

# An agent-based model for bank formation, bank runs and interbank networks

Matheus R. Grasselli

Mathematics and Statistics - McMaster University  
Joint work with Omneia Ismail (McMaster)

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# The quest to understand banking crises

- Financial crises in the past 800 years encompass:

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- However, the principles that govern individual prudence do not necessarily apply to systems as a whole.
- Financial innovation and integration leads to highly interconnected, complex and potentially fragile banking systems.
- Systemic crises are essentially stories of contagion, interdependence, interaction and trust - Kirman (2010).

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- Consider also 40 emerging countries episodes (36 post and 4 pre-WWII).

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- Also the US in 2008 for comparison.

# Incidence of banking crises

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Region or group	Share of years in banking crises since independence or 1800	Number of banking crises
Africa	12.5	1.7
Asia	11.2	3.6
Europe	6.3	5.9
Latin America	4.4	3.6
North America	11.2	10.5
Oceania	4.8	2.0
Advanced economies	7.2	7.2
Emerging economies	8.3	2.8

Table: Reinhart and Rogoff (2009) - Table 10.5

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- Current account deficits/GDP increases prior to the crises
- Drop in real housing prices has 4 to 6 years duration.
- Drop in real equity prices has shorter duration (V-shaped recovery)
- Real GDP growth slows in years  $t - 3, t - 2, t - 1$ , stays near zero in  $t, t + 1, t + 2$  and positive again by  $t + 3$
- Real public debt increases on average by 86% by  $t + 3$

# Capital mobility and banking crises

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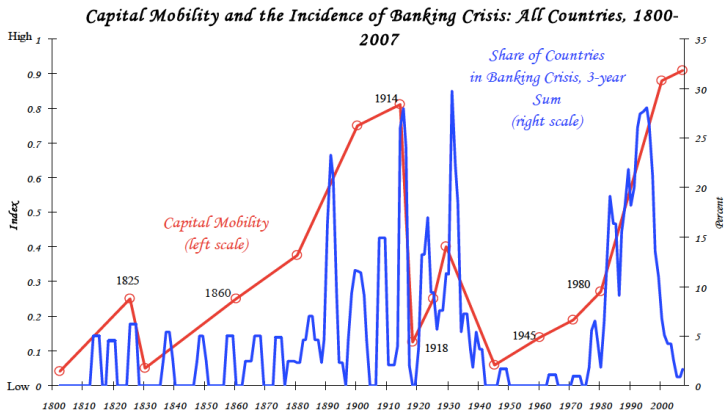


Figure: Reinhart and Rogoff (2009) - Figure 10.1

# Current account balance/GDP and banking crises in advanced economies (1945-2008)

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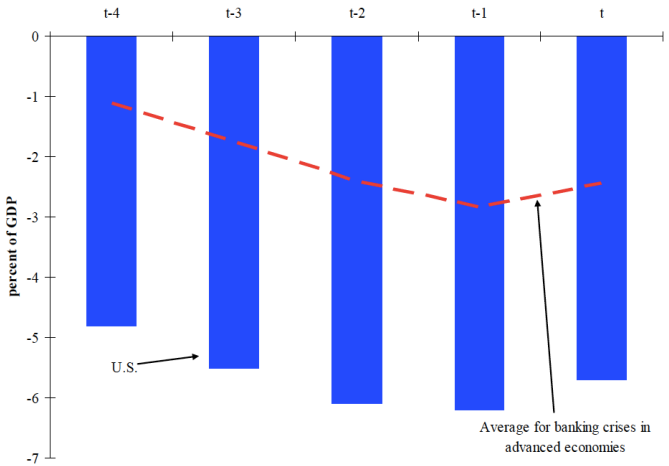


Figure: Reinhart and Rogoff (2009) - Figure 13.5

# Real housing prices and banking crises in advanced economies (1945-2008)

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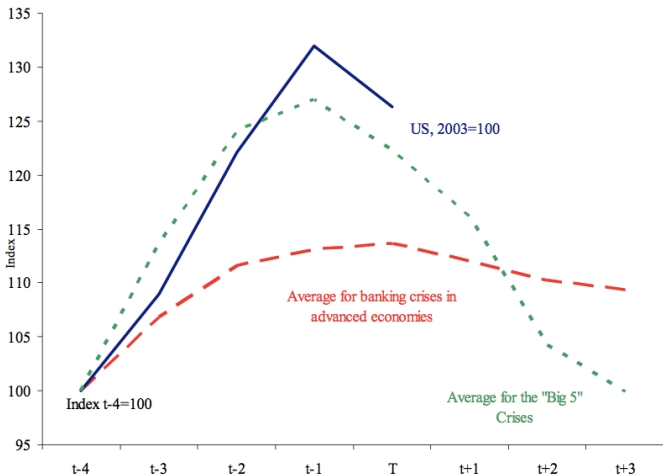


Figure: Reinhart and Rogoff (2009) - Figure 13.3

# Equity prices and banking crises in advanced economies (1945-2008)

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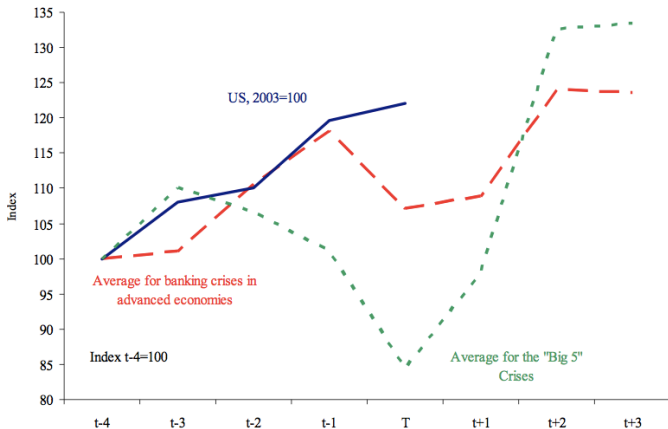


Figure: Reinhart and Rogoff (2009) - Figure 13.4

# Growth in real GDP per capita and banking crises in advanced economies (1945-2008)

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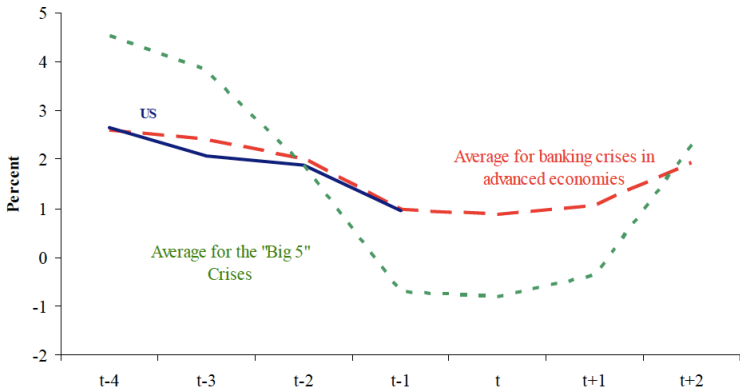


Figure: Figure 13.6 in RR



# Central government debt and banking crises in advanced economies (1945-2008)

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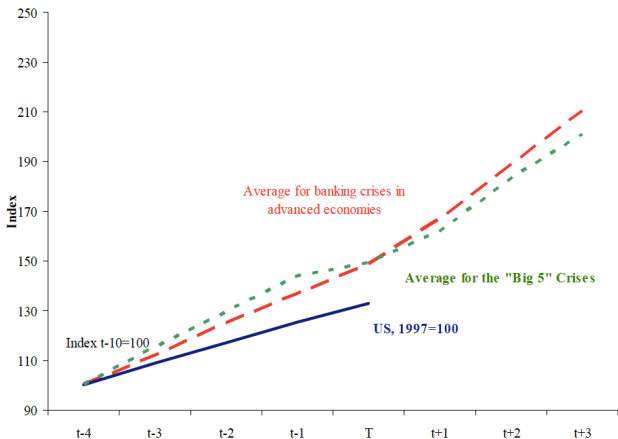


Figure: Reinhart and Rogoff (2009)- Figure 13.7

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- Seeks to explain the aggregate economy using theories based on strong microeconomic foundations.

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- Seeks to explain the aggregate economy using theories based on strong microeconomic foundations.
- Collective decisions of rational individuals over a range of variables for both present and future.
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- Money is neutral in its effect on real variables.
- Largely ignores uncertainty by simply subtracting risk premia from all risky returns and treat them as risk-free.

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- K. Arrow (1986): “In the aggregate, the hypothesis of rational behavior has in general no implications.”
- R. Solow (2006): “Maybe there is in human nature a deep-seated perverse pleasure in adopting and defending a wholly counterintuitive doctrine that leaves the uninitiated peasant wondering what planet he or she is on.”

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- Equilibrium is just one possible outcome, not assumed a priori.
- Dynamic reactions can modify both existing interactions and the structure of the links.



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- For example, an asset can pay  $1 \leq r_1 \leq r_2$  at dates  $T = 0, 1, 2$ .

# Liquidity preferences

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- Sufficiently risk-averse consumers prefer the liquid asset.

# Example: Diamond (2007)

- Let  $A = (r_1 = 1, r_2 = 2)$  represent an illiquid asset and  $B = (r_1 = 1.28, r_2 = 1.813)$  a liquid one.

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- By comparison, the expected utility from holding the liquid asset is

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- Observe, however, that risk-neutral investors would prefer the illiquid asset, since:

$$E[A] = 1.75 > 1.68 = E[B]$$

# Liquidity risk sharing with public information

- Consider an economy with dates  $T = 0, 1, 2$  and consumer preferences given by

$$U(c_1, c_2) = \begin{cases} u(c_1) & \text{with prob } \omega \\ u(c_2) & \text{with prob } 1 - \omega \end{cases} \quad (1)$$

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- Agents are endowed with one unit of the numeraire at time 0 and must decide either to hold it or to invest in an illiquid asset  $(1, R)$ .
- Denoting the consumption of agent of type  $i$  at time  $k$  by  $c_k^i$  the optimal risk sharing for *publicly* observed preferences is

$$c_1^2 = c_2^1 = 0 \quad (2)$$

$$u'(c_1^1) = Ru'(c_2^2) \quad (3)$$

$$\omega c_1^1 + (1 - \omega) \frac{c_2^2}{R} = 1 \quad (4)$$

# A model for banks - Diamond and Dybvig (1983)

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- However, liquidity preferences are private unverifiable information !

# A model for banks - Diamond and Dybvig (1983)

- However, liquidity preferences are private unverifiable information !
- Fortunately, the optimal solution satisfies the self-selection condition  $1 < c_1^1 < c_2^2 < R$ , which in turn implies that there is a contract that implements it as a Nash equilibrium.

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- Fortunately, the optimal solution satisfies the self-selection condition  $1 < c_1^1 < c_2^2 < R$ , which in turn implies that there is a contract that implements it as a Nash equilibrium.
- Suppose now that a bank offers a fixed claim  $r_1$  per unit deposited at time 0.

# A model for banks - Diamond and Dybvig (1983)

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- Denoting by  $f$  the total fraction of withdrawers, we see that  $r_1 = c_1^1$  and  $f = \omega$  is such equilibrium.
- However, it is clear that  $f = 1$  (run) is also an equilibrium.

- Consider  $N$  heterogeneous agents with liquidity preferences at times  $t_k$  given by independent uniform random variables  $\omega^i$  on  $[0, 1]$ : if  $\omega^i < p$ , agent  $i$  is said to be of type 1 (impatient), otherwise it is said to be of type 2 (patient).

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- At  $t_{k+1}$ , define

$$\tilde{\omega}_k^i = \omega^i + (-1)^{b_k^i} \frac{\varepsilon_k^i}{2}, \quad (5)$$

where  $b_k^i \in \{0, 1\}$  are Bernoulli random variables and  $\varepsilon_k^i$  are uniformly distributed on  $[0, 1]$ . Setting  $q = 2p - 1/2$ , agent  $i$  is then deemed to be impatient if  $\tilde{\omega}^i < q$  and patient otherwise.

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- Because of anticipated shocks, individuals explore the society searching to partners to exchange investments.

- We impose some constraints on the individual capacity to go around and seek other individuals to trade.



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- This reflects the inherited limited capability of information gathering and environment knowledge of individual agents.

- We impose some constraints on the individual capacity to go around and seek other individuals to trade.
- This reflects the inherited limited capability of information gathering and environment knowledge of individual agents.
- We use a combination of Von Neumann and Moore neighborhood:

5	1	6
2	X	3
7	4	8

# Matching example

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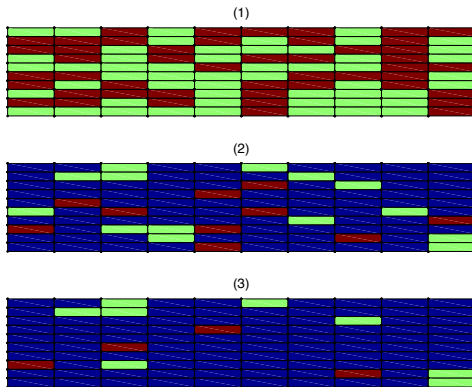


Figure: Society, preference shock, and search for partners.

- We follow the inductive reasoning proposed by Arthur (2000) for individuals with bounded rationality dealing with complex environments.

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- We follow the inductive reasoning proposed by Arthur (2000) for individuals with bounded rationality dealing with complex environments.
- We assume agents make predictions using a memory of 5 periods.

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# Inductive reasoning

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- We assume agents make predictions using a memory of 5 periods.
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  - 7 Today would be the same as the mode for the last five periods.

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- Each predictor makes one of the following forecasts:

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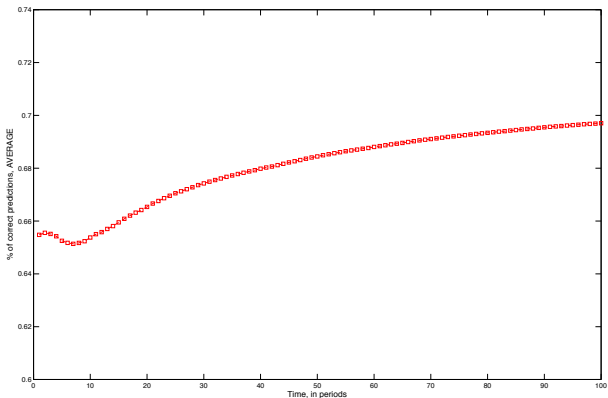
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- Each predictor makes one of the following forecasts:
  - 1 N = agent will not need a partner
  - 2 G = agent will need a partner and will find one
  - 3 B = agent will need a partner and will not find one
- Depending on the realized outcome, a predictor's strength gets updated by

$$\Delta S = \begin{cases} +1 & \text{if the forecast is correct} \\ -1 & \text{if the forecast is incorrect} \end{cases}$$

# Learning simulation

We use 400 persons over a time span of 100 periods in a simulation with 100 realizations:



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# To join or not to join a bank

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- Suppose that agents need to decide between the liquid asset  $(1, 1)$ , the illiquid asset  $(r < 1, R > 1)$  or joining the bank and receiving  $(c_1 > 1, c_2 < R)$ .

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- Suppose that agents need to decide between the liquid asset  $(1, 1)$ , the illiquid asset  $(r < 1, R > 1)$  or joining the bank and receiving  $(c_1 > 1, c_2 < R)$ .
- For example, an agent who current has late preferences might have the following payoff table:

	forecast	strength	payoff (join)	payoff (not join)
1	N	-2	$c_2$	R
2	G	0	$c_1$	1
3	N	+1	$c_2$	R
4	B	-1	$c_1$	r
5	G	+1	$c_1$	1
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- The decision is based on the weighted sum of payoffs.

- We follow the work of Howitt and Clower (1999, 2007) on the emergence of economic organizations.

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- The bank is established if there are  $x_k^i$  and  $y_k^i$  such that  $x_k^i + y_k^i \leq 1$  and

$$y_k^i = c_1 W_k^i$$

$$R x_k^i = c_2 (1 - W_k^i),$$

where  $(c_1, c_2)$  is the promised consumption.

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- Individuals become aware of bank existence only if the bank lies in their neighbourhood
- In addition we give the bank the reach of its new members

# Experiment: bank formation

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# Experiment (continued): established banks

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Day 100

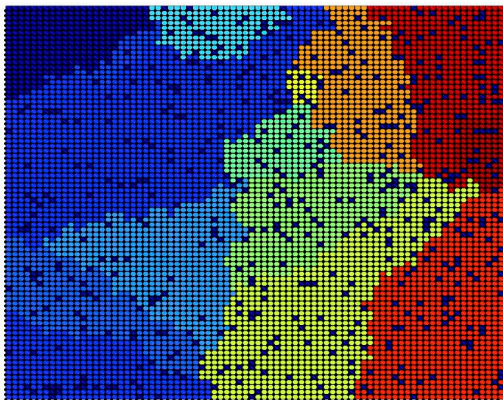


Figure: Banks at  $T=100$  with  $c_1 = 1.1$ ,  $c_2 = 1.5$  and  $R = 2$

# Experiment (continued): number of depositors

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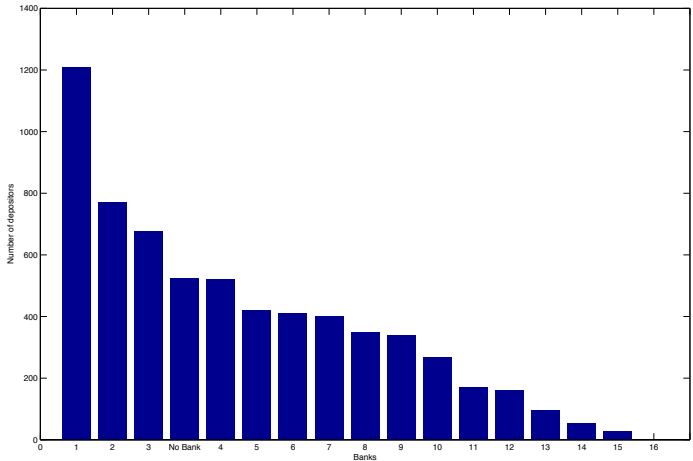
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- We say that a bank is subject to a run if late consumers receive less than  $c_1$  at the end of the period.
- If a bank survives at period  $k$ , it updates the estimate of early consumers according to

$$W_{k+1}^i = W_k^i + \alpha(\bar{W}_k^i - W_k^i) \quad (6)$$

reflecting adaptation through a parameter  $\alpha \in (0, 1)$ .

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# Experiment: established banks (with possible runs)

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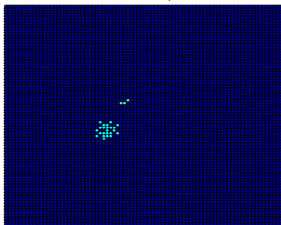
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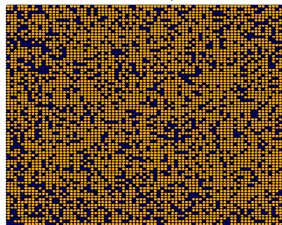
Bank runs

Interbank networks

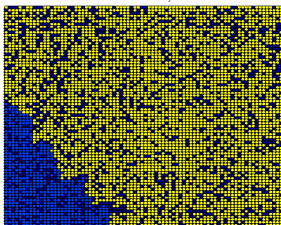
Banks in Society



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- In addition, they deem the estimate to be adequate if the fraction of reserves lost in a given period is less than a certain threshold.
- They use the same set of predictors as clients to forecast the adequacy of their estimates as being 'adequate', 'inadequate' or 'undetermined'.
- Banks with inadequate or undetermined estimates have an incentive to exchange deposits with other banks and try to protect their reserves.

# Experiment: adequacy of estimates through time

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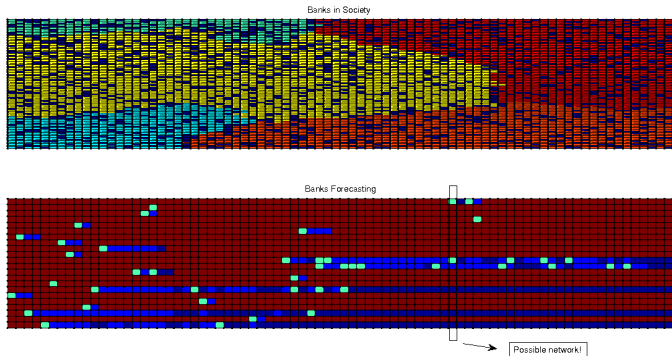


Figure: Banks at  $T=100$  with  $c_1 = 1.1$ ,  $c_2 = 1.5$  and  $R = 2$  and adequacy of estimates over time.

# Experiment: possible network

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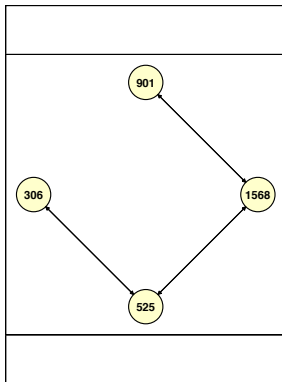


Figure: Snapshot of possible interbank loans

# Number of established banks with and without interbank links

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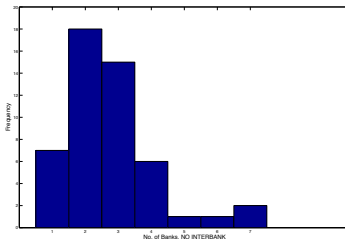
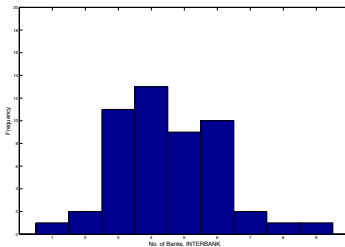
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  - 2 Choose the largest reach  $M$  around the base
  - 3 Randomly select  $2M^2$  cells around the base to form a community
  - 4 Alter half of the communities to early preferences and half of the communities to late preferences.

# Examples of correlated liquidity shocks

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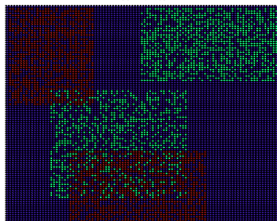
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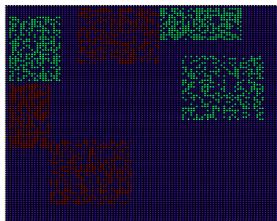
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Communities



Communities





# Experiment: bank formation and runs with correlated shocks

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# Experiment: adequacy of estimates through time (with correlated shocks)

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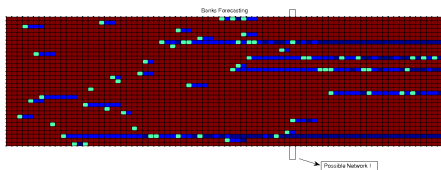
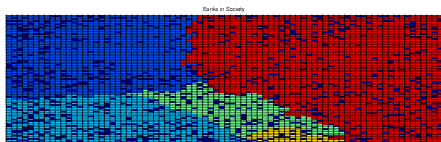


Figure: Banks at  $T=100$  with  $c_1 = 1.1$ ,  $c_2 = 1.5$  and  $R = 2$  and adequacy of estimates over time.

# Number of established banks under correlated shocks

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Banking crises throughout history

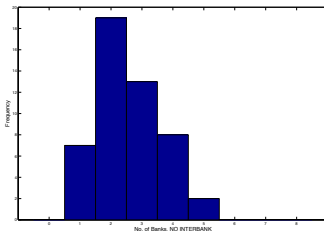
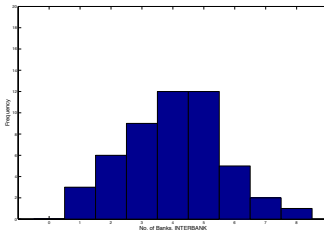
DSGE x ABM

The pre-banking society

Bank formation

Bank runs

Interbank networks



An agent-based model for bank formation, bank runs and interbank networks

Matheus R. Grasselli

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# Concluding remarks

- We modelled individual liquidity preferences in a society.
- Changes in preferences lead agents to search for trading partners.
- Banks arise as providers of liquidity, but are inevitably subject to possible runs.
- Interbank loans redistributed the effect of correlated liquidity shocks across the society.

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- Banks arise as providers of liquidity, but are inevitably subject to possible runs.
- Interbank loans redistributed the effect of correlated liquidity shocks across the society.
- Ultimately want to adjust model parameters to reproduced different observed networks and use it as a testbed for policy implications.