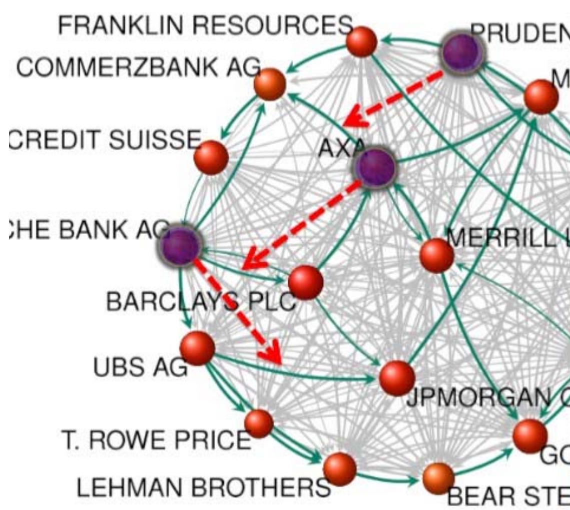
The Price of Complexity in Financial Networks

Joseph Stiglitz
Columbia Univ.

FINEXUS Conference, Zurich 11-13 January 2017



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)

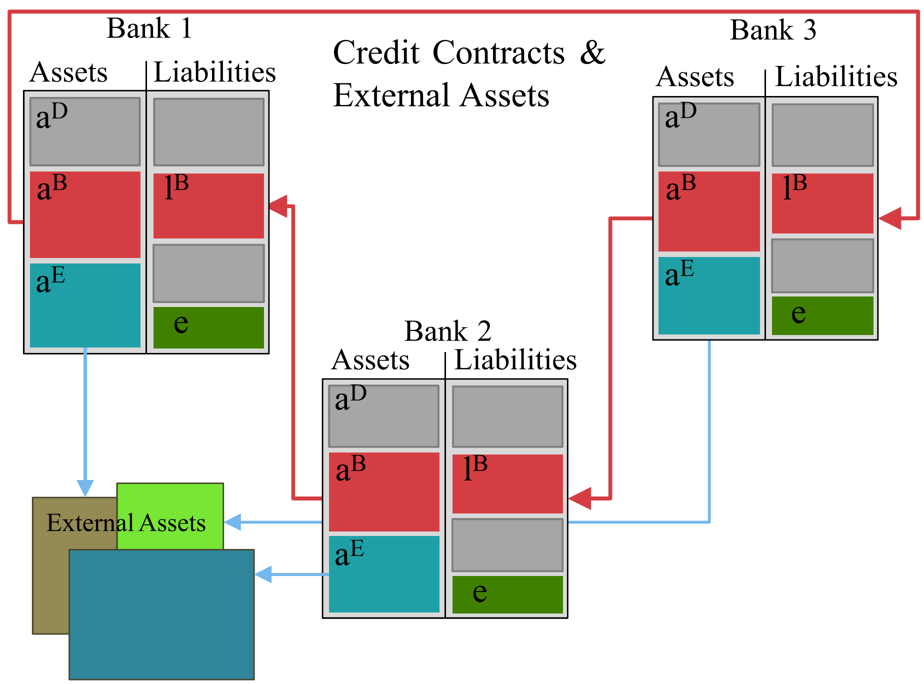
And no presumption about efficient decentralizability

Current arrangements undermine decentralizability

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

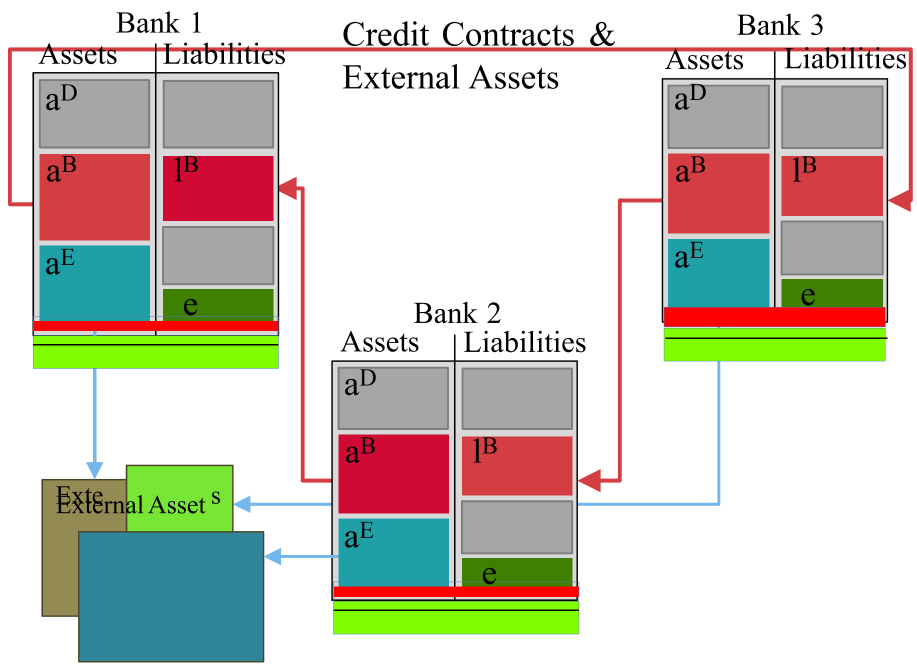
- Default of firm A in loans to firm B affect abiity of B to pay firm C
- Thus, to assess riskiness of C in making loan to firm B it has to know B's linkages with every other firm
- In short, with bankruptcy, there has to be full knowledge of circumstances of all interlinked firms
- Derivatives increase linkages, and thus undermine decentralizability
- Complexity of derivatives makes assessments of risk even more difficult
- Structure and amount of linkages affect systemic risk (default cascades) (Allen and Gale, 2001, Greenwald and Stiglitz, 2003)

General model set-up



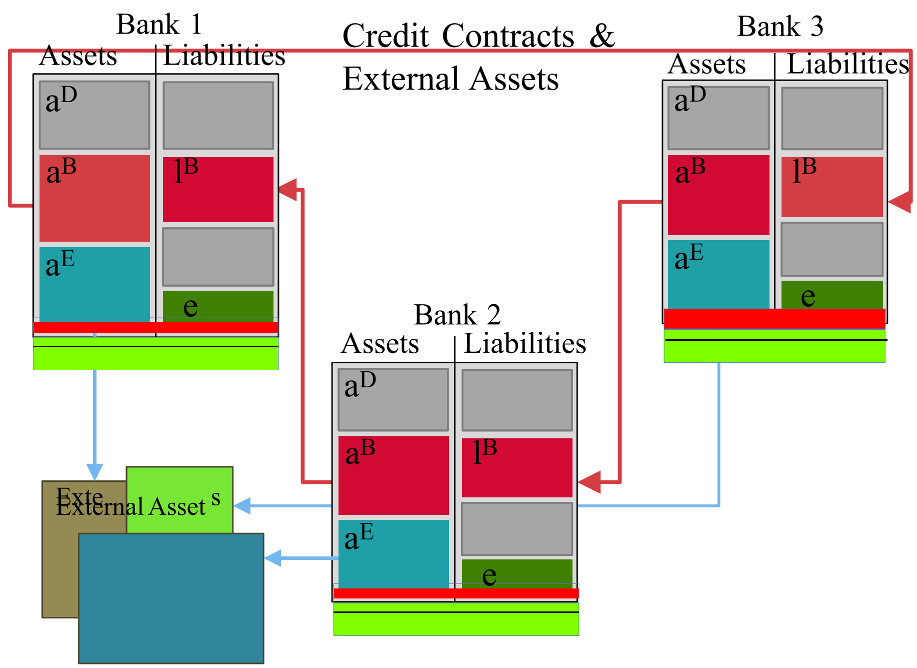
- Time 0: banks allocate assets/liabilities (with any rule).

General model set-up



- Time 2: unknown shocks hit banks' external assets, some banks may default.

General model set-up



- 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^{nd} and 3^{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, μ expected return and $\sigma < 0$ scaling factor. Shock **joint probability distribution**: $p(u_1, \dots, u_n)$: correlation is accounted for.

Liabilites (obligation of players to internal/external creditors)

- ℓ_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 liabilitiy 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

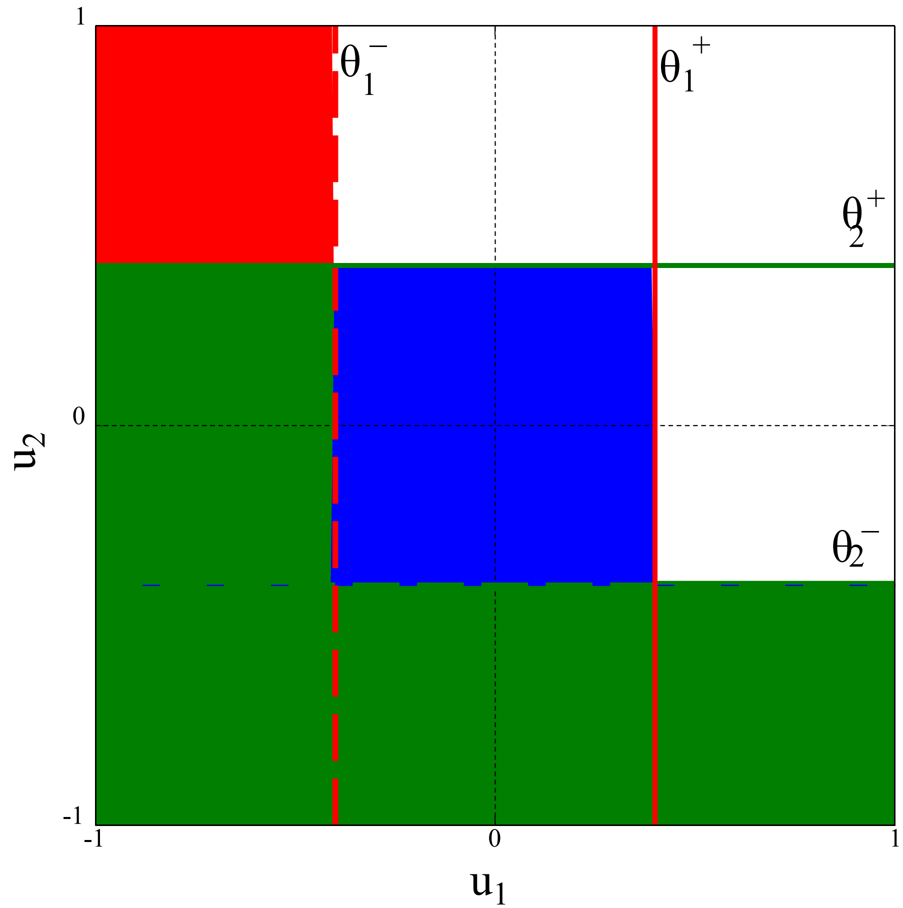
$\epsilon_i(1 + \mu + \sigma u_i) + \beta_i \sum_j B_{ij} x_j^B(2) - \lambda_i < 0$, where ϵ_i leverage over external assets, β_i leverage over interbank assets, $\lambda_i = \epsilon_i + \beta_i - 1$ debt leverage.

- Default indicator: $\chi_i = 1$ (i's default) and $\chi_i = 0$ otherwise.
- u_i stochastic: default condition, with θ_i default threshold:

$$u_i < \theta_i \equiv \frac{1}{\epsilon_i \sigma} (-\epsilon_i \mu + \beta_i \left(1 - \sum_j B_{ij} x_j^B(\chi_j) - 1\right))$$

  - No bank defaults $\theta_i = \theta_i^- = -\frac{1}{\epsilon_i \sigma}(\epsilon_i \mu_i + 1)$
  - All banks default $\theta_i = \theta_i^+ = \frac{1}{\epsilon_i \sigma}(-\epsilon_i \mu + \beta_i(1 - R) - 1)$.

Default condition



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:

$\partial P^{\text{sys,ring}}/\partial R \propto (\beta/(\sigma))^3$;

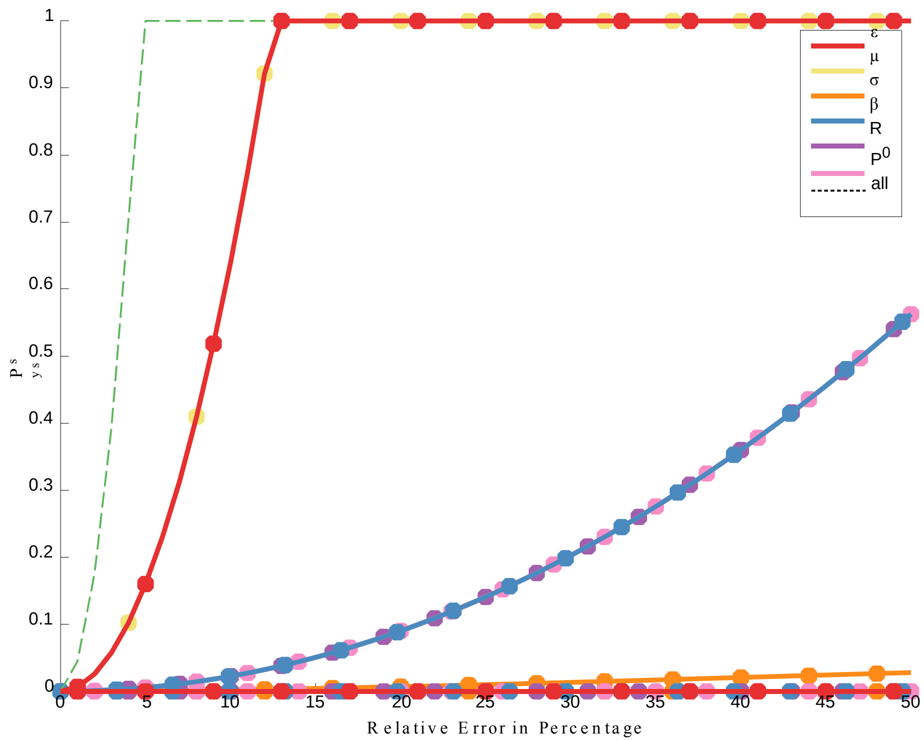
$\partial P^{\text{sys,chain}}/\partial R \propto (\beta/(\sigma))^2$;

$\partial P^{\text{sys,star}}/\partial R \propto \beta/(\sigma)$.

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

University of Zurich[UZH]

Numerical Results



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

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

Acemoglu, D., Ozdaglar, A., and Tahbaz-Salehi, A. (2015). Systemic Risk and Stability in Financial Networks. *American Economic Review*, 105(2):564–608.

Acharya, V. V. (2009). A theory of systemic risk and design of prudential bank regulation. *Journal of Financial Stability*, 5(3):224–255.

Acharya, V. V. and Merrouche, O. (2010). Precautionary hoarding of liquidity and inter-bank markets: Evidence from the sub-prime crisis. Technical report, National Bureau of Economic Research.

Adrian, T. and Shin, H. S. (2008). Financial Intermediaries, Financial Stability, and Monetary Policy. *Brookings Panel on Economic Activity, September*.

Allen, F., Babus, A., and Carletti, E. (2012). Asset commonality, debt maturity and systemic risk. *Journal of Financial Economics*, 104(3):519–534.

Allen, F. and Gale, D. (2001). Financial contagion. *Journal of Political Economy*, 108(1):1–33.

Anand, K., Craig, B., and Von Peter, G. (2015). Filling in the blanks: Network structure and interbank contagion. *Quantitative Finance*, 15(4):625–636.

Anand, K., Gai, P., and Marsili, M. (2012). Rollover risk, network structure and systemic financial crises. *Journal of Economic Dynamics and Control*, 36(8):1088–1100.

Bardoscia, M., Battiston, S., Caccioli, F., and Caldarelli, G. (2015a). DebtRank: A microscopic foundation for shock propagation. *PLoS ONE*, 10(6):e0134888.

Bardoscia, M., Battiston, S., Caccioli, F., and Caldarelli, G. (2016). Pathways towards instability in financial networks. page 7.

Bardoscia, M., Caccioli, F., Perotti, J. I., Vivaldo, G., and Caldarelli, G. (2015b). Distress propagation in complex networks: the case of non-linear DebtRank. page 8.

University of Zurich[UZH]

Bargigli, L., Di Iasio, G., Infante, L., Lillo, F., and Pierobon, F. (2014). The multiplex structure of interbank networks. *Quantitative Finance*, pages 1–19.

Barucca, P., Bardoscia, M., Caccioli, F., D'Errico, M., Visentin, G., Caldarelli, G., and Battiston, S. (2016). Network Valuation in Financial Systems. *ssrn.com/abstract=2795583.*

Battiston, S., D. Delli Gatti, B. Greenwald, and J. E. Stiglitz "Credit Chains and Bankruptcy Propagation in Production Networks," *Journal of Economic Dynamics and Control*, Volume 31, Issue 6, June 2007, pp. 2061-2084

Battiston, S., D. Delli Gatti, M. Gallegati, B. Greenwald, and J. E. Stiglitz "Default Cascades: When Does Risk Diversification Increase Stability?" *Journal of Financial Stability*, 8(3), pp.138-149.

Battiston, S.,Guido Caldarelli, Co-Pierre Georg, Robert May, and J. E. Stiglitz, "Complex Derivatives," *Nature Physics*, 9(March): 123-125.

Battiston, S., Caldarelli, G., D'errico, M., and Gurciullo, S. (2016a). Leveraging the network : a stress-test framework based on DebtRank. *Statistics and Risk Modeling*, pages 1–33.

Battiston, S., Caldarelli, G., May, R., Roukny, T., and Stiglitz, J. E. (2016b). The Price of Complexity in Financial Networks. *forthcoming on PNAS; ssrn 2594028.*

Battiston, S., Delli Gatti, D., Gallegati, M., Greenwals, B., and Stiglitz, J. E. (2012a). Liaisons dangereuses: Increasing connectivity, risk sharing, and systemic risk. *Journal of Economic Dynamics and Control*, 36(8):1121–1141.

Battiston, S., Farmer, J. D., Flache, A., Garlaschelli, D., Haldane, A. G., Heesterbeek, H., Hommes, C., Jaeger, C., May, R., and Scheffer, M. (2016c). Complexity theory and financial regulation. *Science*, 351(6275):818–819.

University of Zurich[UZH]

Battiston, S., Gatti, D. D., Gallegati, M., Greenwald, B., and Stiglitz, J. E. (2012b). Default cascades: When does risk diversification increase stability? *Journal of Financial Stability*, 8(3):138–149.

Battiston, S., Puliga, M., Kaushik, R., Tasca, P., and Caldarelli, G. (2012c). DebtRank: Too Central to Fail? Financial Networks, the FED and Systemic Risk. *Scientific Reports*, 2:1–6.

Beale, N., Rand, D. G., Battey, H., Croxson, K., May, R. M., and Nowak, M. A. (2011). Individual versus systemic risk and the Regulator's Dilemma. *Proceedings of the National Academy of Sciences*, 108(31):12647–12652.

Billio, M., Pelizzon, L., Lo, A., and Getmansky, M. (2011). Econometric Measures of Connectedness and Systemic Risk in the Finance and Insurance Sectors. *Journal of Financial Economics, forth.*

.

.

University of Zurich[UZH]

Bonanno, G., Caldarelli, G., Lillo, F., and Mantegna, R. N. (2003). Topology of correlation-based minimal spanning trees in real and model markets. *Phys. Rev. E*, 68(4):46130.

Boss, M., Elsinger, H., Summer, M., and Thurner, S. (2004). Network topology of the interbank market. *Quantitative Finance*, 4(6):677–684.

Brock, W. A., Hommes, C. H., and Wagener, F. O. O. (2009). More hedging instruments may destabilize markets. *Journal of Economic Dynamics and Control*, 33(11):1912–1928.

Caballero, R. J. and Simsek, A. (2013). Fire sales in a model of complexity. *The Journal of Finance*, 68(6):2549–2587.

Caccioli, F., Shrestha, M., Moore, C., Doyne Farmer, J., and Farmer, J. D. (2014). Stability analysis of financial contagion due to overlapping portfolios. *Journal of Banking & Finance*.

Cajueiro, D. O. and Tabak, B. M. (2008). The role of banks in the Brazilian interbank market: Does bank type matter? *Physica A: Statistical Mechanics and its Applications*, 387(27):6825–6836.

Cimini, G., Squartini, T., Gabrielli, A., and Garlaschelli, D. (2014a). Estimating topological properties of weighted networks from limited information. *Physical Review E*, 92(4):40802.

Cimini, G., Squartini, T., Garlaschelli, D., Gabrielli, A., and Garlaschelli, D. (2014b). Systemic risk analysis in reconstructed economic and financial networks. *arXiv preprint arXiv:1411.7613*, 5.

Cimini, G., Squartini, T., Musmeci, N., Puliga, M., Gabrielli, A., Garlaschelli, D., Battiston, S., and Caldarelli, G. (2014c). Reconstructing topological properties of complex networks using the fitness model. In *Social Informatics*, pages 323–333. Springer.

Craig, B. and Von Peter, G. (2010). Interbank tiering and money center banks. *Available at SSRN 1687281*, (10-14).

University of Zurich UZH

De Masi, G., Fujiwara, Y., Gallegati, M., Greenwald, B., and Stiglitz, J. E. (2009). An Analysis of the Japanese Credit Network. page 23.

de Masi, G., Iori, G., and Caldarelli, G. (2006). Fitness model for the Italian interbank money market. *Physical Review E*, 74(6).

Delli Gatti, D. Mauro Gallegati, Bruce Greenwald, Alberto Russo, and J. E. Stiglitz "Business Fluctuations in a Credit-Network Economy," *Physica A*, Vol. 370, pp. 68-74.

Delli Gatti, D. Mauro Gallegati, Bruce Greenwald, Alberto Russo, and J. E. Stiglitz "Business Fluctuations and Bankruptcy Avalanches in an Evolving Network*Journal of Economic Interaction and Coordination,* 4(2), November 2009, pp. 195-212.

D'Errico, M., Battiston, S., Peltonen, T., and Scheicher, M. (2015). Passing the hot potato: the flow of risk in the CDS market. *European Central Bank Working Paper Series, forthcoming.*

Di Guilmi, C., M. Gallegati, S. Landini, and J. E. Stiglitz "Dynamic Aggregation of Heterogeneous Interacting Agents and Network: An Analytical Solution for Agent Based Models,", *Journal of Economic Dynamics and Control*, forthcoming

Di Iasio, G., Battiston, S., Infante, L., and Pierobon, F. (2013). Capital and Contagion in Financial Networks. *MPRA Paper No. 52141.*

Diamond, D. W. and Rajan, R. G. (2011). Fear of Fire Sales, Illiquidity Seeking, and Credit Freezes. *The Quarterly Journal of Economics*, 126(2):557–591.

Eisenberg, L. and Noe, T. H. (2001). Systemic Risk in Financial Systems. *Management Science*, 47(2):236–249.

Elliott, M., Golub, B., and Jackson, M. O. (2014). Financial Networks and Contagion. *American Economic Review*, 104(10):3115–3153.

Elsinger, H., Lehar, A., and Summer, M. (2006). Risk Assessment for Banking Systems. *Management Science*, 52(9):1301–1314.

Farhi, E. and Tirole, J. (2012). Collective Moral Hazard, Maturity Mismatch and Systemic Bailouts. *American Economic Review*, 102(1).

Fink, K., Krüger, U., Meller, B., and Wong, L.-H. (2016). The credit quality channel: Modeling contagion in the interbank market. *Journal of Financial Stability*, 25:83–97.

Fourel, V., Heam, J.-C., Salakhova, D., and Tavolaro, S. (2013). Domino Effects when Banks Hoard Liquidity: The French network.

Fricke, D. and Lux, T. (2012). Core-periphery structure in the overnight money market: Evidence from the e-mid trading platform. Technical report, Kiel Working Papers.

Gai, P., Haldane, A., and Kapadia, S. (2011). Complexity, concentration and contagion. *Journal of Monetary Economics*, 58(5):453–470.

Gai, P. and Kapadia, S. (2010). Contagion in financial networks. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 466(2120):2401–2423.

Galbiati, M., Delpini, D., and Battiston, S. (2013). The power to control. *Nature Publishing Group*, 9(3):126–128.

Galbiati, M. and Soramaki, K. (2010). Liquidity-saving mechanisms and bank behaviour. *Available at SSRN 1650632*, (400).

University of Zurich[UZH]

Garlaschelli, S., Castri, M., and Servedio, G. (2005). The scale-free nature of market investment networks. *Physica A: Statistical Mechanics and its Applications*, 350(2):491–499.

Georg, C.-P. (2013). The effect of the interbank network structure on contagion and common shocks. *Journal of Banking & Finance.*

Glasserman, P. and Young, H. P. (2015). How likely is contagion in financial networks? *Journal of Banking & Finance*, 50:383–399.

Glattfelder, J. B. and Battiston, S. (2009). Backbone of complex networks of corporations: The flow of control. *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics*, 80(3):36104.

Iori, G., De Masi, G., Precup, O. V., Gabbi, G., and Caldarelli, G. (2008). A network analysis of the Italian overnight money market. *Journal of Economic Dynamics and Control*, 32(1):259–278.

Jeanne, O. and Korinek, Anton (2010) "Excessive Volatility in Capital Flows: A Pigouvian Taxation Approach,", American Economic Review 100(2), pp. 403-407, May 2010.

Jeanne, Olivier and Anton Korinek (2012), Macroprudential Regulation Versus Mopping Up After the Crash, NBER Working Paper 18675.

Kaushik, R. and Battiston, S. (2012). Credit Default Swaps Drawup Networks: Too Tied To Be Stable? *PloS one*, 8(7):15

Kiyotaki, N. and Moore, J. (2002). Balance-Sheet Contagion. *The American Economic Review*, 92(2):46–50

Korinek, Anton (2011), Systemic Risk-Taking: Amplification Effects, Externalities, and Regulatory Responses, mimeo.

Korinek, Anton "Capital Flows, Crises, and Externalities," Chapter 5 in Allen, Franklin et al., The Global Macro Economy and Finance: Proceedings of the 16th IEA World Congress, Volume III, Palgrave Macmillan, 2012.

Korinek, Anton (2011) "The New Economics of Prudential Capital Controls: A Research Agenda," IMF Economic Review 59(3), pp. 523-561, August 2011.

Korinek, Anton (2011) "Hot Money and Serial Financial Crises," IMF Economic Review 59(2), pp. 306-339, June 2011.

Korinek, Anton , A. Roitman and C. Vegh (2010) "Decoupling and Contagion," with Agustin Roitman and Carlos Vegh, American Economic Review 100(2), pp. 393-397, May 2010.

Korinek, Anton (2011) "Systemic Risk-Taking: Amplification Effects, Externalities, and Regulatory Responses" mimeo

Korinek, Anton and Damiano Sandri (2016) "Capital Controls or Macroprudential Regulation?", forthcoming, Journal of International Economics, 2016.

Martinez, C. and Leon, C. (2015). The cost of collateralized borrowing in the Colombian money market: does connectedness matter? *Journal of Financial Stability*.

Martinez Jaramillo, S., Alexandrova-Kabadjova, B., Bravo-Benítez, B., and Solorzano-Margain, J. (2012). An Empirical Study of the Mexican Banking System's Network and its Implications for Systemic Risk.

May, R. M. and Arinaminpathy, N. (2010). Systemic risk: the dynamics of model banking systems. *Journal of the Royal Society, Interface / the Royal Society*, 7(46):823–838.

Mistrulli, P. E. (2011). Assessing financial contagion in the interbank market: Maximum entropy versus observed interbank lending patterns. *Journal of Banking & Finance*, 35(5):1114–1127.

Musmeci, N., Battiston, S., Caldarelli, G., Puliga, M., and Gabrielli, A. (2013). Bootstrapping topological properties and systemic risk of complex networks using the fitness model. *Journal of Statistical Physics*, 151(3-4):1–15.

Onnela, J.-P., Kaski, K., and Kertész, J. (2004). Clustering and information in correlation based financial networks. *The European Physical Journal B-Condensed Matter and Complex Systems*, 38(2):353–362.

University of Zurich[UZH]

Poledna, S., Molina-Borboa, J. L., Martínez-Jaramillo, S., van der Leij, M., and Thurner, S. (2015). The multi-layer network nature of systemic risk and its implications for the costs of financial crises. *Journal of Financial Stability*, 20:70–81.

Poledna, S. and Thurner, S. (2014). Elimination of systemic risk in financial networks by means of a systemic risk transaction tax. *arXiv preprint arXiv:1401.8026*.

Puliga, M., Caldarelli, G., and Battiston, S. (2014). Credit Default Swaps networks and systemic risk. *Scientific Reports*, 4(August):1–24.

Roukny, T., Battiston, S., and Stiglitz, J. E. (2016). Interconnectedness as a Source of Uncertainty in Systemic Risk. *SSRN 2726631*.

Roukny, T., Bersini, H., Pirotte, H., Caldarelli, G., and Battiston, S. (2013). Default Cascades in Complex Networks: Topology and Systemic Risk. *Scientific Reports*, 3:1–31.

Roukny, T., George, C.-P., and Battiston, S. (2014). A Network Analysis of the Evolution of the German Interbank Market. *Deutsche Bundesbank Discussion Paper 22/2014*.

Schuldenzucker, S., Seuken, S., and Battiston, S. (2015). Clearing Payments in Financial Networks with Credit Default Swaps.

Silva, T. C., Guerra, S. M., Tabak, B. M., and de Castro Miranda, R. C. (2016). Financial networks, bank efficiency and risk-taking. *Journal of Financial Stability*.

Solorzano-Margain, J. P., Martinez-Jaramillo, S., and Lopez-Gallo, F. (2013). Financial contagion: extending the exposures network of the Mexican financial system. *Computational Management Science*, pages 1–31.

Soramäki, K., Bech, M. L., Arnold, J., Glass, R. J., and Beyeler, W. E. (2007). The topology of interbank payment flows. *Physica A: Statistical Mechanics and its Applications*, 379(1):317–333.

Squartini, T., van Lelyveld, I., and Garlaschelli, D. (2013). Early-warning signals of topological collapse in interbank networks. *Scientific reports*, 3:3357.

University of Zurich[UZH]

Stiglitz, J. E. (2000). The contributions of the economics of information to twentieth century economics. *Quarterly Journal of economics*, pages 1441–1478.

Stiglitz, J. E. (2010), "Risk and Global Economic Architecture: Why Full Financial Integration May be Undesirable," *American Economic Review*, 100(2), May 2010, pp. 388-392.

Stiglitz, J.E. (2010) "Contagion, Liberalization, and the Optimal Structure of Globalization," *Journal of Globalization and Development,* 1(2), Article 2, 45 pages.

Stiglitz, J. E. and Greenwald, B. C. N. (2003). *Towards a New Paradigm in Monetary Economics*. Cambridge Univ. Press, Cambridge.

Tabak, B. M., Souza, S. R. S., and Guerra, S. M. (2013). Assessing the Systemic Risk in the Brazilian Interbank Market. *Working Paper Series, Central Bank of Brazil.*

Tasca, P. and Battiston, S. (2013). Diversification and Financial Stability. *SSRN eLibrary*.

Tasca, P. and Battiston, S. (2016). Market Procyclicality and Systemic Risk. *Quantitative Finance*.

Thurner, S. and Poledna, S. (2013). DebtRank-transparency: Controlling systemic risk in financial networks. *Scientific reports*, 3:1888.

Upper, C. (2011). Simulation methods to assess the danger of contagion in interbank markets. *Journal of Financial Stability*, 7(3):111–125.

Upper, C. and Worms, A. (2004). Estimating Bilateral Exposures in the German Interbank Market: Is there a Danger of Contagion? *European Economic Review*, 48(4):827–849.

Vitali, S. and Battiston, S. (2011). Geography versus topology in the european ownership network. *New Journal of Physics*, 13:63021.

Vitali, S. and Battiston, S. (2014). The community structure of the global corporate network. *PloS one*, 9(8):e104655.

Vitali, S., Glattfelder, J. B., and Battiston, S. (2011). The network of Global corporate control. *PLoS ONE*, 6(10).

University of Zurich[UZH]