Cybersecurity and financial stability

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\textsuperscript{a}This paper represents the authors’ personal opinions and does not necessarily reflect the views of the Deutsche Bundesbank or the Financial Markets Authority of New Zealand.
Two observations

- Digital transformations of banks gathering pace...

The Sum of Bank IT Spending Across North America, Europe, Asia-Pacific, and Latin America Will Grow to US$309 billion by 2022

Classification of cyber attacks

Recent examples
Two observations

- Digital transformations of banks gathering pace ..

- ... but so too are cyber attacks on financial institutions
Our research agenda

- **Kashyap and Wetherilt (2019)** emphasise the role of shared services (e.g., digital platform) in creating common vulnerabilities that amplify cyber shocks.

- **Duffie and Younger (2019)** argue that cyber attacks can morph into wholesale bank runs.

- **Eisenbach et al (2021)** estimate there to be negative spillovers in wholesale funding markets following a cyber attack on a large U.S. based bank.
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- **Eisenbach et al (2021)** estimate there to be negative spillovers in wholesale funding markets following a cyber attack on a large U.S. based bank.

- **Our paper**: theoretical model of cybersecurity and financial stability.

  - **Key message**
    - Cybersecurity is a public good = \[
      \begin{align*}
        \text{Free riding problem} & \downarrow \\
        \text{Rollover risk} & \uparrow
      \end{align*}
    \]
Our model

- Banks own safe legacy assets funded by equity and debt (subject to runs)
- IT infrastructure (software / hardware) required to manage assets
  - Outsourced to a ‘platform’ that serves multiple banks
  - But, the platform has a vulnerability that can be exploited using malicious code to cause outages (e.g., Stuxnet exploited vulnerabilities in industrial control systems)
  - Attackers must deploy their code in banks’ systems that interface with the platform
- Banks have initial endowments and choose how much to invest in
  - Cybersecurity (public good) → monitor and repel unauthorised intrusions
  - Operational resilience (private good) → backup systems to mitigate outages
The ‘cyber’ ingredients

- Cybersecurity is a **weakest-link public-good** (Varian, 2004)
  - Platform correlates cyber risks (Lipp et al., 2018, Canella et al., 2019).
  - Draw on Cornes (1993) in modelling cybersecurity as a “weaker-link” public good – positive externalities, and higher marginal product for lower investment levels.

- Three elements of cyber attacks
  - Attack intensity is uncertain → ‘attribution problem’ (Hayden, 2011)
  - Cause outages that temporarily suspended operations (Cloudflare, 2021)
  - Generate long-lasting damages for victims (Lewis et al., 2020)

- Disruptions mitigated through investments in operational resilience (e.g., data vaults, resilience planning), which is a private good

- Sheltered Harbor is a certification for banks that implement robust safeguards
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Related Literature


Model
Environment and agents

\[ \chi = \left( S_i S_j \right)^{1/2} \]

Platform

i: endowment \( W_i \)

\[ I = D + E \]

\[ D = 1 - E \]

\[ E > 0 \]

j: endowment \( W_j \)

\[ I = D + E \]

\[ D = 1 - E \]

\[ E > 0 \]

Safe investment Return \( R > 1 \); Face value of debt \( F > 0 \)
Investment decisions \((t = 0)\)

Bank i's investment in cybersecurity

\[ \chi = \left( S_i S_j \right)^{1/2} \]

Platform

Digital services required

Bank i's investment in operational resilience

i: endowment \(W_i\)

\[ I = D + E \]

E > 0

Digital services required

Bank j's investment in cybersecurity

j: endowment \(W_j\)

\[ I = D + E \]

E > 0

Safe investment Return \(R > 1\); Face value of debt \(F > 0\)
Investment decisions ($t = 0$)

- Digital services required
- Safe investment Return $R > 1$; Face value of debt $F > 0$
Cyber attack and disruption to the platform ($t = 1$)

If $\ell_b \in (0, 1)$ of debt is withdrawn, bank $b$ fails due to illiquidity whenever

$$
R \left( 1 - \alpha (1 - h(O_b)) \right) - \ell_b F D < 0
$$
Rollover decisions

- Attack intensity: $\lambda \in [0, \bar{\lambda}]$

- Outage shock: $\alpha \in [0, 1]$

- Rollover decisions delegated to fund managers ([Rochet and Vives, 2004])
  - Fund managers’ ‘conservatism’, $\gamma \leq 1 \rightarrow$ measure of rollover risk
  - Larger $\gamma \rightarrow$ greater incentives to withdraw

- Fund manager $k$ (bank $b$) receives a noisy private signal

$$x_{bk} = \alpha + \varepsilon_k,$$

with $\varepsilon_k \in [-\varepsilon, \varepsilon]$; withdraw decision based on the signal
Platform resumes operations and debts mature \((t = 2)\)

Bank \(b\) fails due to *insolvency* whenever
\[
R \left( 1 - \alpha \delta (1 - h(O_b)) \right) - \ell_b FD < (1 - \ell_b) FD
\]
Equilibrium
Focus on threshold strategies

- Fund manager $k$ rolls over debt with bank $b$ whenever $x_{bk} < x^*_b$

Equilibrium consists of

- At $t = 1$: given choices $(O^*_b, S^*_b)$ the threshold strategy $x^*_b$ maximises fund managers expected payoff and the bank fails whenever $\alpha > \alpha^*_b$ following a successful cyber attack

- At $t = 0$: given $(x^*_b, \alpha^*_b)$, bank $b$ chooses $(O^*_b, S^*_b)$ to maximise expected equity value given the budget constraints, and the choices of the other bank
Bank failure

- **Illiquidity** threshold: $\alpha_{IL}^{LB}(\ell_b) \equiv \frac{R-\ell_bFD}{R(1-h(O_b))}$
- **Insolvency** threshold: $\alpha_{IN}^{LB} \equiv \frac{R-\ell_bFD}{R\delta(1-h(O_b))}$
Bank failure

- **Illiquidity** threshold: \( \alpha^L_b(\ell_b) \equiv \frac{R-\ell_bFD}{R(1-h(O_b))} \)

- **Insolvency** threshold: \( \alpha^I_b \equiv \frac{R-FD}{R\delta(1-h(O_b))} \)
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- **Illiquidity** threshold: $\alpha_b^{IL}(\ell_b) \equiv \frac{R-\ell_bFD}{R(1-h(O_b))}$

- **Insolvency** threshold: $\alpha_b^{IN} \equiv \frac{R-FD}{R\delta(1-h(O_b))}$
Outage shocks and bank fragility

Proposition

There exist a unique failure threshold:

\[ \alpha_b^* = \begin{cases} 
\alpha_b^{IN} & \text{if } \gamma < \hat{\gamma} \\
\alpha_b^{IL}(\gamma) & \text{if } \gamma \geq \hat{\gamma}
\end{cases} \]

- Funding conditions matter: illiquidity risk arises only when \( \gamma \) is large
- Greater investment in cybersecurity increases fragility
Optimal investment choices

- Bank $b$ chooses its investments in cybersecurity and operational resilience
  - Maximise expected equity value, $\pi_b$
  - Taking as given the investment by other banks, $\vec{S}_{-b}$

\[
\max_{O_b, S_b} \pi_b \equiv \text{Probability cyber attack fails} \times \text{Equity value}
\]

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\text{Probability cyber attack fails} \times \text{Equity value}
\]

\[
\text{Probability cyber attack successful} \times \text{Equity value depending on outage}
\]

where $EV_2(\alpha, O_b) = R(1 - \alpha \delta(1 - h(O_b))) - FD$, and $O_b + S_b = W_b$
Optimal investment choices

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\text{Probability cyber attack fails} & \text{Equity value} \\
\text{Probability cyber attack successful} & \text{Equity value depending on outage}
\end{cases} \\
\text{Prob} \left( \lambda \leq \chi(S_b, \vec{S}_{-b}) \right) \times \left[ R - FD \right] + \text{Prob} \left( \lambda > \chi(S_b, \vec{S}_{-b}) \right) \times \int_0^{\alpha^*_b(O_b)} EV_2(\alpha, O_b) d\alpha
\]

where \( EV_2(\alpha, O_b) = R(1 - \alpha \delta(1 - h(O_b))) - FD \), and \( O_b + S_b = W_b \)

- Trade-off
  - Investing more in cybersecurity reduces the incidents of successful cyber attacks and thereby the likelihood of earning higher returns
  - But, conditional on the cyber attack being successful the bank is more fragile and susceptible to failing the more it invests in cybersecurity
Benchmark 1: No free-riding problem and no rollover risk

- Planner accounts for how each banks’ decisions influence other banks

- When $\gamma < \hat{\gamma}$, failure driven by insolvency: failure threshold $\alpha_b^{IN}$

- **Samuelson Condition**

  $\sum_{b=1}^{N} \left\{ \frac{(R - FD) - \int_{0}^{\alpha_b^{IN}} EV_2(\alpha, O_b) d\alpha}{(\bar{\lambda} - \chi) \int_{0}^{\alpha_j^{IN}} \left( \frac{\partial EV_2}{\partial O_j} \right) d\alpha} \right\} \equiv \partial \pi_b / \partial \chi = \frac{1}{\partial \chi / \partial S_j}.$

- Free-riding leads to under-provision of cybersecurity
Benchmark 2: No free-riding problem but with rollover risk

- When $\gamma \geq \hat{\gamma}$ → failure driven by illiquidity; failure threshold $\alpha_b^{IL}(\gamma)$

- **Samuelson Condition**

\[
\sum_{b=1}^{N} \frac{1}{N} \left( \bar{\lambda} - \chi \right) \left[ EV_2(\alpha_b^{IL}(\gamma)) \frac{\partial \alpha_b^{IL}(\gamma)}{\partial O_j} + \int_{0}^{\alpha_b^{IL}(\gamma)} \left( \frac{\partial EV_2}{\partial O_j} \right) d\alpha \right] = \frac{1}{\partial \chi / \partial S_j}.
\]

- **Two effects of rollover risk on marginal rate of substitution**
  1. MB from an extra unit of cybersecurity is higher ($\alpha_b^{IL}(\gamma) < \alpha_b^{IN}$)
  2. MB from higher operational resilience is also higher (since run is ‘inefficient’)

- First effect dominates → over-provision of cybersecurity (relative to Benchmark 1)
Assume $\gamma \geq \hat{\gamma}$ → failure driven by illiquidity

**Proposition**

Bank $b$'s investments, $(S^*_b, O^*_b)$, given beliefs $(\vec{S}^e_{-b}, \vec{O}^e_{-b})$, solves:

$$\frac{\partial \pi_b}{\partial \chi} = \frac{1}{\frac{\partial \chi}{\partial S_b}}.$$  

*Cybersecurity investment is increasing in the endowment, $\partial S^*_b / \partial W_b > 0$, iff $W_b \leq \hat{W}$.***

- Two countervailing effects from an increase in $W_b$
  1. Mechanical increase in $O_b$ (for given $S_b$) → reduces MRS
  2. Diminishing returns from investing in operational resilience → increases MRS

- Second effect dominates when $W_b \leq \hat{W}$

- But, what are the consequences on the system level?
System-wide equilibrium

Proposition

There exist two Nash equilibria: all banks, \( b = 1, \ldots, N \)
(i) invest nothing in cybersecurity, \( S_b^* = 0 \), and \( O_b^* = W_b \) in operational resilience;
(ii) invest \( S_b^* \in (0, W_b) \) in cybersecurity and \( O_b^* = W_b - S_b^* \) in operational resilience.

\[ \text{Proposition} \]

Suppose \( W_1 < \hat{W} < W_2 \). Following a mean-preserving spread increase in banks’ endowments, equilibrium cybersecurity, \( \chi^* = (S_1^* \times S_2^*)^{1/2} \), is reduced.
Normative implications
Normative implications

- Compare laissez faire outcome with Benchmark 1

\[ \text{Proposition} \]

There exists a critical \( \gamma_c \), such that for \( \gamma \leq \gamma_c \), there is under-investment in cybersecurity, \( S^*_b < S^*_P \); while, for \( \gamma > \gamma_c \), there is over-investment, \( S^*_b > S^*_P \).

For small \( \gamma \rightarrow \) run risk is low \( \rightarrow \) weak incentives to invest in cybersecurity

\( \Rightarrow \) compared with Benchmark 1, free-riding exerts a stronger influence \( \rightarrow \) under-investment in cybersecurity and under-provision of the public good

For larger \( \gamma \rightarrow \) run risk is higher \( \rightarrow \) stronger incentives to invest in cybersecurity

Benchmark not impacted by rollover risk \( \rightarrow \) influence of rollover risk dominates \( \rightarrow \) over-investment in cybersecurity and a too low operational resilience.
Normative implications

- Compare laissez faire outcome with Benchmark 1

**Proposition**

There exists a critical $\gamma_c$, such that for $\gamma \leq \gamma_c$, there is under-investment in cybersecurity, $S_b^* < S_b^P$; while, for $\gamma > \gamma_c$, there is over-investment, $S_b^* > S_b^P$.

- For small $\gamma$ → run risk is low → weak incentives to invest in cybersecurity
  ∴ compared with Benchmark 1, free-riding exerts a stronger influence → under-investment in cybersecurity and under-provision of the public good

- For larger $\gamma$ → run risk is higher → stronger incentives to invest in cybersecurity
  Benchmark not impacted by rollover risk → influence of rollover risk dominates → over-investment in cybersecurity and a too low operational resilience.
Normative implications ($\gamma < \gamma^C$)

- Benchmark outcome can be achieved by
  1. Imposing at $t = 0$ banks invest optimally (e.g., stress-tests)
  2. Penalising banks at $t = 2$ that did not exhibit 'due care' following a cyber attack (e.g., recent SEC penalties on financial institutions)
Testable hypotheses
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Prediction

An increase in intensity of cyber attacks reduces relative investment in cybersecurity.

- \( \lambda \uparrow \rightarrow \) given \( \chi \), more likely that security is breached leading to outages and disruptions \( \rightarrow \) MRS decreases \( \rightarrow \) less investment in cybersecurity
Testable hypotheses

**Prediction**

An increase in intensity of cyber attacks reduces relative investment in cybersecurity.

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**Prediction**

An increase in bank capital reduces investment in cybersecurity.

- \( E \uparrow \rightarrow \) banks have more to lose if they fail following a successful cyber attack \( \rightarrow \) MRS decreases \( \rightarrow \) less investment in cybersecurity
**Prediction**

*An increase in intensity of cyber attacks reduces relative investment in cybersecurity.*

- $\tilde{\lambda} \uparrow \rightarrow$ given $\chi$, more likely that security is breached leading to outages and disruptions $\rightarrow$ MRS decreases $\rightarrow$ less investment in cybersecurity

**Prediction**

*An increase in bank capital reduces investment in cybersecurity.*

- $E \uparrow \rightarrow$ banks have more to lose if they fail following a successful cyber attack $\rightarrow$ MRS decreases $\rightarrow$ less investment in cybersecurity

**Prediction**

*The more banks are subject to rollover risk, the more they invest in cybersecurity.*

- $\gamma \uparrow \rightarrow$ MRS increases $\rightarrow$ more investment in cybersecurity
We develop a model to study cybersecurity and financial stability
- Common IT infrastructure correlate risks across banks
- Cybersecurity is a weakest-link public good

Investment in cybersecurity trades-off lowering the probability of a successful cyber attack and raising fragility in the event of a successful attack

Laissez faire outcome is constrained inefficient $\rightarrow$ role for regulation/supervision of cybersecurity

Several testable implications for investment in cybersecurity (go through even after endogenising face value of debt)
Conclusion

- We develop a model to study cybersecurity and financial stability
  - Common IT infrastructure correlate risks across banks
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- Investment in cybersecurity trades-off lowering the probability of a successful cyber attack and raising fragility in the event of a successful attack

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Thank you!
Classification of cyber events

- Federal Information Security Management Act of 2002
Classification of cyber events

- Federal Information Security Management Act of 2002

- **Confidentiality** of data is breached
  - Losses may stem from liability due to damages caused to customers or from competitors learning about a bank’s trading strategies

- **Availability** of data is compromised
  - Losses may stem from bank capital or liquidity becoming immobilised

- **Integrity** of data is impaired
  - Losses may stem from inability to perform core activities
Recent attacks on financial institutions

- Europe & South-East Asia (May 2021): Insurance firm AXA subject to ransomware attack → integrity of data processed by a third-party IT firm compromised

- Hungary (September 2020): Telecommunications systems suffered DDoS attack → availability of data and services compromised for banks

- New Zealand (August 2020): Network provider suffered DDoS attack → NZ Stock Exchange shut down operations → availability of data and services compromised for banks
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**Key ingredient**
- Disruptions involved common IT infrastructure (platforms)