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

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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

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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 et al. (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), 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), Grossman et al. (2023a), Grossman et al. (2023b)
- **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

1. Introduction
2. Model
3. The Impacts of Shocks: Contrasting Short and Long Runs
4. Complexity, Fragility, Globalization
5. The Impact in the Medium Run

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.

Iceberg costs, Prices

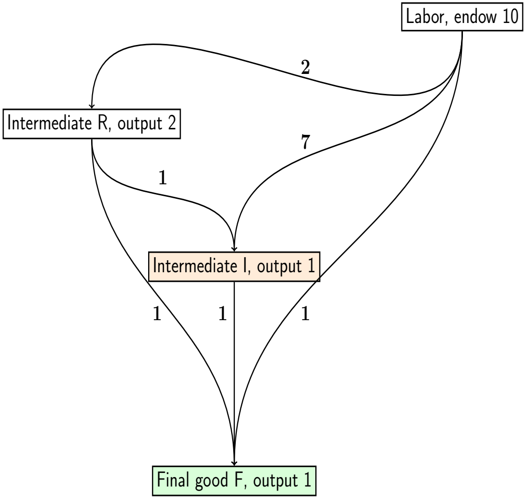
- $\theta_{\tau\tau'} \geq 1$ units of $O(\tau)$ shipped from τ for 1 unit to get to τ'.
- Iceberg cost on labor $\theta_{n\tau} \geq 1$.
- No iceberg costs on final goods.
- Local prices before iceberg costs $p \in \mathbb{R}_+^{N+|T|}$

Example: Technologies

$$\tau_R = (\underbrace{-1}_{\text{labor}}, \underbrace{1}_{R}, \underbrace{0}_{I}, \underbrace{0}_{F})$$

$$\tau_I = (\underbrace{-7}_{\text{labor}}, \underbrace{-1}_{R}, \underbrace{1}_{I}, \underbrace{0}_{F})$$

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



Arrow-Debreu (1954) Technologies

Constant returns to scale technologies τ

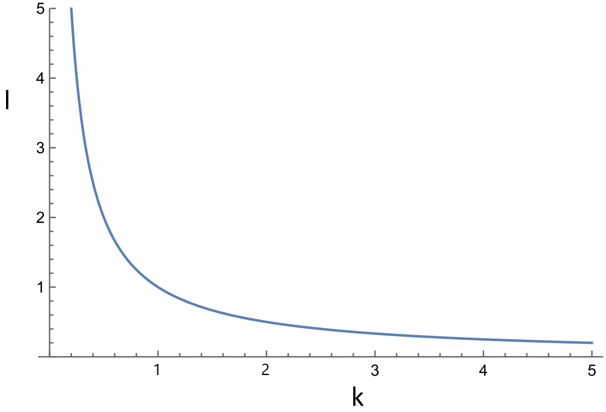
$$\left(\text{labor}, \quad \underbrace{m_1, \ldots, m_M}_{\text{intermediate}}, \quad \underbrace{f_1, \ldots, f_F}_{\text{final goods}}\right)$$

e.g., $(-2, 0, -3, 0, 1)$: 2 units labor & 3 units m_2 make 1 unit f_2.

Arrow-Debreu (1954) Technologies

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

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



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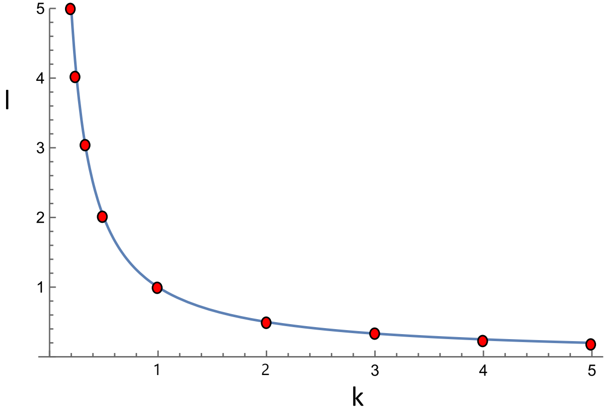
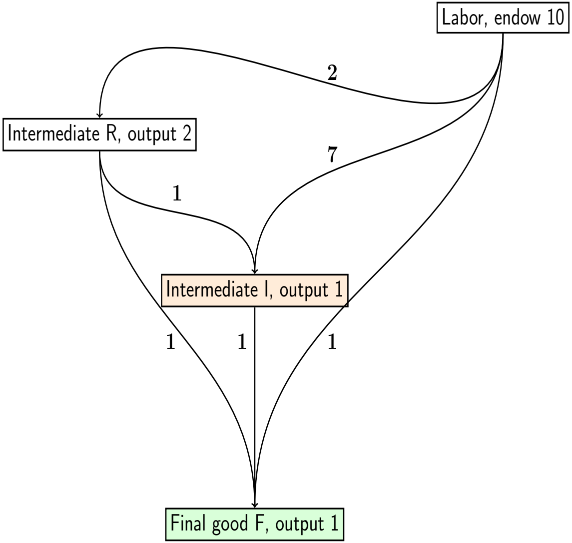


Equilibrium

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



Example Equilibrium

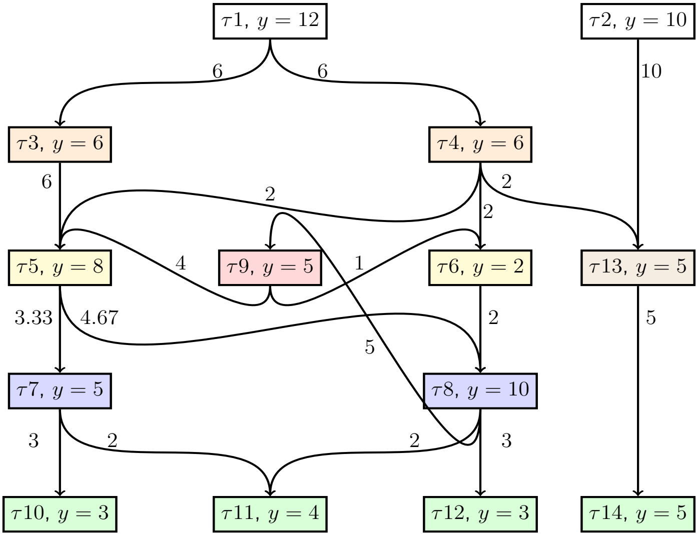
$$p = \left(\underbrace{\frac{1}{10}}_{\text{labor}}, \underbrace{\frac{1}{10}}_{R}, \underbrace{\frac{8}{10}}_{I}, \underbrace{1}_{F} \right)$$

producers earn 0 profits,

markets clear,

labor buys full output

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



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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

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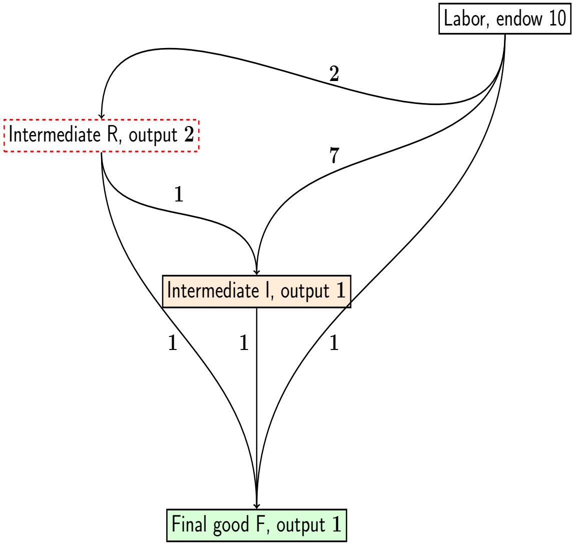
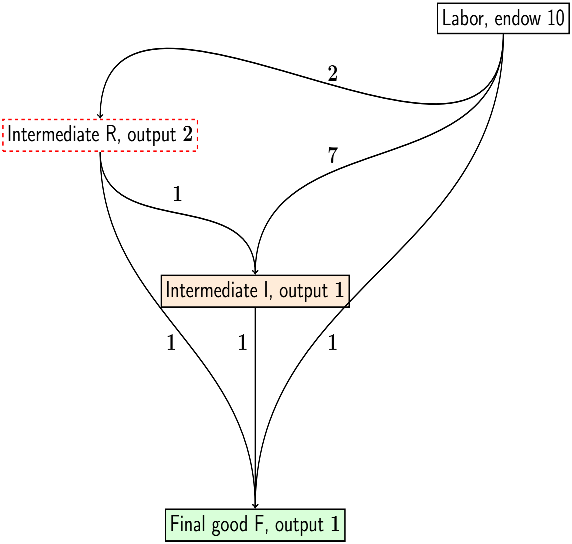
- Sufficient statistic: spending on shocked technology.
- Intuition—adjust by sourcing more inputs at the margin.
- Network matters in background as it determines equilibrium
  - but don't need to see network to estimate long-run impact.



$$p = (\underbrace{\frac{1}{10}}_{\text{labor}}, \underbrace{\frac{1}{10}}_{R}, \underbrace{\frac{4}{5}}_{I}, \underbrace{1}_{F})$$

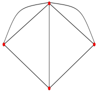


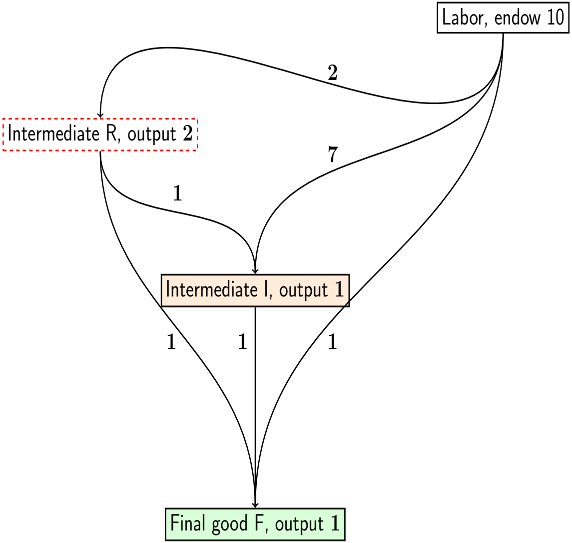
$$p = (\underbrace{\frac{1}{10}}_{\text{labor}}, \underbrace{\frac{1}{10}}_{R}, \underbrace{\frac{4}{5}}_{I}, \underbrace{1}_{F})$$

$p_R y_R = 1/10 * 2;$
$GDP = \sum_f p_f c_f = 1;$

Marginal impact:

$$\frac{p_R y_R}{\text{GDP}} = \frac{1}{5}$$





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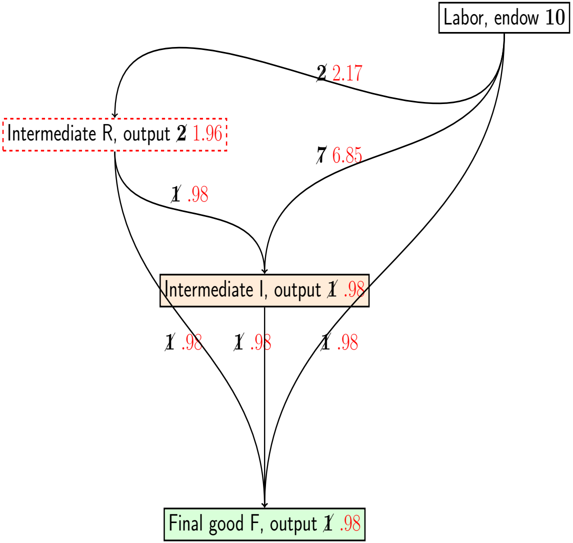
Extrapolating for a 10% shock, (source more)

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



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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."*

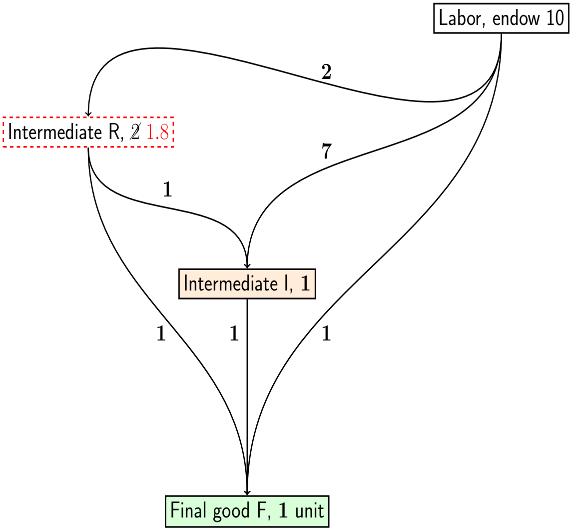
Short-Run Impact of a Shock

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

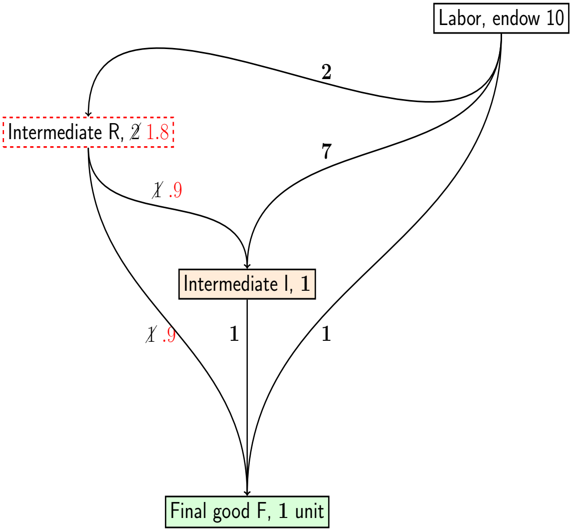
Now: Opposite benchmark with no adjustments.
(Our result holds away from the margin.)

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

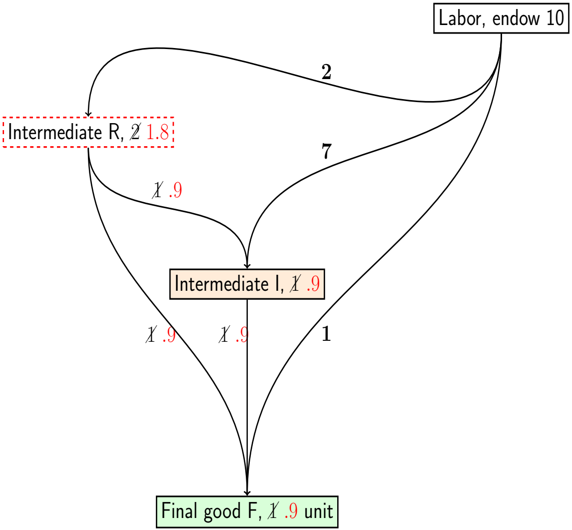
Short Run Disruption 10%



Short Run Disruption 10%



Short Run Disruption 10%



Short Run Disruption 10% | Long Run Disruption 2%

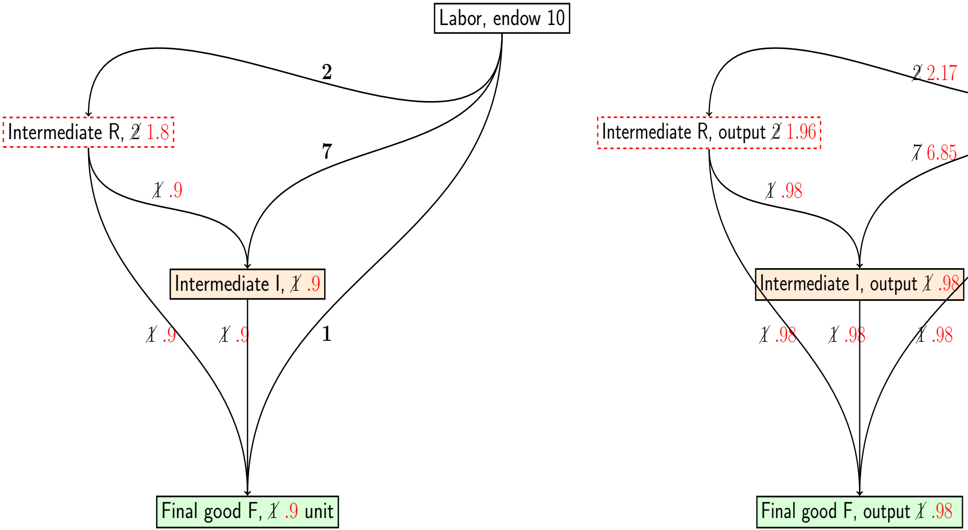
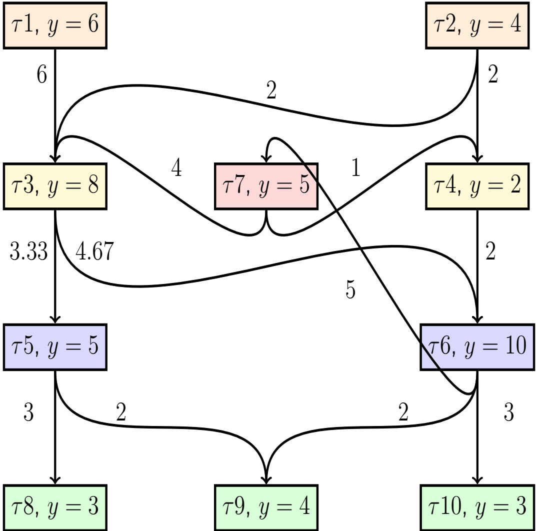


Figure: Shock Propagation Algorithm



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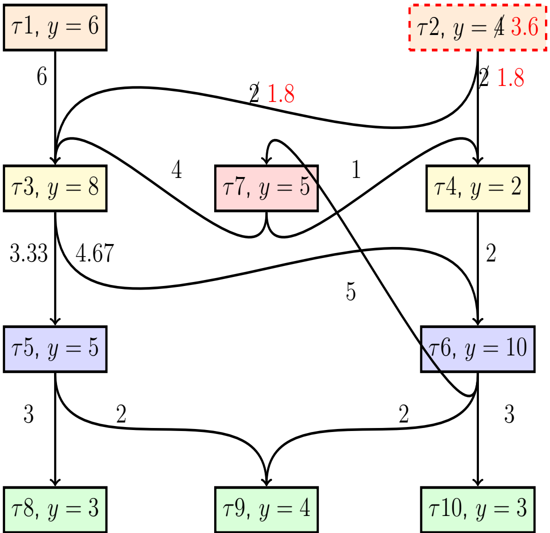

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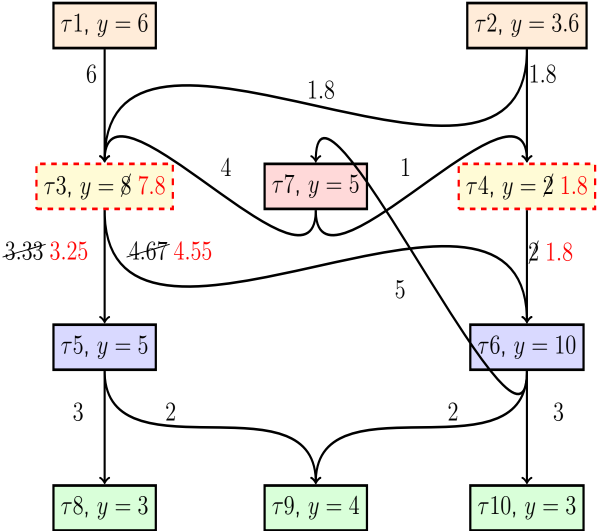

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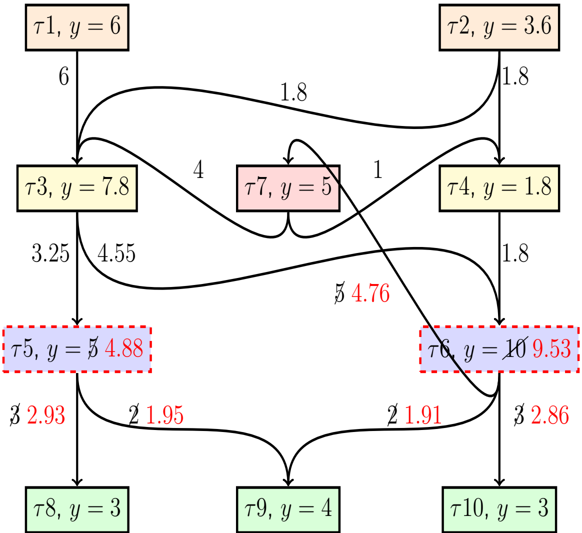

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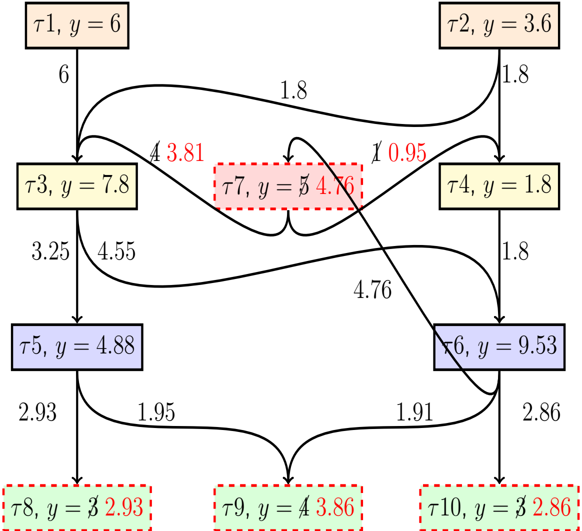

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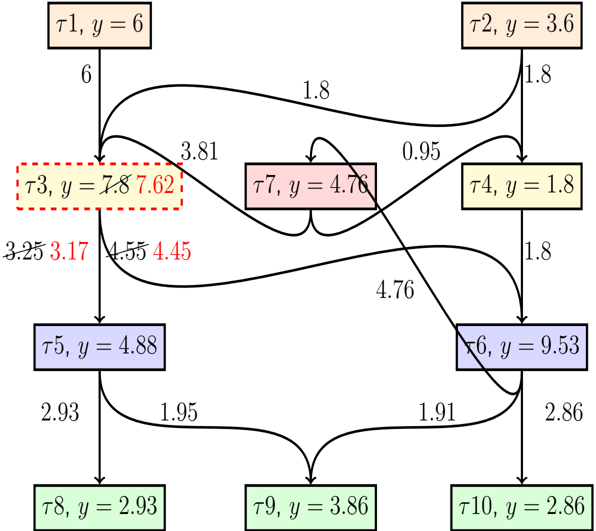

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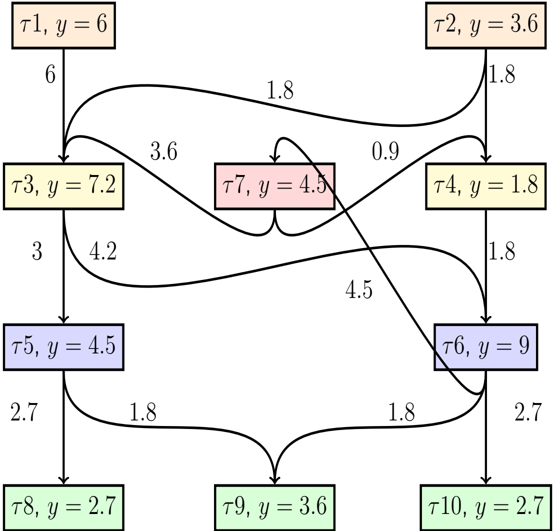

Short-Run Impact: The Minimum Disruption Problem

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

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.

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: for low iceberg 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

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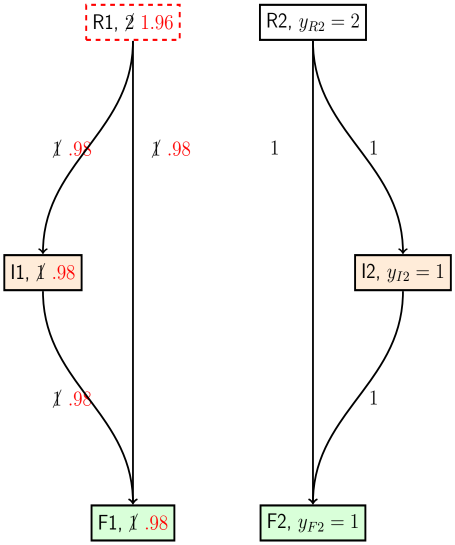
$$\frac{\partial \log(U)}{\partial \log(\lambda)} = \frac{\partial \log(GDP)}{\partial \log(\lambda)} = \frac{(1-\lambda) p_\tau y_\tau}{GDP}.$$

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%



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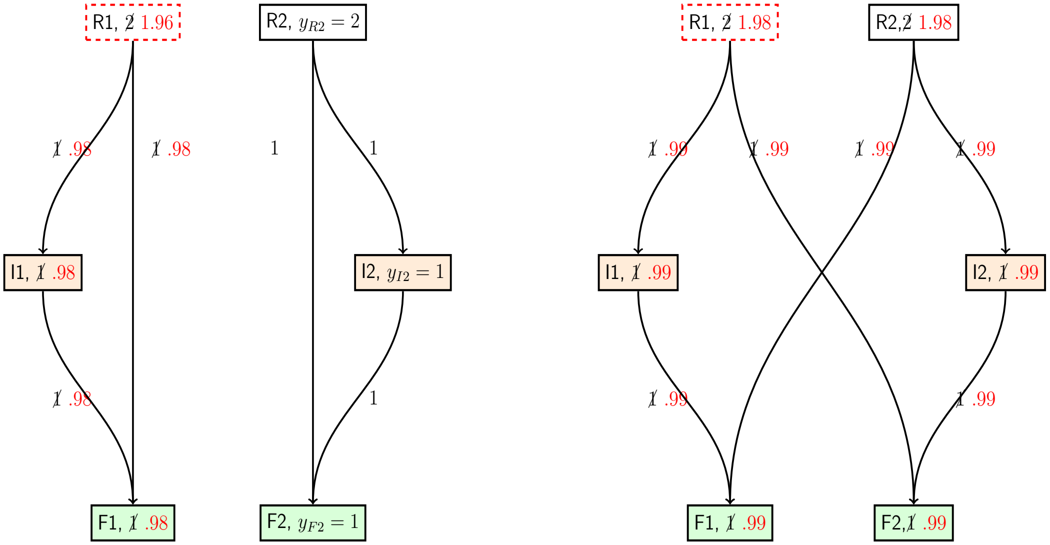
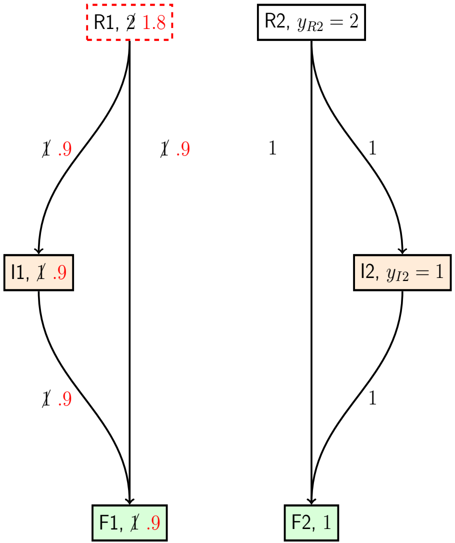


Short Run: Network Matters: Impact 5% or 10%



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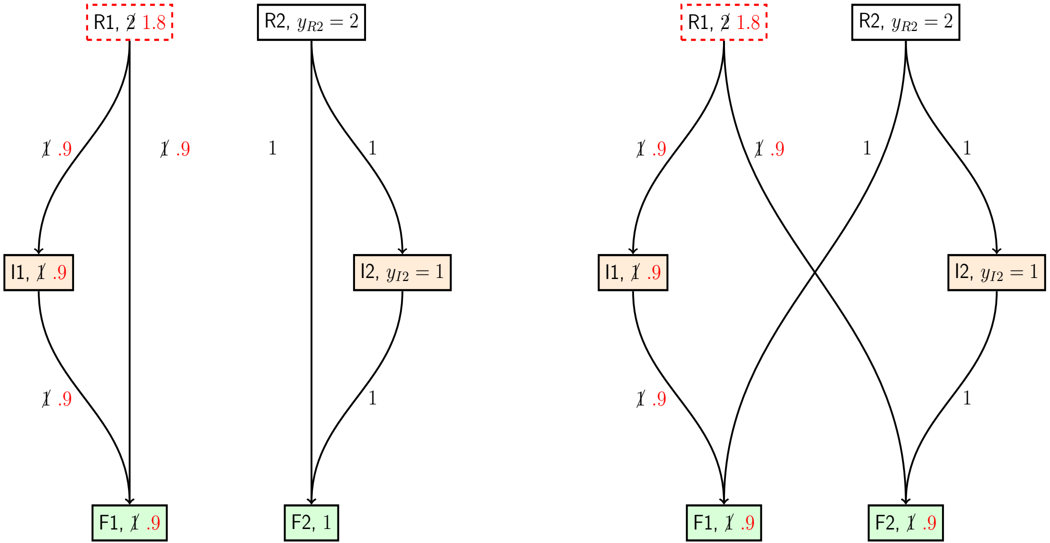

Short Run vs Long Run

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.

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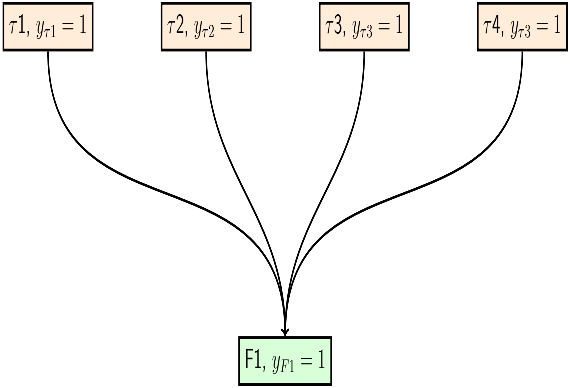
Supply Chain Complexity and Disruption

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

- Probability π disrupt any given technology, independent.
- $S =$ average # inputs used produce a final good.
- $q =$ E[(cost of random input)/(cost per final good)].
- $m =$ average number of final goods downstream from random input.

Horizontal Supply Chain (all labor inputs = 1)



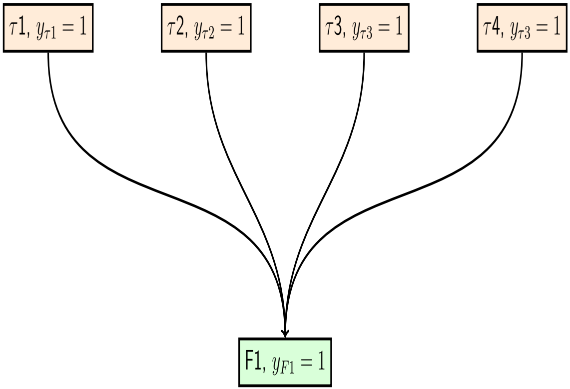
Labor endowment: 5

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

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

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

Horizontal Supply Chain (all labor inputs = 1)



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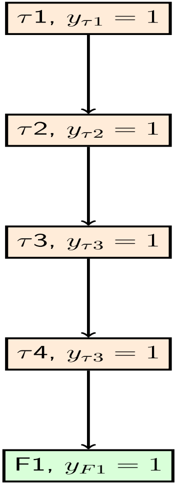
Complexity inputs/final good: $S = 4$.

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

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

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

Vertical Supply Chain (all labor inputs = 1)



Labor endowment: 5

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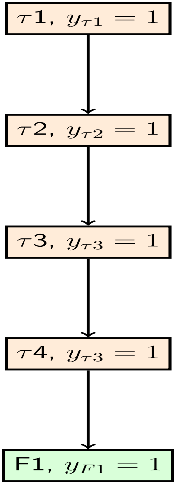
Complexity inputs/final good: $S = 4$.

Average input cost / final good cost: $q = .5$

Vertical Supply Chain (all labor inputs = 1)



Labor endowment: 5

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

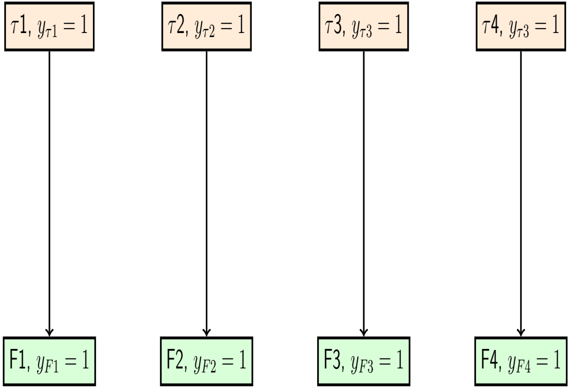
Complexity inputs/final good: $S = 4$.

Average input cost / final good cost: $q = .5$

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

Long Run expected impact: $2(1-\lambda)\pi$

Parallel Supply Chains (intermediate labor inputs = 1, final goods = 1/4)



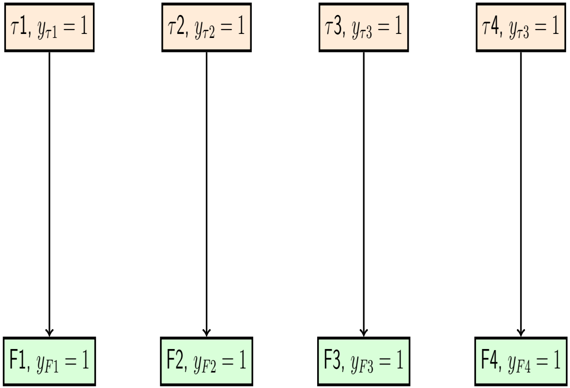
Labor endowment: 5

$$p = \Bigg(\underbrace{\frac{1}{5}}_{\text{labor}}, \underbrace{\frac{1}{5}}_{\tau 1}, \underbrace{\frac{1}{5}}_{\tau 2}, \underbrace{\frac{1}{5}}_{\tau 3}, \underbrace{\frac{1}{5}}_{\tau 4}, \underbrace{\frac{1}{4}}_{F1}, \underbrace{\frac{1}{4}}_{F2}, \underbrace{\frac{1}{4}}_{F3}, \underbrace{\frac{1}{4}}_{F4}$$

Complexity inputs/final good: $S = 1$.

Average input cost / final good cost: $q = .8$

Parallel Supply Chains (intermediate labor inputs = 1, final goods = 1/4)



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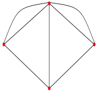
Complexity inputs/final good: $S = 1$.

Average input cost / final good cost: $q = .8$

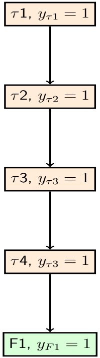
Short Run expected impact: $(1 - \lambda)\pi$

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



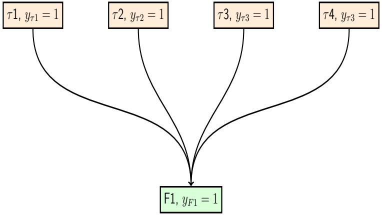
SR $4(1-\lambda)\pi$

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



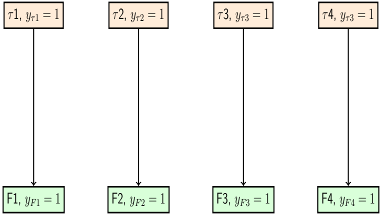
SR $4(1-\lambda)\pi$

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



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

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



Supply Chain Complexity and Disruption

Proposition (Complexity and Fragility)

For small π

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

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

Supply Chain Complexity and Disruption

Short Run:

- Increased number of goods (S) per supply chain to disrupt,
- Each would disrupt the final good fully (by $1 - \lambda$).
- Overall effect $(1 - \lambda)\pi S$.

Long Run:

- Increased number of goods (S) per supply chain to disrupt,
- But each has a fractional value (q) relative to final good.
- Overall effect $(1 - \lambda)\pi S q$.

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'.

Competing Effects of dropping costs:

- Increased diversity: new technologies/goods become viable as can source inputs that were previously too expensive.
- Increased specialization: only most efficient technology is used.

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- Increased specialization: only most efficient technology is used.

- ∼90% of most advanced computer chips assembled in Taiwan,
- Materials cross borders > 70 times before final assembly.

Specialization

Proposition (Specialization)

Generically, if transportation costs are sufficiently low there is a unique equilibrium with full specialization: There exists a cost threshold $\bar{\theta} > 1$ such that if $\max_{\tau,\tau'} \theta_{\tau\tau'} < \bar{\theta}$, then $y_\tau > 0$ and $y_{\tau'} > 0$ implies that $O(\tau) \neq O(\tau')$.

Fragility and globalization

Corollary (Globalization)

If transportation costs are sufficiently low, then in generic economies the upper bound is tight for any shock.

As supply chains consolidate: If shocks are not perfectly correlated across different producers of the same good, then the probability of the disruption of the final good decreases, but the expected short-run size of that disruption conditional upon occurrence increases.

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...

Outline

1. Introduction
2. Model
3. The Impacts of Shocks: Contrasting Short and Long Runs
4. Complexity, Fragility, Globalization
5. The Impact in the Medium Run

Medium Run

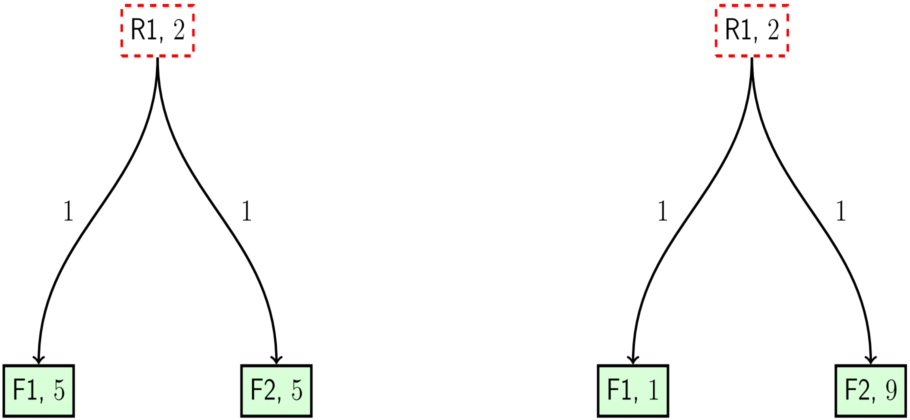
No new sourcing: existing supply chains in place

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.

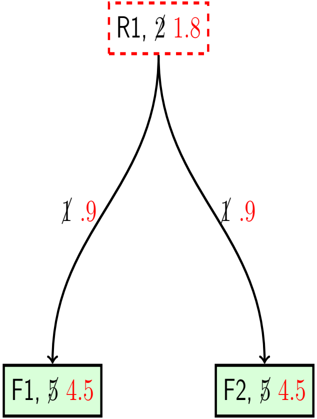
Medium Run Shock Impact



Equal-Valued Final Goods

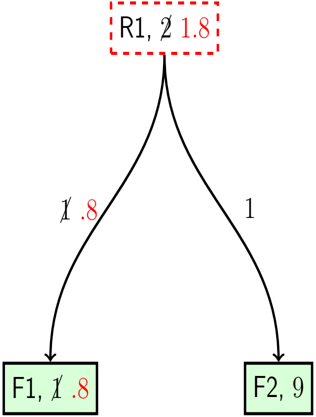
Unequal-Valued Final Goods

Medium Run Shock Impact



Impact 1/10

Same as Short Run



Impact 1/50

Close to Long Run

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

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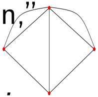

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