The Price of Complexity in Financial Networks

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Networks and standard economic analysis

• Primitive economies have a simple structure—limited interdependence
  • Farmers produce food and other necessities
  • With inputs that are mostly produced by themselves or locally

• But modern economies have long been recognized to have high interdependencies
  • Sraffa’s “Production of Commodities by means of commodities”

• Great achievement of mid 20th century was analysis of general equilibrium system
  • Establishing fundamental theorems of welfare economics—providing conditions under which, even with such interdependencies, economy was still efficient
    • Ability to decentralize efficiently
  • But Greenwald-Stiglitz theorem (1986) undermined presumption of efficiency of market economy
    • Pervasive pecuniary externalities impaired ability to efficiently decentralize
  • Whenever risk markets are incomplete and/or information is imperfect/asymmetric (that is, always) markets are inefficient.
Interconnectedness and risk

• In interconnected system, shock to one unit of system may (is likely to) have effects on others
  • But in some cases, impacts can be spread throughout the system
  • Net effect is limited (approaches zero with sufficient diversification)
• With complete set of Arrow-Debreu securities, economy is still efficient
  • Risks are correctly priced, and taken into account in actions by parties
• But sometimes, complete set of Arrow-Debreu securities is not needed
  • Conditions under which portfolio separation theorem hold (very restrictive) (Cass-Stiglitz, 1970, Stiglitz, 1969, forthcoming)
Without complete set of risk markets, presumption markets are not efficient (Greenwald-Stiglitz, 1986 theorem)

• Even with rational expectations (Newbery-Stiglitz, 1982)

• With strong policy implications
  • Free trade may not be Pareto efficient (Newbery-Stiglitz, 1984)
  • Capital market liberalization may lead to increased volatility (Stiglitz, 2008)

And no presumption about efficient decentralizability
Current arrangements undermine decentralizability

With credit linkages between different firms (banks) in the economy

• Default of firm A in loans to firm B affect ability of B to pay firm C
• Thus, to assess riskiness of C in making loan to firm B it has to know B’s linkages with every other firm
• In short, with bankruptcy, there has to be full knowledge of circumstances of all interlinked firms
• Derivatives increase linkages, and thus undermine decentralizability
• Complexity of derivatives makes assessments of risk even more difficult
Time 0: banks allocate assets/liabilities (with any rule).
Time 2: unknown shocks hit banks’ external assets, some banks may default.
Time $T > 2$: debt contracts mature. Defaulted banks’s assets are liquidated, creditors get recovery rate $R$ (endogenous or exogenous).
Transparency, complexity, and pricing

• If linkages (existence, magnitude) secret, then it is impossible to accurately estimate risk

• Risk assessments based on inferences
  • Banks (firms) treated as average of those with similar observed characteristics (“pooling” equilibrium)

• If each firm knows this, then there is moral hazard
  • Incentive to increase risk (more linkages), knowing that prices won’t reflect this increased risk

• Equilibrium linkages (about amounts and form) not Pareto efficient (illustration of Greenwald-Stiglitz theorem)
Financial structure and risk

- Nature of financial structure affects magnitude of (unpriced) externalities
- Trading through an adequately capitalized clearing house
  - Except in extreme events bankruptcy of firm (bank) absorbed by clearing house
    - Systemic risk can be further limited by joint and several liability of those who participate in clearing house
  - No 2\textsuperscript{nd} and 3\textsuperscript{rd} round effects
- Thus enhanced ability for effective decentralization
- And reduces the magnitude of “unpriced” risk
Critical distinction: conservative vs. non-conservative systems

• In conservative systems, the wealth (in period 2, after shock) does not depend on the organization of the system (financial architecture)

• In non-conservative system, defaults have a cost, and so number and structure of defaults makes a difference, and this can be affected by the structure of the network

• Complex simultaneity problem: ex ante, probability of default of i \{set of states in which i goes bankrupt\} depends on probability of default of j \{set of states in which i goes bankrupt\}
  • With general interlinkages, there may be no solution or multiple solutions
  • Real world problem: untangling bankruptcies when there is systemic bankruptcy, as in East Asia

• Analytic results below based on Battiston, Caldarelli, Roukny, May, Stiglitz, 2016, The Price of Complexity in Financial Networks, PNAS
General model set-up

**External assets** (investments outside the financial network)
- \( a_i^E (2) = a_i^E (1) (1 + \mu + \sigma u_i) \), with \( u_i \) a r.v. with mean 0 and variance 1, \( \mu \) expected return and \( \sigma < 0 \) scaling factor. Shock **joint probability distribution**: \( p(u_1, ..., u_n) \): correlation is accounted for.

**Liabilities** (obligation of players to internal/external creditors)
- \( \ell_j \) constant for bank \( j \). Unitary value of \( j \)'s obligation for \( j \)'s counterparties, so transfer is given by: \( x_j^B (2) = 1 \) OR \( x_j^B (2) = R \) (if default) with \( R \) recovery rate (endogenous or exogenous).

**Interbank assets** (investment in the debt of other players in the financial network)
- \( B_{ij} \): fraction of \( i \)'s interbank assets invested at time 1 in the liability of \( j \).
  - \( x_j^B \): unitary value of \( j \)'s interbank liability, \( x_j^B (1) = 1 \) \( \forall j \).
- Interbank assets of bank \( i \), \( a_i^B (2) = a_i^B (1) \sum_j B_{ij} x_j^B (2) \).
Default condition

Special case: R exogenous

- Default condition: iff negative equity at time 2
  \[ e_i(2) = a_i^E(2) + a_i^B(2) - \ell_i = \]
  \[ = a_i^E(1)(1 + \mu + \sigma u_i) + a_i^B(1) \sum_j B_{ij} x_j^B(2) - \ell_i < 0 \]

- \( e_i(2) < 0 \) iff \( \frac{e_i(2)}{e_i(1)} < 0 \), thus we can rewrite
  \[ e_i(1 + \mu + \sigma u_i) + \beta_i \sum_j B_{ij} x_j^B(2) - \lambda_i < 0, \]
  where \( e_i \) leverage over external assets, \( \beta_i \) leverage over interbank assets, \( \lambda_i = e_i + \beta_i - 1 \) debt leverage.

- Default indicator: \( \chi_i = 1 \) (i’s default) and \( \chi_i = 0 \) otherwise.

- \( u_i \) stochastic: default condition, with \( \theta_i \) default threshold:
  \[ u_i < \theta_i \equiv \frac{1}{\varepsilon_i \sigma} (-\varepsilon_i \mu + \beta_i \left( 1 - \sum_j B_{ij} x_j^B(\chi_j) - 1 \right)) \]
  - No bank defaults \( \theta_i = \theta_i^- = -\frac{1}{e_i \sigma} (\varepsilon_i \mu_i + 1) \)
  - All banks default \( \theta_i = \theta_i^+ = \frac{1}{e_i \sigma} (-\varepsilon_i \mu + \beta_i (1 - R) - 1) \).
Default condition

\[ \theta_1^{-} \quad \theta_1^{+} \quad \theta_2^{+} \quad \theta_2^{-} \]

-1 \quad 0 \quad 1

\[ u_1 \quad u_2 \]
Multiple equilibria

- Depending on shocks, there may exist multiple equilibria
- If firm i goes bankrupt, firm j goes bankrupt
- If firm I does not go bankrupt, firm j does not go bankrupt
Some implications

• Intrinsic uncertainty about the magnitude of systemic risk
• Small errors on contract characteristics or network structure can lead to large errors in probability of systemic default
• Mechanism: errors, e.g. on recovery rate $R$ on individual contracts get compounded multiplicatively along chains of connected banks
• Network complexity may not only increase systemic risk but also reduce accuracy of the estimation of system risk
**Analytical Example**

### Network architectures and systemic risk

Systemic default probability in the three architecture increases from star to chain to ring:

\[ P_{\text{sys,ring}} \geq P_{\text{sys,chain}} \geq P_{\text{sys,star}} \]

as long as \( \beta(1 - R)/(\sigma) > 1 \) (empirically relevant).

### Network architectures and errors on systemic risk

Sensitivity of the default probability on the recovery rate \( R \) increases from star to chain to ring:

- \( \partial P_{\text{sys,ring}}/\partial R \propto (\beta/(\sigma))^3 \);
- \( \partial P_{\text{sys,chain}}/\partial R \propto (\beta/(\sigma))^2 \);
- \( \partial P_{\text{sys,star}}/\partial R \propto \beta/(\sigma) \).

as long as \( \beta/(\sigma) > 1 \) (empirically relevant).
Numerical Results

Small errors on contracts characteristics lead to large errors on systemic risk

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Some other general results

• Nature of impacts depends on conservation of losses vs. amplification, on
convexity or concavity of relevant functions
  • In epidemiology, “contagion” entails amplification
  • Real bankruptcy costs imply system is not conservative
  • Processes with trend reinforcement exhibit similar properties
    • Negative balance sheet shock forces borrower to pay higher interest rates
  • In conservative systems with concave loss functions, spreading risks typically is
welfare enhancing
  • In non-conservative system (and most systems are not conservative), it may well not be
  • In many of standard models (Eisenberg-Noe) there are no bankruptcy costs (there is
conservation), so network only affects distribution of impacts of shock, not its
aggregate value, and hence are not useful for assessing consequences of systemic
risk
• Not optimal to fully diversify (Battiston et al, (2012a), Stiglitz (2010a, 2010b))
  • Before crisis Fed thought that risk had been fully diversified away
    • Contagion in crisis was exacerbated by greater linkages
    • IMF (and policy makers more generally) had intellectually incoherent position
    • Advocating diversification, integration before crisis
  • Worried about contagion after crisis
  • There is an optimal degree of diversification
• Circuit breakers can help prevent cascades (Stiglitz, 2010a, 2010b)
  • Can capital controls be thought of in an analogous way

Systemic Risk
• Not just a matter of too big to fail
• Too “central” to fail
• Too interlinked to fail
• To correlated to fail
Extensions of analysis: I. Endogenous interest rate

• High probability of default implies high (nominal) interest rate
• High interest rate implies high default rate
• Implication: Especially in non-conservative system, may be multiple equilibrium
• But even with given interest rate, there may be multiplicity of equilibria
• Sunspot equilibria

Greenwald-Stiglitz, 2003
Bail-outs, endogenous market structure, and endogenous risk taking

• Likelihood of bailout is affected by judgments concerning systemic risk
• Rational for banks to collectively engage in actions to increase bailouts (transfer from government to banks)
• Government needs to respond to curtail such actions
• Question: if there are many small institutions, so each institution believes his actions will not themselves change systemic risk, is the equilibrium efficient? If not, is there a bias towards excessive risk (as if there had been some coordination)?
  • Equilibrium in general is not Pareto efficient—macro-economic market externalities (generalization of Greenwald-Stiglitz pecuniary externalities)
Risk-taking

- Incentives to undertake more risky projects affected by expectation of bail-outs (and market structure)
- Incentives to form linkages affected by bail-outs
  - Examples of moral hazard issue
  - Bail-outs may lead to more “center-periphery” structure
- Incentives to undertake strategies that are too correlated to fail enhanced
- There are regulatory frameworks and bail-out commitments that lead to Pareto improvements

(Altinoglu-Stiglitz (in progress); Sturm (in progress))
Large number of outstanding questions

• Does “diversity” lead to more or less systemic stability? May-Wigner theorem vs. common wisdom
  • Important for design of structural reforms
    • Implying move away from universal banks
  • Growing belief that policy should focus more on structure than on behavior
    • Behavior too difficult to control directly
    • Is affected by structure

• Are there other simple structural reforms that could be easily implemented?
  • Analysis of consequences of bans on certain types of linkages—naked CDS’s

• Key question now on policy agenda is balance of structural vs. behavioral constraints
  • Motivated by difficulty of monitoring behavior, ease of circumvention
  • Easier to “observe” structure
Research questions

• Consequences of different sources of risk and design of appropriate policy responses

• Risks associated with variation in asset values
  • Especially with mark to market
  • Especially when variation in values possibly unrelated to any observed shock

• Risks associated with funding sources
  • Could/should withdrawal of funding be seen as signal of underlying weakness in institution, observable to some market participants, but not to regulator?
    • Or as just random noise
  • Implications for (a) differences in policy responses; (b) appropriate liquidity requirements
  • Especially in presence of (i) rational or (ii) irrational
Research questions: non-linearities

• Non-linearities should be at the center of the research agenda
  • Reason we are interested in circumstances generating systemic failures
    • Some structures better able to handle small disturbances, but worse at handling large (correlated) shocks
    • Assessment of desirability critically depends on costs of systemic crises
• Bankruptcy and associated disruption costs give rise to natural non-linearities
  • And naturally lead to non-conservative systems
• Policy interventions also give rise to non-convexities
  • Typically occur only with systemic disturbances
  • In absence of commitment devices, private sector will inevitably exploit
Research questions: interaction between uncertainties, information imperfections, and imperfections in risk markets

• With perfect information and perfect risk markets, presumption that market equilibrium (whatever the structure) is efficient
  • Still interesting questions of description
• With perfect information and imperfect risk markets, no longer presumption that market equilibrium is efficient
• But most interesting questions arise with imperfect risk markets and imperfect information
  • Strong presumption that markets will not be efficient
• Typically, there will be (partial) pooling equilibrium, giving rise to moral hazard—incentives for actions leading to excessive risk taking
  • And when a crisis occurs, there is likely to be liquidity crisis (which is just a credit rationing equilibrium—Stiglitz-Weiss)
• Insufficient attention has been paid to (partial) separating equilibria, where banks may take (costly) actions to signal that they are better than others
  • Analysis of what kinds of actions they can take, what are externalities associated with those actions
• Theory of second best—improvements in markets (more risk markets, even better information) may actually make matters worse
  • Agenda of “completing the market” —sold as moving closer to Arrow-Debreu market with a full set of risk markets—actually made matters worse
  • Need to understand better why
Research questions: Modeling I

Key question: why should there be any interbank lending at all?

• Why shouldn’t all derivative/future contracts be done through clearing houses
• Why shouldn’t all interbank lending be done through Central Bank
  • What social functions do they serve? Wouldn’t it be better if ultimate beneficiaries did own risk assessments and bore consequences of their decisions
  • Large costs: increased complexity, diversion of banks from “real” activities, undermines decentralizability of the economy
  • Small fraction of activities associated with outsiders (Turner (2015), Kay (2015))
  • Hard to identify any benefit
  • Explaining: Regulatory and tax arbitrage; agency problems within the financial institutions themselves; facilitating corporate non-transparency

• Adverse selection process in place—worst, non-standard contracts traded through government-insured banks in non-transparent transactions
• Worse example of “political economy”: Citibank written provision undoing Lincoln amendment pushing these transactions out of government insured institutions
Research questions: Modelling II

- Ultimately, we want to link financial sector with the real economy
- These are important linkages
  - often indirect, through common ownership of assets (liabilities)
  - Firms lend to each other (trade credit), with networked effects on the financial system
- How important are production linkages?
  - Observing pattern of sales (linkages) may tell us little
  - With well-functioning markets, shocks are diversified, and to the extent that they are not, consequences show up in prices, with diffuse effects
  - Risk is still important, but structure of networks is not; amplification effects that might occur in network will not occur
  - Network effects are important when there are a limited number of suppliers with long term enforceable contracts
  - Are there other conditions under which production risks matter?
- Systemic effects linked—correlated access to finance in the presence of shocks
  - Here, structure of network—both production (because of implications for structure of trade-finance network) and finance (linkages between banks and firms, and linkages of banks with each other
Research questions: regulation, supervision, and bail-outs

What kinds of policy interventions will lead to best (better) outcomes

• Can the government make **credible commitments not to bail-out**?

• Or can it at least make credible commitments to ensure that the bail-outs have less perverse incentive effects

• Need to understand political-economy of bailout
  • Does it arise from need to protect ordinary depositors
  • Or (as in US) from power of financial interests
    • Implication: Living wills are unlikely to prove effective

• **Bankruptcy law** provides another channel for transferring losses from one party to another
  • US bankruptcy law transferred burden of bank losses on derivatives to other creditors
  • What is best way to design bankruptcy law
Research questions: regulation, supervision, and bail-outs

• Designing macro-prudential regulations—focusing on systemic risk, rather than the risk of a single bank
• Basle I and II increased systemic risk
• Have to understand the sources of *correlated* shocks (e.g. business cycle risks in general, on asset side (value of mortgages), on liability side (withdrawal of funds)
• Design of regulations and incentive for regulatory arbitrage may contribute to systemic risk through increasing complexity
  • Argument for simple liquidity ratios and high capital adequacy requirements
  • Cost of capital requirements low if Modigliani-Miller theorem correct
  • Banks have never been able to explain why MM analysis shouldn’t apply
    • Other than lower capital requirements gives them higher chance of bailout and transfer from public
Concluding comments

• Research over past decade has shown that *networks* matter—a subject that had been almost totally neglected in past

• Enormous accomplishments in an area of great complexity in short period of time
  • Undermining long held beliefs: full diversification is not desirable, beyond a point, market integration and risk diversification may lead to increased systemic risk
  • Raising new concerns: risks of bankruptcy cascades, systemic risk
  • Asking new questions: complexity may lead to higher *fundamental* uncertainty about systemic risk—cannot, within standard model, even assess whether there is systemic risk or not
  • Framing new approaches to policy: increased focus on *structure* rather than policy; increased focus on *systemic* risk, rather than risk of the failure of a single bank
Concluding comments

• But large number of questions remain to be addressed
  • Most importantly, deeper understanding of links between the financial sector and the real, and the stability of one on the other
  • How various policies affect both behavior and structure of the financial network


