Strategic Formation and Reliability of Supply Chain Networks

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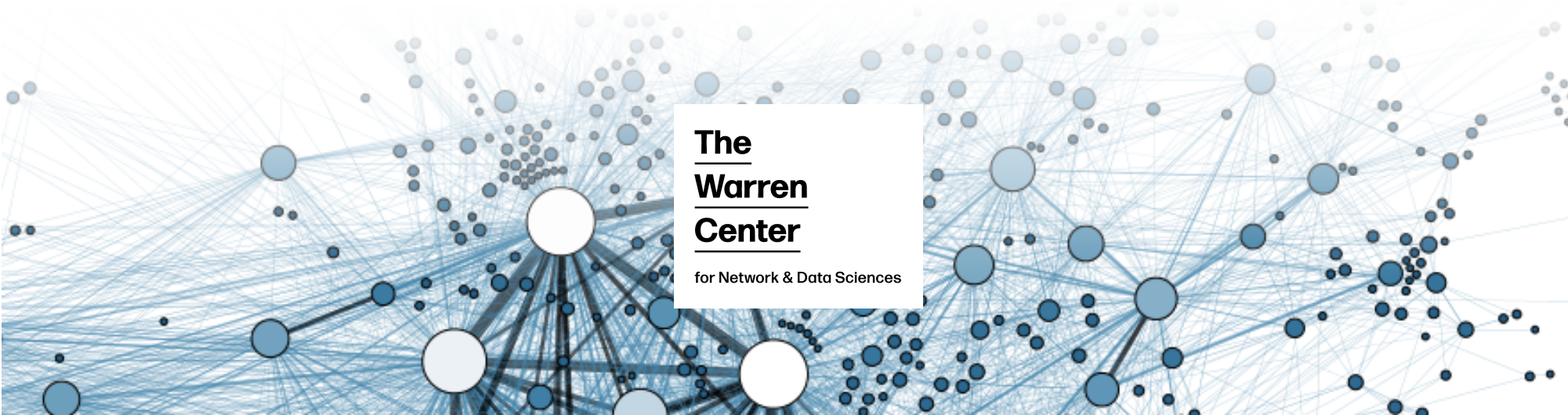
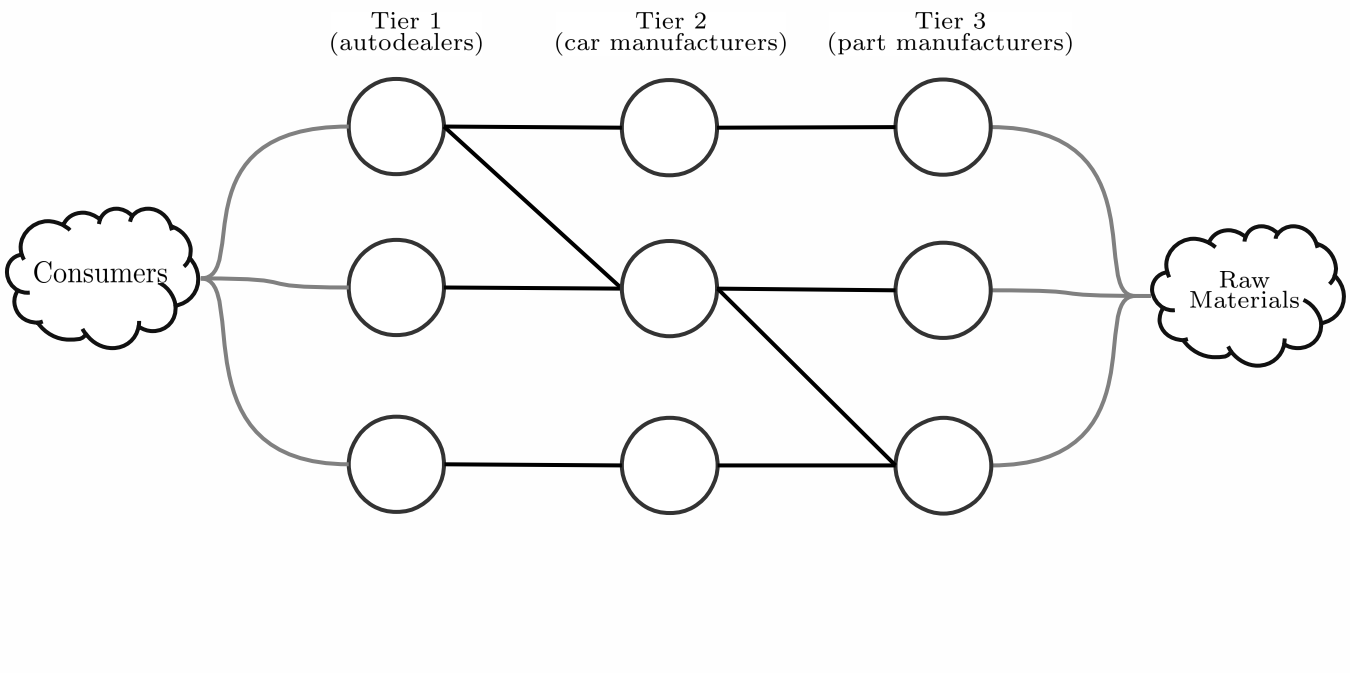
Joint work with Rakesh V. Vohra (Penn)



Supply Chain Networks



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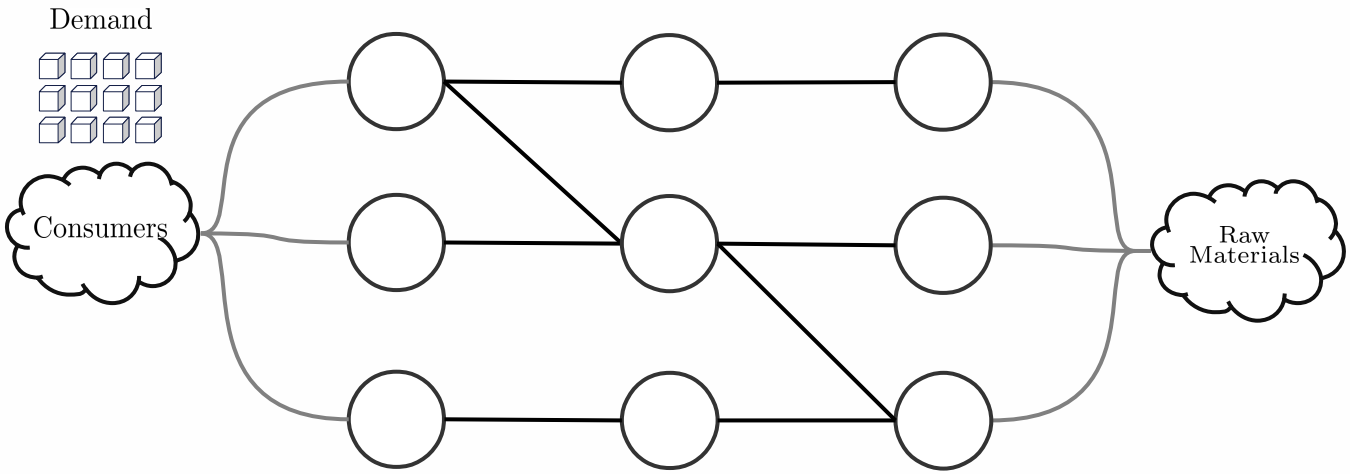

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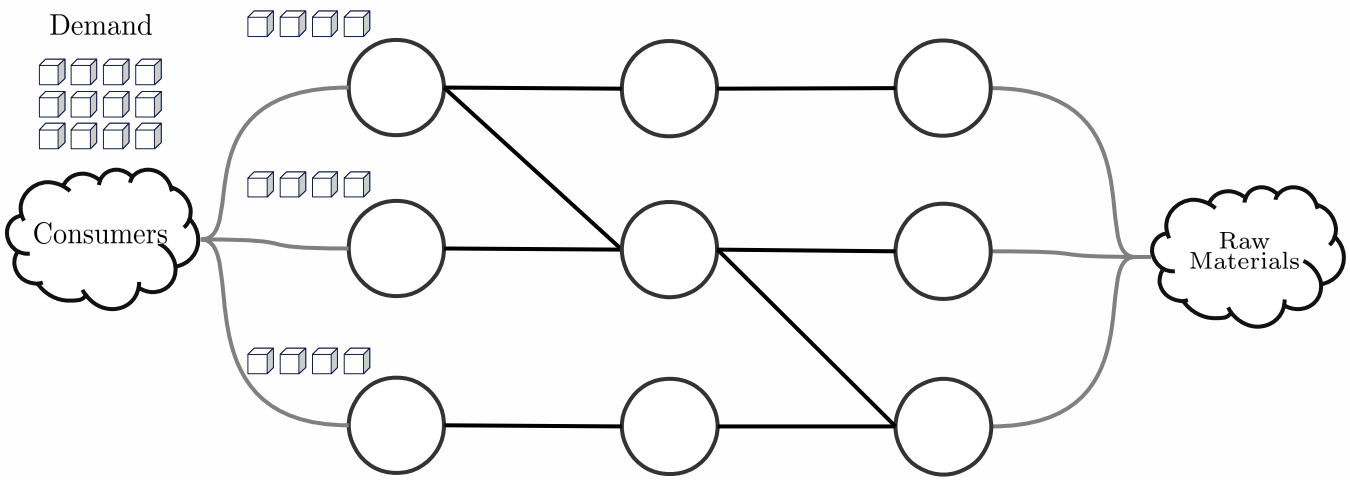

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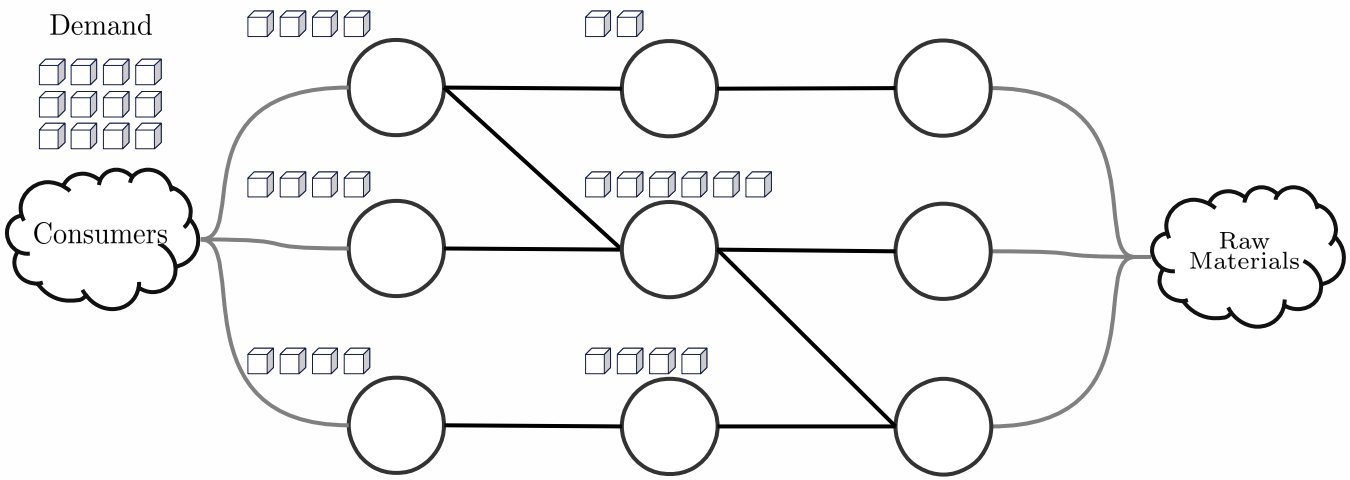

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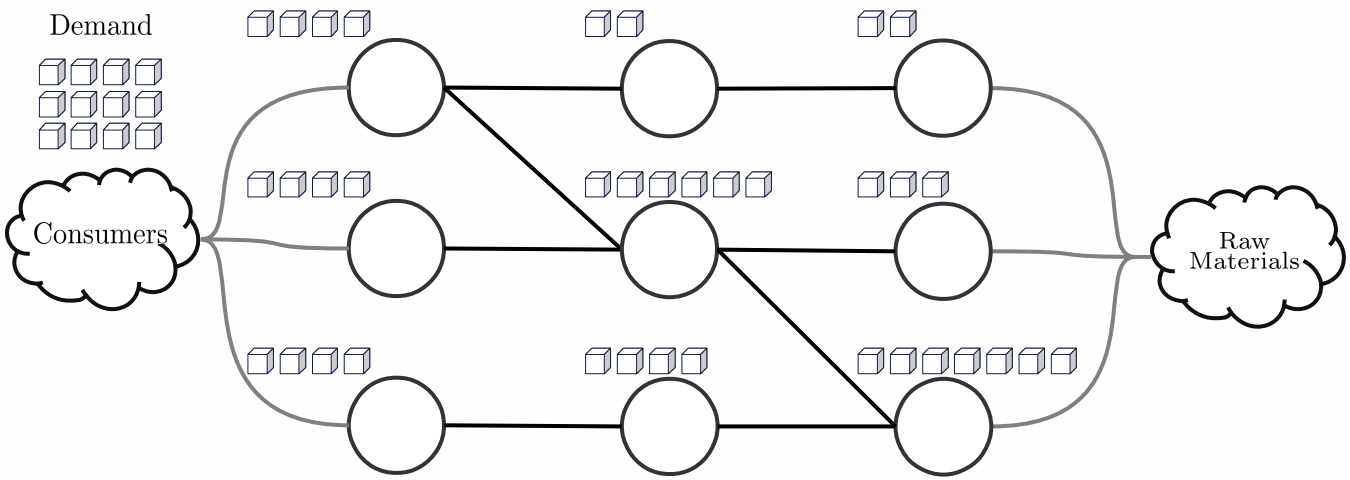

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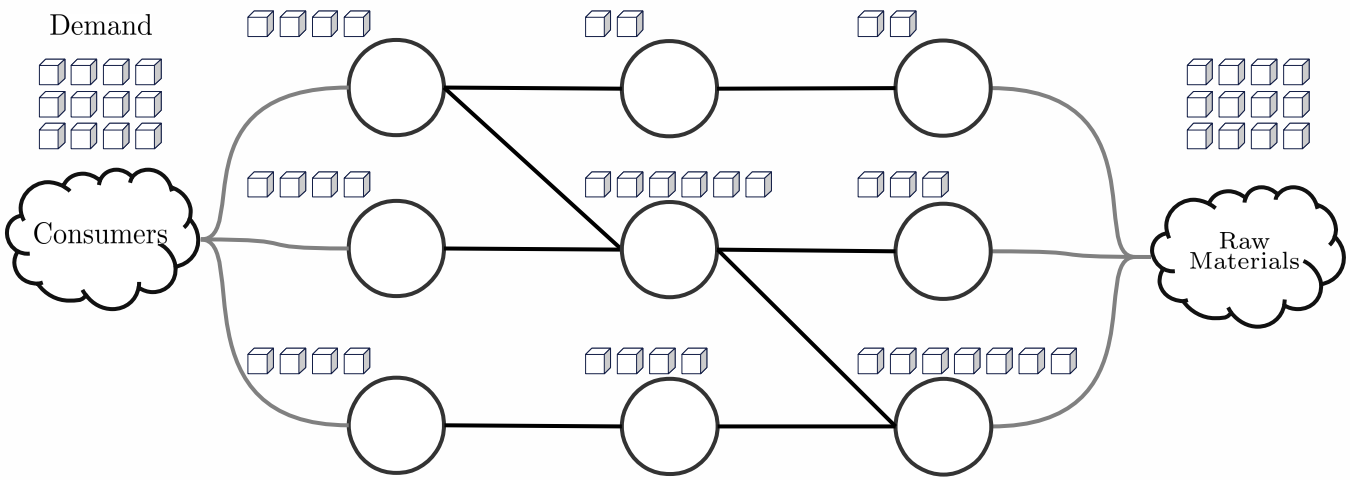

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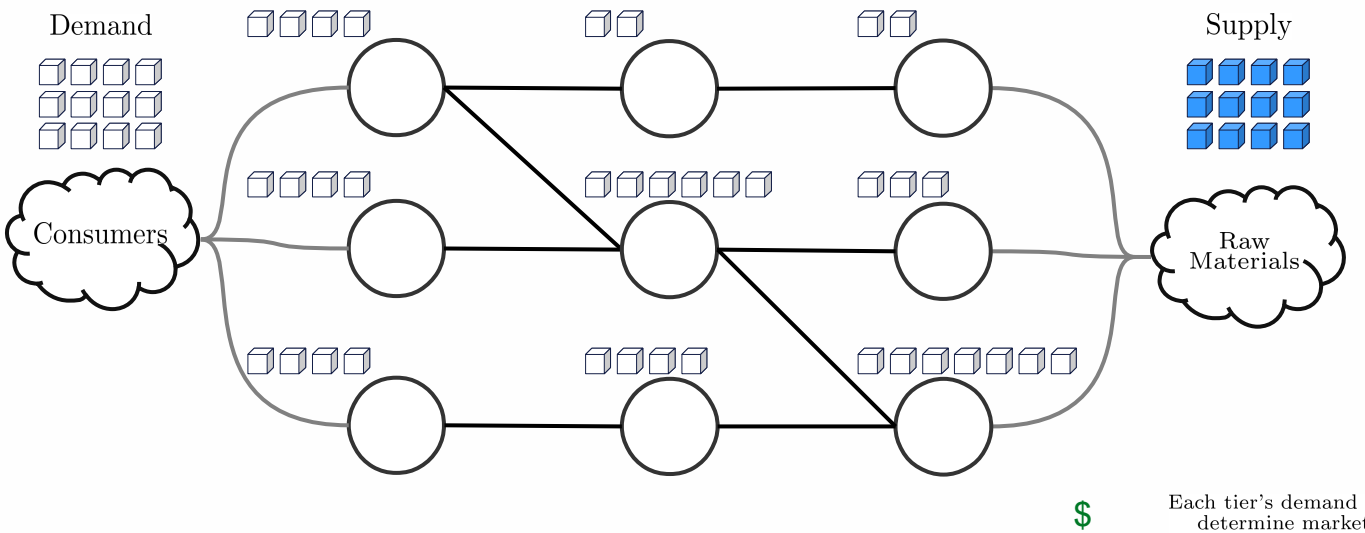

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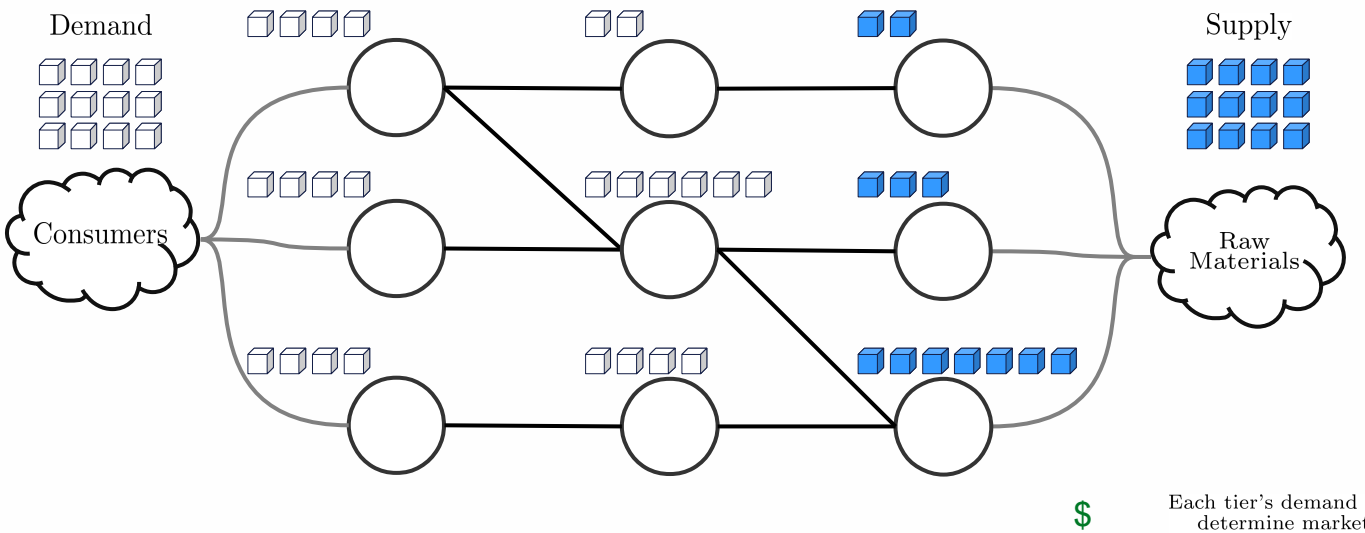

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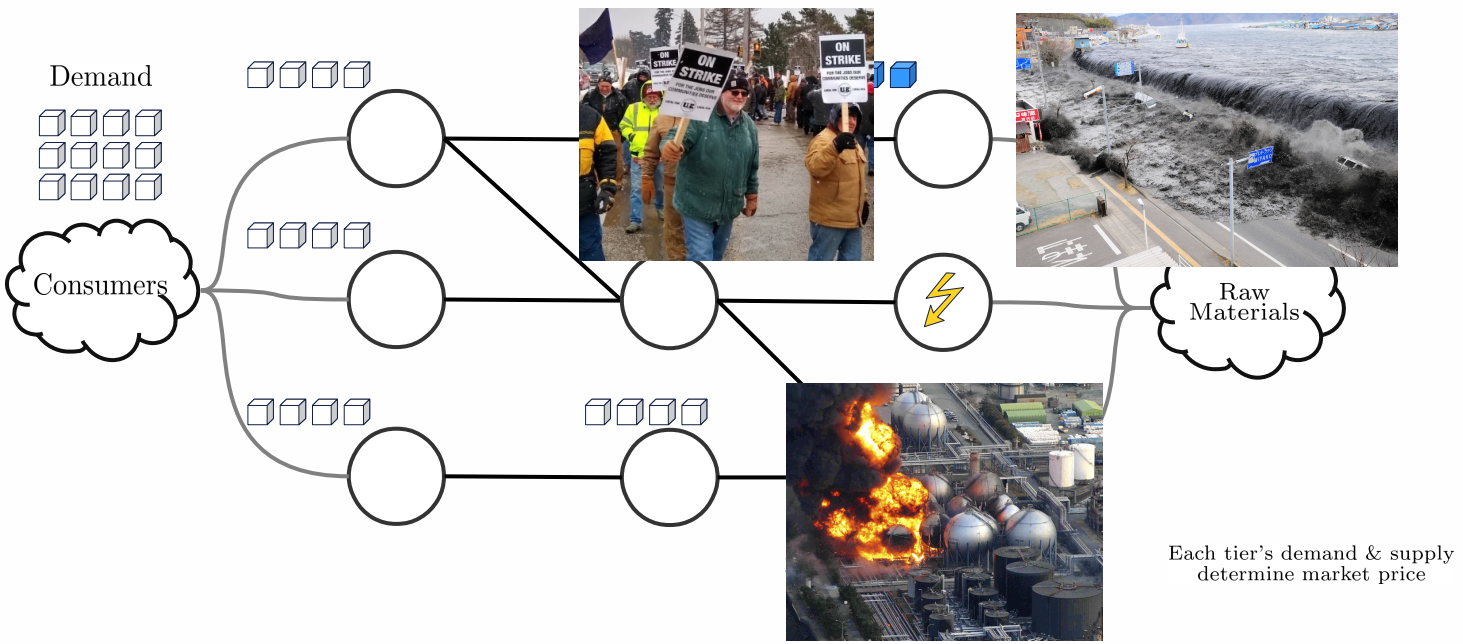
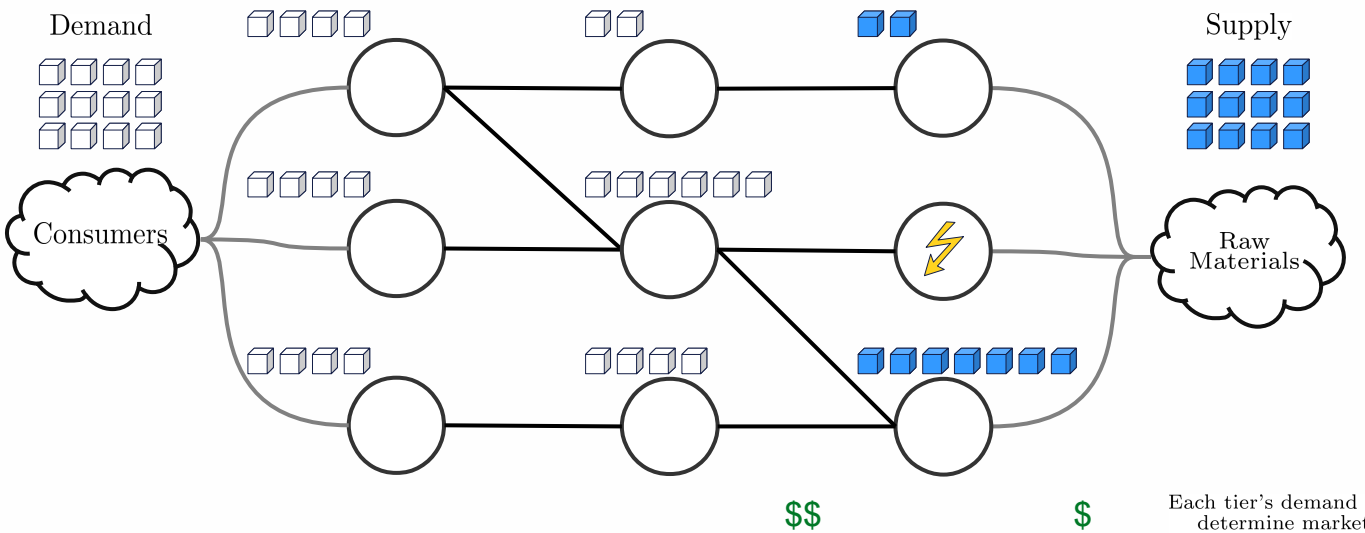


Each tier's demand & supply determine market price

Supply Chain Networks



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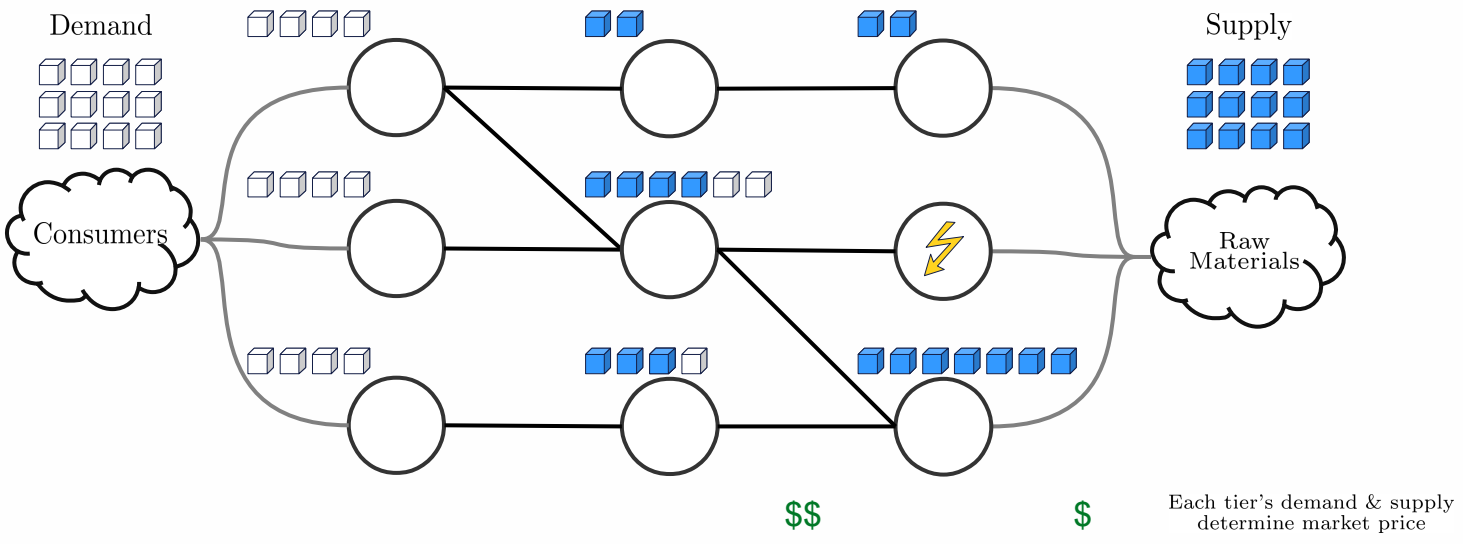

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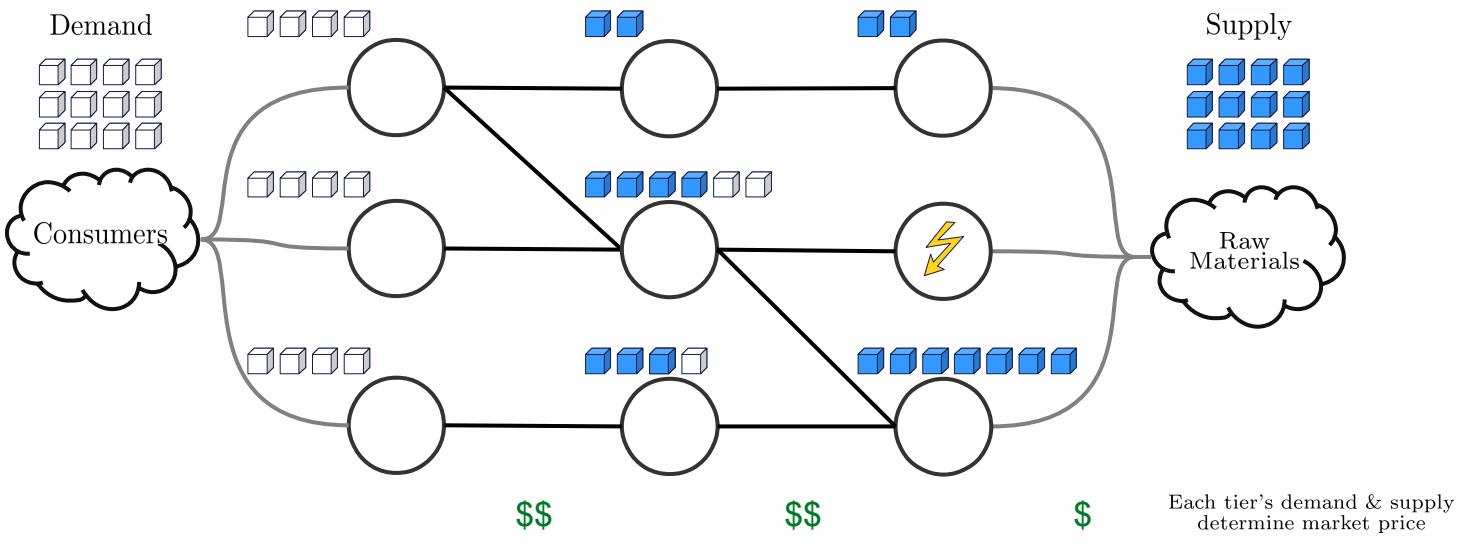

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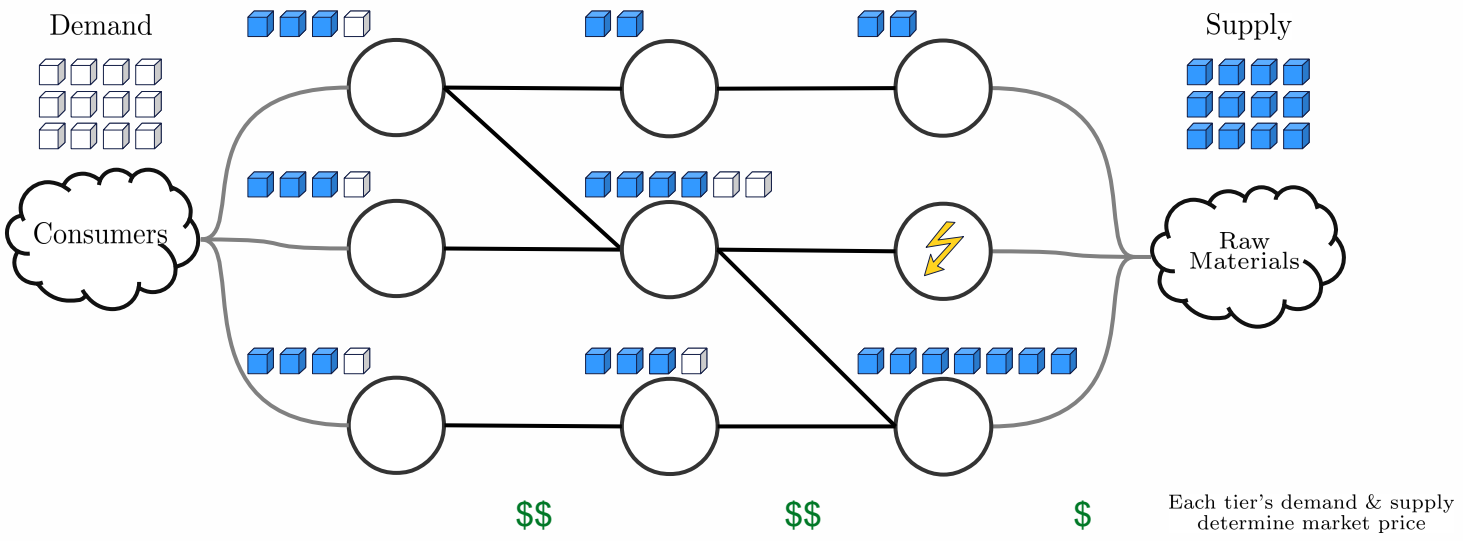

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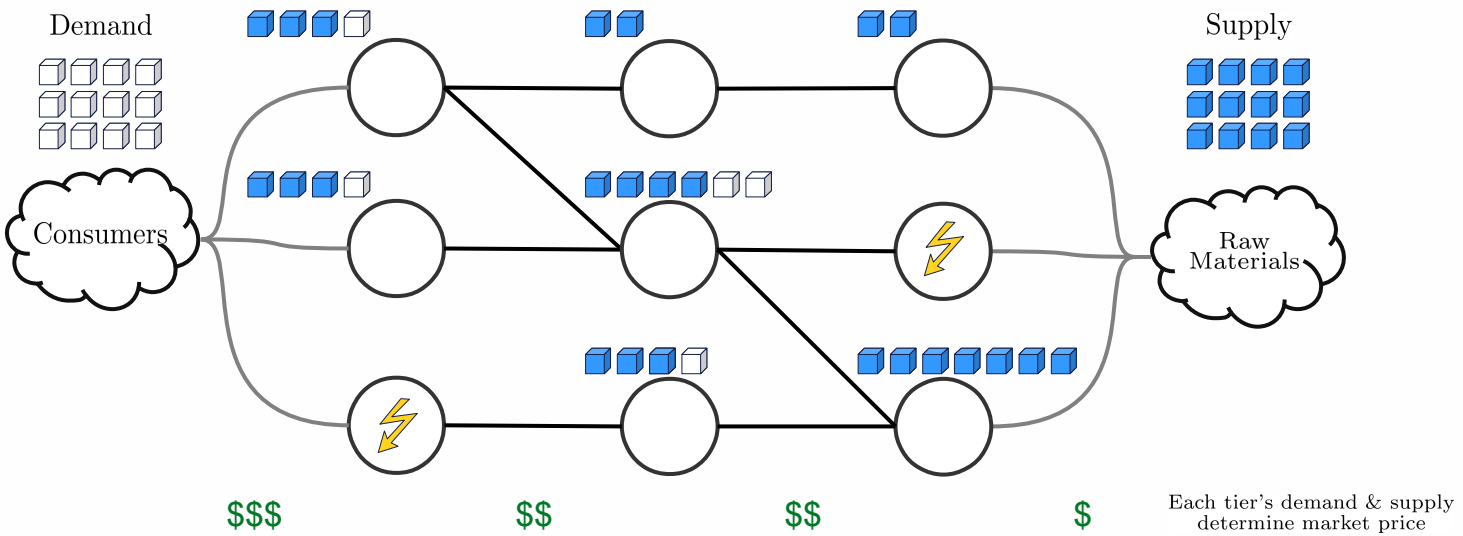

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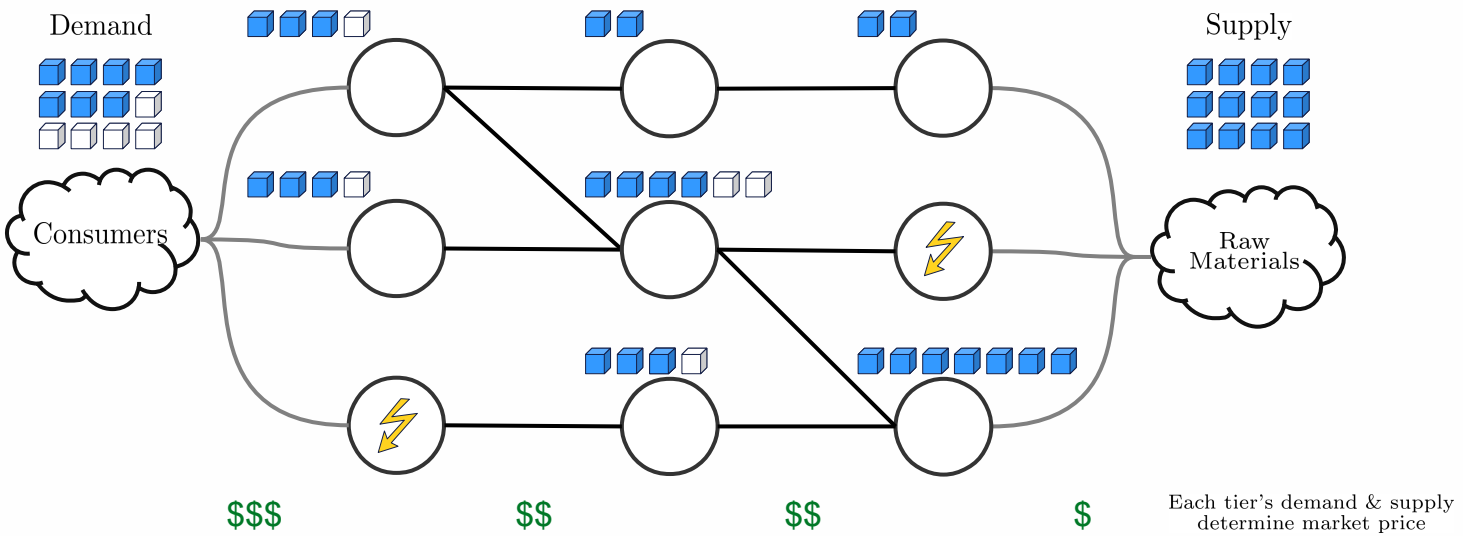

Motivation and Problem Statement

- Supply chains experience disruptions (production failures, delays / congestion)
- Supplier and consumer welfare critically depend on network structure
- Centrally planned supply chains guard against failures via multi-sourcing

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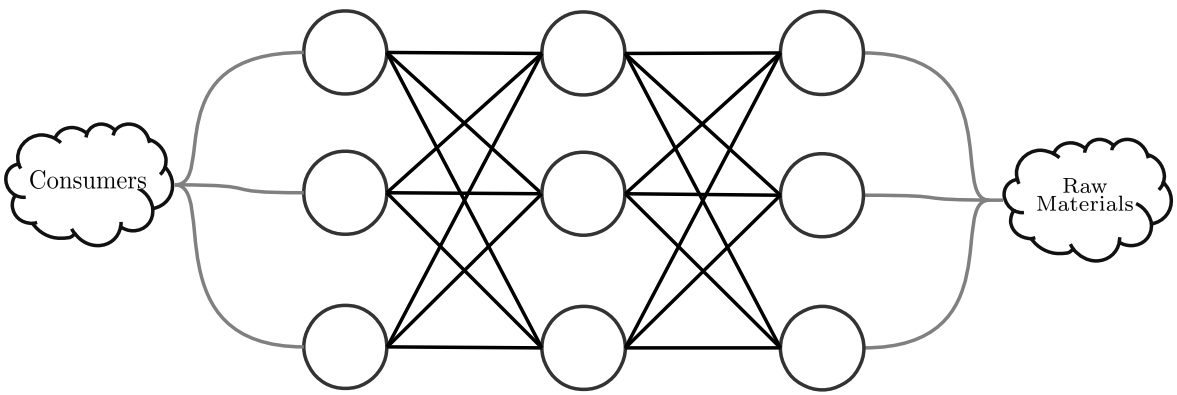
- Centrally planned supply chains guard against failures via multi-sourcing
  - ▷ one option – complete k-partite network
  - ▷ dense $\rightarrow$ expensive (cost of link $\sim$ cost of a contract)



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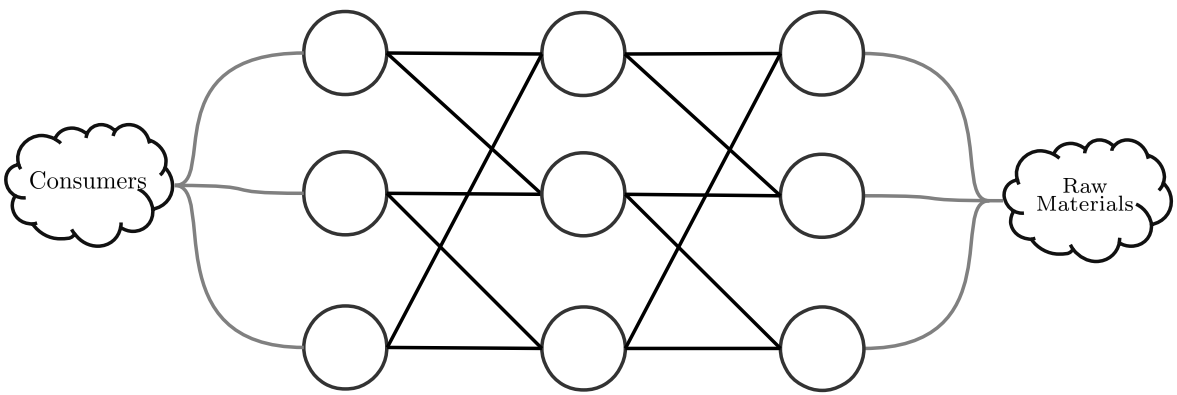
- Centrally planned supply chains guard against failures via multi-sourcing
  - some alternatives – k-partite ℓ-chains and (vertex) expanders
  - sparse $\rightarrow$ lower link maintenance costs



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- Supplier and consumer welfare critically depend on network structure
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- **Main Question:**

If rational agents make independent sourcing decisions without coordination, will they form a resilient supply chain network?

Novel Aspects: strategic network formation + disruptions + competition

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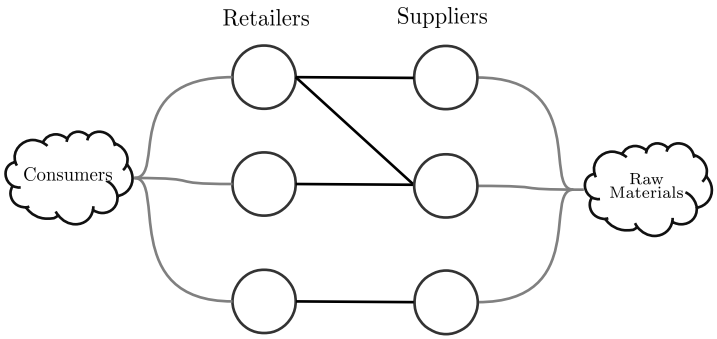
Novel Aspects: strategic network formation + disruptions + competition

- More technically:
  - ▷ Players – retailers and suppliers (except top-tier suppliers)
  - ▷ Strategy – whom to link to upstream
  - ▷ Agents engage in a single-shot network formation game with costly links
  - ▷ Q: Are there (Nash) equilibria networks? Are they resilient?

Supply Chain Network Formation w/o Congestion



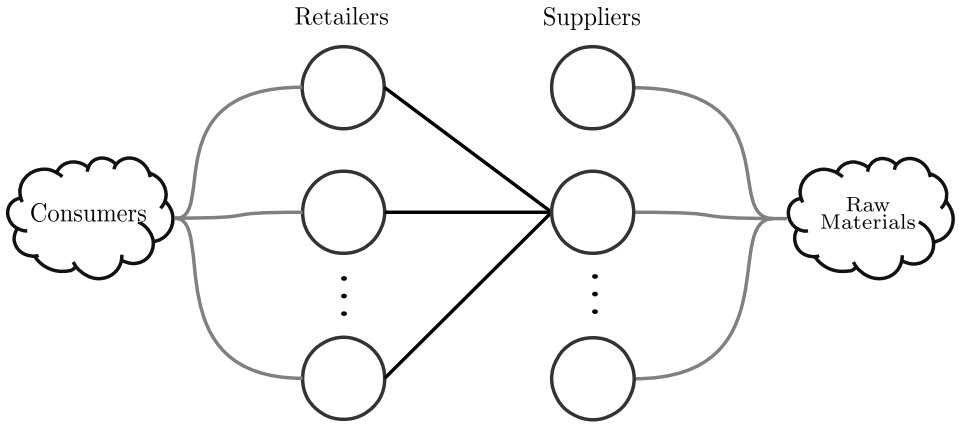
- Retailers have the following payoff structure

$$\text{payoff}_i = -\underset{\text{quantity}}{\text{procured}} \times \underset{\text{market price}}{\text{upstream tier's}} + \underset{\text{quantity}}{\text{sold}} \times \underset{\text{market price}}{i\text{'s tier's}} - \underset{\text{for all created links}}{\text{linking cost}}$$

  - ▷ linking cost $\sim$ cost of signing a contract
  - ▷ no congestion / no supply caps
- Retailers engage in network formation game:
  - ▷ Retailers make sourcing decisions before production realization
  - ▷ Production (failures) are realized
  - ▷ Market prices are realized under market clearance assumption
  - ▷ Retailers buy/sell and collect payoff
- Q: What are pure strategy Nash equilibrium networks of this game?

Supply Chain Network Formation w/o Congestion – Equilibria

- Unique (up to agent labeling) non-empty Nash equilibrium



  - ▷ one link per retailer
  - ▷ retailers concentrate links on a single supplier

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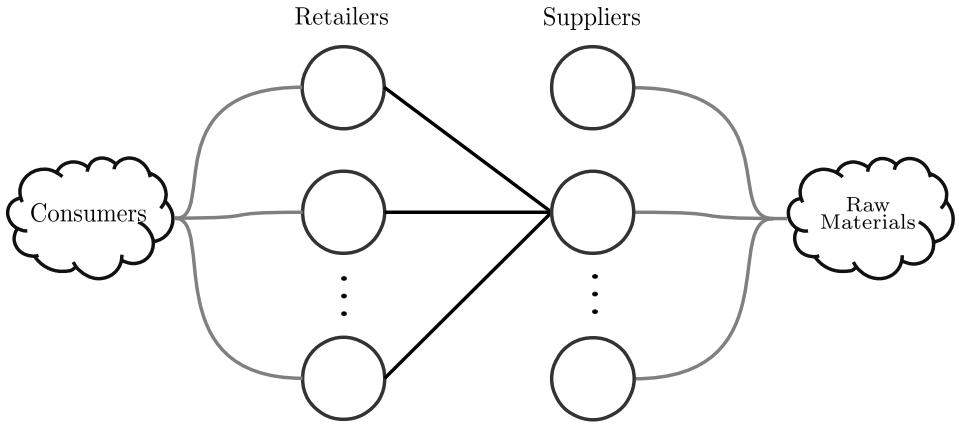

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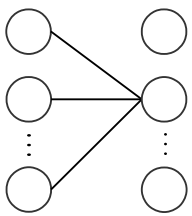
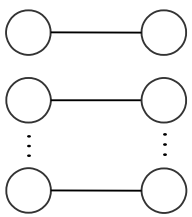
- Retailers benefit from supply variance:



  - ▷ linked supplier fails – no trade
  - ▷ linked supplier succeeds – full output (lowest market price)



  - ▷ lower output / higher market price on average

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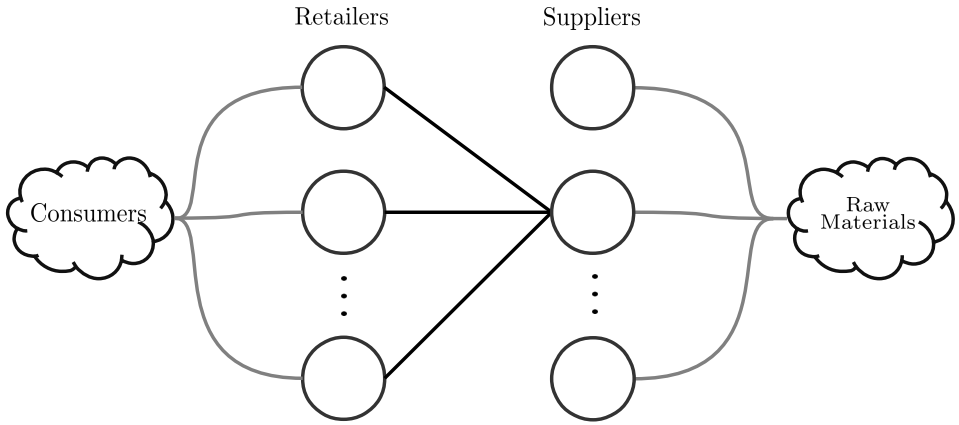

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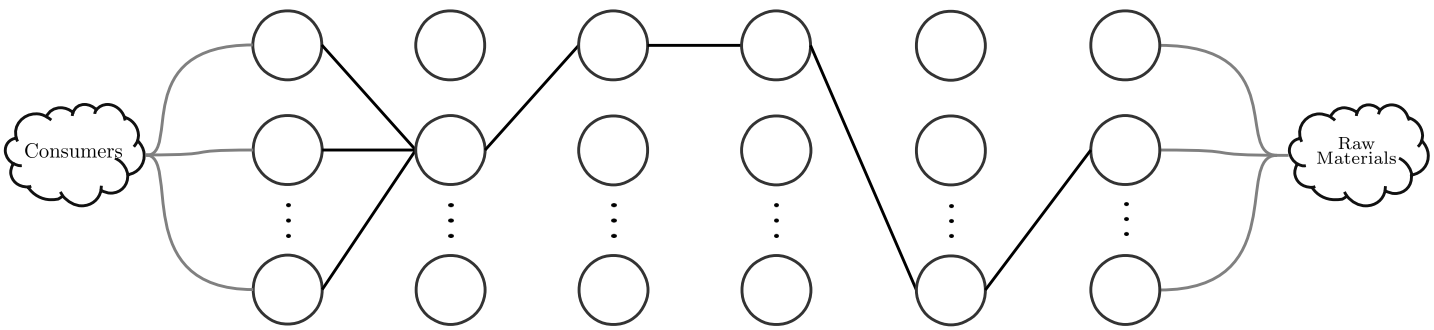
- Multi-tier supply chains: a unique (up to labeling) non-empty equilibrium



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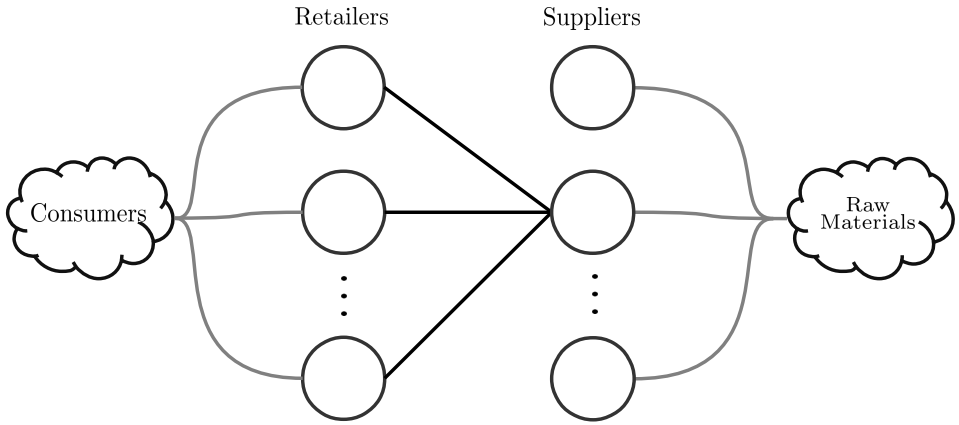
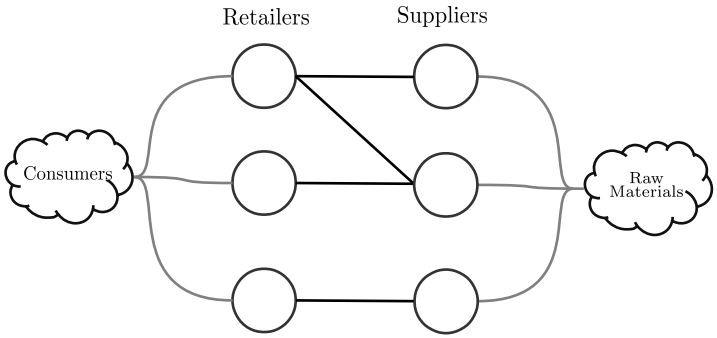


  - ▷ one link per retailer
  - ▷ retailers concentrate links on a single supplier
- Takeaway:
  - ▷ when there is no "congestion", retailers benefiting from supply variance form not-so-resilient networks

Supply Chain Network Formation with Congestion



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  - ▷ linking cost $\sim$ cost of signing a contract
  - ▷ larger production amount per supplier $\rightarrow$ larger congestion cost
  - ▷ congestion cost $\sim$ soft constraint on supply or delay penalties
- Retailers engage in network formation game:
  - ▷ Retailers make sourcing decisions before production realization
  - ▷ Production (failures) are realized
  - ▷ Market prices are realized under market clearance assumption
  - ▷ Retailers buy/sell and collect payoff
- **Q:** Are pure strategy Nash equilibrium networks of this game resilient?

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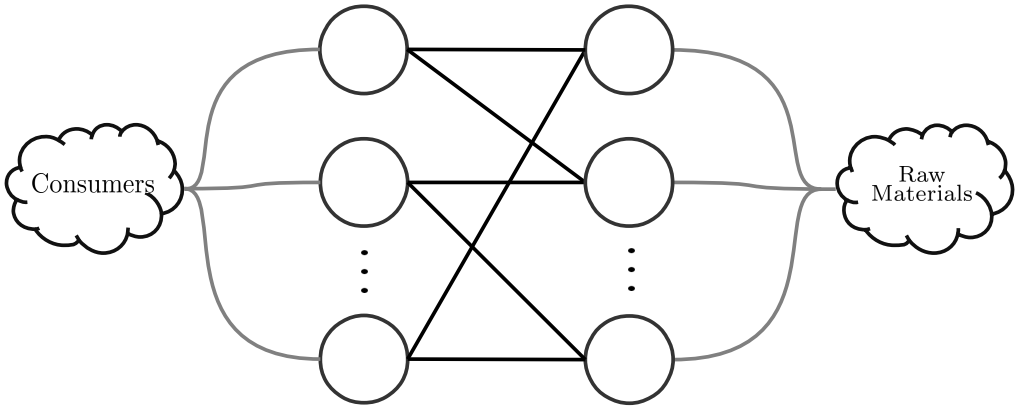


- Symmetric equilibria – expander-like (known as resilient from central planning perspective)

  (generally, non-unique; observation—other non-empty equilibria are structurally similar)

- Result from combination of two forces:
  - ▷ supplier base reduction / link concentration (securing better prices)
  - ▷ supplier base diversification (avoiding congestion)

Supply Chain Network Formation with Congestion – More Reliability?

- Do suppliers have an incentive to improve their reliability?
- Two ways to improve reliability:
  - reducing congestion – unconditionally beneficial
  - increasing mean yield – beneficial up to some point; past that – hurts
    - (retailers, however, would prefer as high mean yield as possible!)

Summary and Open Problems

Core Novelty: a model for endogenous supply chain network formation capturing disruptions and competition.

Insights

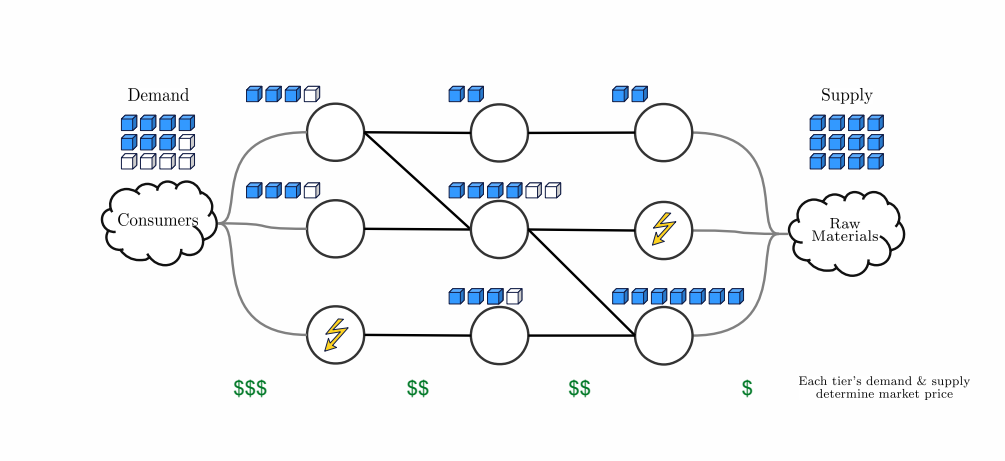
1. when there is no congestion, retailers create sparse networks concentrating links, benefiting from supply variance.
2. when congestion is added, symmetric equilibria are expander-like (resilient!).
3. reducing congestion – always good for a supplier; boosting mean yield – not always.

Open Problem

What is the optimal balance between multi-sourcing and over-ordering?

- In our model, retailers choose links, yet, not order quantities; what if we let them do both?
- Without congestion, (structurally) same networks are formed.
- With congestion – open problem.

Questions



Model capturing endogenous network formation + disruptions + competition

$$\text{payoff}_i = -\underbrace{\text{procured quantity}}_{} \times \underbrace{\text{upstream tier's market price}}_{} + \underbrace{\text{sold quantity}}_{} \times \underbrace{i\text{'s tier's market price}}_{} - \underbrace{\text{linking cost for all created links}}_{} - \underbrace{\text{“congestion cost”}}_{}$$

(https://victoramelkin.com/pub/supply-chains/)