# Cybersecurity and financial stability[a]

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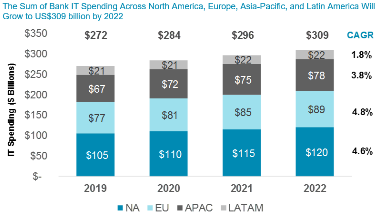
[a]This paper represents the authors' personal opinions and does not necessarily reflect the views of the Deutsche Bundesbank or the Financial Markets Authority of New Zealand.

# Two observations

- Digital transformations of banks gathering pace ..



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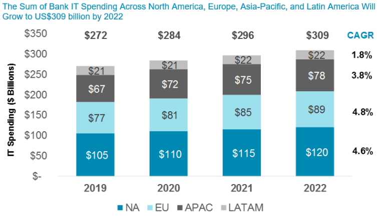
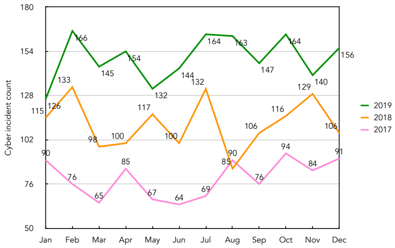



- … but so too are cyber attacks on financial institutions




Classification of cyber attacks
Recent examples

# 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** $= \begin{cases} \text{Free riding problem} & \downarrow \\ \text{Rollover risk} & \uparrow \end{cases}$

# 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) $\rightarrow$ monitor and repel unauthorised intrusions
  - **Operational resilience** (private good) $\rightarrow$ 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

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- 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)

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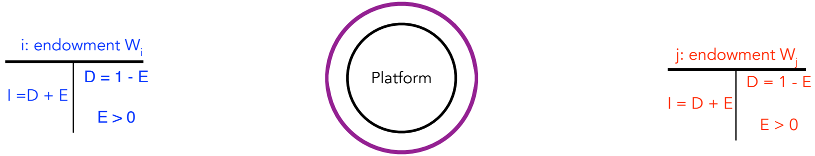
  - Generate **long-lasting damages** for victims (Lewis et al., 2020)
- Disruptions mitigated through investments in **operational resilience** (e.g., data vaults, resilience planning), which is a **private good**
  - Sheltered Harbor is a certification for banks that implement robust safeguards

# Related Literature

- Investment in cybersecurity (theory): Gordon and Loeb (2002), Varian (2004), Anderson and Moore, (2006), Grossklag et al (2008), Kamhoua et al (2014)
- Investment in cybersecurity (empirical): Aldasoro et al (2020), Gogolin et al (2021), Jamilov et al (2021)
- Cybersecurity and financial stability: Kashyap and Wetherilt (2019), Duffie and Younger (2019), Eisenbach et al (2021)

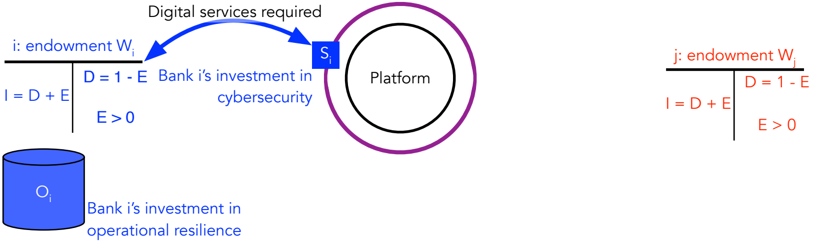
# Model

# Environment and agents




Safe investment Return R>1; Face value of debt F>0

# Investment decisions ($t = 0$)

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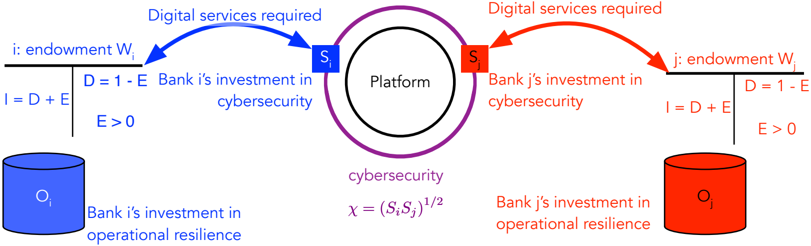
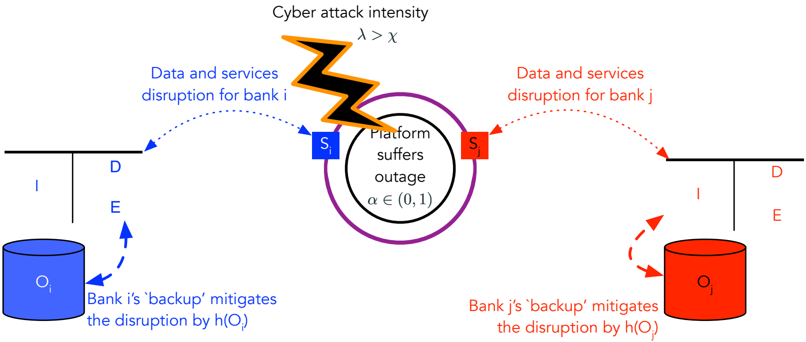



Safe investment Return R>1; Face value of debt F>0

# 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 $R\Big(1 - \alpha\big(1 - h(O_b)\big)\Big) - \ell_b FD < 0$

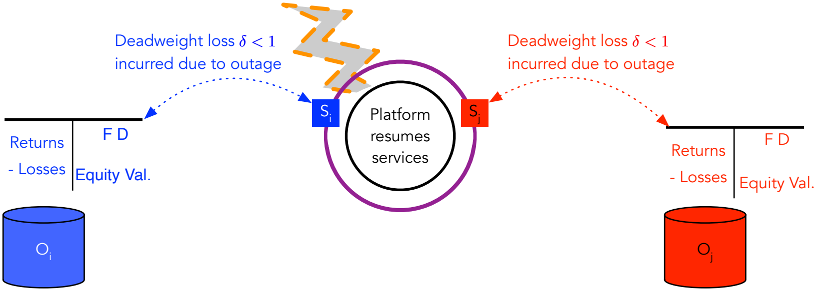
# Rollover decisions

- 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 $R\Big(1 - \alpha\delta\big(1 - h(O_b)\big)\Big) - \ell_b FD < (1 - \ell_b)FD$

# Equilibrium

# Symmetric pure strategy PBE

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

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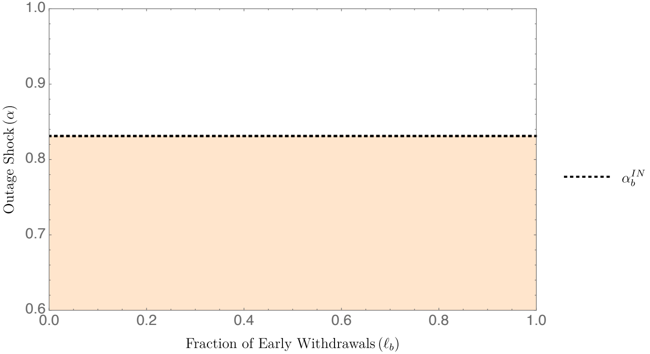

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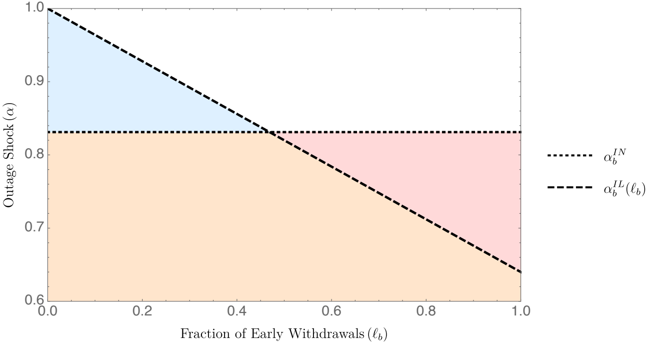

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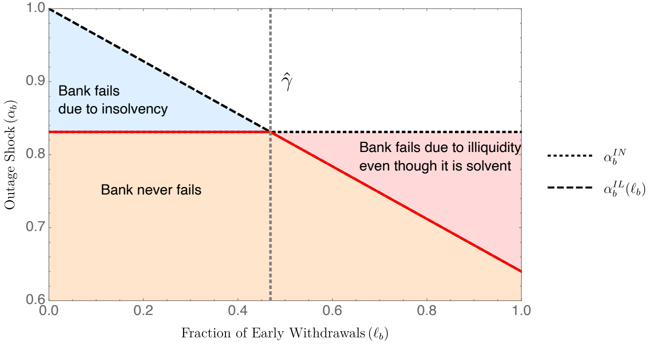

# Outage shocks and bank fragility

**Proposition**

*There exist a unique failure threshold:*

$$\alpha_b^* = \begin{cases} \alpha_b^{IN} & \text{if} \quad \gamma < \widehat{\gamma} \\ \\ \alpha_b^{IL}(\gamma) & \text{if} \quad \gamma \geq \widehat{\gamma} \end{cases}.$$

- 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 the investment by other banks, $\vec{S}_{-b}$

$$
\begin{aligned}
\max_{O_b, S_b} \pi_b \quad \equiv \quad & \overbrace{\text{Prob}\left(\lambda \leq \chi(S_b, \vec{S}_{-b})\right)}^{\text{Probability cyber attack fails}} \times \overbrace{[R - F\,D]}^{\text{Equity value}} \\
+ \quad & \underbrace{\text{Prob}\left(\lambda > \chi(S_b, \vec{S}_{-b})\right)}_{\text{Probability cyber attack successful}} \times \underbrace{\int_0^{\alpha_b^*(O_b)} EV_2(\alpha, O_b) d\alpha}_{\text{Equity value depending on outage}}
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where $EV_2(\alpha, O_b) = R(1 - \alpha\,\delta(1 - h(O_b)) - F\,D$, and $O_b + S_b = W_b$

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- **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 $\gamma < \widehat{\gamma}$, failure driven by insolvency: failure threshold $\alpha_b^{IN}$
- **Samuelson Condition**

$$\sum_{b=1}^{N} \frac{\overbrace{(R - F\,D) - \int_0^{\alpha_b^{IN}} EV_2(\alpha, O_b) d\alpha}^{\equiv \partial \pi_b / \partial \chi}}{\underbrace{(\bar{\lambda} - \chi) \int_0^{\alpha_j^{IN}} \left( \partial EV_2 / \partial O_j \right) d\alpha}_{\equiv \partial \pi_j / \partial O_j}} = \frac{1}{\partial \chi / \partial S_j}.$$

- Free-riding leads to under-provision of cybersecurity

# Benchmark 2: No free-riding problem but with rollover risk

- When $\gamma \geq \widehat{\gamma} \rightarrow$ failure driven by illiquidity; failure threshold $\alpha_b^{IL}(\gamma)$
- **Samuelson Condition**

$$\sum_{b=1}^{N} \frac{\overbrace{(R - F\,D) - \int_0^{\alpha_b^{IL}(\gamma)} EV_2(\alpha, O_b)\,d\alpha}^{\equiv \partial \pi_b / \partial \chi}}{\underbrace{(\bar{\lambda} - \chi)\left[EV_2(\alpha_b^{IL}(\gamma))\frac{\partial \alpha_b^{IL}(\gamma)}{\partial O_j} + \int_0^{\alpha_b^{IL}(\gamma)} \left(\partial EV_2 / \partial O_j\right) d\alpha\right]}_{\equiv \partial \pi_j / \partial O_j}} = \frac{1}{\partial \chi / \partial S_j}.$$

- 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 $\rightarrow$ over-provision of cybersecurity (relative to Benchmark 1)

# Laissez-faire outcome

- Assume $\gamma \geq \widehat{\gamma} \rightarrow$ failure driven by illiquidity

**Proposition**

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

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

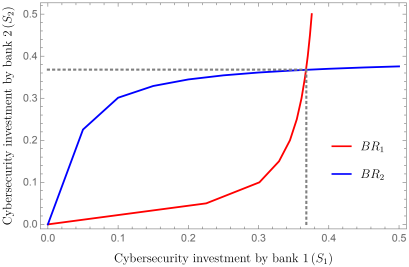
*Cybersecurity investment is increasing in the endowment, $\partial S_b^* / \partial W_b > 0$, iff $W_b \leq \widehat{W}$.*

- Two countervailing effects from an increase in $W_b$
  1. Mechanical increase in $O_b$ (for given $S_b$) $\rightarrow$ reduces MRS
  2. Diminishing returns from investing in operational resilience $\rightarrow$ increases MRS
- Second effect dominates when $W_b \leq \widehat{W}$
- 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.*




**Proposition**

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

# Normative implications

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- Compare laissez faire outcome with Benchmark 1

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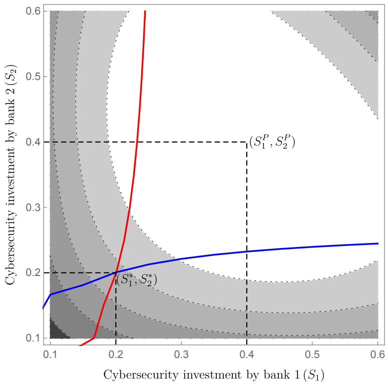
**Proposition**

*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 $\gamma \rightarrow$ run risk is low $\rightarrow$ weak incentives to invest in cybersecurity $\therefore$ 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 ($\gamma < \gamma^C$)




- 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.*

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

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**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

# Conclusion

- 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)

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**Thank you!**

# Classification of cyber events

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- **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

return

# 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

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- **Key ingredient**
  - Disruptions involved common IT infrastructure (platforms)

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