and Tahbaz-Salehi (2023), Grossman et al. (forthcoming, 2023a,b)
- **Trade networks:** e.g., Furusawa and Konishi (2007); Chaney (2014); Bernard et al. (2019); Grossmand et al. (2021)
- **Micro network structure:** e.g., Bimpikis et al. (2018), Bimpikis et al. (2019), Amelkin and Vohra (2020)

Outline

Model

- $n \in \{1, \ldots, N\}$ countries,
- $m \in \{1, \ldots, M\}$ intermediate goods,
- $f \in \{1, \ldots, F\}$ final goods,
- L_n units of labor country n,
- T_n (finite) set technologies country n.

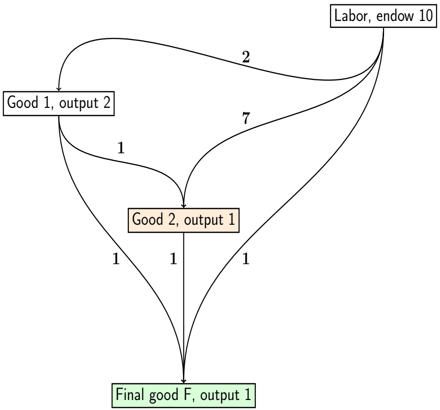
Example: Technologies

Cobb Douglas Example

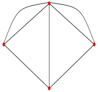
$$\tau_1 = (\underbrace{-1}_{\text{labor}}, \underbrace{1}_{1}, \underbrace{0}_{2}, \underbrace{0}_{F})$$

$$\tau_2 = (\underbrace{-7}_{\text{labor}}, \underbrace{-1}_{1}, \underbrace{1}_{2}, \underbrace{0}_{F})$$

$$\tau_F = (\underbrace{-1}_{\text{labor}}, \underbrace{-1}_{1}, \underbrace{-1}_{2}, \underbrace{1}_{F})$$

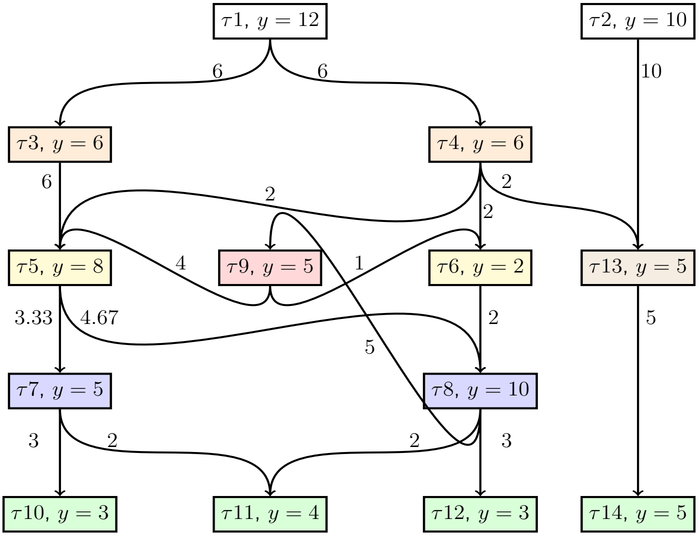


Equilibrium



- Laborers/Consumers
  - supply labor inelastically, L_n in country n;
  - maximize homothetic preferences for final goods, $U(c_1, \dots, c_F)$.
- Producers
  - maximize profits $p_\tau y_\tau - \sum_{\tau'} p_{\tau'} x_{\tau'\tau}$,
  - s.t feasible production: $-\tau_k y_\tau = \sum_{\tau' : O(\tau') = k} x_{\tau'\tau}$.
- Markets clear - standard Arrow-Debreu equilibrium.

Example w Cycles (Labor Omitted, Final Goods in Green)



Outline

1. Introduction
2. Model
3. The Impacts of Shocks: Contrasting Short and Long Runs
4. Complexity, Fragility, Globalization

Impact of Shock

For τ with output k, we normalized $\tau_k = 1$.

Let's vary τ_k to capture shocks/disruptions

Analyze/contrast:

- **Long run**: new equilibrium using shocked technologies,
- **Short run**: work with existing supplies/shortages.

Long-Run: Hulten's Theorem

Proposition (Hulten's Theorem)

Consider a generic equilibrium and technology τ, with $O(\tau) = k$, used in positive amounts in equilibrium. Then

$$\frac{\partial \log(U)}{\partial \log(\tau_k)} = \frac{\partial \log(GDP)}{\partial \log(\tau_k)} = \frac{p_\tau y_\tau}{GDP}.$$

Long-Run: Hulten's Theorem

$$\frac{\partial \log(U)}{\partial \log(\tau_k)} = \frac{p_\tau y_\tau}{GDP}$$

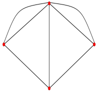
- Sufficient statistic: *fraction of GDP spent on shocked technology*.

Long-Run: Hulten's Theorem

$$\frac{\partial \log(U)}{\partial \log(\tau_k)} = \frac{p_\tau y_\tau}{GDP}$$

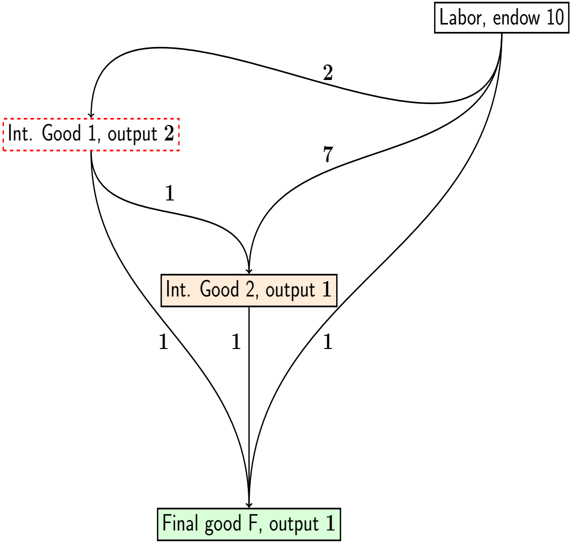
- Sufficient statistic: *fraction of GDP spent on shocked technology*.
- Intuition—adjust by sourcing more of that input at its cost.

Long-Run: Hulten's Theorem



$$\frac{\partial \log(U)}{\partial \log(\tau_k)} = \frac{p_\tau y_\tau}{GDP}$$

- Sufficient statistic: *fraction of GDP spent on shocked technology*.
- Intuition—adjust by sourcing more of that input at its cost.
- Network matters in background as it determines equilibrium
  - but don't need to see network to estimate long-run impact.



$$p = (\underbrace{\frac{1}{10}}_{\text{labor}}, \underbrace{\frac{1}{10}}_{Int.1}, \underbrace{\frac{4}{5}}_{Int.2}, \underbrace{1}_{Final})$$

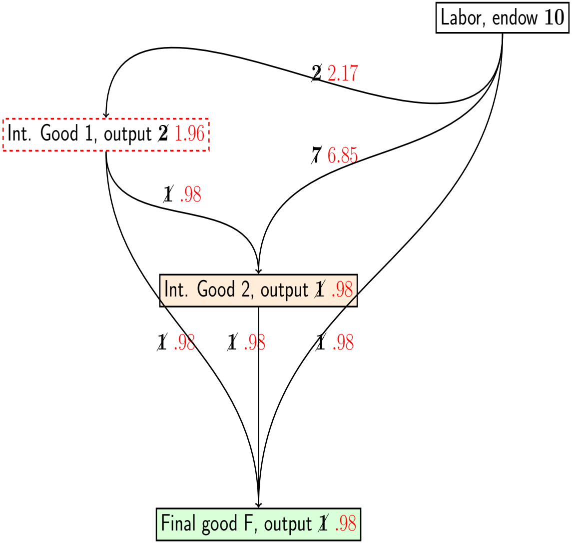
$p_1 y_1 = 1/10 * 2;$
$GDP = \sum_f p_f c_f = 1;$

Marginal impact:

$$\frac{p_1 y_1}{\text{GDP}} = \frac{1}{5}$$

Extrapolating for a 10% shock,
(source more)

Long Run impact: $1/50$th of GDP



$$p = \Big(\underbrace{\frac{1}{10}}_{\text{labor}}, \underbrace{\frac{1}{10}}_{Int.1}, \underbrace{\frac{4}{5}}_{Int.2}, \underbrace{1}_{Final} \Big)$$

$p_1 y_1 = 1/10 * 2;$
$GDP = \sum_f p_f c_f = 1;$

Marginal impact:

$$\frac{p_1 y_1}{\text{GDP}} = \frac{1}{5}$$

Extrapolating for a 10% shock, (source more)

Long Run impact: $1/50$th of GDP

Larry Summers 2013

"There would be a set of economists who would sit around explaining that electricity was only 4% of the economy, and so if you lost 80% of electricity, you couldn't possibly have lost more than 3% of the economy...[However,] *we would understand that* [...] *when there wasn't any electricity, there wasn't really going to be much economy."*

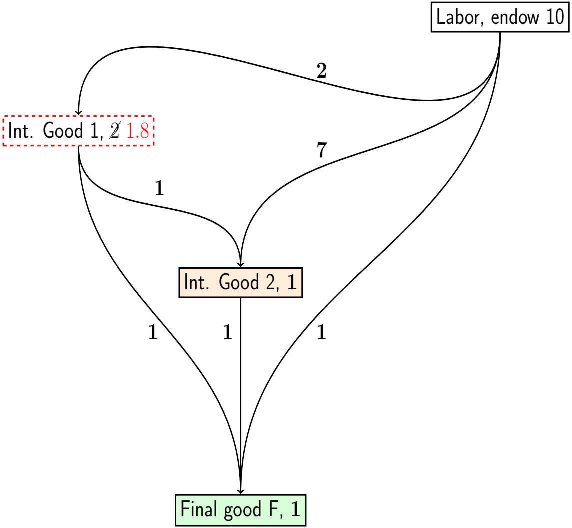
Short-Run Impact of a Shock

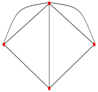
Hulten: Production is perfectly flexible and fully adjusts.
(Marginal result.)

Now: Opposite benchmark with no adjustments.
(Our result holds away from the margin.)

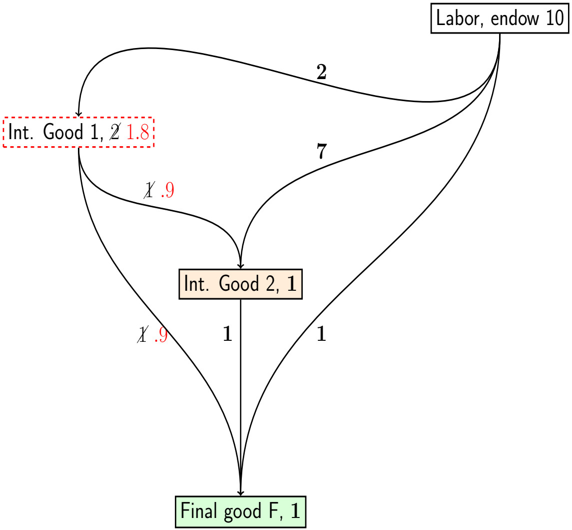
- Cannot adjust the technologies being used.
- Cannot source additional units from alternative suppliers.
- Prices cannot adjust—rationing of disrupted goods is proportional

Short Run Disruption 10%

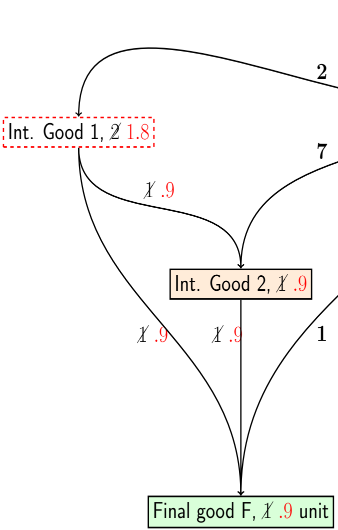




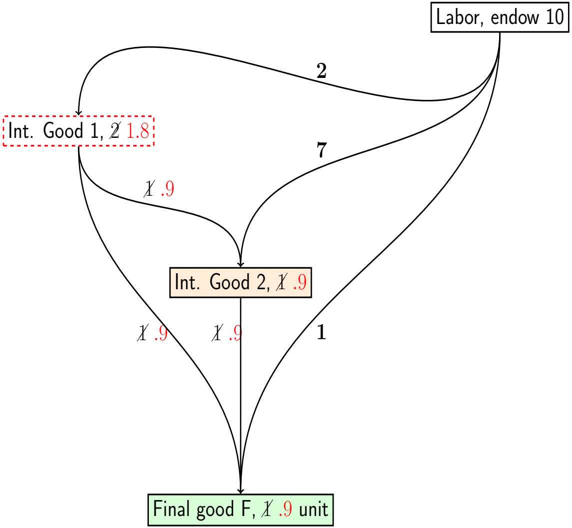
Short Run Disruption 10%



Short Run Disruption 10%



Short Run Disruption 10%



Long Run Disruption 2%

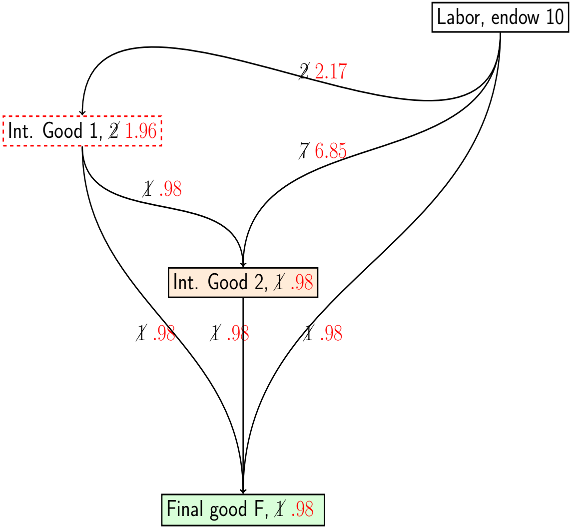


Figure: Shock Propagation Algorithm

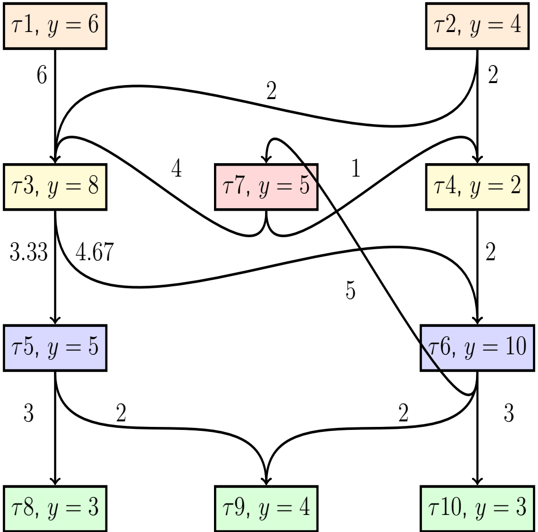


Figure: Shock Propagation Algorithm

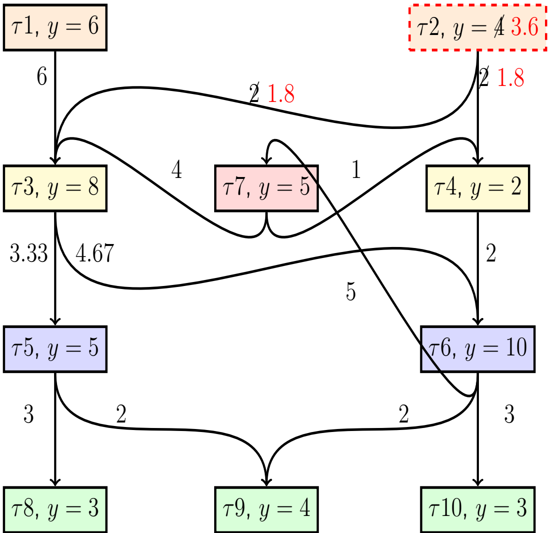


Figure: Shock Propagation Algorithm

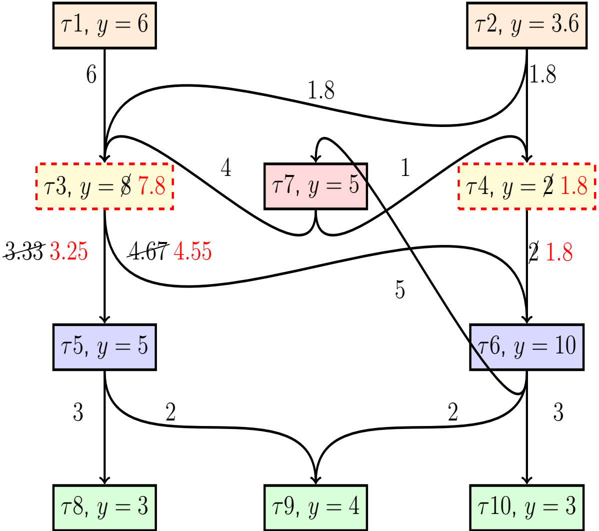


Figure: Shock Propagation Algorithm

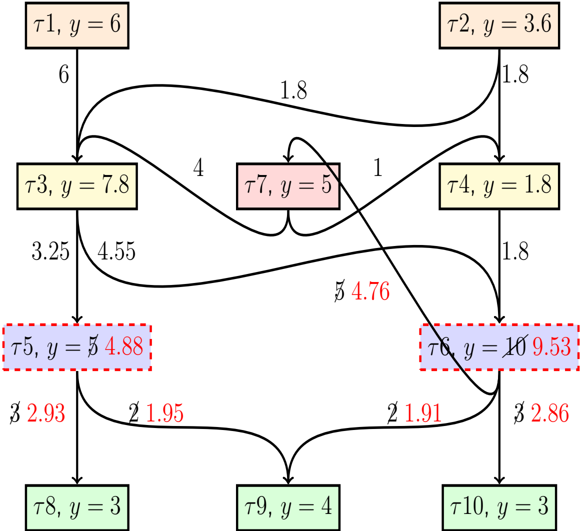


Figure: Shock Propagation Algorithm

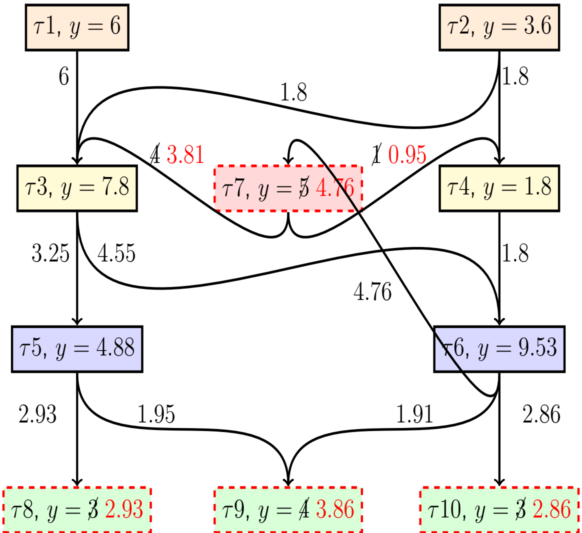


Figure: Shock Propagation Algorithm

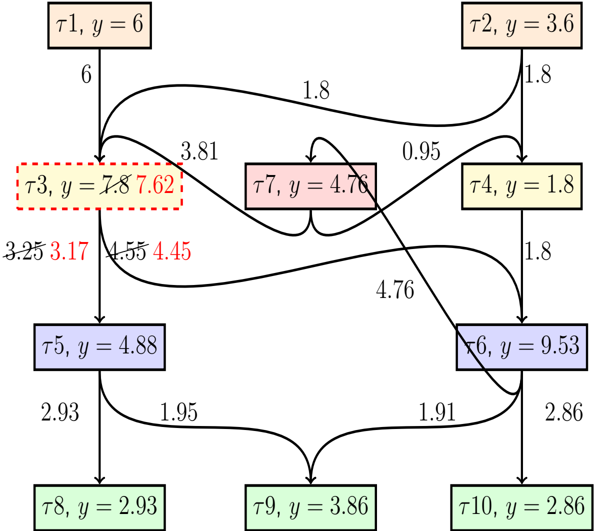
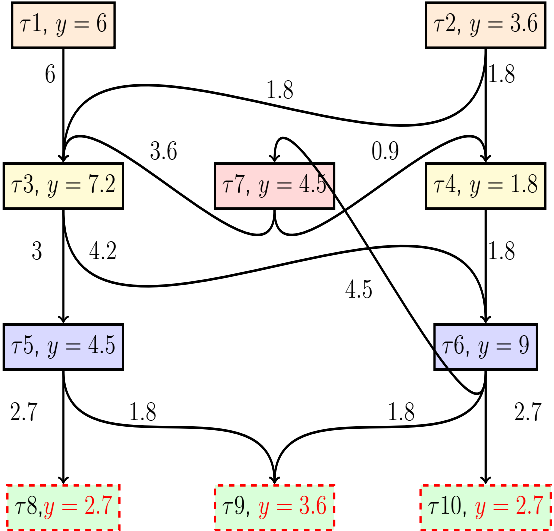


Figure: Shock Propagation Algorithm



Short-Run Impact: The Minimum Disruption Problem

$$\max_{(\hat{y}_\tau)_\tau} \sum_{\tau : O(\tau) \in F} p_\tau \hat{y}_\tau$$

subject to

1. shock constraints: $\hat{y}_\tau \leq \lambda y_\tau$ for all $\tau \in T^{shocked}$,
2. technology constraints: $\hat{y}_\tau \leq \left(\min_{\text{Inputs used by } \tau} \frac{\text{New input level}}{\text{Original input level}} \right) y_\tau$ for active τ,
3. proportional rationing: $\hat{x}_{\tau\tau'} = x_{\tau\tau'} \left(\frac{\hat{y}_\tau}{y_\tau} \right)$ for active $\tau'\tau$,
4. inactive technologies stay inactive.

Shock Propagation Algorithm

Define an algorithm that traces shock (like example): it converges to a solution of the minimum disruption problem.

Let $F(T^{shocked})$ be the final goods on directed paths from shocked technologies.

Proposition (Upper Bound)

Consider a shock that reduces the output of technologies $\tau \in T^{shocked}$ to $\lambda < 1$ of their original levels. The proportion of lost GDP is bounded above by

$$(1-\lambda)\left(\frac{\sum_{f \in F(T^{shocked})} p_f c_f}{GDP}\right).$$

Sufficient Conditions for Bound to Bite

- All producers of given good and any "substitute" for it in a supply chain are shocked.

- Globalization/Low shipping costs: for low enough transportation costs generically get unique technologies used.

- Other sufficient conditions (graph-cut) in paper.

Short Run vs Long Run

Long Run, Hulten's Theorem,

$$\frac{\partial \log(U)}{\partial \log(\lambda)} = \frac{\partial \log(GDP)}{\partial \log(\lambda)} = \frac{(1-\lambda)p_\tau y_\tau}{GDP}.$$

Short Run, when bound bites

$$\frac{\Delta \log(U)}{\Delta \log(\lambda)} = \frac{\Delta \log(GDP)}{\Delta \log(\lambda)} = \frac{(1-\lambda)\sum_{f\in F(\tau)} p_f c_f}{GDP}.$$

Short Run vs Long Run

Long Run, Hulten's Theorem,

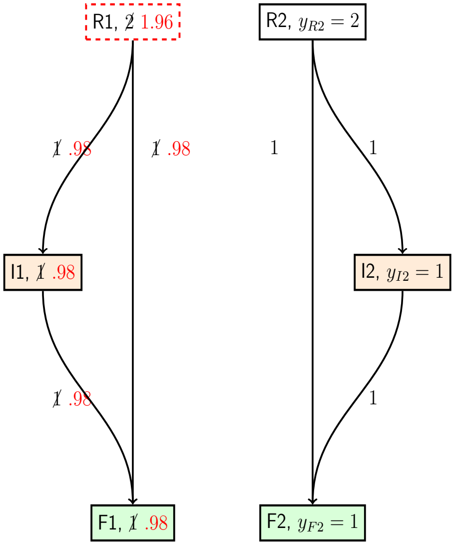
$$\frac{\partial \log(U)}{\partial \log(\lambda)} = \frac{\partial \log(GDP)}{\partial \log(\lambda)} = \frac{(1-\lambda) p_\tau y_\tau}{GDP}.$$

Short Run, when bound bites

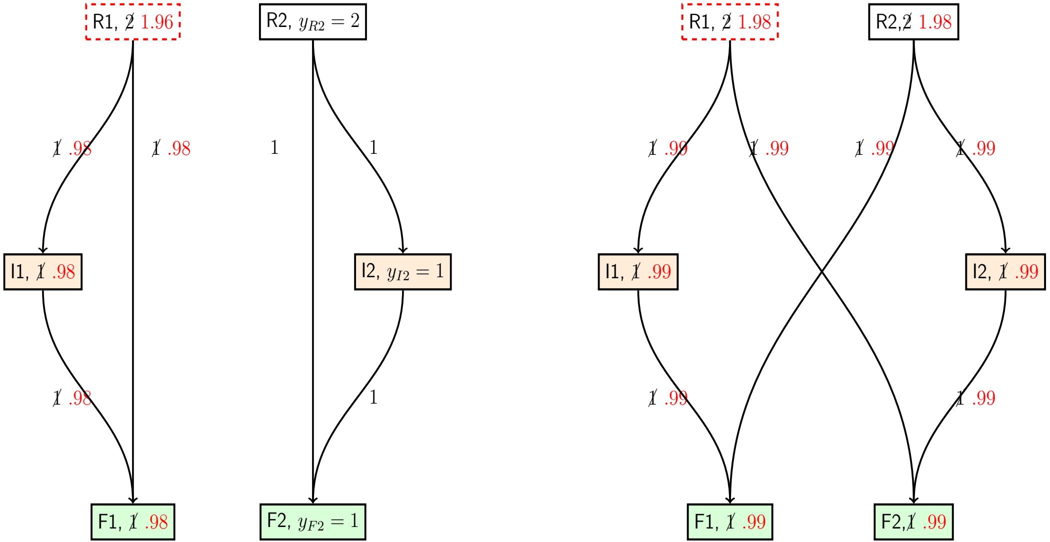
$$\frac{\Delta \log(U)}{\Delta \log(\lambda)} = \frac{\Delta \log(GDP)}{\Delta \log(\lambda)} = \frac{(1-\lambda) \sum_{f \in F(\tau)} p_f c_f}{GDP}.$$

- Long Run: shocking more expensive technologies has a larger impact.
- Short Run: shocking technologies that are used in more final goods has a larger impact.

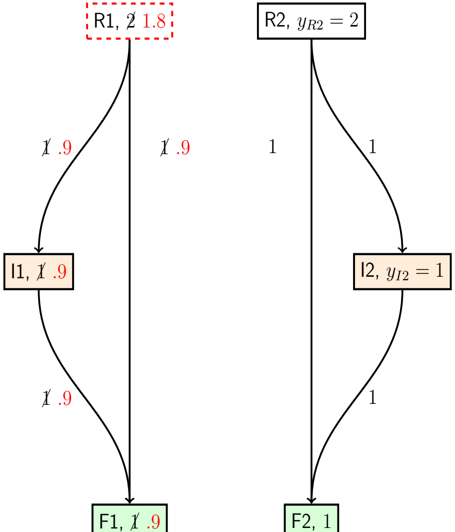
Long Run: Network Irrelevant, Impact 1%



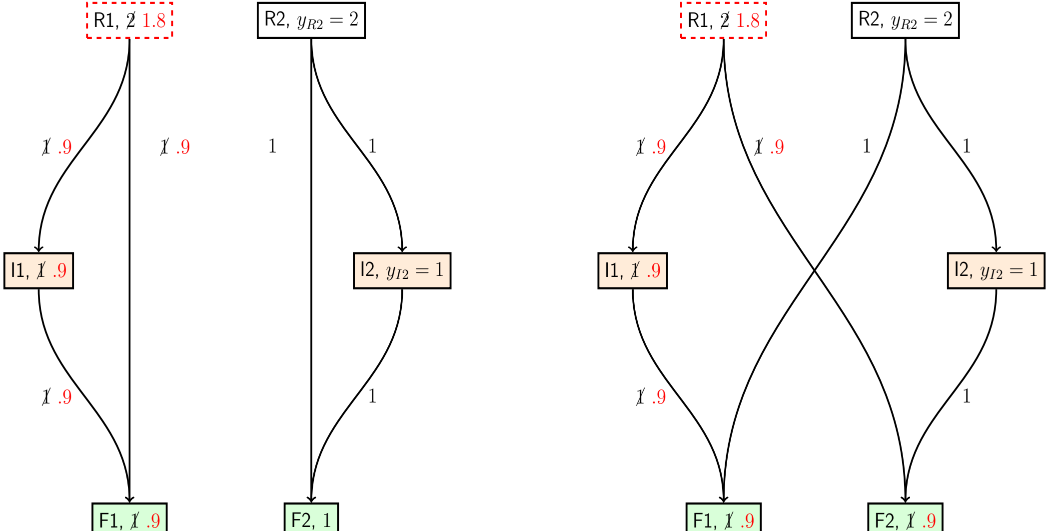
Long Run: Network Irrelevant, Impact 1%



Short Run: Network Matters, All Downstream Goods Impacted 5% or 10%



Short Run: Network Matters, All Downstream Goods Impacted 5% or 10%



Short Run vs Long Run

Short Run:

- Network position matters,
- Disrupt all final goods downstream

Long Run:

- (Much) cheaper than Short Run,
- Relative cost of input matters,
- Network matters, but only to extent changes costs.

Outline

Supply Chain Complexity and Disruption

Under the bound, randomly disrupt any technology to $\lambda < 1$:

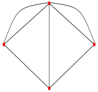
- Probability π disrupt any given intermediate technology, independent.
- $S =$ complexity: average $\#$ inputs used produce a final good.

Supply Chain Complexity and Disruption

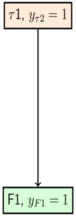
Proposition (Complexity and Fragility)

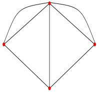
For small π

$$\text{Short-Run} \quad \mathbb{E}\left[\frac{\Delta GDP}{GDP}\right] \approx -S\pi(1-\lambda),$$

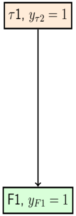


SR $\color{red}{1}\pi(1-\lambda)$

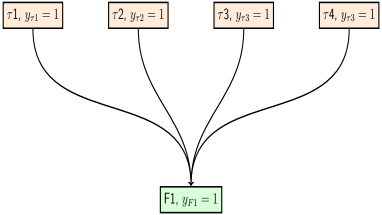


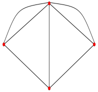


SR $1\pi(1-\lambda)$



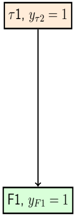
SR $4\pi(1-\lambda)$



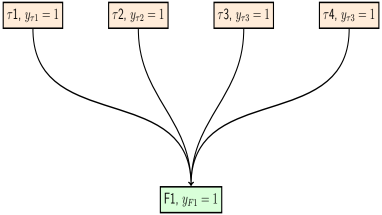


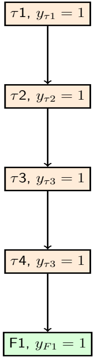
SR $4\pi(1-\lambda)i$

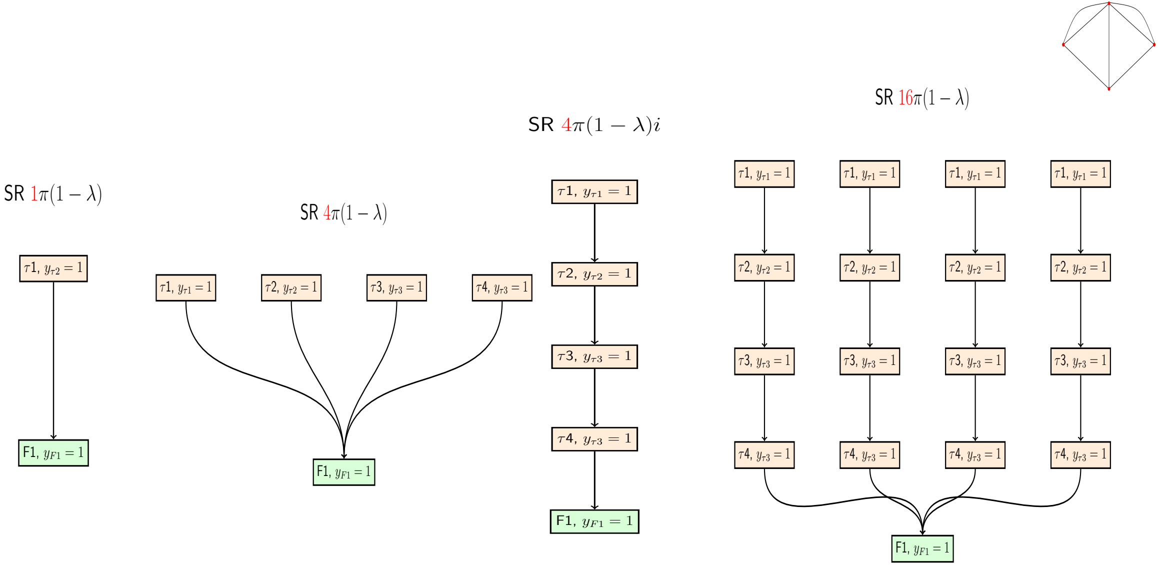
SR $1\pi(1-\lambda)$



SR $4\pi(1-\lambda)$







SR $1\pi(1-\lambda)$
$\tau 1,\ y_{\tau 2}=1$
F1, $y_{F1}=1$
SR $4\pi(1-\lambda)$
$\tau 1,\ y_{\tau 1}=1$
$\tau 2,\ y_{\tau 2}=1$
$\tau 3,\ y_{\tau 3}=1$
$\tau 4,\ y_{\tau 3}=1$
F1, $y_{F1}=1$
SR $4\pi(1-\lambda)i$
$\tau 1,\ y_{\tau 1}=1$
$\tau 2,\ y_{\tau 2}=1$
$\tau 3,\ y_{\tau 3}=1$
$\tau 4,\ y_{\tau 3}=1$
F1, $y_{F1}=1$
SR $16\pi(1-\lambda)$
$\tau 1,\ y_{\tau 1}=1$
$\tau 2,\ y_{\tau 2}=1$
$\tau 3,\ y_{\tau 3}=1$
$\tau 4,\ y_{\tau 3}=1$
F1, $y_{F1}=1$

Supply Chain Complexity and Disruption

Under the bound, randomly disrupt any technology to $\lambda < 1$:

- Probability π disrupt any given intermediate technology, independent.
- $S =$ average # inputs used produce a final good.
- $RC =$ E[(cost of random input)/(costs of final goods impacted)].

Supply Chain Complexity and Disruption

Proposition (Complexity and Fragility)

For small π

$$\text{Short-Run} \quad \mathbb{E}\left[\frac{\Delta GDP}{GDP}\right] \approx -S\pi(1-\lambda),$$

$$\text{Long-Run} \quad \mathbb{E}\left[\frac{\Delta GDP}{GDP}\right] \approx -S\pi(1-\lambda)RC$$

Supply Chain Complexity and Disruption

Proposition (Complexity and Fragility)

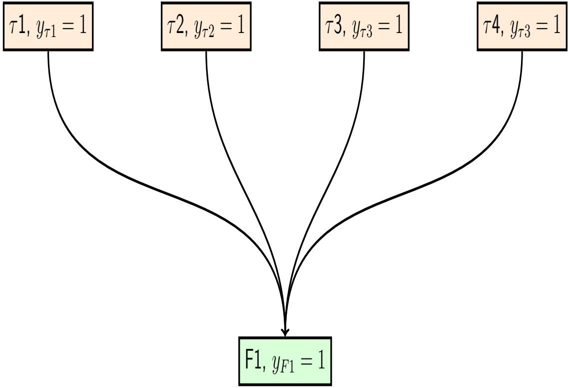
For small π

$$\text{Short-Run} \quad \mathbb{E}\left[\frac{\Delta GDP}{GDP}\right] \approx -S\pi(1-\lambda),$$

$$\text{Long-Run} \quad \mathbb{E}\left[\frac{\Delta GDP}{GDP}\right] \approx -S\pi(1-\lambda)RC$$

Same probabilities of disruption, but different expected costs (much lower in long run)

Horizontal Supply Chain (all labor inputs = 1)



Labor endowment: 5

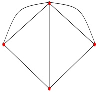
$$p = \left(\underbrace{\frac{1}{5}}_{\text{labor}}, \underbrace{\frac{1}{5}}_{\tau 1}, \underbrace{\frac{1}{5}}_{\tau 2}, \underbrace{\frac{1}{5}}_{\tau 3}, \underbrace{\frac{1}{5}}_{\tau 4}, \underbrace{1}_{F} \right)$$

Complexity inputs/final good: $S = 4$.

Average input cost / final good cost: $q = .2$

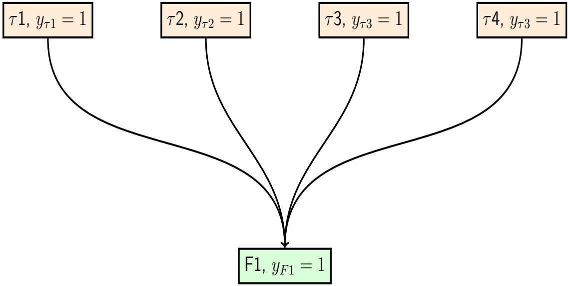
Short Run expected impact: $4(1-\lambda)\pi$

Long Run expected impact: $.8(1-\lambda)\pi$



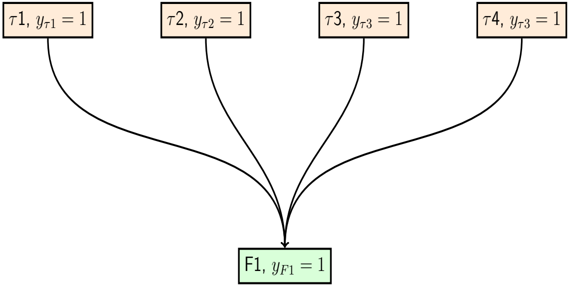
SR $4\pi(1-\lambda)$

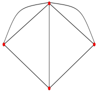
LR $.8\pi(1-\lambda)$



SR $4\pi(1-\lambda)$

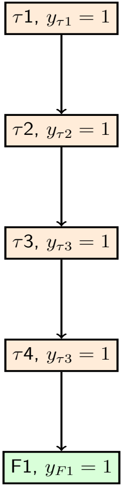
LR $.8\pi(1-\lambda)$





SR $4\pi(1-\lambda)$

LR $2\pi(1-\lambda)$



Supply Chain Complexity and Disruption

Short Run:

- *shape (breadth vs depth) of supply chain is irrelevant* (S matters),
- More final goods, lower S, impact compartmentalized.

Long Run :

- *shape of supply chain matters as it affects relative costs*,
- number of final goods does not matter, relative costs of inputs does.

Trade Costs and Globalization

$\theta_{\tau\tau'} \geq 1$ units of $O(\tau)$ shipped from τ for 1 unit to get to τ'.

Effects of dropping costs:

- Increased specialization: only most efficient technology is used.
- Increased complexity: new technologies/goods become viable that source more inputs from more locations.

Trade Costs and Globalization

$\theta_{\tau\tau'} \geq 1$ units of $O(\tau)$ shipped from τ for 1 unit to get to τ'.

Effects of dropping costs:

- Increased specialization: only most efficient technology is used.
- Increased complexity: new technologies/goods become viable that source more inputs from more locations.

Example:

- $\sim$90% of most advanced computer chips assembled in Taiwan,
- Very complex supply chain and some materials cross borders > 70 times before final assembly.

Fragility and Globalization: Consolidating Supply chains

Consider two supply chains for some final good f, and shocks that are independent across technologies with the same proportional disruption.

Proposition

If the set of technologies that lie on a directed path to τ_f is smaller in chain 2 ($\mathcal{G}^2(\tau_f) \subsetneq \mathcal{G}^1(\tau_f)$), then the probability of a disruption to τ_f is lower, but the expected short-run impact conditional on disruption is higher, in chain 2 than 1.

Fragility and Globalization: Consolidating Supply chains

Consider two supply chains for some final good f, and shocks that are independent across technologies with the same proportional disruption.

Proposition

If the set of technologies that lie on a directed path to τ_f is smaller in chain 2 ($\mathcal{G}^2(\tau_f) \subsetneq \mathcal{G}^1(\tau_f)$), then the probability of a disruption to τ_f is lower, but the expected short-run impact conditional on disruption is higher, in chain 2 than 1.

Lower transportation costs lead to specialized production and consolidation (and the bound holds).

Consolidating supply chains leads to fewer chances of disruption, but each technology then accounts for a larger fraction of that input, and hence a larger disruption.

Fragility and Globalization

- More specialized production—fewer, larger producers,
- Larger shocks, but fewer producers and so (possibly) less frequent.
- As cross more borders, could face more political/transport risk...

Summary

- Short and long run can differ dramatically, both very tractable.
- Short run depends on all downstream goods, long run only on cost of shocked goods
- Short run network 'rewiring' matters, not in long run
- Medium run depends on relative values of downstream goods
- Increasingly complex chains are more vulnerable
- Globalization/specialization leads to less likely but bigger shocks

Externalities!

- Competition is inefficient (missing markets)
- Competition pushes to cheaper sourcing, low inventories
- Unless compensated for resilience, leads to excessive specialization/fragility
- Policy implications of model:
  - Short run:
    - target ‘central’ technologies
    - build inventories, substitutes (decrease centrality)
    - build parallel chains
  - Long run:
    - target ‘expensive’ technologies
    - support diverse technologies for same goods
    - favor technologies enabling shallower supply chains

Discussion

Medium Run

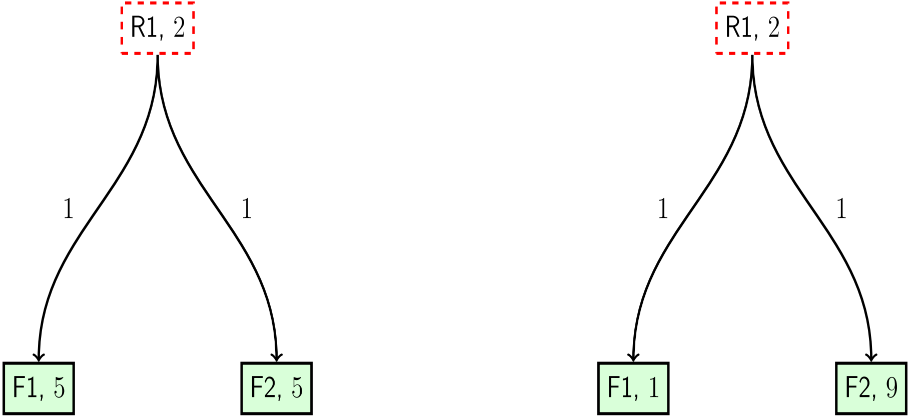
No new sourcing: existing supply chains in place

Prices can steer rationed goods to most needed technologies

If multiple flows affected:

- Different supply chains have similar final good values: looks like short run,
- Different supply chains have very different final good values: looks more like long run, only disrupt lowest value chains.

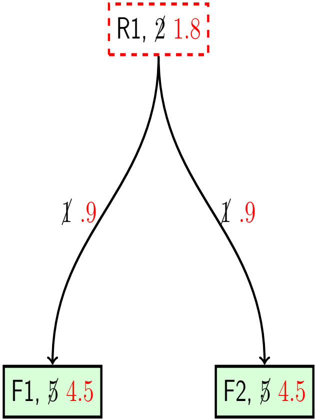
Medium Run Shock Impact



Equal-Valued Final Goods

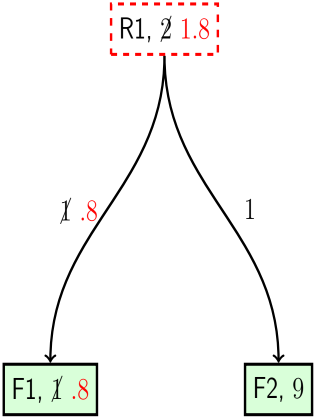
Unequal-Valued Final Goods

Medium Run Shock Impact



Impact 1/10

Same as Short Run



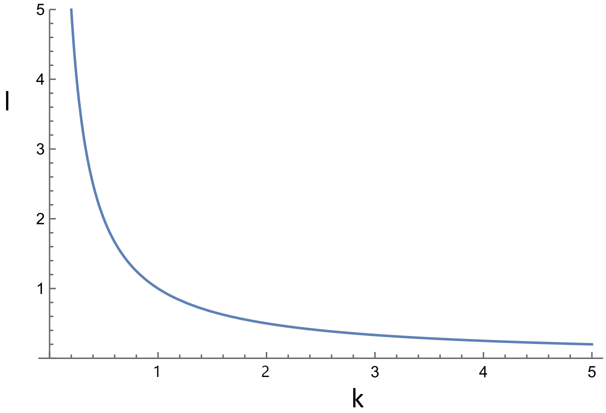
Impact 1/50

Close to Long Run

Arrow-Debreu (1954) Technologies

Suppose country n can produce according to $y = L^\alpha K^{1-\alpha}$

Then $T_n = \{(-l, -k, 1) : l^\alpha k^{1-\alpha} = 1\}$

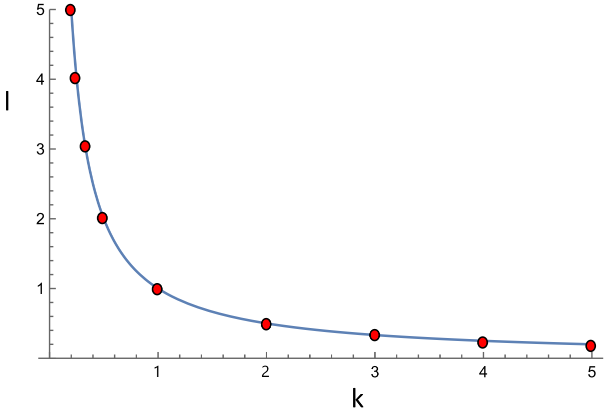


Return to Technologies

Arrow-Debreu (1954) Technologies

Suppose country n can produce according to $y = L^{\alpha}K^{1-\alpha}$

Then $T_n = \{(-l, -k, 1) : l^{\alpha}k^{1-\alpha} = 1\}$



Return to Technologies

Acemoglu, D. and P. D. Azar (2020): "Endogenous Production Networks," *Econometrica*, 88, 33–82.

Acemoglu, D., V. M. Carvalho, A. Ozdaglar, and A. Tahbaz-Salehi (2012): "The Network Origins of Aggregate Fluctuations," *Econometrica*, 80, 1977–2016.

Acemoglu, D. and A. Tahbaz-Salehi (2020): "Firms, Failures, and Fluctuations: The Macroeconomics of Supply Chain Disruptions," Tech. rep., National Bureau of Economic Research.

Amelkin, V. and R. Vohra (2020): "Strategic Formation and Reliability of Supply Chain Networks," in *Proceedings of the 21st ACM Conference on Economics and Computation*, 77–78.

Antràs, P. and D. Chor (2022): "Global value chains," *Handbook of international economics*, 5, 297–376.

Baldwin, R. and R. Freeman (2022): "Risks and global supply chains: What we know and what we need to know," *Annual Review of Economics*, 14, 153–180.

Baqaee, D. and E. Farhi (2021): "Entry vs. rents: Aggregation with economies of scale," Tech. rep., National Bureau of Economic Research, working Paper No. 27140.

BAQAEE, D. AND E. RUBBO (2022): "Micro propagation and macro aggregation," Tech. rep., National Bureau of Economic Research, working Paper No. 30538.

BAQAEE, D. R. (2018): "Cascading failures in production networks," *Econometrica*, 86, 1819–1838.

BERNARD, ANDREW B.AND MOXNES, A. (2018): "Networks and trade," *Annual Review of Economics*, 10, 65–85.

BERNARD, A. B., E. DHYNE, G. MAGERMAN, K. MANOVA, AND A. MOXNES (2022): "The origins of firm heterogeneity: A production network approach," *Journal of Political Economy*, 130, 1765–1804.

BERNARD, A. B., A. MOXNES, AND Y. U. SAITO (2019): "Production networks, geography, and firm performance," *Journal of Political Economy*, 127, 639–688.

BIMPIKIS, K., O. CANDOGAN, AND S. EHSANI (2019): "Supply Disruptions and Optimal Network Structures," *Management Science*, 65, 5504–5517.

BIMPIKIS, K., D. FEARING, AND A. TAHBAZ-SALEHI (2018): "Multisourcing and miscoordination in supply chain networks," *Operations Research*, 66, 1023–1039.

Brummitt, C. D., K. Huremović, P. Pin, M. H. Bonds, and F. Vega-Redondo (2017): "Contagious Disruptions and Complexity Traps in Economic Development," *Nature Human Behaviour*, 1, 665.

Bui, H., Z. Huo, A. A. Levchenko, and N. Pandalai-Nayar (2022): "Information frictions and news media in global value chains," Tech. rep., National Bureau of Economic Research, working Paper No. 30033.

Carvalho, V. M., M. Nirei, Y. U. Saito, and A. Tahbaz-Salehi (2021): "Supply chain disruptions: Evidence from the great east japan earthquake," *The Quarterly Journal of Economics*, 136, 1255–1321.

Carvalho, V. M. and A. Tahbaz-Salehi (2019): "Production networks: A primer," *Annual Review of Economics*, 11, 635–663.

Chaney, T. (2014): "The network structure of international trade," *American Economic Review*, 104, 3600–3634.

Dhyne, E., G. Magerman, and S. Rubínová (2015): "The Belgian production network 2002-2012," Tech. rep., NBB Working Paper.

Di Giovanni, J., e. Kalemli-Özcan, A. Silva, and M. A. Yildirim (2022):

"Global supply chain pressures, international trade, and inflation," Tech. rep., National Bureau of Economic Research.

Elliott, M. and B. Golub (2022): "Networks and economic fragility," *Annual Review of Economics*, 14, 665–696.

Elliott, M., B. Golub, and M. V. Leduc (2022): "Supply network formation and fragility," *American Economic Review*, 112, 2701–47.

Furusawa and H. Konishi (2007): "Free trade networks," *Journal of International Economics*, 7, 310–335.

Grossman, G., E. Helpman, and S. Redding (2023a): "When tariffs disrupt global supply chains," Tech. rep.

Grossman, G. M., E. Helpman, and H. Lhuillier (forthcoming): "Supply Chain Resilience: Should Policy Promote International Diversification or Reshoring?" *Journal of Political Economy*.

Grossman, G. M., E. Helpman, and A. Sabal (2023b): "Resilience in Vertical Supply Chains," Tech. rep., National Bureau of Economic Research.

Grossmand, G., E. Helpman, and S. Redding (2021): "When tariffs disrupt global supply chains," *American Economic Review*.

König, M. D., A. Levchenko, T. Rogers, and F. Zilibotti (2022): "Aggregate fluctuations in adaptive production networks," *Proceedings of the National Academy of Sciences*, 119, e2203730119.

Kopytov, A., B. Mishra, K. Nimark, and M. Taschereau-Dumouchel (2021): "Endogenous production networks under supply chain uncertainty," *Available at SSRN 3936969*.

Leontief, W. W. (1936): "Quantitative Input and Output Relations in the Economic Systems of the United States," *The Review of Economic Statistics*, 105–125.

Long Jr, J. B. and C. I. Plosser (1983): "Real business cycles," *Journal of political Economy*, 91, 39–69.

Magerman, G., K. De Bruyne, E. Dhyne, and J. Van Hove (2016): "Heterogeneous firms and the micro origins of aggregate fluctuations," Tech. rep., NBB Working Paper.

Oberfield, E. (2018): "A Theory of Input-Output Architecture," *Econometrica*, 86.

Pellet, T. and A. Tahbaz-Salehi (2023): "Rigid production networks," *Journal of Monetary Economics*.