Benjamin Golub

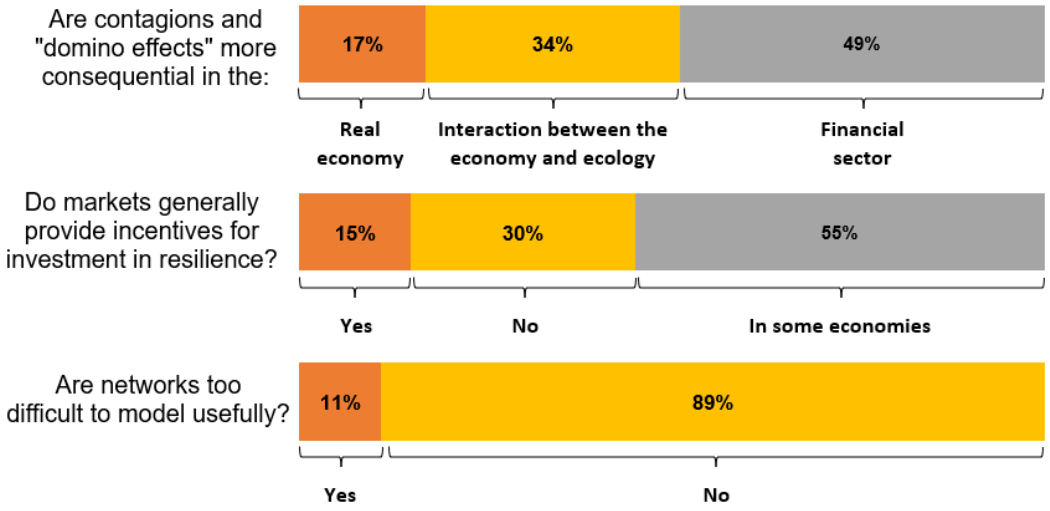
Networks in Contagion and Resilience

On Thursday, March 21, Benjamin Golub joined Markus' Academy for a conversation on "Networks in Contagion and Resilience." Benjamin Golub is a professor of economics and computer science at Northwestern University.

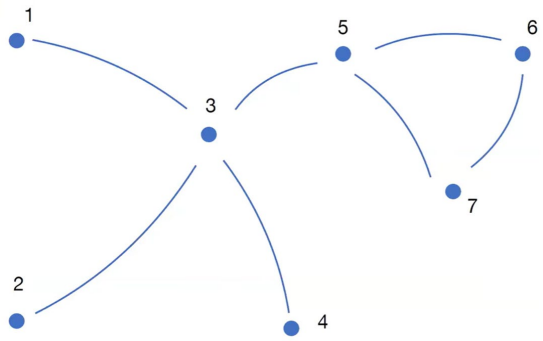
A few highlights from the discussion.

- **A summary in five bullets**
    - Networks come up naturally when we think about the mechanics of resilience: they mediate disruption because they describe externalities, spillovers and strategic reactions to these
    - The talk provided an overview of the literature on network theory, focusing on the real economy's production networks. Golub started by covering the canonical toy model of a network game.
    - Attempts to integrate this basic model into macro models faced some fundamental challenges, with recent advances in the literature showing that these can be overcome by applying linear algebra and associated statistical techniques
    - Golub concluded by presenting his recent work on supply chain disruption, which leveraged percolation theory from physics. It highlighted novel externalities in the formation of supply chains and the fact that resilience policy might be more subtle than previously thought
    - Overall, much work remains to be done in network theory, and much can be gained from leveraging the tools from our allied disciplines

- **[0:00] Markus' introduction and poll questions:**
    - How should we measure the value of resilience? One proposal is to measure the discounted present value of the benefits from adaptability. This measure also allows for measuring the costs of non-resilience
    - Adverse feedback loops are characterized by two things: externalities and strategic complementarities. Agents' reactions to externalities will depend on the structure of the network, for example on the extent of its centralization. Fully distributed networks tend to be more resilient, where knocking out one node will not have much of an effect (one example of this kind of network is our brain)
    - Micro resilience is not necessarily good for macro resilience. This is the fallacy of composition. Often one may want to shut down certain parts of the network to ensure the survival of the whole



- **[6:50] The basic network toy model**
  - Networks come up naturally when we think about the mechanics of resilience: they mediate disruption because they describe externalities, spillovers and strategic reactions to these
  - Arguably the most important economic network is the real production network, with supply and demand shocks propagating through the network. In the context of financial stability there has also been a lot of interest in cascades of defaults, fire sales and liquidity crunches.
  - Consider a toy model where we depict a network as nodes and links:



  - Formally, an “adjacency matrix” describes the network, and has a positive entry if there is a link between nodes *i* and *j*. The size of the entry can then describe the strength of the relationship
  - Think of the model as a set of firms that are investing in a new technology. Firms’ payoffs will depend on their own investment, the spillovers they get from other firms also investing, and their investment cost
  - With simple first order conditions one can obtain an expression of how much each firm will invest as a function of their direct return on investment and of how much everyone else invests. This is the “reduced form” peer effect
  - We can further solve for the endogenous terms (how much everyone else is investing) and obtain an expression for how much each firm will invest as a

function of the links, the strength of the spillovers, and everyone's private returns (with all of these being exogenous). This is the "structural" peer effect equation
    - This equation allows us to study the effect of giving an innovation subsidy to a single firm in the network. It will allow us to study the "zero order" direct effect of the subsidy on the receiving firm and the "first order" effect of how much his neighbors will increase investment from the positive spillovers they are seeing, but also the "second order" effect from the fact that the "neighbors of the neighbors" will also invest more due to the spillovers (this goes ad infinitum).
    - Ultimately, the total effect of giving a single firm a subsidy will be driven by how "central" the firm was in the network. Note this measure of centrality was developed by Bonachic (1987) and need not be about how connected you are to firms, but rather how connected you are to other central firms

- **[19:31] How does this fit into economics?**
    - These ideas in economics didn't start with network games, they go back to Leontieff (1936) and his work on supply and demand shocks propagating through production networks
    - Most recently they were revived in micro theory (Ballester et al. 2006) and the econometrics of peer effects (Bramoullé et al. 2009). An applied example is Chetty et al. (2015) being interested in the peer effects through neighborhoods on intergenerational mobility
    - The "second generation" models that emerged used the idea of centrality to study things like (1) the impact of production networks on GDP (Acemoglu et al. 2012), (2) how financial networks react to cascading bankruptcies (Elliot et al. 2014 and Acemoglu et al. 2015), or (3) how rumors filter through financial markets to form market opinions (DeMarzo et al. 2003)
    - Focusing on macro, models embedding production networks in general equilibrium arrived at a fundamental problem: the network implications of productivity shocks on welfare are only of second order importance
    - So as Baqaee and Fahri (2019) showed, if you care about first order outcomes you don't need to look at the network. If you want to understand how networks matter you need to go beyond a simple static version of Leontieff's theory
    - This led to a "third generation" of production network models. Their key insight is that to see why networks are interesting you have two options: (1) in a static model you have to start with a distorted economy or (2) build dynamic models
    - For example Baqaee and Farhi (2020) built a model where markups distort the allocation in equilibrium. The first order welfare effects of productivity shocks will come not just from the technology shock (which the 2nd generation models also had) but also from how the production network (and its degree of centrality) responds to the shock, bringing changes in allocative efficiency

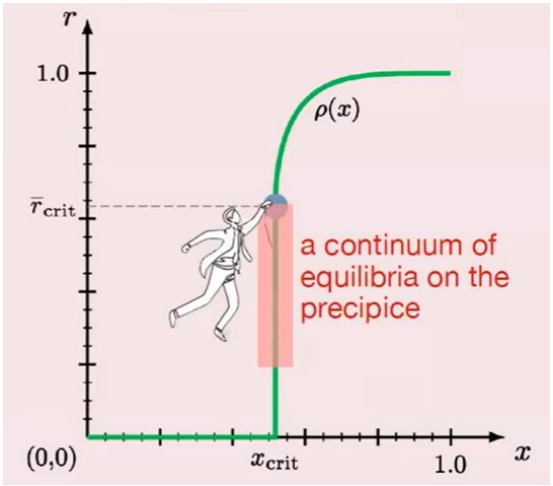
- **[31:18] How do networks matter intuitively? A second toy model**
    - The problem with Baqaee and Farhi (2020) is that the formulas are complicated and unintuitive. How does the network matter for welfare intuitively? Further, to

make a statement about the importance of networks it makes an assumption about the nature of the distortion, but how much can you trust that assumption?
    - Because of these questions, we need a flexible toolkit (independent of distortion assumptions) to marry the network structure and the economic fundamentals
    - Galeotti et al. (2020) build on the toy model from the first section to allow for both positive and negative externalities. By diagonalizing the adjacency matrix (sandwich formula of eigenvectors and eigenvalues) each agents' role in the network is simplified into their corresponding eigenvalue in the diagonalization
    - This approach allows for policy recommendations. With positive externalities (the R&D spillover model from before) the policymaker should subsidize firms in proportion to a new measure of centrality: the correlation of the firm's eigenvalue with the **first** eigenvector of the decomposition
    - Now consider negative spillovers, for example the provision of public goods. If the policymaker simply subsidizes someone to provide a public good, the intervention will crowd itself out, because the neighbors will free ride on the agent that got the subsidy
    - The optimal intervention should be attentive to this by targeting neighbors in opposite ways: subsidizing certain agents, but also taxing the lack of effort of the recipient's neighbors. The policymaker will then subsidize or tax according to the correlation of each firm's eigenvalue with the **last** eigenvector
    - Now, under this approach whether an agent is subsidized or taxed will be extremely sensitive to the details of the network structure. What if the policymaker doesn't know it precisely? What can a policymaker do with what is statistically accessible? Parise and Ozfaglar (2023) apply the statistical properties of eigenvalues under sampling to this framework
    - What if the model is dynamic (effects happen over several rounds)? Liu and Tsyvinski (2024) develop a model where production is much easier to shut down than to restart, which entails that negative productivity shocks leave scar tissue
    - They conclude that the agents with the higher measure of centrality (again the correlation of the firm's eigenvalue with the first eigenvector) take the longest time to recover. Because of this, one can largely describe the effect of an aggregate shock with a small number of eigenvectors: focusing on the firms that take a long time to recover because they are very exposed to the network
    - They then map these parts of the network to specific sectors to conclude that sectors with a lot of produced inputs (like cars) take a long time to recover

- **[45:54] Supply chain formation and fragility**
    - The limitation of these papers is that ultimately they assume a return to the original steady state, so they are not about resilience in the sense that they don't allow for diverging to a worse steady state.
    - However this is what seems to have happened after the financial and covid crises (Helper and Soltas 2021)
    - Some papers allowed for full shutdowns within networks (Elliot et al. 2014 or Baqaee 2018), but they did not capture the idea that these shutdowns can be

bigger than the sum of their parts. To make progress we can leverage percolation theory, which has been used in physics and to study the spread of viruses

- Elliot et al. (2022) develops a theory of a supply chain network that seeks to avoid the fallacy of composition with percolation theory, studying individual firms' supply chains before studying aggregate production
- Each good requires many prior steps of inputs, and crucially each of these inputs are not available generically and need to come from other specific suppliers
- The provision of each input (and sub input) relies on a link between the supplier and the firm using the input, and each of a firm's link has an identical but independent probability of working. Firms can choose at a cost how high they want this probability to be
- There are love-of-variety consumers whose utility is increasing in the number of different goods they can consume (i.e. the number of working supply chains)
- If a firm produces it earns profits from the sale of its goods, and a firm wants to be reliable when their competitors aren't
- For each firm the object of study is the probability that it will not be able to produce because too many of its links didn't work. After aggregating one can study the share of functioning firms (the reliability of the network)
- One expected result is that everyone relying on a single supplier (e.g. Taiwanese microchips) can be a channel for fragility, but even in fully diversified sourcing structures there are other effects we should worry about
- The key point of the paper is that the reliability of supply chains (y axis in the chart) and the probability that links work (x axis) is highly non linear:



- If a firm chooses a probability of links working under the critical value it will never be able to produce, but beyond the critical value the benefits of additional investments in resilience are comparatively small. This result is analogous to the discontinuous "phase transitions" we see in physics
- In equilibrium all firms will effectively choose the bare minimum probability of links working that allows them to produce (*MA note: this is a simplification*)

    - This equilibrium is suboptimal. It makes the network very sensitive to aggregate shocks to the probability of links working, because these shocks destroy firm relationships that are difficult to rebuild
    - The problem is the following externality: in any given step of the supply chain a firm does not internalize the full downstream benefits of their investment in resilience
    - Interestingly, improving the profitability from selling goods is not the optimal policy because it does not solve this externality. Any reasonable parametrization for the improvement to profitability (i.e. subsidies) will be ineffective because it will simply crowd out investment in resilience, bringing firms back to the critical level
    - As a result (and going beyond the model), it might be better for the government to provide life support when there are supply chain disruptions, rather than to subsidize long term investments in resilience. This will not affect firm incentives much in equilibrium because disruptions will only happen rarely
    - Another intervention might be to encourage firms to diversify and standardize their suppliers, but this may pose a tradeoff in that the higher costs may disincentivize innovation

Timestamps:

- **[0:00] Markus' introduction and poll questions:**
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- **[31:18] How do networks matter intuitively? A second toy model**
- **[45:54] Supply chain formation and fragility**

Snippets:

- [7:48] "Networks come up very naturally" - [10:21] "heterogeneity we see in relationship plays"
    - Delta the intermediate silence [9:28] - [9:45]. From "there is a poll" up until right before "there is an application".
- [11:55] "Let me just jump right in" - [12:23] "if nodes i and j are linked"
- [12:53] "imagine you have a bunch of firms" - [18:39] "most increase the total"
    - Cut the silence [13:04] - [13:10]
    - Delete [14:23] "you have to make an assumption" - [14:33] up until "then you can write"
    - Delete [15:28] "let me just give you" - [15:48] up until "so I want to give you"
- [21:53] "In the second generation" - [23:25] "a lot has been done with them"
- [24:57] "I would like to tell about about a crisis" - [26:05] "only second order for welfare"
- [27:35] "I am spotlighting the work of Baqaee" - [28:43] "tell you about the static view"
- [29:23] "In a 2020 QJE paper Baqaee" - [32:02] "even without the macroeconomic richness in this third generation literature"

- [33:55] “I'm gonna come back to this game” - [39:00] “shapes what you want to care about”
- [46:05] “I wanted to basically say” - [49:36] “fabric of global logistics”
    - Delete: [48:47] “I wanna give you a flavor” - [49:05] “I think i’ve structured it”
- [50:04] “what were interested it” - [54:26] “for a long time lost”
    - Delete markus’ interruption: from right after [52:24] “branching supply network” - up until [52:50] ”Im going to assume”
- [59:25] “the main mathematical thing we are studying” - [59:45] “probability that this firm can produce”
- [1:05:51] “what we do in the main part of the paper” - [1:06:34] “firms are more likely to end up on the precipice”
- [1:08:24] “what we find” - [1:09:08] “its a non generic outcome”
- [1:10:03] “what's the trick?” - [1:10:32] “full social surplus”
- [1:11:00] “what if we subsidize?” - [11:11:41] “good job with it”
- [1:12:26] “if you were to add a generalist” - [1:14:40] “long run policies”
    - Note the order change with the next snippet
- [1:12:20] “the point that i want to end on” - [1:12:29] “big mistakes”