Financial Networks

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The physics of financial networks

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SURVEY ARTICLE

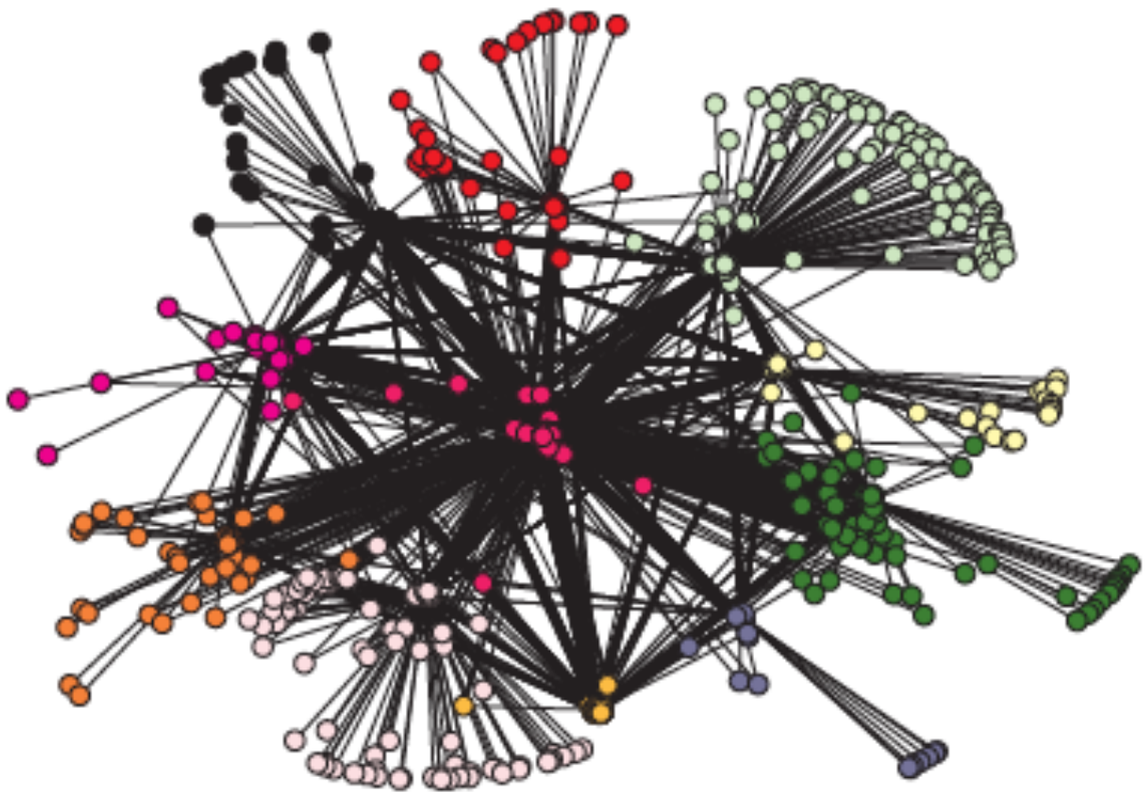
Network models of financial systemic risk: a review

Fabio Caccioli[1,2,3] · Paolo Barucca[4,5] · Teruyoshi Kobayashi[6]

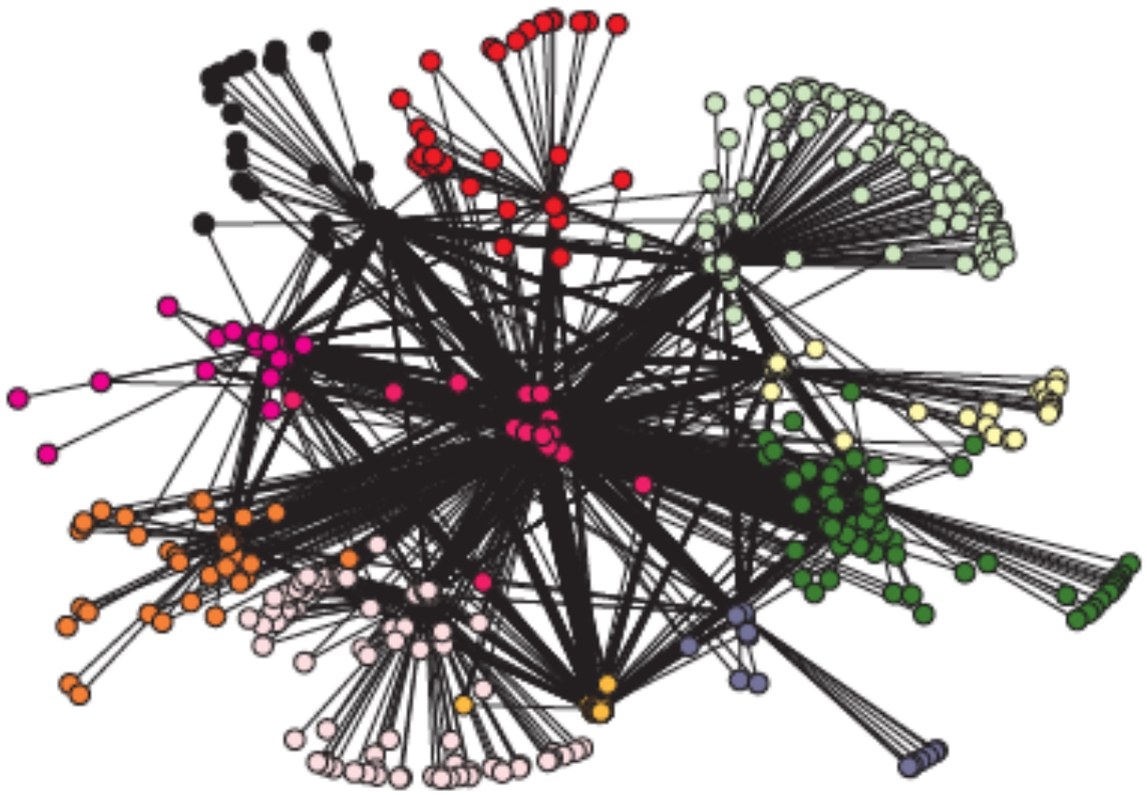
Systemic risk

- the risk that the financial system breaks down
- it arises endogenously from interactions and interconnections between different players in financial markets
- Interactions between financial institutions can be modeled through networks

how do shocks propagate through the network?



(figure from Boss et al, 2004 Quantitative Finance)



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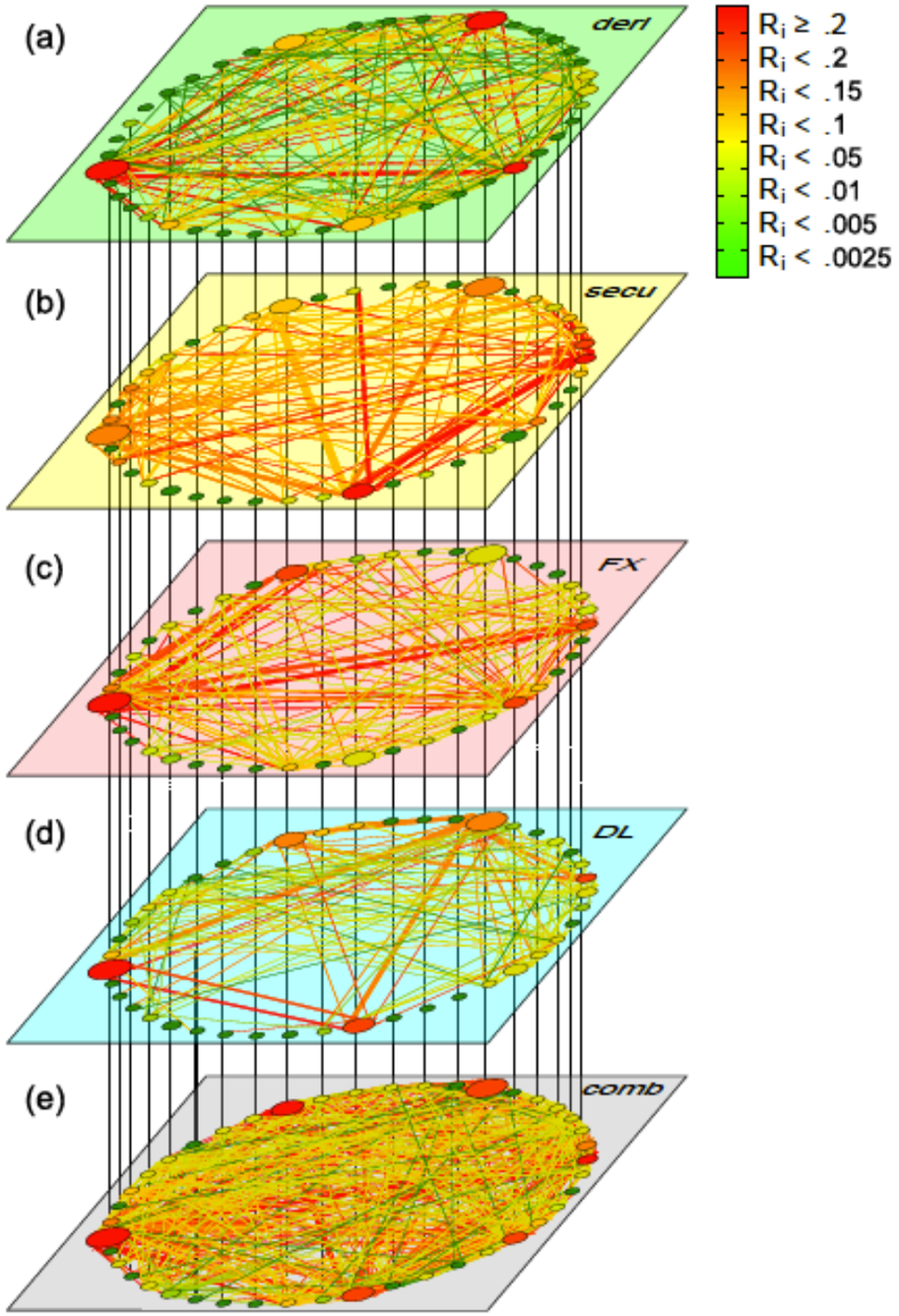


(figure from Poledna et al, Journal of Financial Stability (2015))

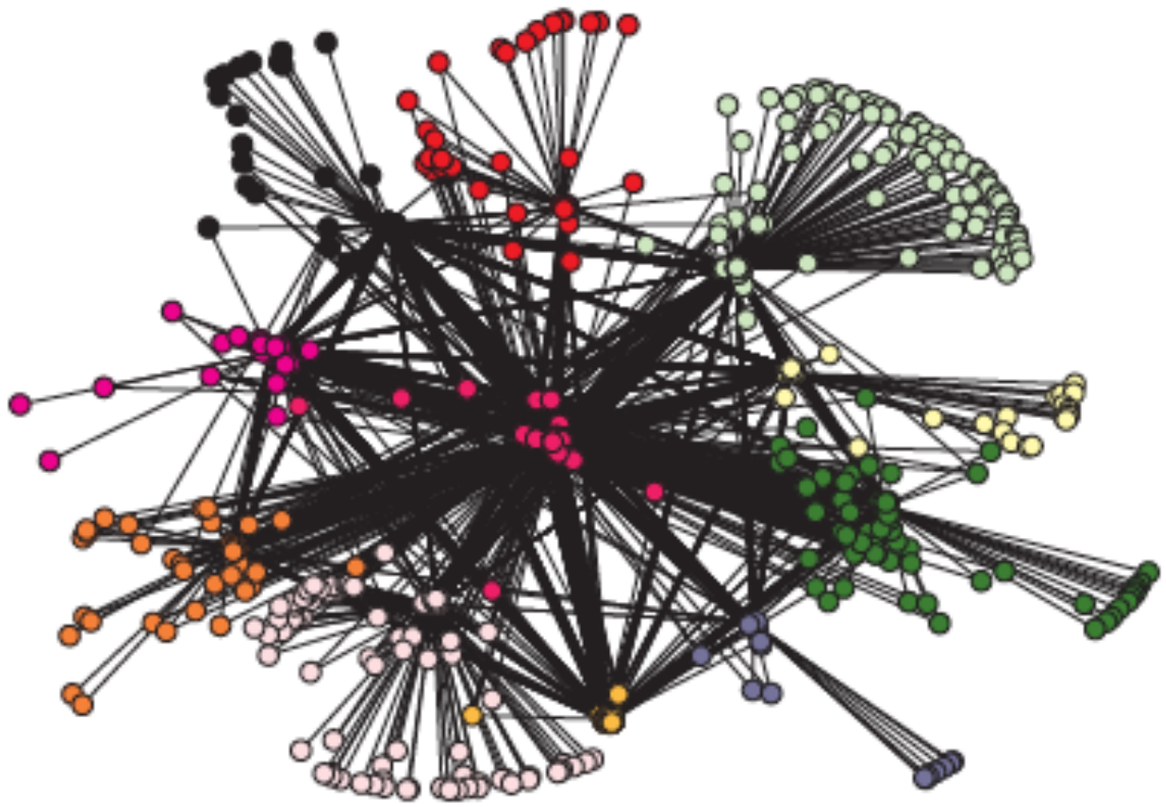
Interbank networks

- Most studies have so far focused on static single layer networks, which represent a snapshot of interbank exposures at a given time

- Although a complete picture is difficult to gather, studies performed on different layers of national systems suggest the existence of some stylized facts

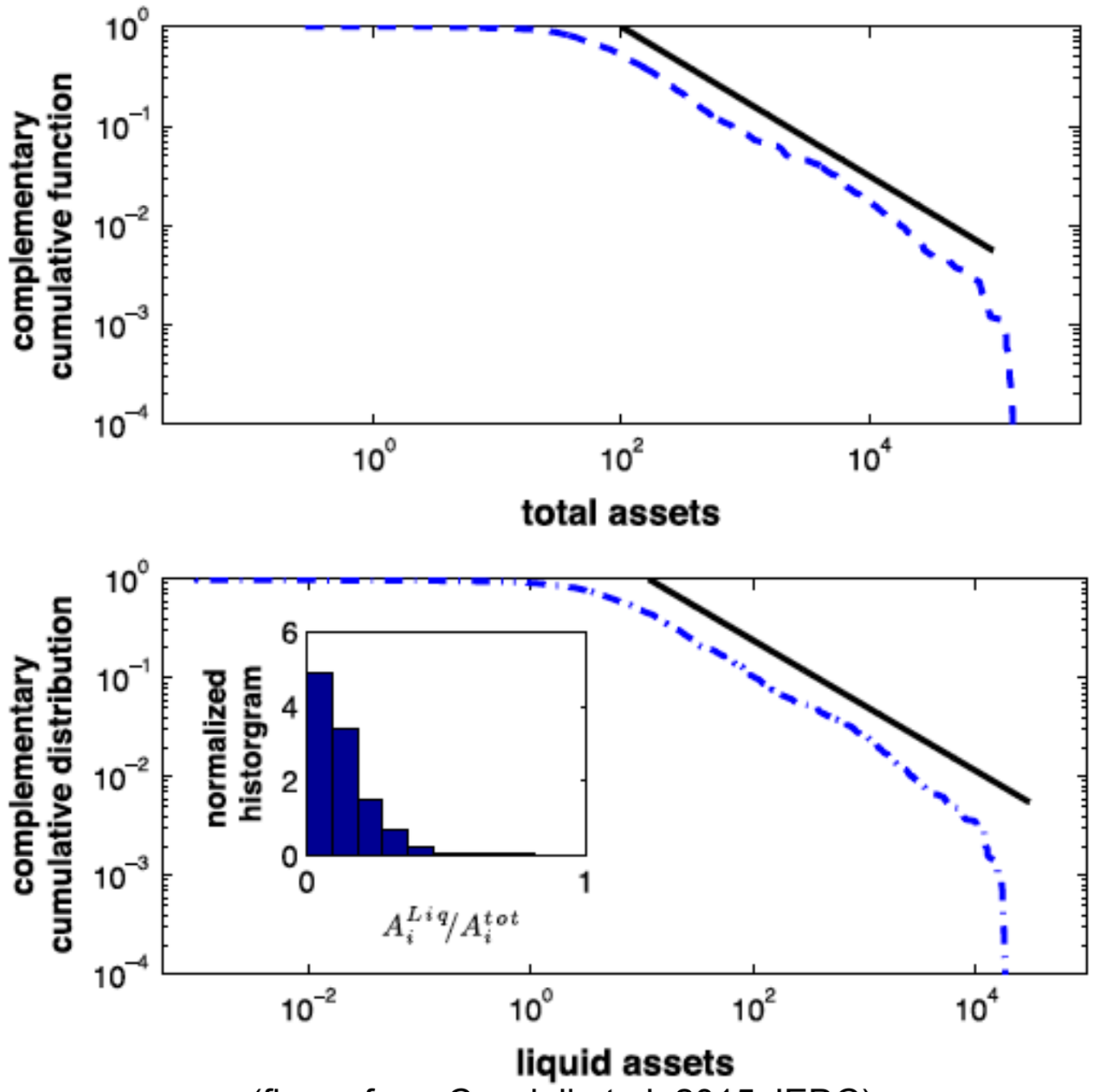
- We now look at one specific representative example

A specific example: The Austrian banking system



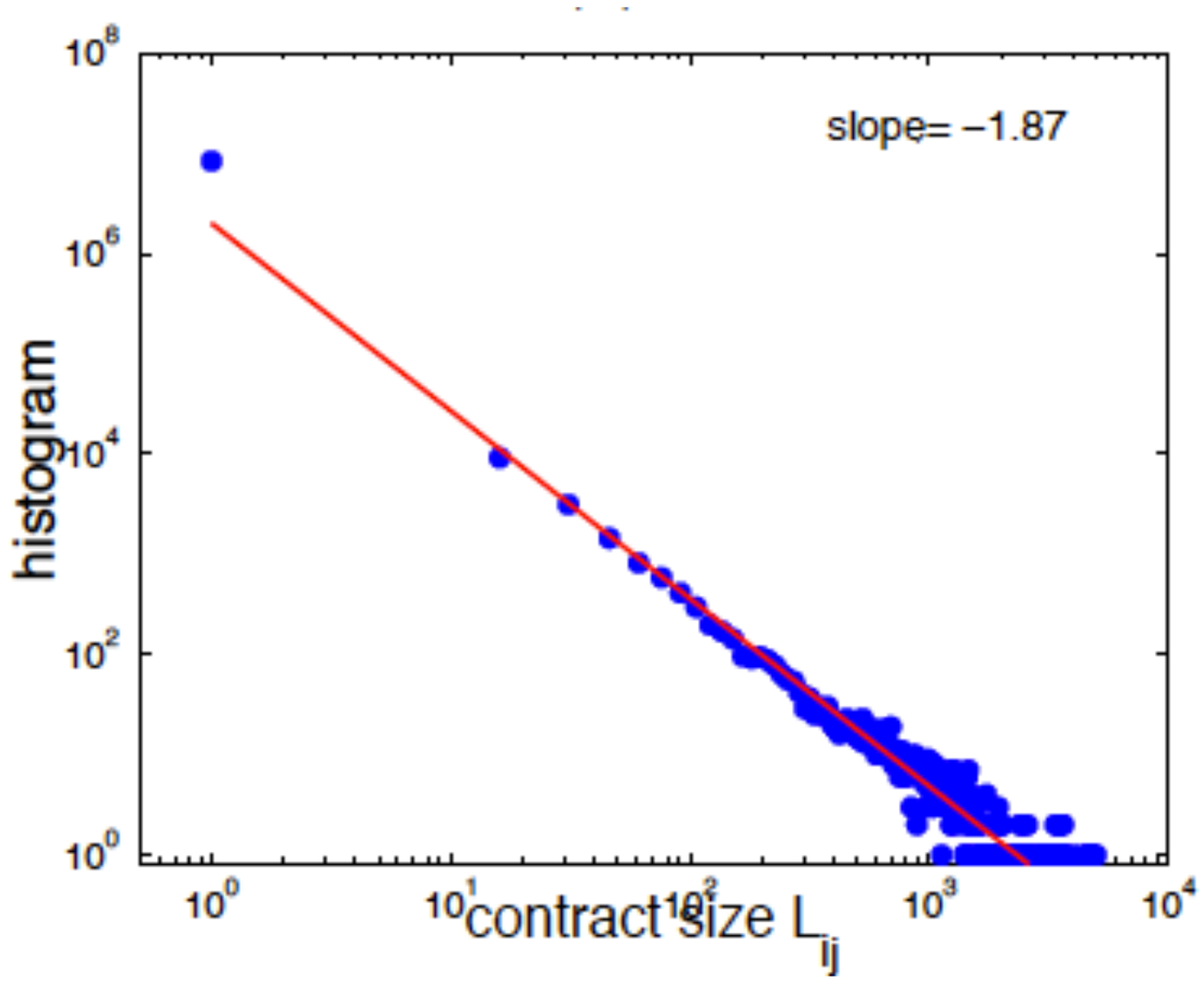
(figure from Boss et al, 2004 Quantitative Finance)

Size distribution



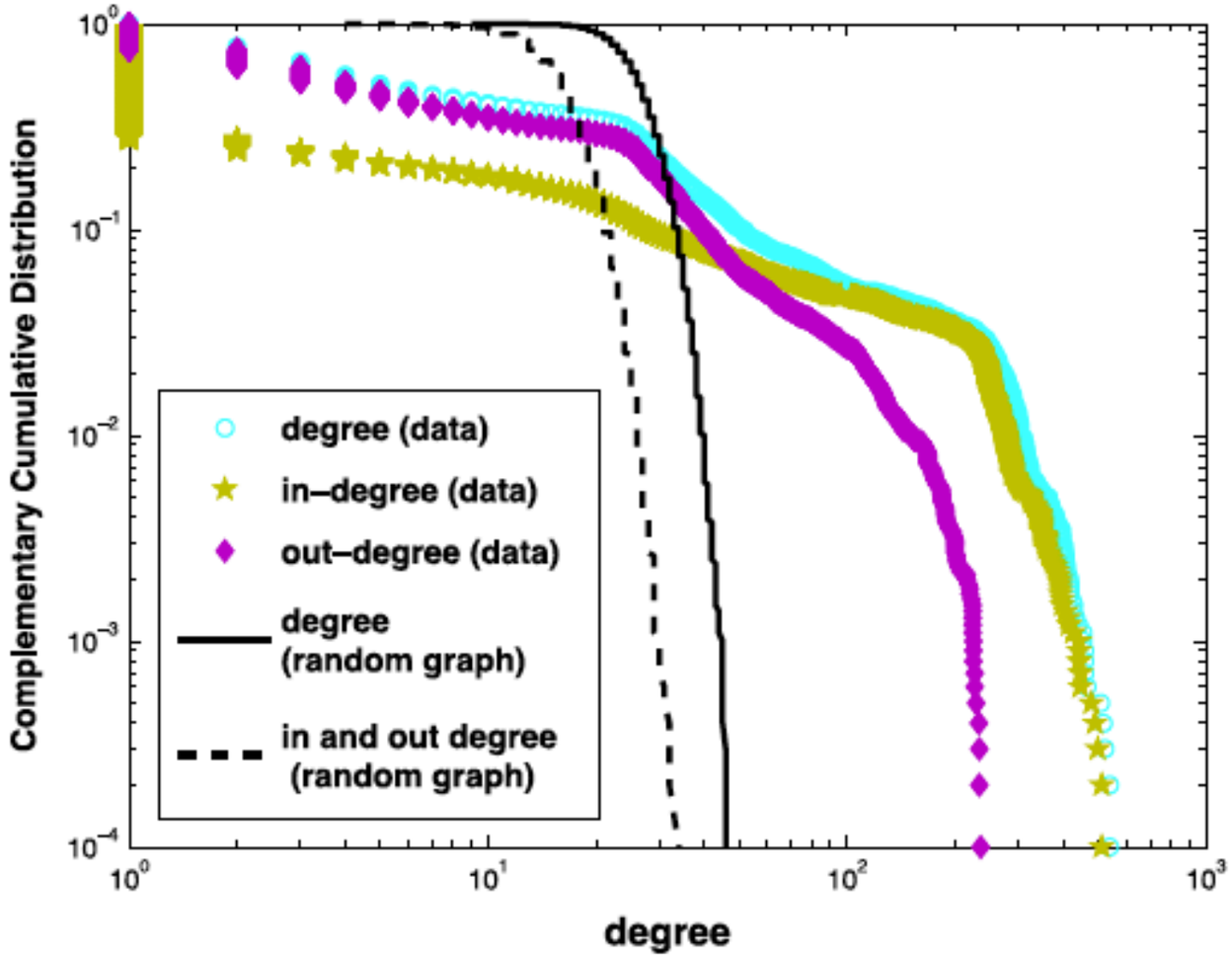
(figure from Caccioli et al, 2015 JEDC)

Distribution of interbank exposures



(figure from Boss et al, 2004 Quantitative Finance)

Network topology



(figure from Caccioli et al, 2015 JEDC)

The degree distribution is quite heterogeneous compared with that of Erdős–Rényi graphs

Network topology

F. Caccioli et al. / Journal of Economic Dynamics & Control 51 (2015) 50–63

Table 1
Network metrics.

Quantity	Mean	Standard deviation
Average degree	26	1
Number of hubs	45	2
Fraction of links of top 5% nodes	0.89	0.02
Assortativity	−0.62	0.03
Average local clustering	0.87	0.02

Summary statistics of network metrics. All quantities are computed averaging over the 12 quarters at our disposal. The average degree is the average number of links per node. The number of hubs is measured as the number of nodes with more than 100 connections. The fraction of links of the top 5% nodes is the number of connections involving at least one of the 5% mostly connected nodes divided by the total number of links in the network. The assortativity is measured as the correlation coefficient between degrees of neighboring nodes, while the local clustering is the average over all nodes of the fraction of a node's counterparties with an interbank relationship. The Austrian banking network between 2006 and 2008 shares the main stylized facts previously observed for other networks: sparseness, heavy tailed degree distribution, negative assortativity and large local clustering. More information can be found in Appendix A.

Core-Periphery

- A core-periphery network has a core of highly interconnected nodes and a periphery of banks that are not highly connected between them, but are connected to the core

- The core intermediates between peripheral banks

- It is possible to measure the “core-periphery-ness” of a network by measuring the distance between its adjacency matrix and that of a perfect core-periphery network

- However, one needs to pay attention to over-fitting

Summary of empirical facts

- Heavy-tailed degree distributions (hubs)
- Disassortativity
- High average clustering (counterparty risk externality)
- Core-periphery structure

Payment systems

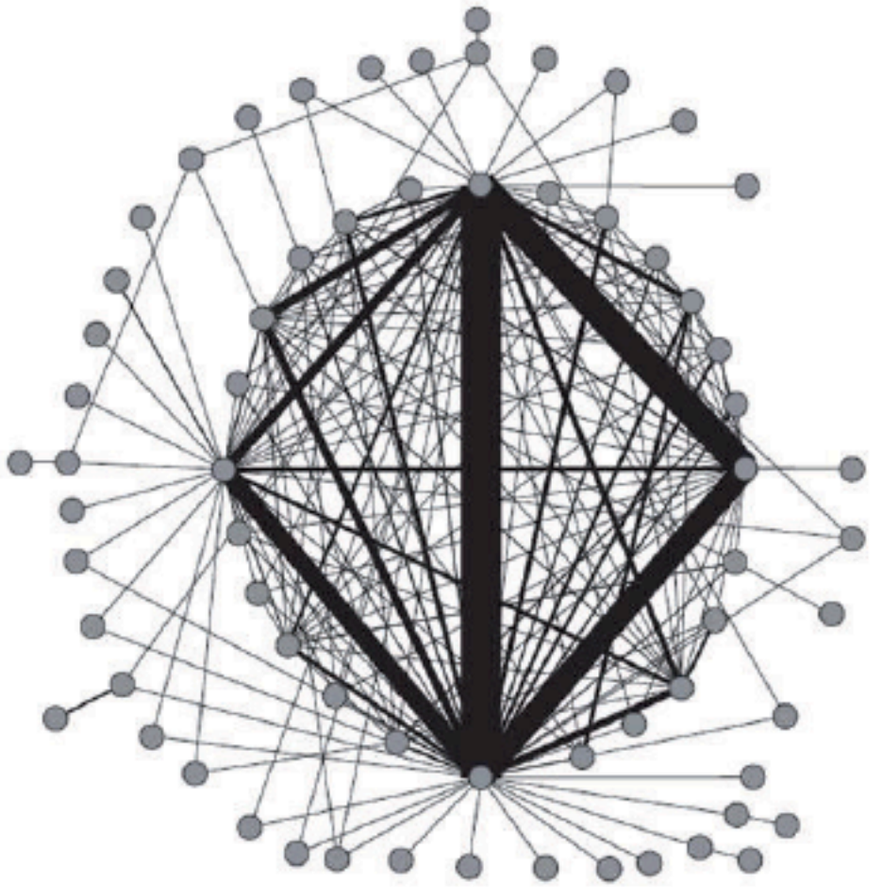
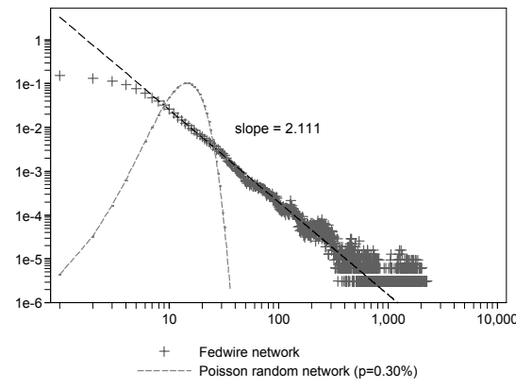


Figure 1: Core of the Fedwire interbank payment network on a representative day. Each node represents a bank and the width of links between the nodes scale with value of payments exchanged by the two banks. The links depicted cover 75% of daily value transferred.

Soramaki et al, 2007

Payment systems



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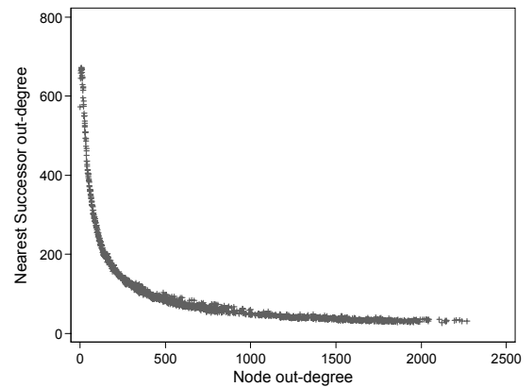

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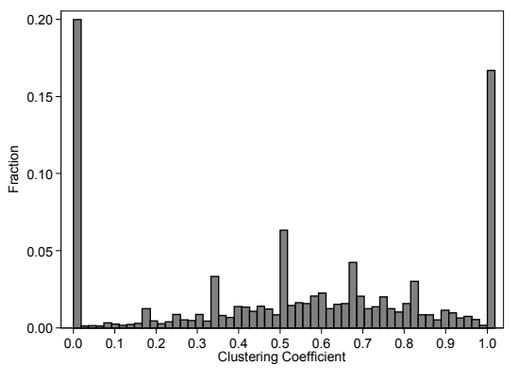

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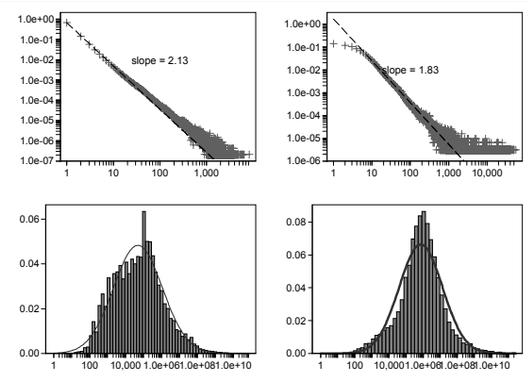


d

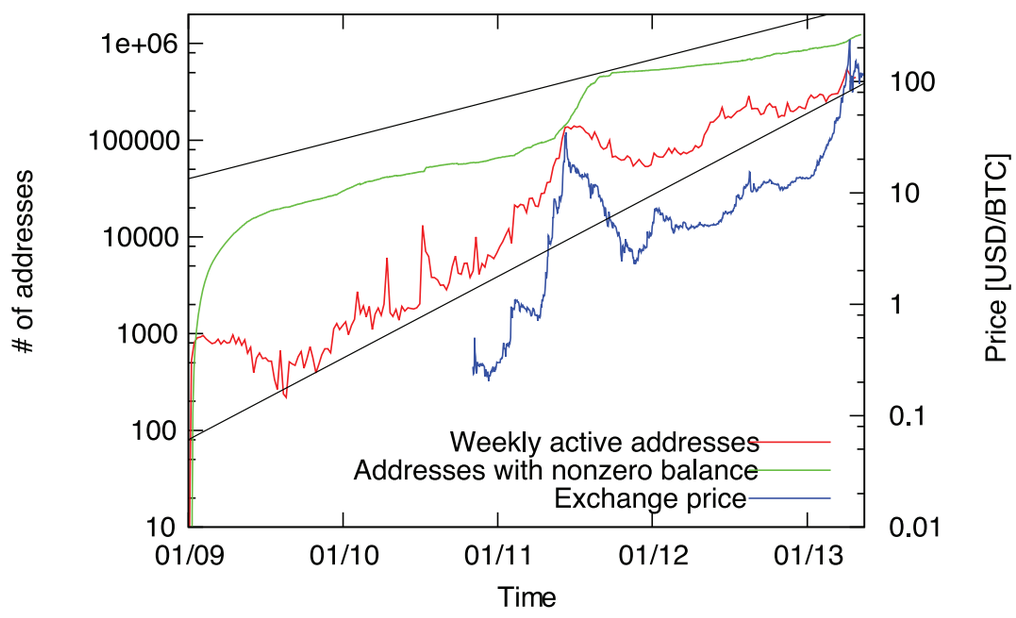
FIG. 3: a) Out-degree Distribution. b) Average nearest successor out-degree as a funtion of out-degree. c) Distribution of clustering coefficient d) Top left hand corner: Volume link weight distribution. Top right hand corner: Volume out-strength distribution. Bottom left hand corner: Value link weight distribution. Bottom right hand corner: Value out-strength distribution.

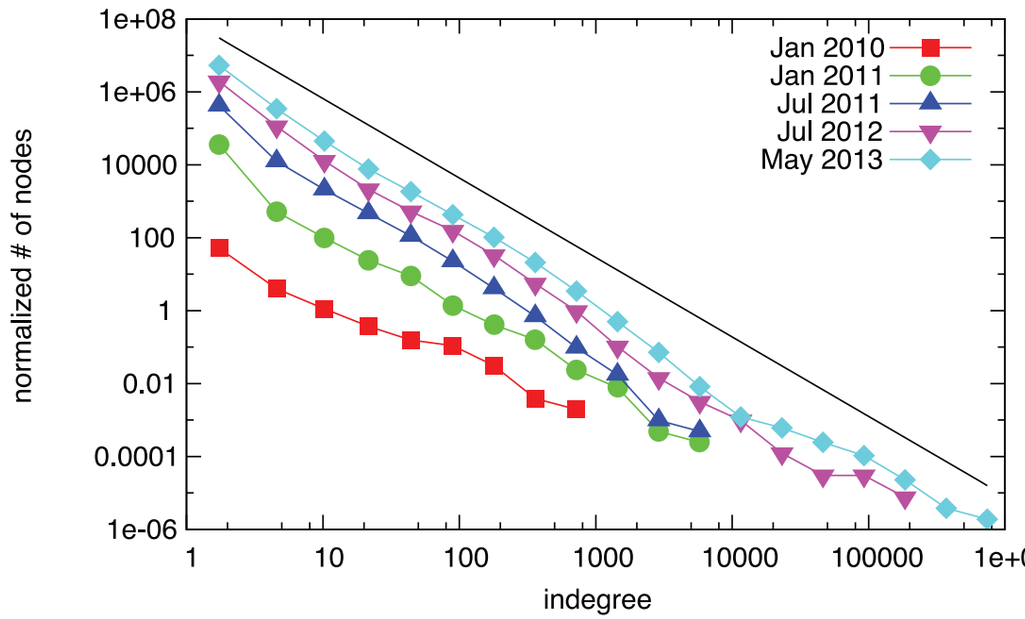
Soramaki et al 2007

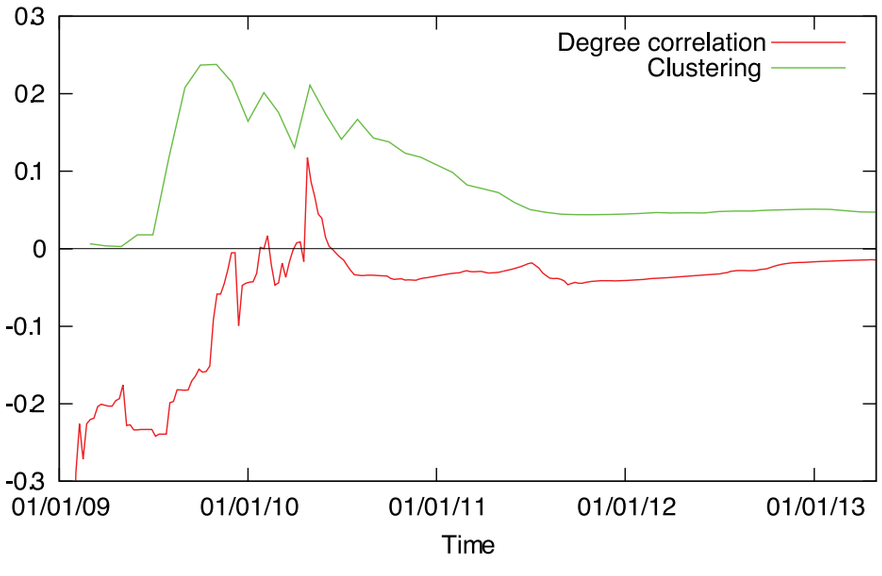
OPEN ACCESS Freely available online PLoS ONE 9(2): e86197. doi:10.1371/journal.pone.0086197 PLOS | ONE

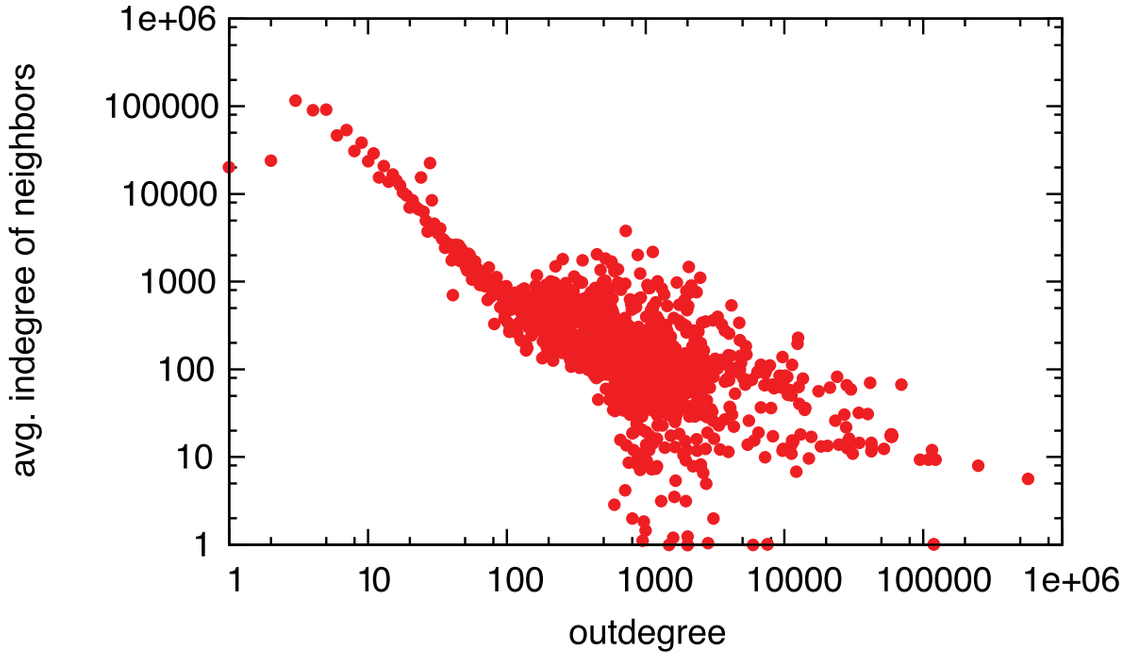
Do the Rich Get Richer? An Empirical Analysis of the Bitcoin Transaction Network

Dániel Kondor[1]*, Márton Pósfai[1,2], István Csabai[1], Gábor Vattay[1]









Risk management

- Traditional approach to risk management focuses on individual institutions
- The assumption is that if individual institutions are stable than the whole system is stable
- However financial institutions are not isolated
- Microprudential approach ignores interaction/network effects
- These can lead to amplification and contagion effects
- goal: incorporate interactions in risk management tools (e.g. stress-testing)

Contagion

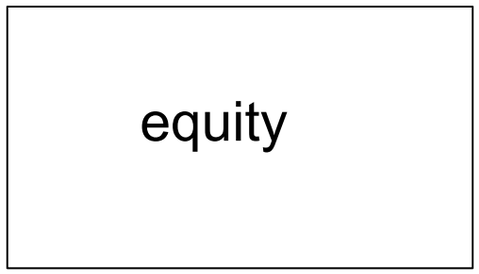
- Two major types of financial distress can spread by contagion: insolvency, and illiquidity

- Insolvency refers to the case in which a default occurs because the values of the assets of a firm drop below the value of its liabilities

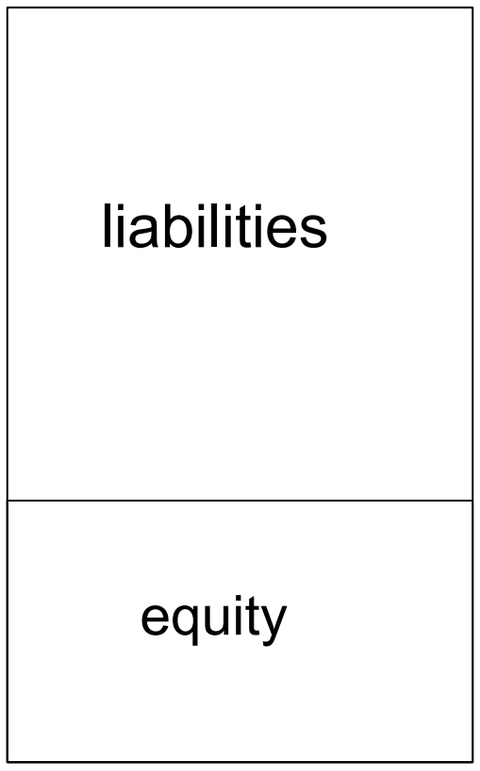
- Illiquidity refers to the situation in which a firm cannot meet its due payments

- We will mainly focus on insolvency in the following

Leverage: investing borrowed money

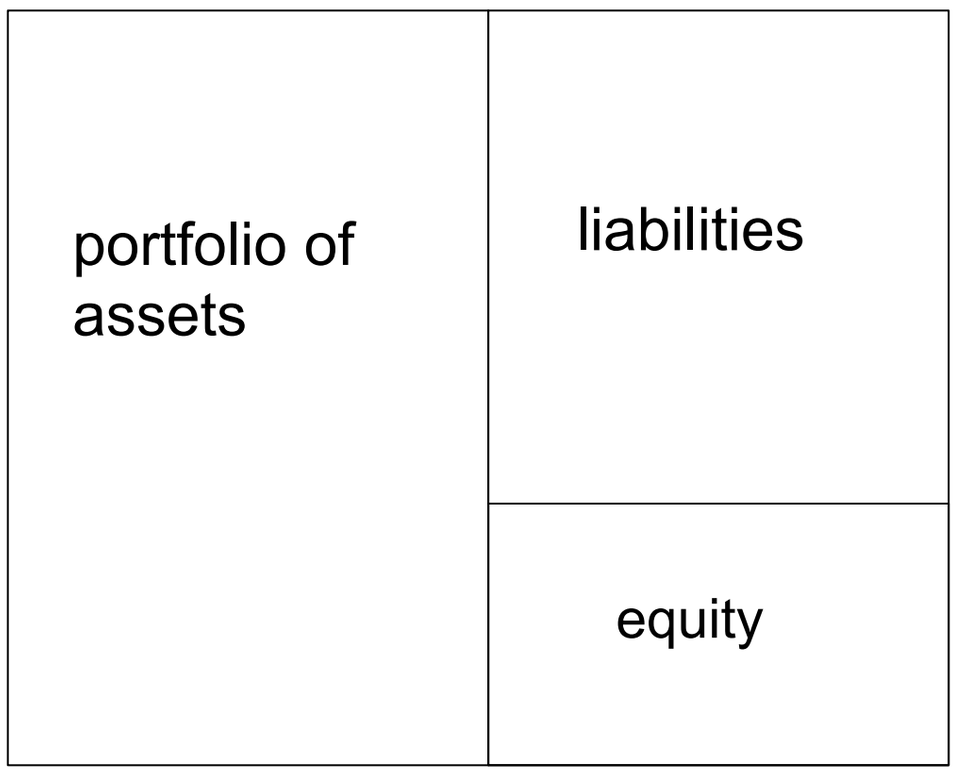


Leverage: investing borrowed money



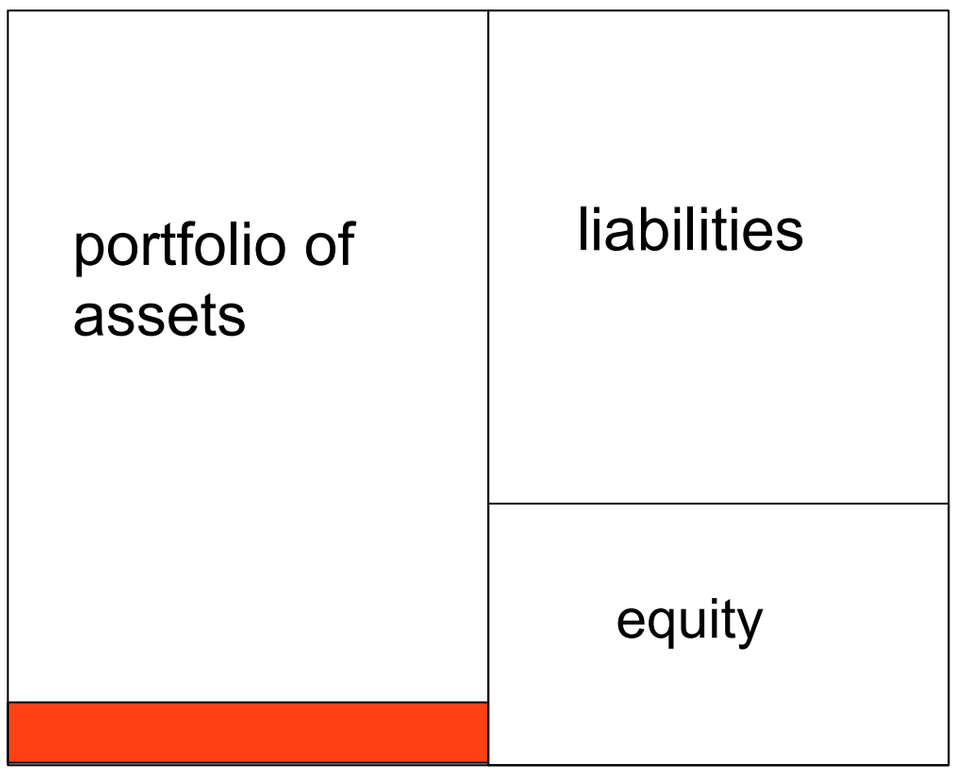
Leverage: investing borrowed money

Balance sheet identity: assets = liabilities + equity



Leverage amplifies shocks

Balance sheet identity: assets = liabilities + equity



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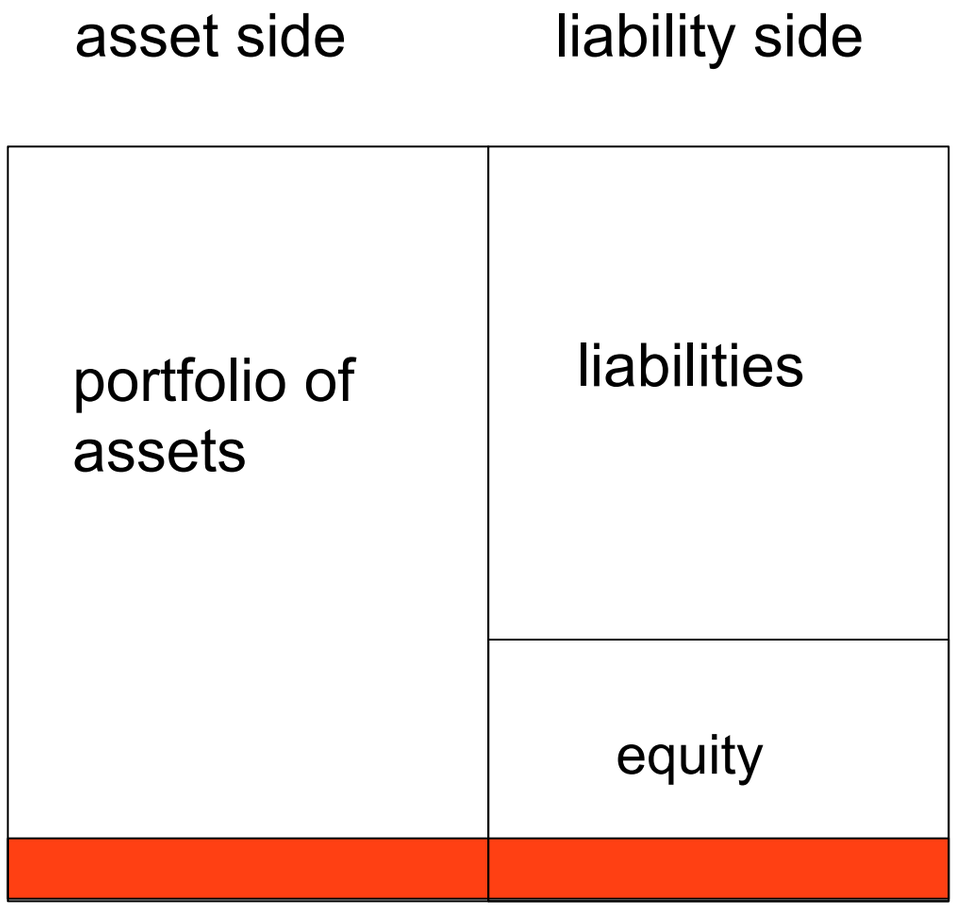
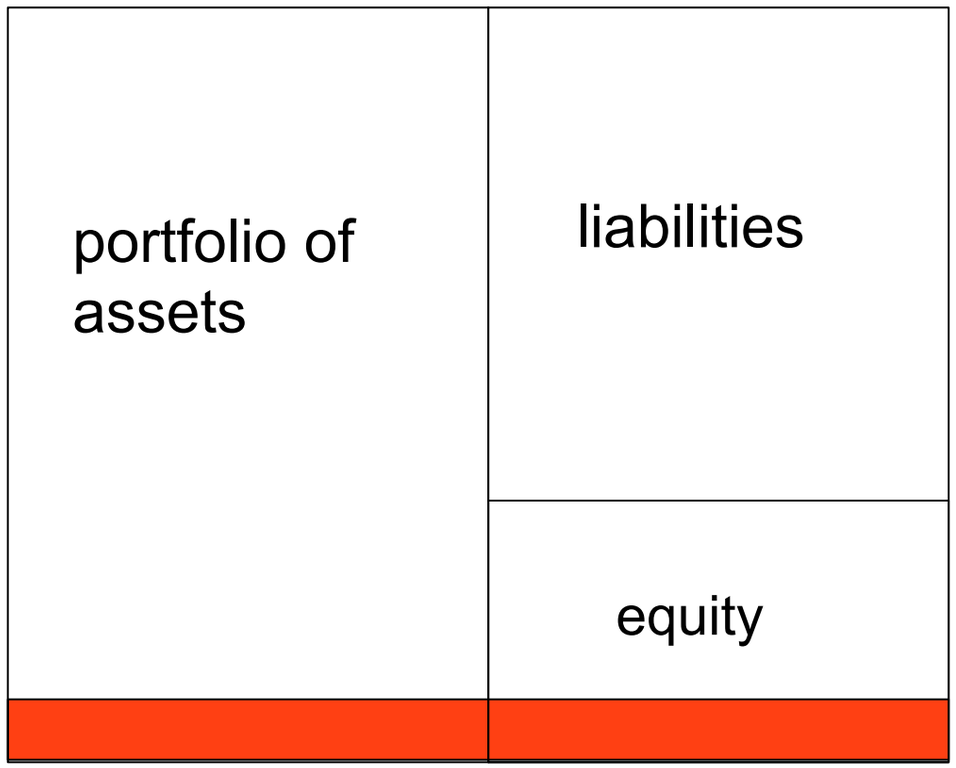


Leverage amplifies shocks

Balance sheet identity: assets = liabilities + equity

asset side | liability side



leverage

$$\lambda = \frac{\text{assets}}{\text{equity}}$$

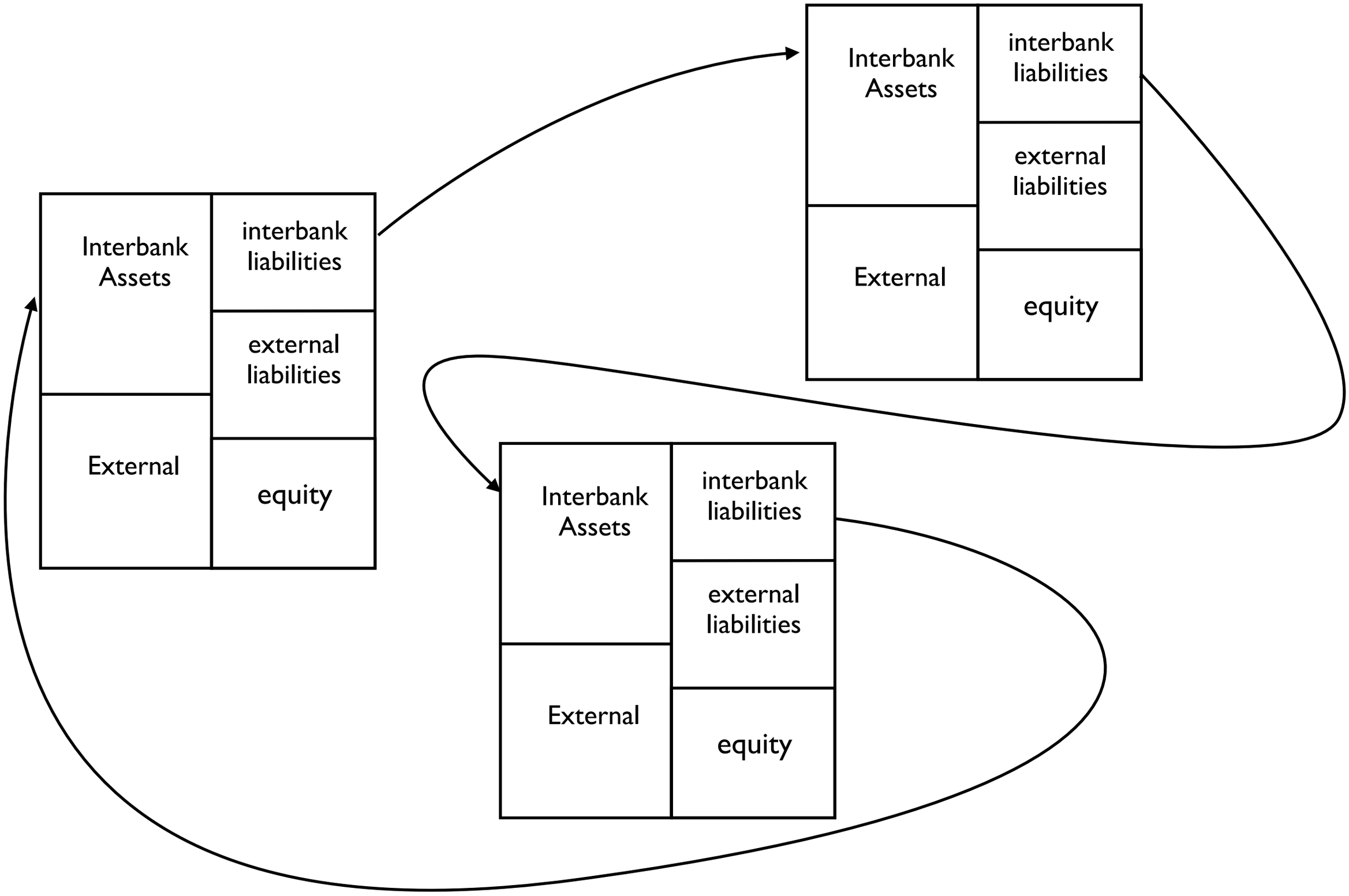
1% asset devaluation

λ % equity loss

Bank

Interbank Assets	interbank liabilities
	external liabilities
External	equity

Network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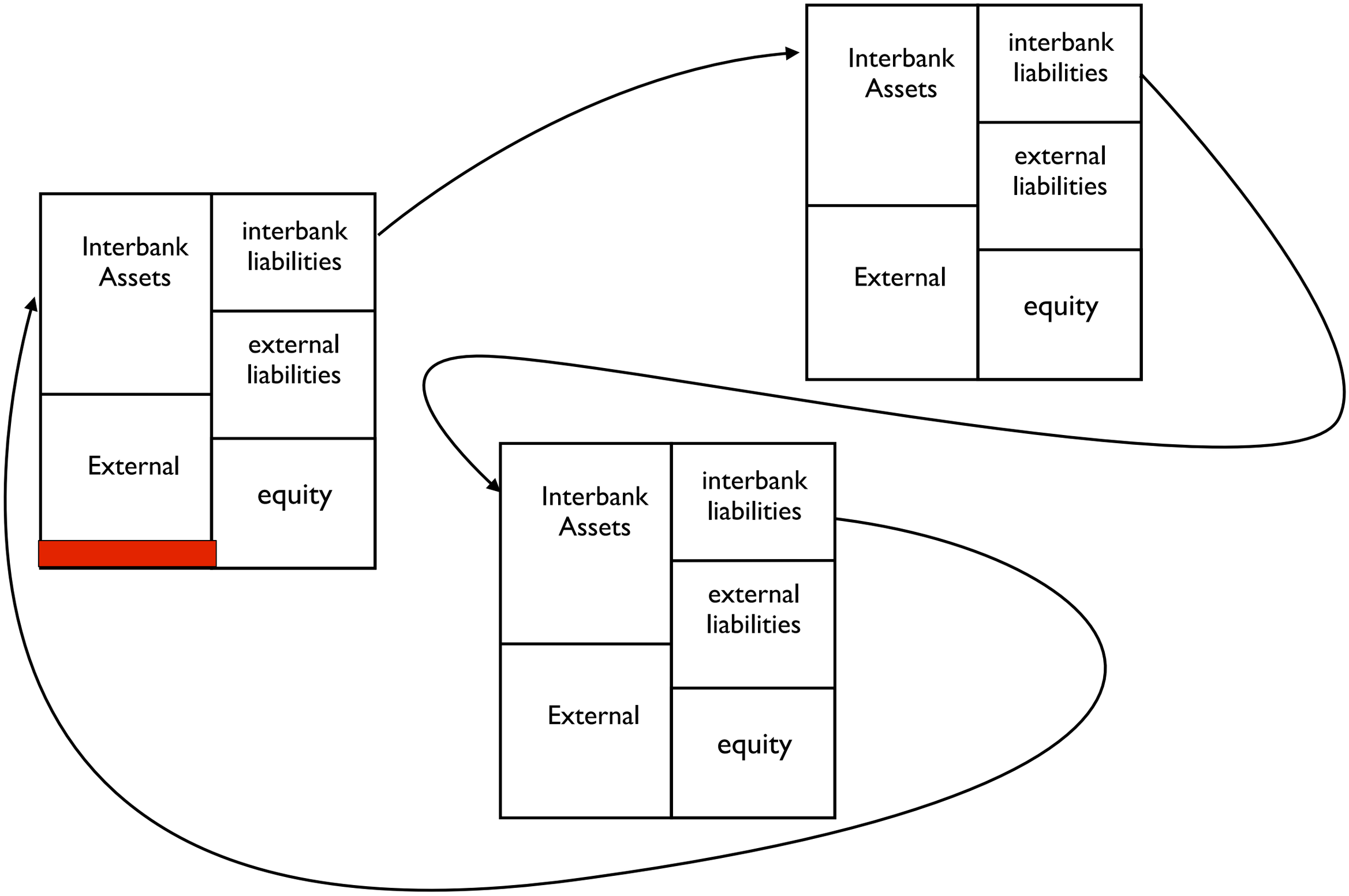
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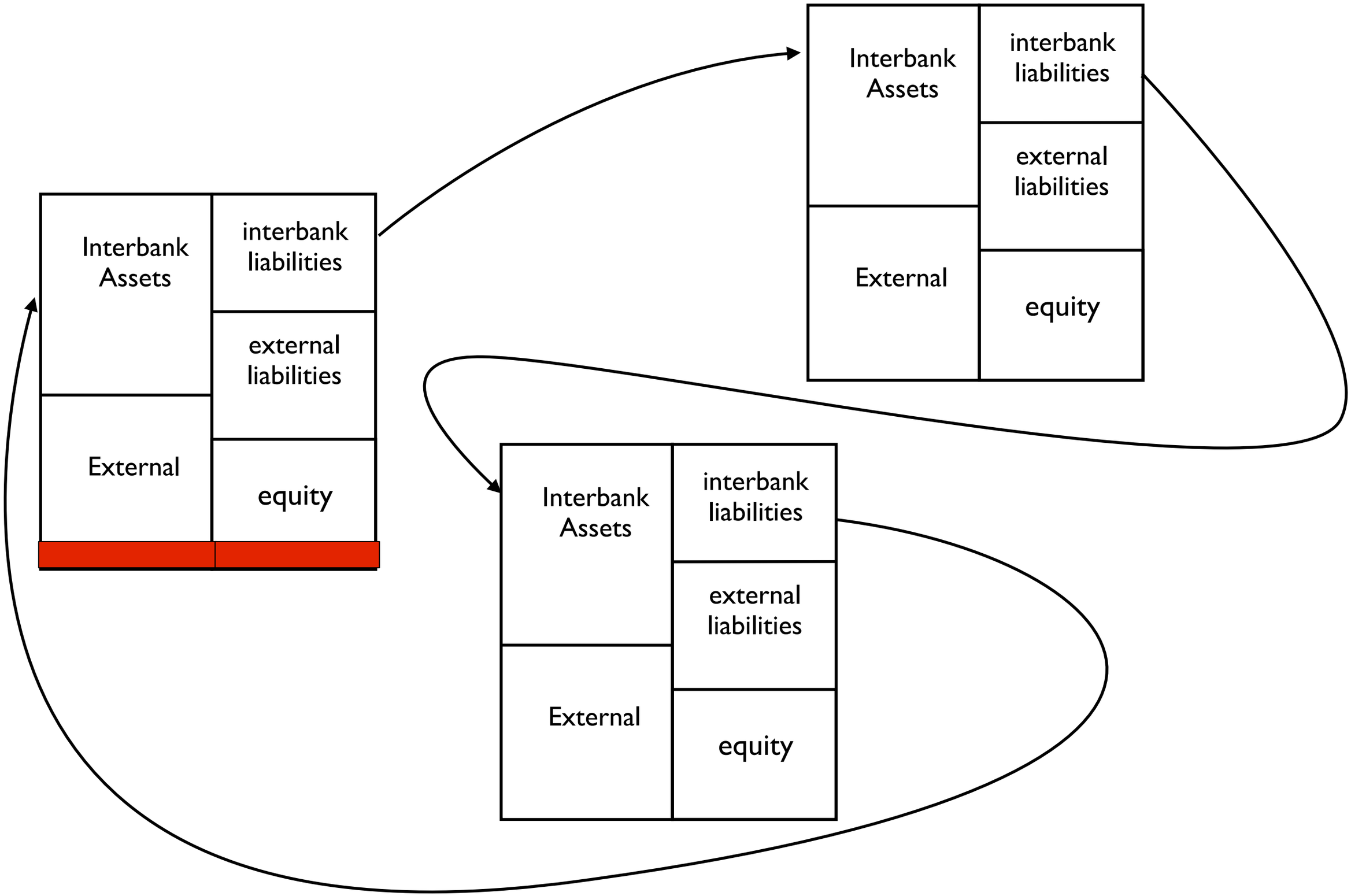
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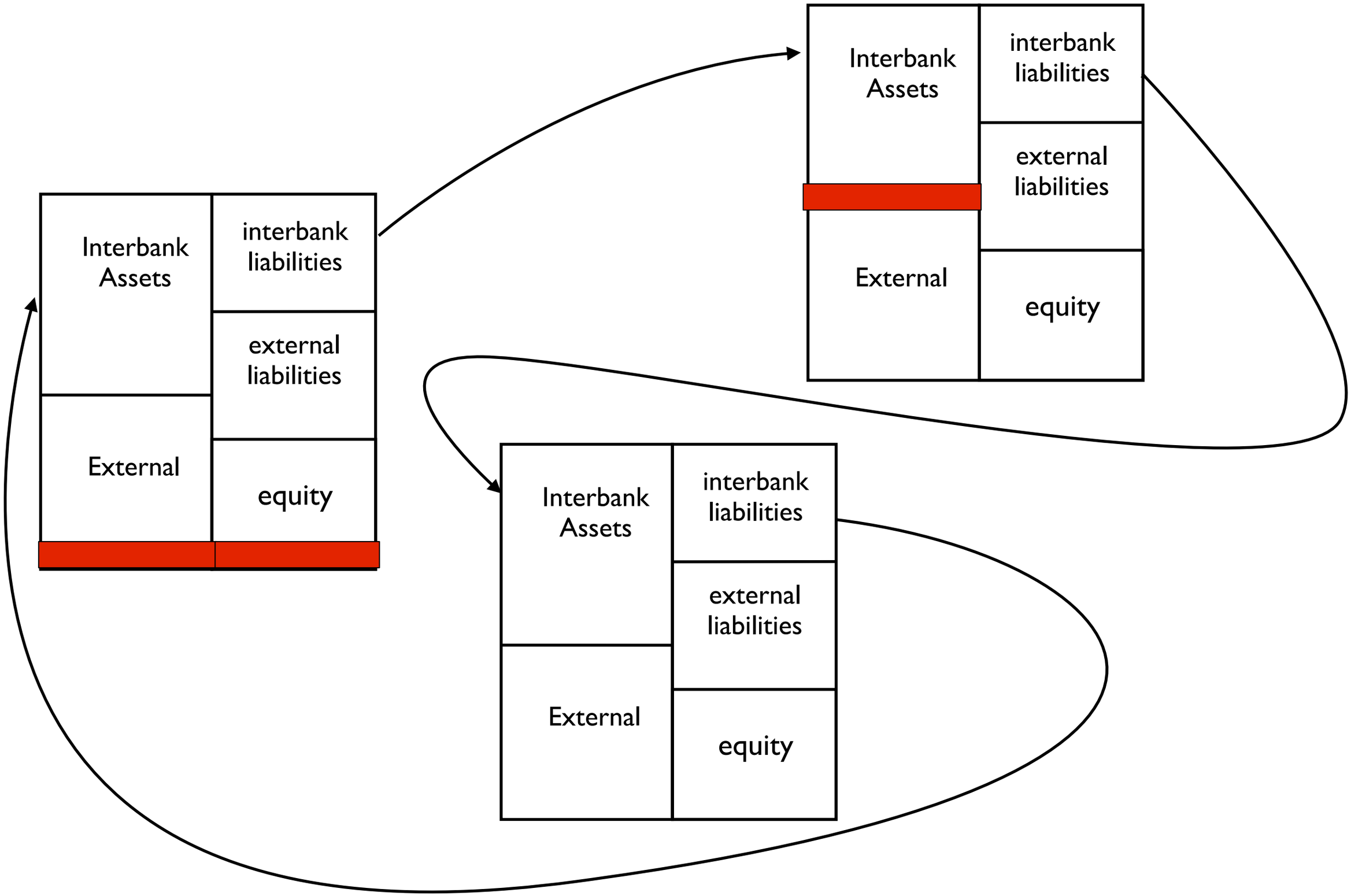
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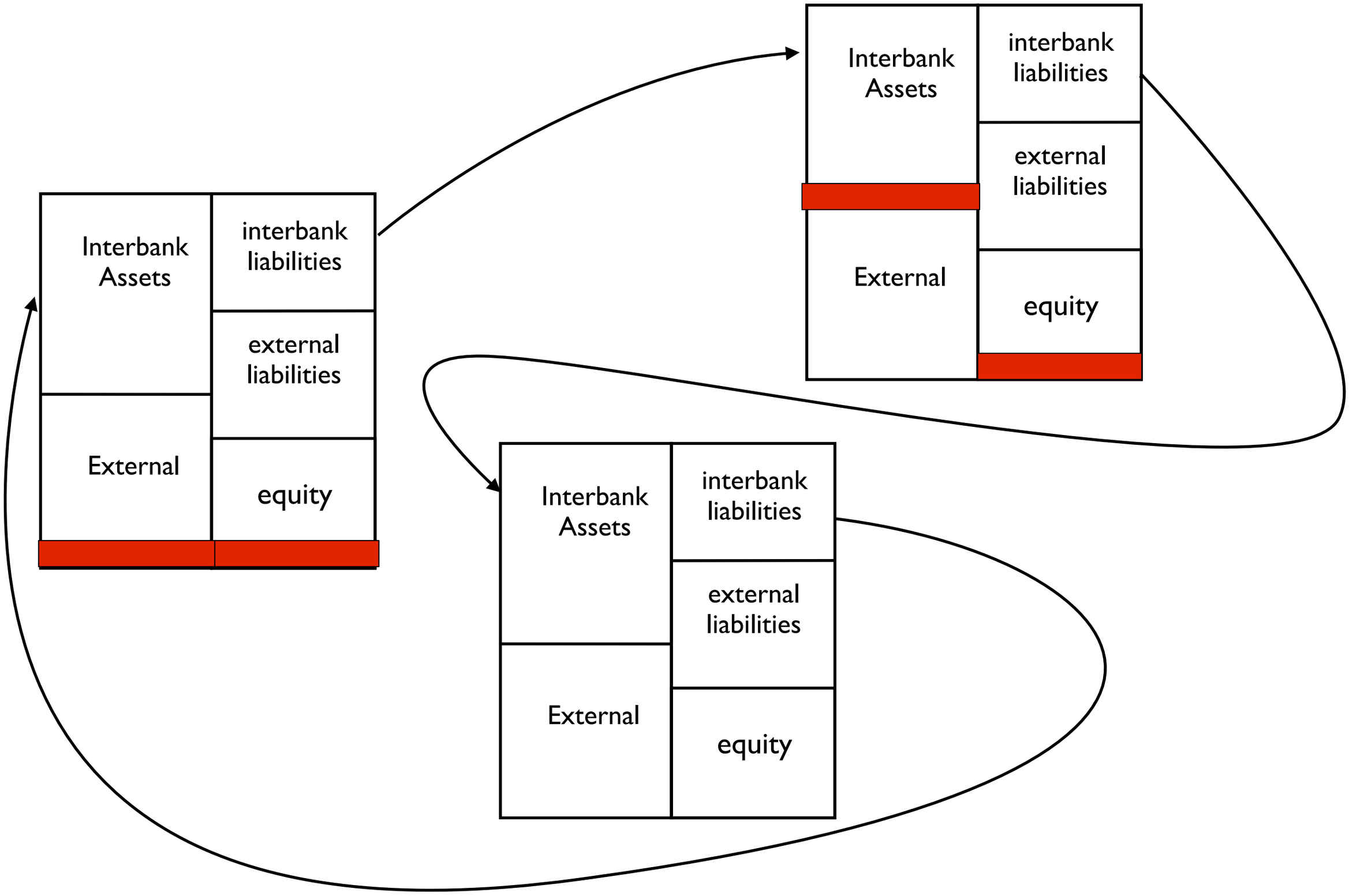
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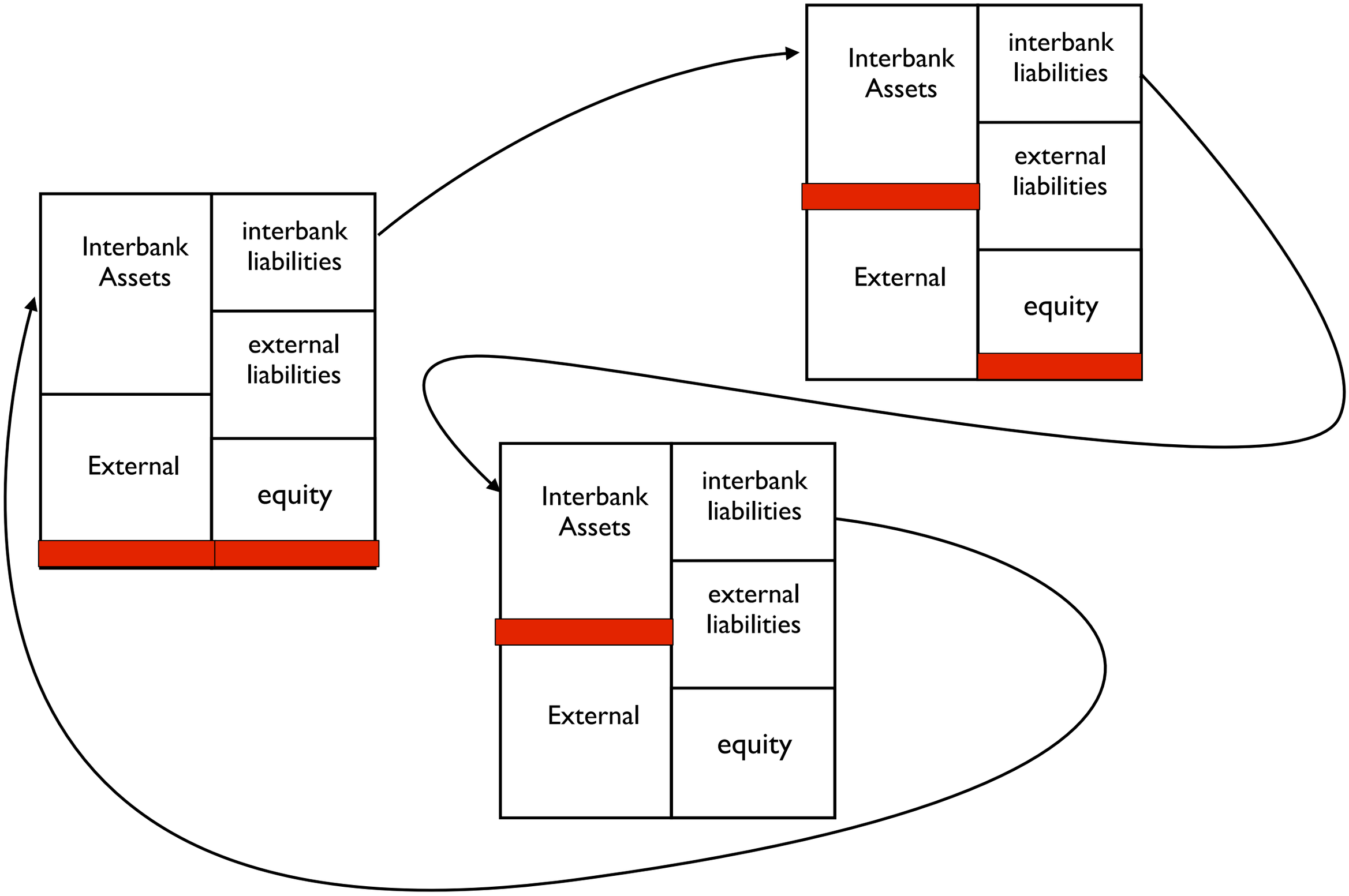
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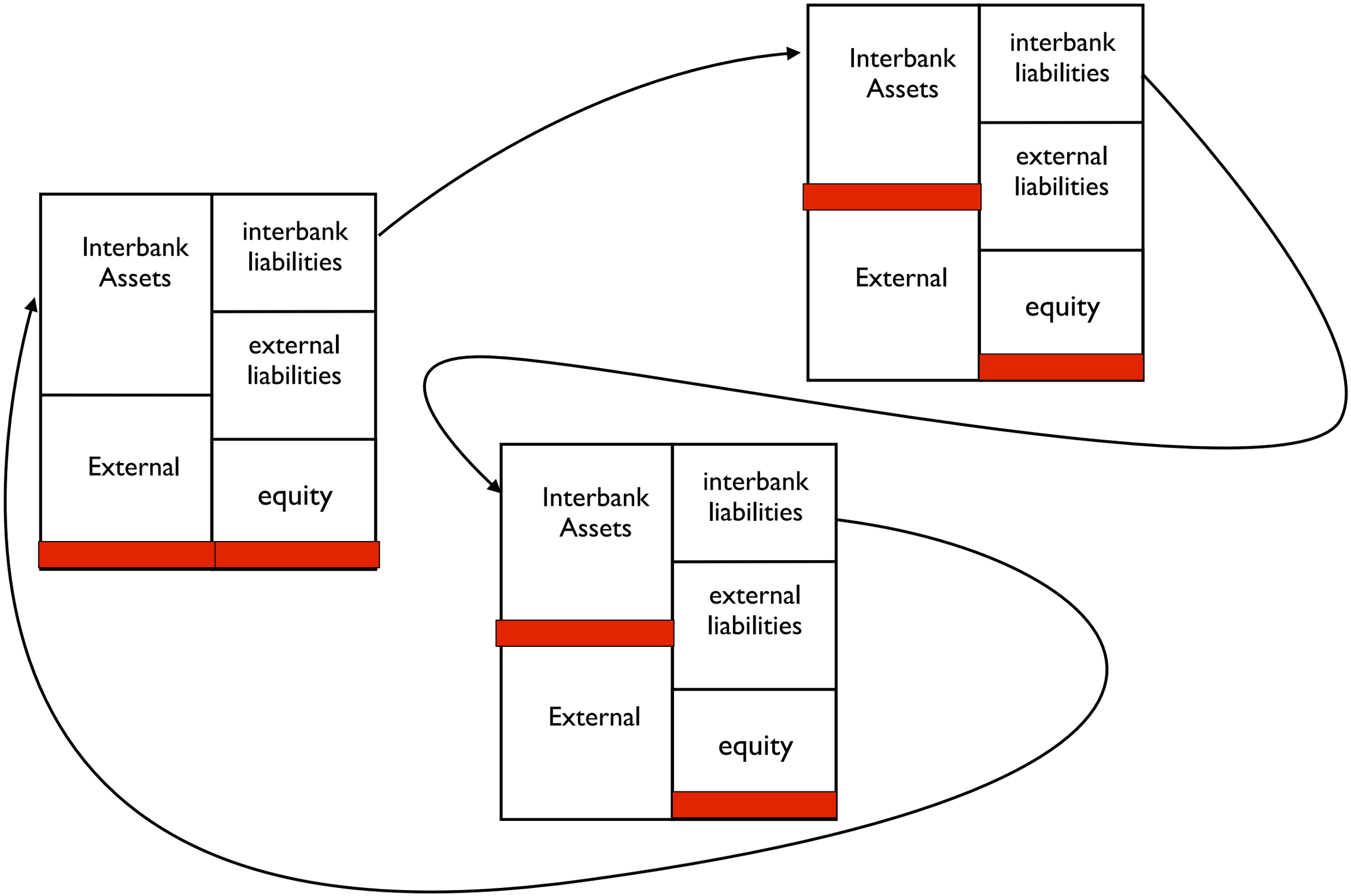
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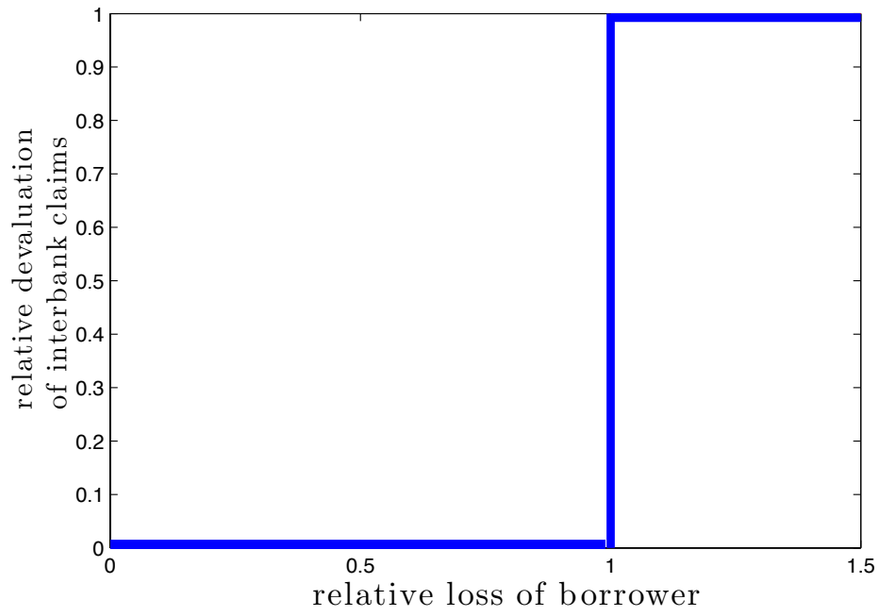
Default contagion

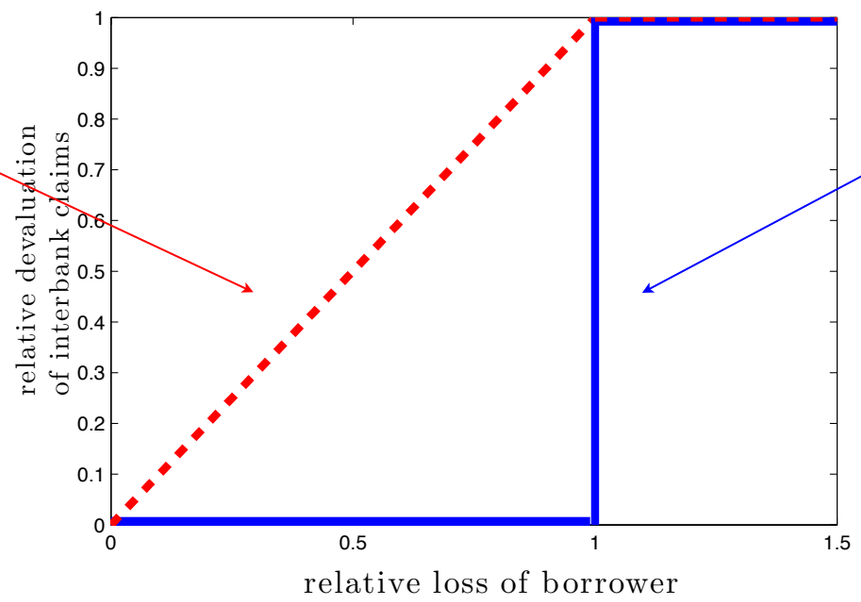
- Cascade models propagate losses only after defaults



Distress contagion

- Cascade models propagate losses only after defaults
- Stress can however propagate before the default of the borrower because of credit quality deterioration

DebtRank



default contagion

Dynamics

- Relative equity loss

$$h_i(t) = \frac{E_i(0) - E_i(t)}{E_i(0)}$$

- Dynamics

$$h_i(t+1) = \beta \sum_j \Lambda_{ij} h_j(t) + u_i$$

exogenous shock

contagion

- Matrix of interbank leverage
  (D'Errico et al JAI 18 (4) 68 (2016))

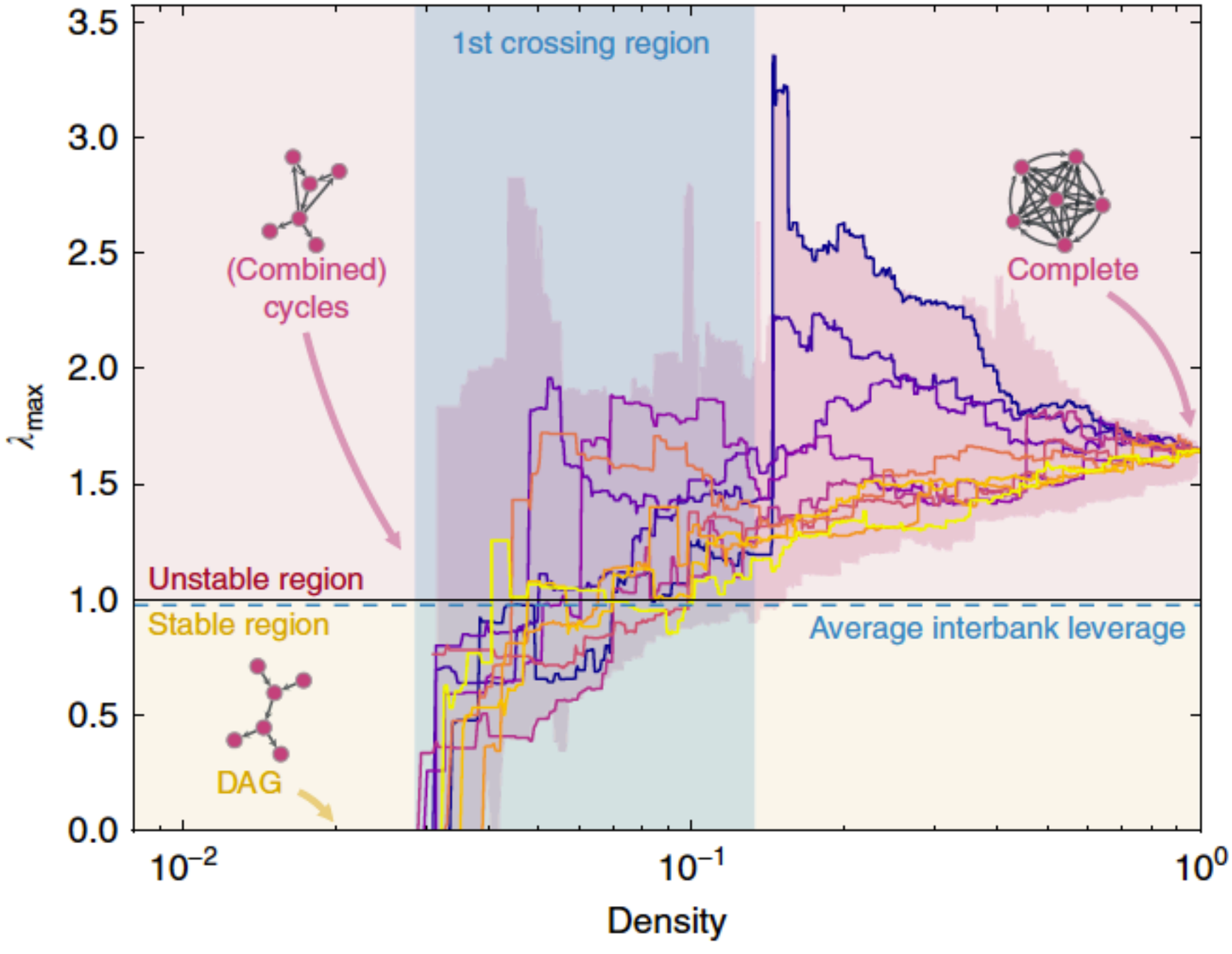
$$\Lambda_{ij} = \frac{W_{ij}}{E_i(0)}$$

W_{ij} → exposure of i towards j

$E_i(0)$ → equity of i

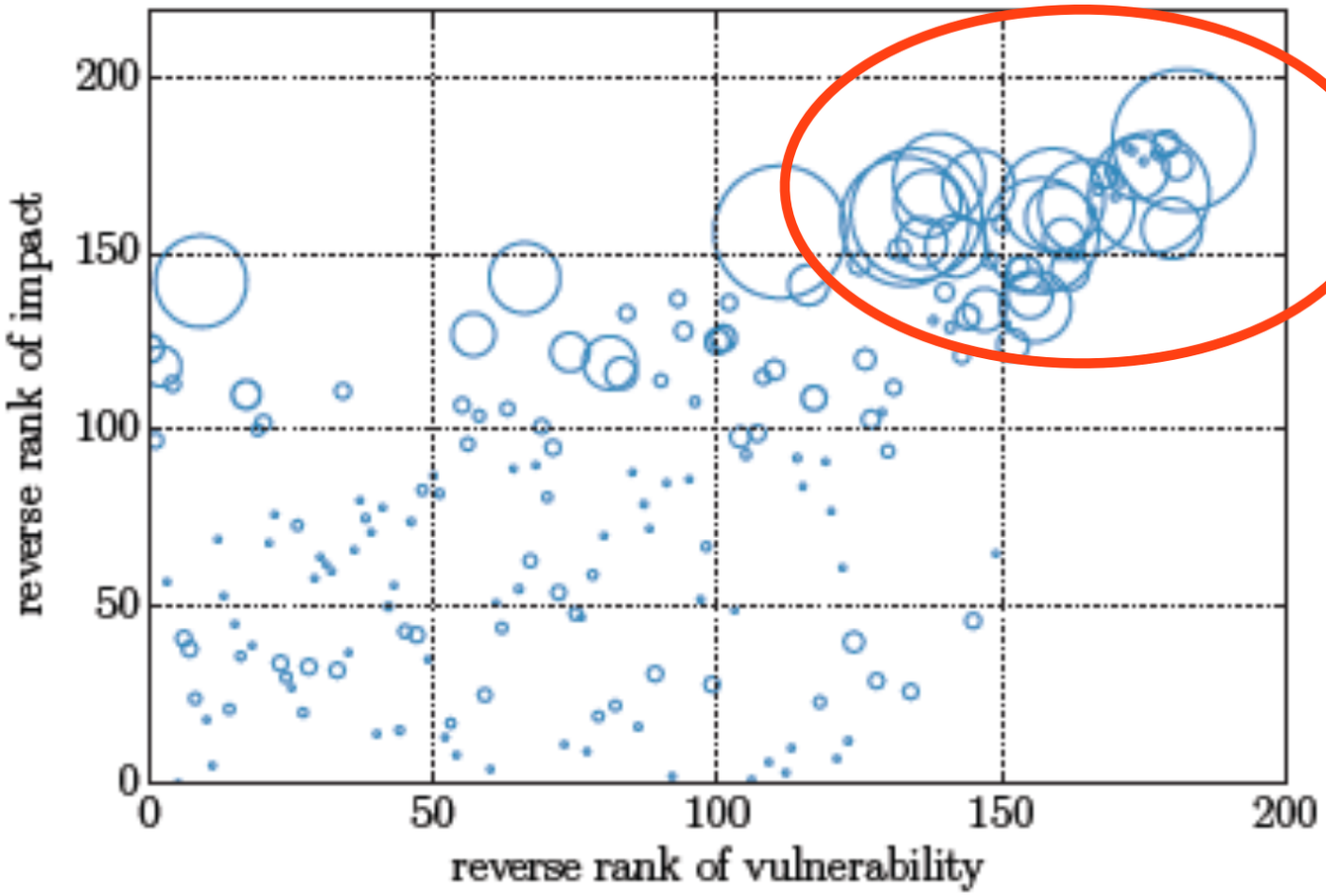
The endogenous amplification of shocks depends on the largest eigenvalue of Λ

Effect of diversification



(Bardoscia, Battiston, Caccioli, Caldarelli (2017))

Ranking banks: Impact and vulnerability



highest impact and vulnerability

Bardoscia, Battiston, Caccioli, Caldarelli (2015)

- The most impactful banks are also the most vulnerable
- Among these there are also small banks

Contagion due to overlapping portfolios

- We have looked at contagion due to direct connections between banks
- However, banks also interact indirectly through their investment portfolios
- Stress can propagate from one bank to others with common assets through prices
- For instance, if a troubled bank needs to liquidate its portfolio in a fire-sale, prices will fall and investors with a similar portfolio suffer mark-to-market losses

UCL

The Guardian
Newspaper of the year

Pensions industry

Bank confirms pension funds almost collapsed amid market meltdown

Official explains how promise to buy up to £65bn of government debt staved off destructive UK financial spiral

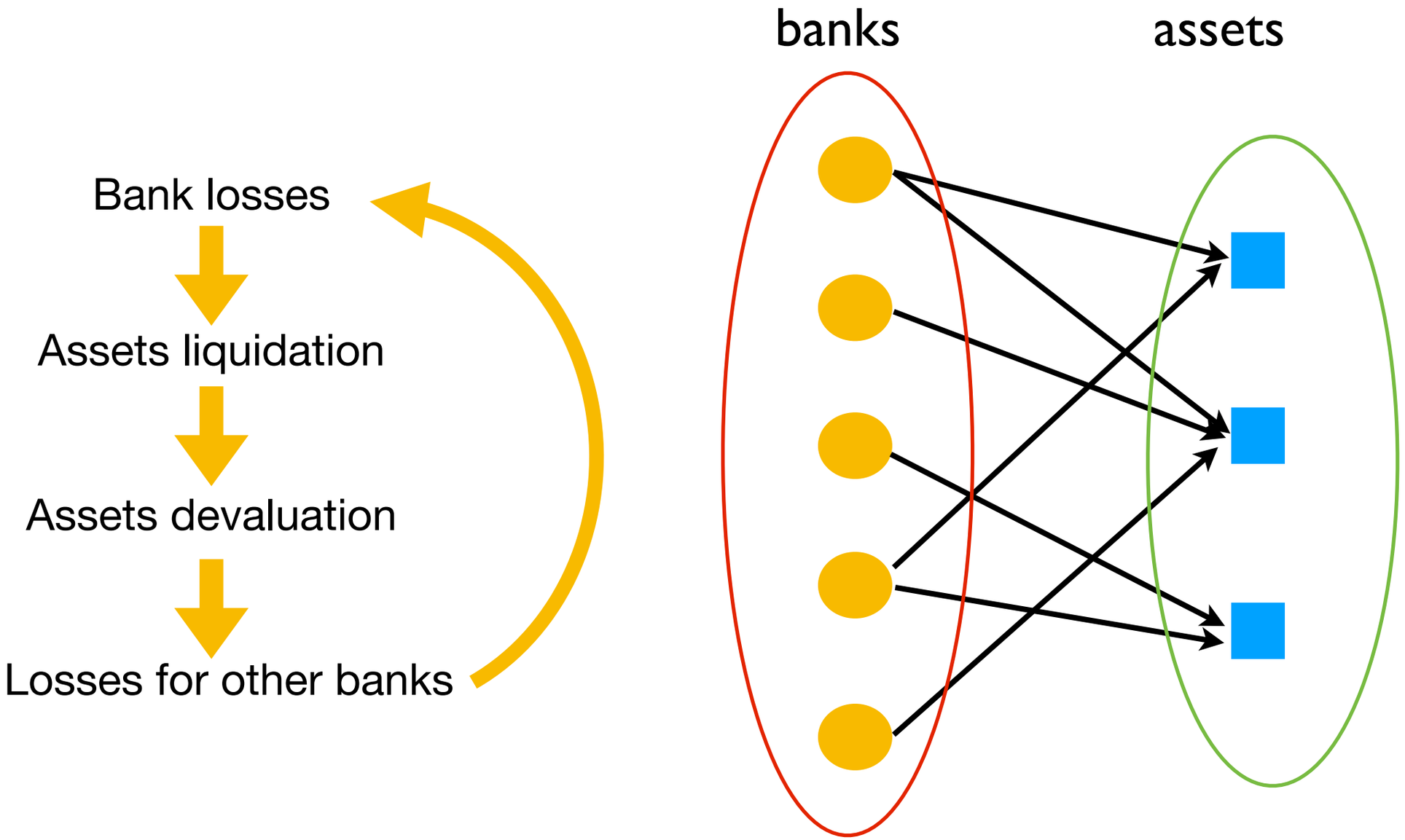
United Kingdom

BoE's Hauser: Mini-budget caused 'full-scale liquidation event' for pension funds

Reuters

October 19, 2022 5:35 PM GMT+2 · Updated a year ago

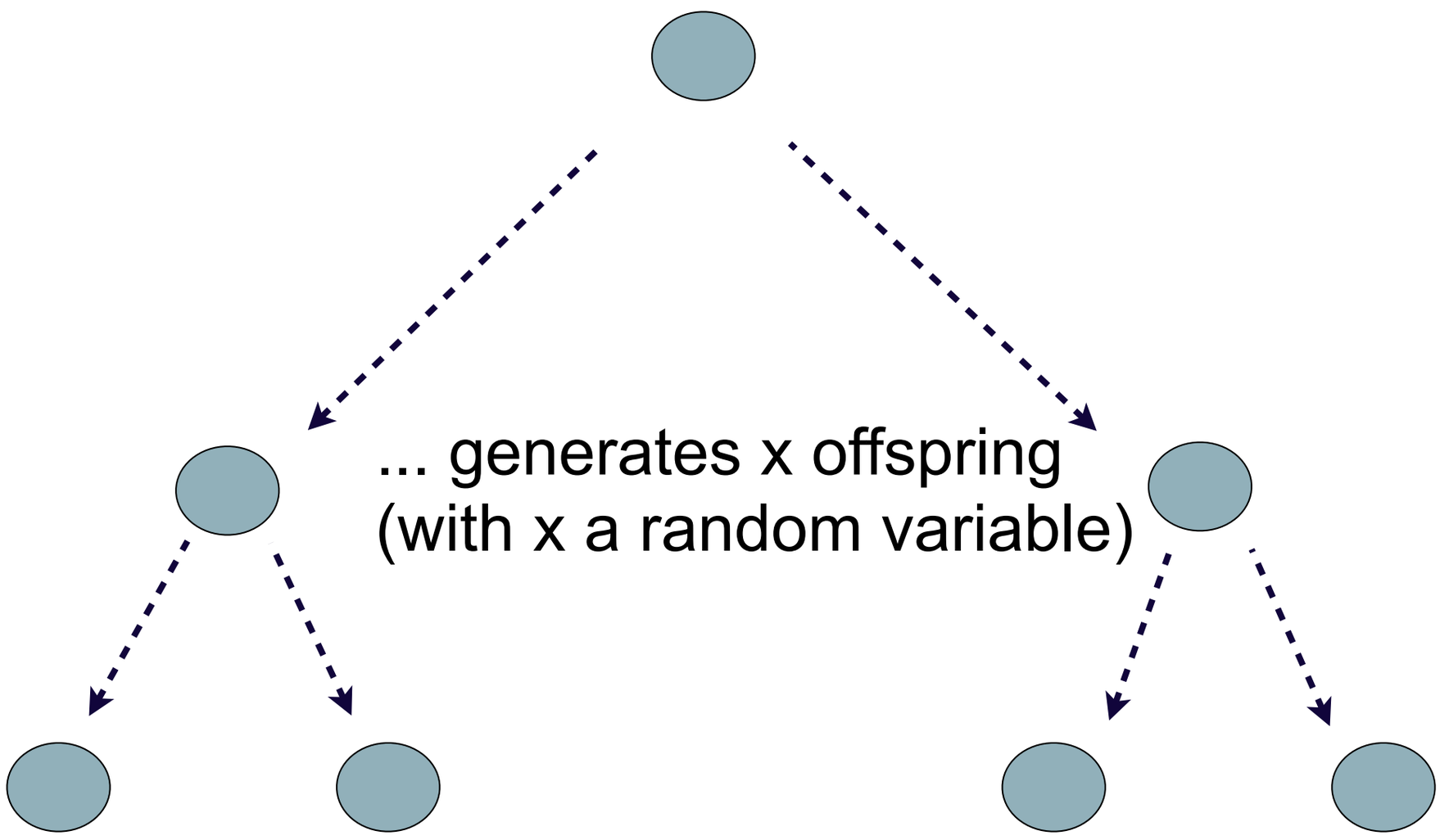
Contagion due to overlapping portfolios



Stress propagates between banks with common assets

Branching Processes

one ancestor...

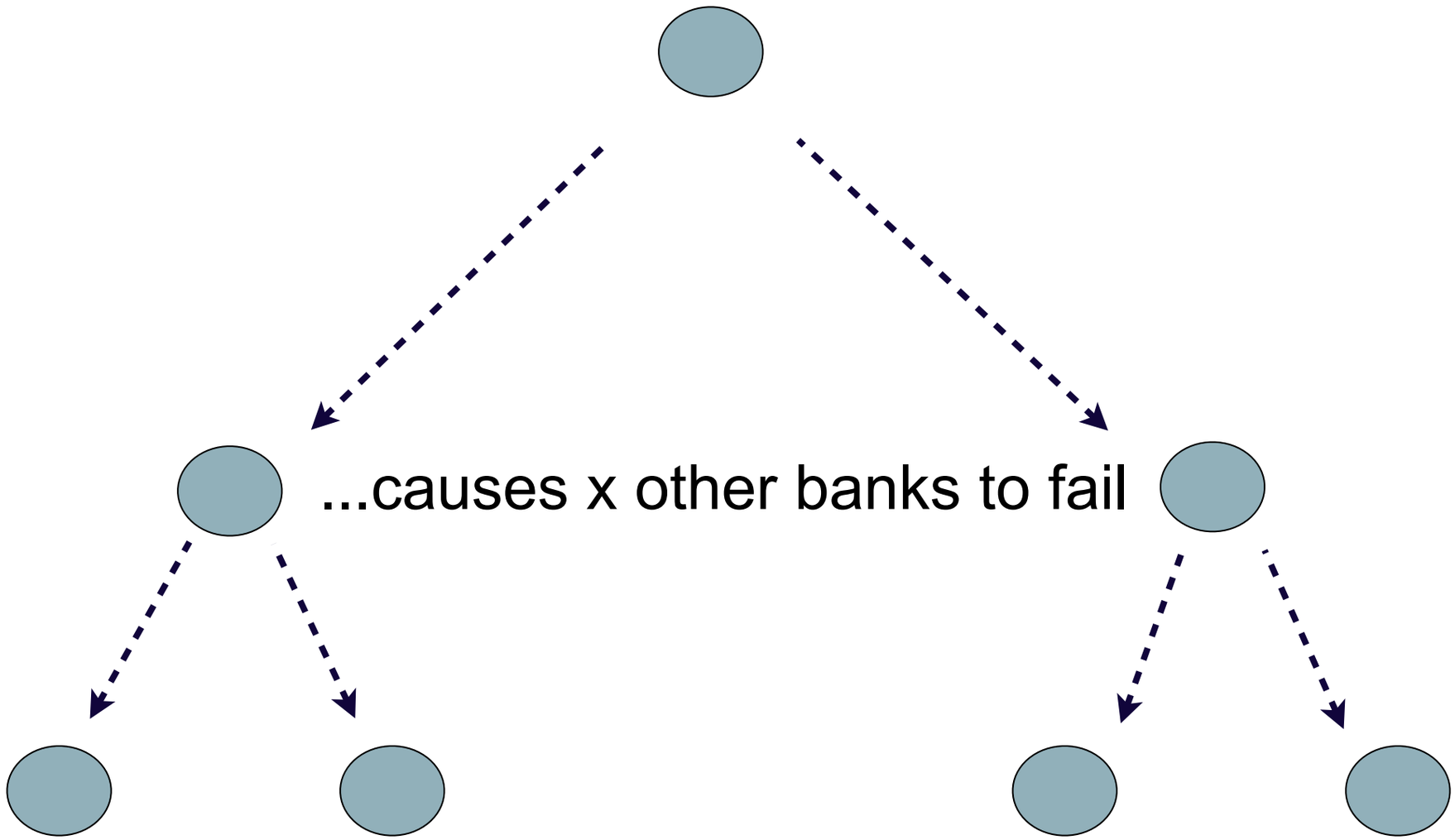


... generates x offspring
(with x a random variable)

the species survives with non-zero probability if E[x]>1

In our case

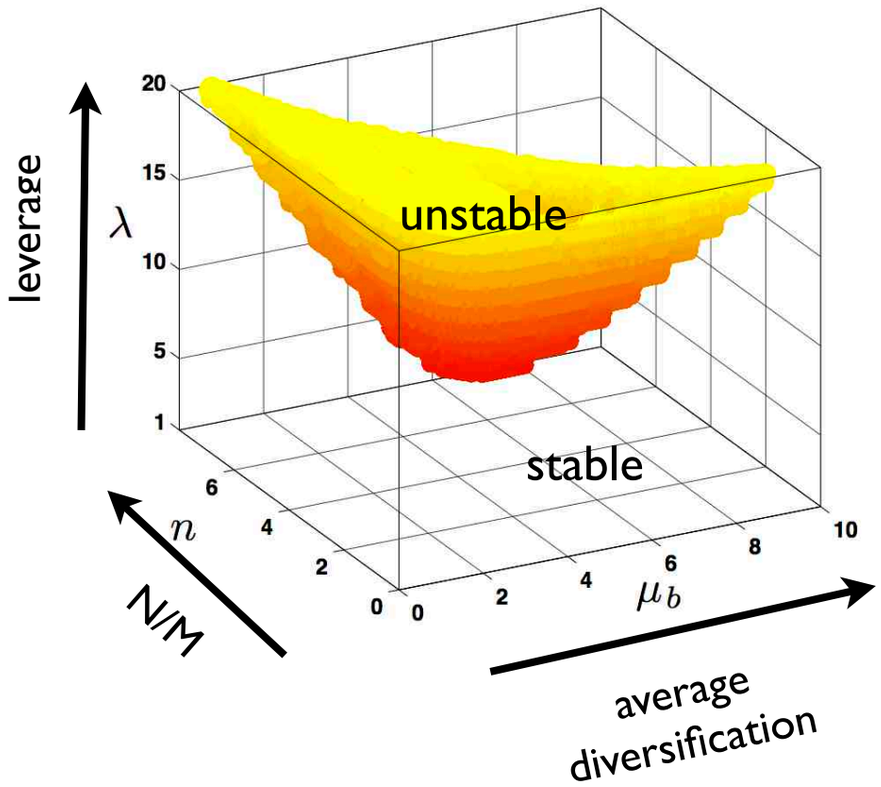
one bankrupted bank...

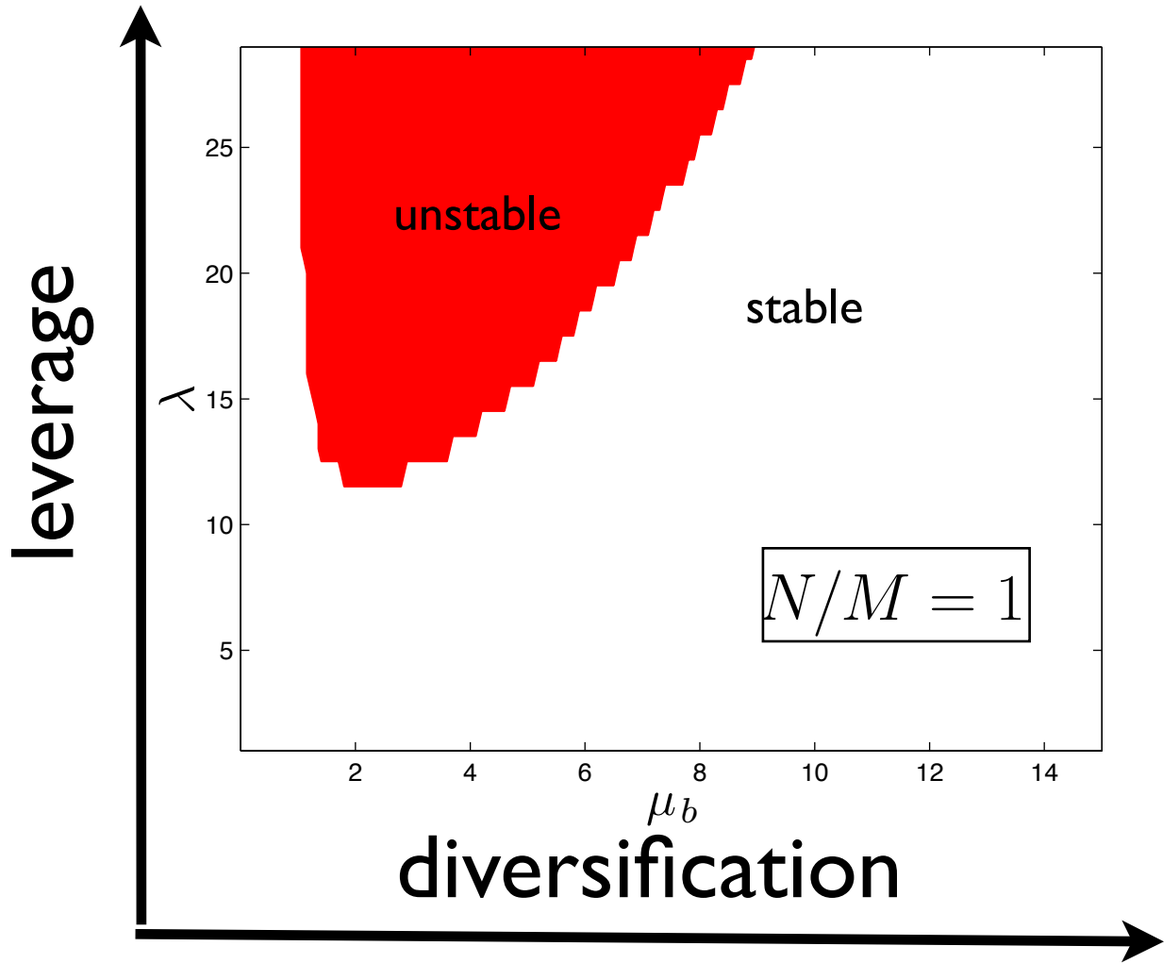


...causes x other banks to fail

global cascades occur with non-zero probability if E[x]>1

Phase diagram

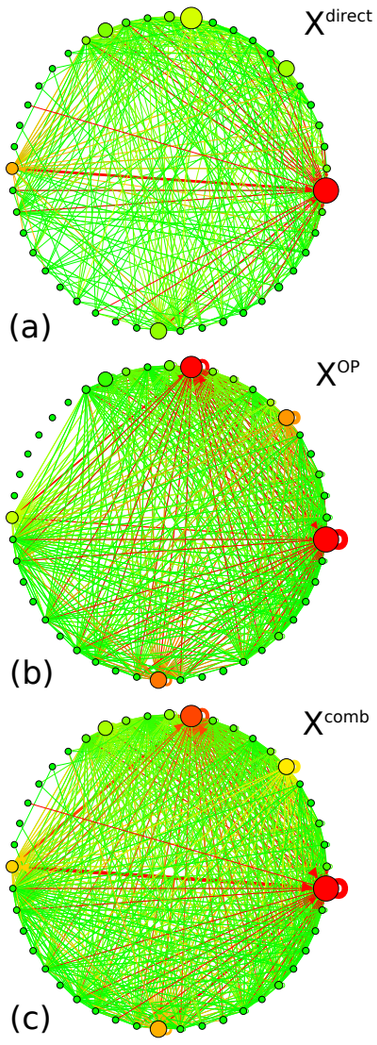


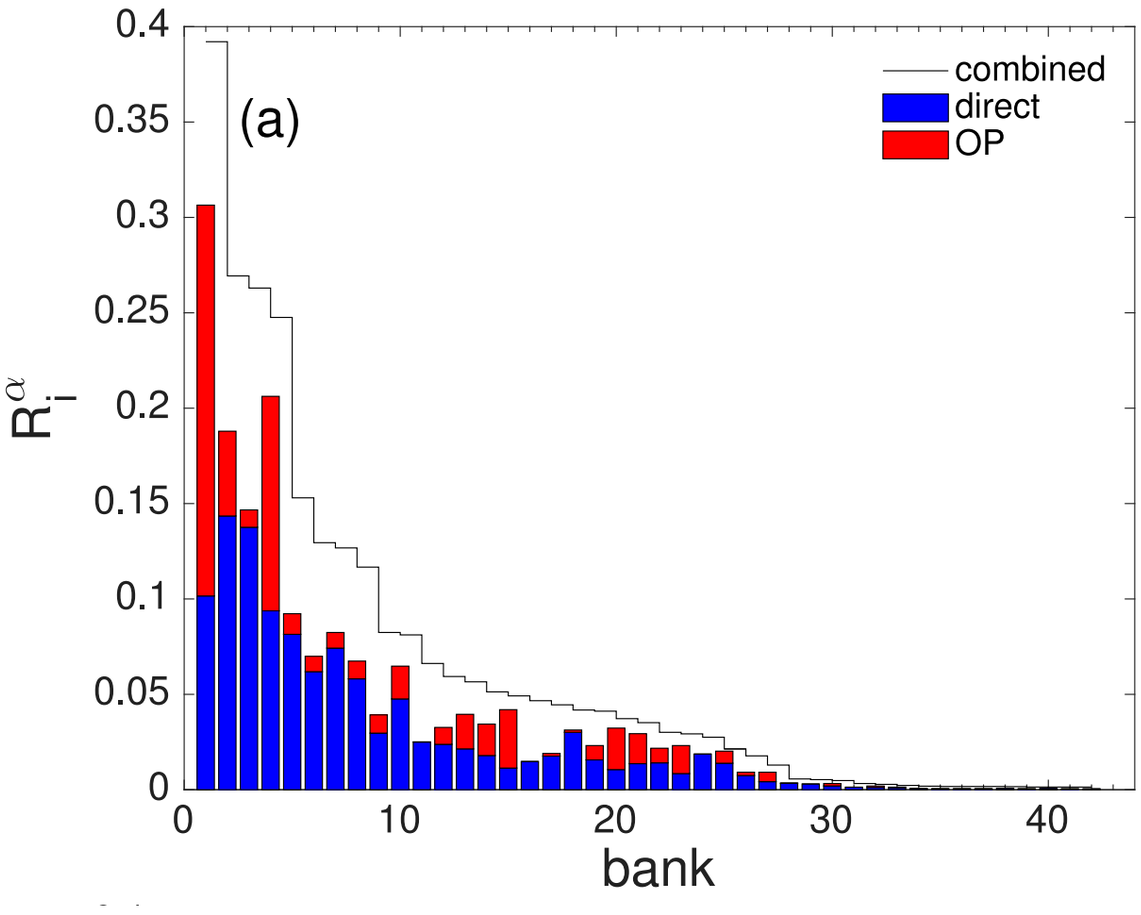


(Caccioli, Shrestha, Moore, Farmer 2014, JBF)

the system is stable if leverage is below a critical threshold

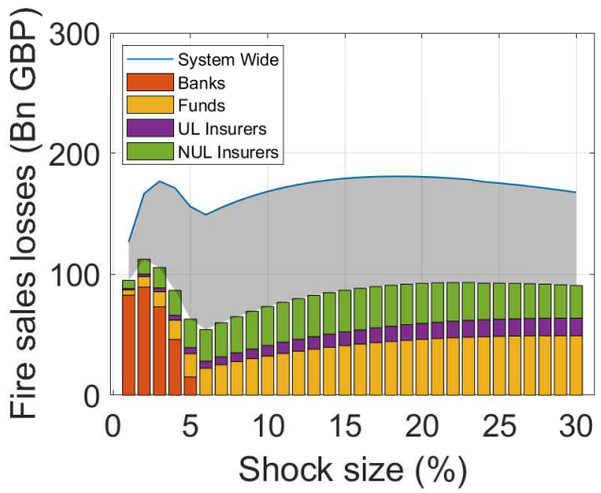
Combination of contagion mechanisms



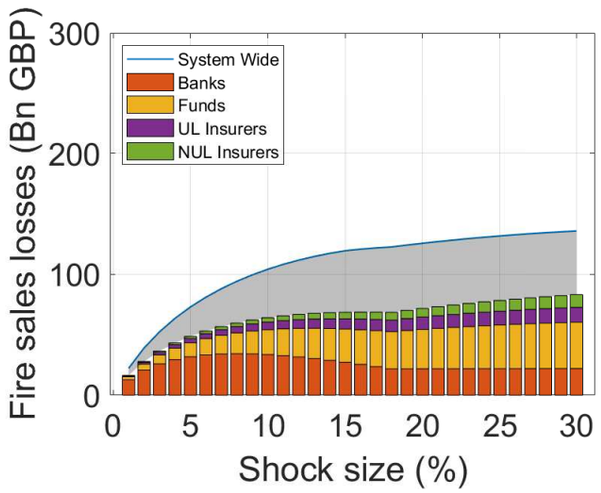


(Poledna Martinez-Jaramillo, Caccioli and Thurner 2021, Journal of Financial Stability)

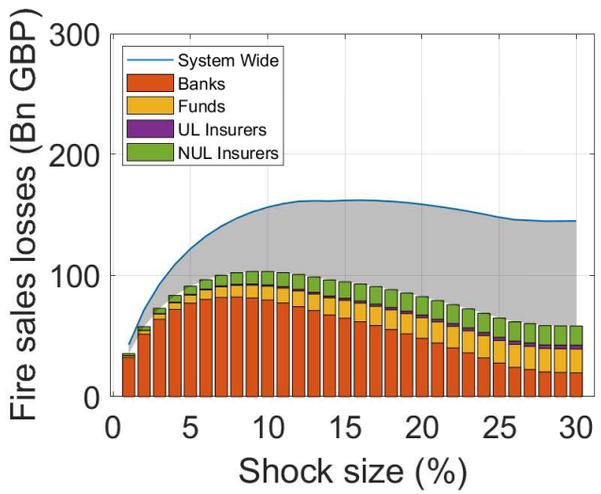
Multiple sectors



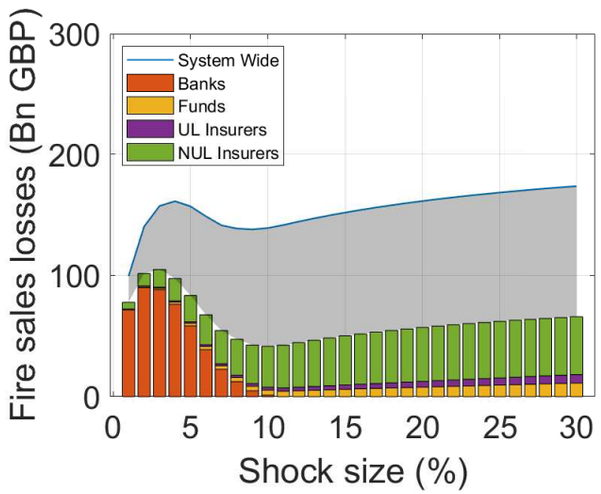
(a) Shock on all assets.



(b) Shock on all equities.



(c) Shock on all corporate bonds.



(d) Shock on all goverment bonds.

Caccioli, Ferrara and Ramadiah 2020, BoE Staff working paper 878

4.8 Roll-over risk

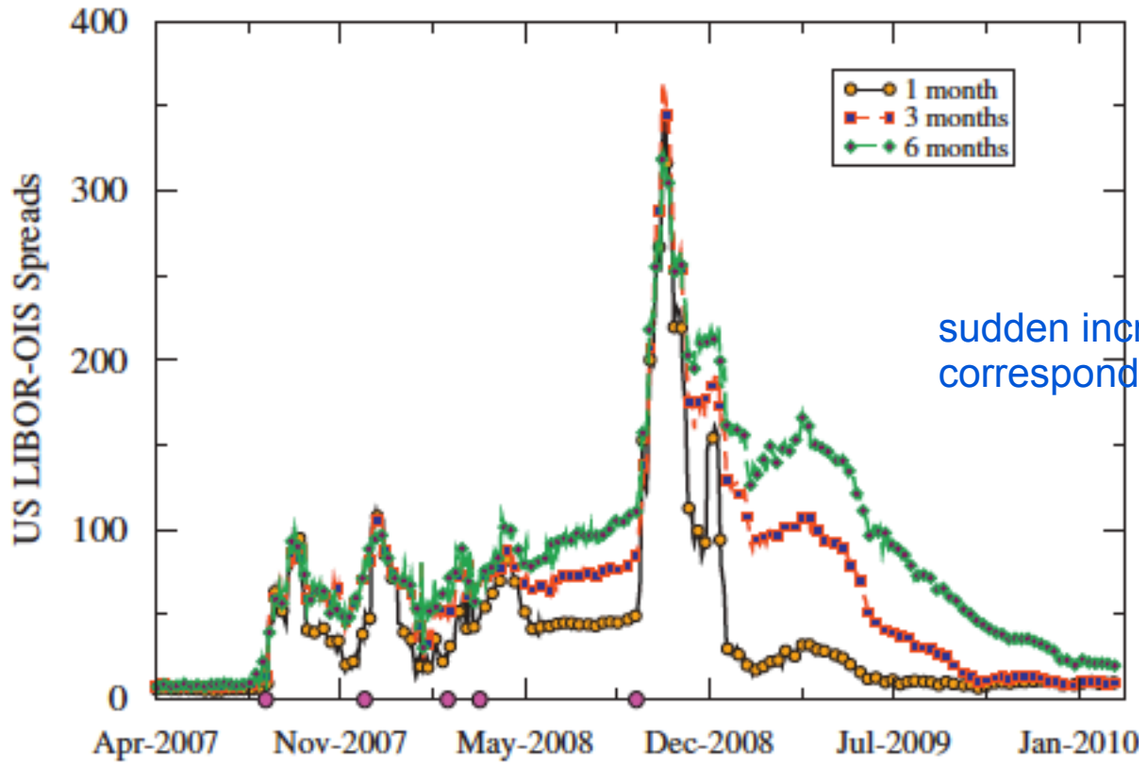
Roll-over risk

- We have looked so far at contagion due to solvency risk, either due to the default of counterparties or to the mark-to-market devaluation of assets

- In the case of counterparty default risk distress goes from the borrower to the lender

- Distress can however also travel from the lender to the borrower, this occurs because of the risk that creditors do not roll-over short-term debt

Interbank interest rate



sudden increases of spreads in correspondence with the arrival of news

Fig. 1. 1 month, 3 month and 6 month US LIBOR-OIS Rates, in basis points, during the financial crisis of 2007–2009. The circles on the time-axis highlight events, which on reading from left to right are: (i) 9 August 2007—BNP Paribas suspends calculation of asset values of three money market funds exposed to US sub-prime mortgages; (ii) 20 November 2007—Freddie Mac announces losses for the third quarter of 2007; (iii) 24 January 2008—Société Générale reveals trading losses resulting from fraudulent activities by a single trader; (iv) 13 March 2008—Bear Stearns files for bankruptcy, and (v) 15 September 2008—Lehman Brothers files for bankruptcy.

figure and caption from Anand et al, 2012

Foreclosure game

- Consider a bank with K depositors, each of which has invested 1$ in the bank
- Consider now a situation in which at a given date each depositor considers whether to withdraw or not their deposit The bank has a certain amount B of cash in its vault:
  - If less than B depositors withdraw, the bank does not default
  - otherwise the bank defaults
- Depositors who withdraw get their money back, but without an interest
- A depositor i who does not withdraw will get an interest rate r_i if the bank does not default, but will loose their investment if the bank defaults

should an investor withdraw or not?

Payoff matrix

	default	no default
withdraw	0	0
roll-over	-1	r_i

let's consider the following strategy:
rollover if $r_i > r^*$,
withdraw if $r_i < r^*$
can we compute r^*?

Indifferent investor

- Consider an investor for which $r_i=r^*$. This investor should be indifferent between withdrawing or rolling-over

- The expected profit of this investor is zero

- Let's denote by $F(K_w \leq B)$ the probability that there are less than B-1 other investors that withdraw

- Then r* must satisfy the equation $F(K_w \leq B)(1+r^*)=1$

Indifferent investor

- Let us consider the simple case in which the number of other investors that withdraw is distributed uniformly between 0 and K-1

- Then $F(K_w \leq B)=(B+1)/K$

- And $r^* = K/(B+1)-1$

Cost of miscoordination

- The payoff matrix can be written in the form

	default	no default
withdraw	0	0
roll-over	$-c_i$	$1-c_i$

- where c_i is the cost miscoordination
- in this case $c^*=(B+1)/K$

Summary

- Networks to model interactions between financial institutions

- DebtRank: accounting for credit quality deterioration

- Overlapping portfolios: stress propagates also without direct connections between banks

- Multi-layer: the interaction between layers matters