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New Challenges for Monetary Policy
A Conference Organized by
the Institute for Monetary and Economic Studies,
Bank of Japan, Held in Tokyo on May 27–28, 2025

Summary	Wataru Hagio, Daisuke Ikeda, and Yojiro Ito
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Advance in Security Proofs of Quantum Key Distribution and Its Challenges towards Practical Implementation	Kazutoshi Kan and Toshihiko Sasaki

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New Challenges for Monetary Policy

Summary of the 2025 BOJ-IMES Conference

by Wataru Hagio, Daisuke Ikeda, and Yojiro Ito

I. Introduction

The Institute for Monetary and Economic Studies (IMES) of the Bank of Japan (BOJ) held the 2025 BOJ-IMES Conference, entitled “New Challenges for Monetary Policy,” on May 27–28, 2025.¹ This year marked the 30th edition from its start in 1983, and participants discussed a wide range of topics from the conduct of policy to economic analyses.

The conference began with the opening remarks delivered by Kazuo Ueda (BOJ). Next, Agustín Carstens (Bank for International Settlements: BIS) gave the Mayekawa Lecture on the importance of trust in public policy. Athanasios Orphanides (Massachusetts Institute of Technology) delivered a keynote speech on challenges for monetary policy and its communication. Also, John Williams (Federal Reserve Bank of New York) and Ryozi Himino (BOJ) had a fireside chat. In the paper presentation sessions, four papers were presented on the theoretical and empirical analyses of inflation and monetary policy, by Annette Vissing-Jorgensen (Federal Reserve Board), Christopher J. Erceg (International Monetary Fund: IMF), Yuriy Gorodnichenko (University of California, Berkeley), and Daisuke Ikeda (BOJ).

The first policy panel discussion was moderated by Takeo Hoshi (The University of Tokyo) and the four panelists, Mário Centeno (Banco de Portugal), Andrew Hauser (Reserve Bank of Australia), Neel Kashkari (Federal Reserve Bank of Minneapolis), and M. Ayhan Kose (The World Bank Group), discussed monetary policy challenges in an uncertain economy. The second policy panel discussion was moderated by Christopher Waller (Federal Reserve Board), and the five panelists, Pierre-Olivier Gourinchas (IMF), Luc Laeven (European Central Bank: ECB), Clare Lombardelli (Bank of England: BOE), Eli M. Remolona, Jr. (Bangko Sentral ng Pilipinas), and Shinichi Uchida (BOJ), discussed monetary policy in a global economy.

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The conference organizers wish to express their sincere gratitude to conference participants for the thought-provoking presentations and discussions. The views expressed throughout this summary are those of the attendants and do not necessarily reflect those of their respective institutions. All remaining errors are the authors' responsibility.

1. See Appendix 1 for the program. See Appendix 2 for a list of participants; their affiliations are as of May 27–28, 2025.

II. Opening Remarks

Ueda shared some thoughts on challenges for monetary policy in Japan.² He explained developments in inflation rates, and said that since 2021 Japan had seen a surge in inflation after the euro area and the US. He continued that the inflation rate in Japan has recently picked up again, driven primarily by increases in food prices, most notably rice prices.

He mentioned that Japan's policy rate remained the lowest among the three economies. He then posed a question: Why has the Bank maintained such an accommodative stance, even after three years of inflation exceeding 2%? He said this was because underlying inflation, which excludes temporary factors, remained below 2%.

He continued that there was no perfect data series that capture underlying inflation, but that one variable the Bank closely monitors to assess underlying inflation was inflation expectations. He said that they now stood between 1.5–2.0%—the highest in 30 years, though still below the 2% target. He noted that this was why the Bank is still maintaining an accommodative policy stance to re-anchor them at 2%.

He pointed out that communicating this policy stance has been difficult, due to the persistent gap between headline inflation, to which the public pays attention, and underlying inflation, to which central banks respond. He added that, while this divergence had always existed to some extent, its recent magnitude and persistence had been particularly problematic in Japan. He also said that this gap would likely remain a major focal point for many central banks as supply shocks became more frequent globally.

He concluded his remarks by hoping that the discussions at this conference about critical issues, such as the measurement of underlying inflation and inflation expectations, how to communicate policies, and managing monetary policy under frequent supply shocks, will offer valuable insights for the global central banking community.

III. The Mayekawa Lecture: Trust and Macroeconomic Stability: a Virtuous Circle

Carstens delivered a lecture on the importance of trust in public policy, drawing on his experience of numerous economic and financial crises.³ He first identified two key lessons learned from several crises. The first is that crises are costly and best avoided. The second is that economies and financial markets always evolve. He said that policies and frameworks that seem appropriate today would therefore ultimately need to change, perhaps very quickly.

He then emphasized the importance of trust. He said that trust refers to society's expectation that public authorities will act predictably in the pursuit of predefined objectives, and that they will succeed in their task. He explained that if the public trusts authorities' actions, they would incorporate those actions into their own behavior, and they would be more willing to accept measures that call for short-term costs but deliver long-term benefits. He emphasized that trust underpinned the effectiveness and legitimacy of policies.

2. For details, see Ueda (2025).

3. For details, see Carstens (2025).

He said that there was a positive feedback loop in the dynamics of trust. He explained that effective and legitimate policies made it easier for the authorities to achieve their objectives, thereby building trust and producing a virtuous circle. He warned that this dynamic could however also work in the other direction, and hence preserving credibility was a constant challenge.

He then stressed that trust in the various aspects of macroeconomic policy—monetary, financial stability and fiscal—was closely interrelated. He gave three specific examples: money, commercial bank money, and public debt.

First, he began with the most fundamental aspect of central banking: the nature of money. He said that the consequences of losing trust in money can be disastrous, ranging from high inflation to sharp exchange rate depreciations. He emphasized that such events also typically go hand in hand with financial instability, sharply lower economic growth, widespread job losses and soaring inequality.

Second, he explained that over time, institutional arrangements within a two-tiered monetary system had developed in such a way that society's trust in the legal tender issued by the central bank has extended to the deposit money handled by commercial banks. He argued that the mere existence of a two-tier monetary system was not enough, however, to guarantee trust, and that the banking system also had to remain solvent via banking regulation and supervision and deposit insurance. He noted that recent episodes of extreme instability had also highlighted the need for greater supervision and regulation of the non-bank sector.

Third, he argued that from a macro-financial point of view, it was important for public debt to be sustainable. He noted that defaults on public debt could also destabilize the whole financial system and threaten monetary stability, since the central bank may be compelled to finance debt service with primary issuance, leading to fiscal dominance over monetary policy.

Finally, he emphasized that expecting policymakers to deploy extraordinary policies to every challenge would erode public trust and that building resilient and robust economies and financial systems would best make policies effective.

From the floor, **Orphanides** mentioned that the definition of trust included the idea that public authorities will act predictably, and that, nevertheless, discretion was often preferred to systematic policy in the real world. He then asked for advice on how to address this challenge. **Carstens** replied that monetary policy frameworks should provide a strong foundation for predictability, and that if central banks used discretion, they should provide detailed explanations and link their actions to the final objective. **Etsuro Shioji** (Chuo University) pointed out that, during the period of unconventional monetary policies, central banks purchased various assets, resulting in increased public pressure on central banks to play a greater role. He then asked how the public's excess expectations could be contained so that they return to normal. **Carstens** replied that, since the Global Financial Crisis (GFC), central banks had been perceived as the only game in town, and he pointed out that they had raised public expectations that monetary policy was a universal tool that could achieve many objectives without causing harm. He added that a little more prudence was needed to draw the line between what central banks could and could not do. **Gorodnichenko** asked how trust in central banks could be maintained amid mounting political pressure. **Carstens** replied that central banks

may need to accept friction with the government to preserve their independence, which would reinforce their credibility. He added that central banks had to be mindful that a part of their job involves generating such friction at the right time. **Kazumasa Iwata** (Japan Center for Economic Research) asked about the implications of cryptocurrencies for the conduct of monetary policy. **Carstens** replied that cryptocurrencies would not fulfill the role of money in terms of its singleness and finality.

Masaaki Kaizuka (NEC Corporation) asked how trust in fiscal policy could be secured in Japan, while there are arguments that there should be independent fiscal institutions which provide fiscal scenarios and monitor fiscal situations, or there should be fiscal rules, as in the EU. **Carstens** replied that, as in the UK, some form of autonomous entity that could evaluate fiscal policies and make an unbiased assessment of their consequences could be appropriate. **Gourinchas** asked if it was useful for central banks to adopt a separation principle, by which different instruments were used to achieve different objectives, in face of a tension between price stability and financial stability. **Carstens** replied that the joint consideration of all policies, including fiscal policy, was important, especially in addressing crises. **Laeven** asked how central banks could focus on a medium-term perspective instead of a short-term one. **Carstens** replied that a medium-term vision should be articulated as part of central banks' communications. **Hauser** asked how central banks could protect themselves from the social trend of declining trust. **Carstens** said that, over the last 20 or 30 years, it had been widely believed that monetary and fiscal policy are very effective in stabilizing and influencing economic growth, which turned out not to be the case. He added that central banks should exercise greater restraint in their proactive approach, particularly when pursuing non-price stability objectives.

IV. Keynote Speech: Challenges for Monetary Policy and Its Communication

Orphanides discussed how the policy framework could be improved by incorporating simple policy rules.⁴ First, he highlighted two interrelated challenges for monetary policy and its communication: the pretence of knowledge; and the proclivity for discretion.

He then discussed the desirable characteristics of simple rules. He said that simple rules are useful if they preserve price stability over time in line with a central bank's target, if they are somewhat countercyclical, and if they are more robust to imperfect knowledge. With regard to the inputs for simple rules, he mentioned that it was useful to incorporate forecasted variables, although using long-term forecasts could be counterproductive.

He showed an example of a "natural growth targeting rule." He explained that this rule requires central banks to respond to deviations in the nominal income growth rate in coming quarters from the normal growth rate, which is the sum of the target rate of inflation and the growth rate of real potential output. Using real-time data and projections for the US, he then demonstrated that the illustrative simple rule could broadly

4. For details, see Orphanides (2025).

capture the evolution of the actual policy rate until 2019, but pointed to a significant discrepancy in 2021 and early 2022. He said that this was an example of how guidance from a rule would have helped the Federal Reserve (Fed) avoid keeping the policy rate too low for too long.

Finally, he concluded his speech by summarizing the main advantages of communicating a benchmark policy rule: a rule can build trust in central banks, protect against major policy mistakes, and promote systematic policy; a rule does not exclude discretionary action, when circumstances warrant, but places a premium on explaining discretion; publishing the policy rate calculated by a rule in real time provides guidance on the policy rate that is explicitly conditional on the evolution of the outlook, thereby improving the central bank's communication.

From the floor, **Peter Kažimír** (National Bank of Slovakia) asked whether policy rules should be reviewed periodically, or whether exceptions or escape clauses should be added, to ensure they remain relevant in the face of unpredictable events such as pandemics, energy crises, and wars. **Orphanides** replied that central banks could deviate from a simple rule in exceptional circumstances and that, in such cases, the fact that central banks had communicated the rule makes it much easier for them to explain why they were deviating from the rule. He emphasized that benchmark policy rules should be examined at regular intervals and adapted as necessary. **Koji Nakamura** (BOJ) mentioned that economic data, such as GDP, were often revised, sometimes significantly, and asked how to address the issue of data revision when adopting simple policy rules for real-time policy judgements. **Orphanides** replied that simple policy rules should be designed to reduce the possibility of serious errors, for example, by incorporating variables that involve smaller degrees of real-time uncertainty.

Daniel Rees (BIS) said that, in the Summary of Economic Projections published by the Fed, there could be cases where the interest rate prescribed by a policy rule using projected variables such as inflation rates differed significantly from the projected interest rate. He asked how the right balance could be achieved between economic projections and the prescription of a policy rule. **Orphanides** replied that economic forecasts for the next few quarters fit a policy rule as its inputs, but policies should not be guided by forecasts longer than a 1-year horizon. **Kose** commented that, although the Fed had not followed the policy rules, the actual policy rates were similar to the rule-based rates, except for 2021–2022, which was a commendable result, considering the economic situation. He asked how policy rules should be designed in small open economies that are significantly affected by global shocks. **Orphanides** agreed that Fed's monetary policy had been reasonable most of the time, but the deviations in 2021–2022 were too large. He said that the fundamental principle of adjusting policy rates upwards when the inflation rate rose did not change, even when focusing on economies more influenced by global shocks. **Erceg** said central banks had been actively using balance sheet policies, such as quantitative easing (QE), and asked how to limit discretion with respect to such balance sheet policies. **Orphanides** replied that, while it would require further research, it would be possible to formulate balance sheet policy rules, and that there would be some advantages to taking a more systematic approach to balance sheet policies.

V. Fireside Chat

Himino hosted the fireside chat and welcomed **Williams** as a guest speaker. He asked several questions, and in response, **Williams** first discussed monetary policy under high uncertainty. He pointed out that a policy that is optimal in one economic model might perform poorly in another model. He argued that in the face of high uncertainty, it was better not to try to find the optimal policy, but rather to think of an approach that will work well in multiple scenarios.

Next, he discussed inflation expectations. He argued that the fact that the inflation rate in the US had been low and stable for decades before the pandemic was influential in shaping inflation expectations. He noted that people's perceptions of inflation have changed over the past five years and that the distribution of inflation expectations among generations that had experienced low inflation before had shifted upwards. He warned that inflation expectations could therefore shift in detrimental ways and well-anchored inflation expectations should not be taken for granted.

He turned to r -star and discussed how it could be affected by global factors. He said that AI could boost productivity growth and potentially increase r -star, while some other factors, such as changes in trade policy, could bring down r -star. He added that it was hard to predict which factors are more dominant.

Finally, he reflected on the heightened volatility of asset prices in April 2025. He noted that trade policy announcements had shocked the US markets, but there was no market dysfunction. He continued that it was different from March 2020, when there was a dash for cash, and that there were no issues in the repo or the uncollateralized call markets.

From the floor, **Carstens** stressed that the autonomy of central banks was crucial to counterbalancing a rise in uncertainty and added that institutional design was essential to ensuring this autonomy. **Williams** agreed with the comment and replied that many economies had independent central banks because they had been proven to work well in providing strong support for price stability. **Indrajit Roy** (Reserve Bank of India) asked whether exchange rate fluctuations should be taken into account in estimating r -star for emerging economies. **Williams** replied that factors such as exchange rates had to be given due consideration if the model was extended to emerging economies. **Gorodnichenko** asked how to deal with radical uncertainty, citing the examples of pandemic, wars, and the potential impact of AI on the labor market. **Williams** replied that a risk management approach continued to be useful even when faced with extreme uncertainty. **Orphanides** said that an independent central bank could promote price stability, thereby significantly reducing the risk premium on long-term government bonds. **Williams** agreed with the comment and replied that low and stable inflation rates would reduce the risk premium, particularly with regard to the inflation risk premium in long-term yields.

VI. Paper Presentation Sessions

1. Reserve Demand, Interest Rate Control, and Quantitative Tightening

Vissing-Jorgensen developed a theoretical framework for reserve demand and supply,

estimated reserve demand using US data, and discussed its implications for monetary policy.⁵ She noted that, before the GFC, reserves had been scarce. After the GFC, reserve supply significantly expanded due to unconventional monetary policies such as QE, and the Fed began paying interest on reserves (IOR). She raised three key questions: What is the role of reserve demand in interest rate control? What frameworks can limit interest rate volatility from shocks? How can reserve demand guide quantitative tightening (QT)?

To address these questions, she developed a theoretical model in which banks' demand for reserves is derived from a bank optimization problem, and reserve supply is determined by the Fed's securities holdings and its lending and investment facilities. She used this framework to understand both how the Fed controls the equilibrium interest rate on average and how this rate is influenced by shocks to reserve demand and reserve supply. Moreover, she derived empirical specifications from the theoretical model and estimated reserve demand for the US.

She presented three main findings. First, she explained that, on the demand side, the reserve demand curve was downward sloping because the convenience benefits of additional reserves decline for a given amount of liquid deposits, such as savings. She also said that the demand curve could shift in response to a change in banks' needs for liquidity, which arises mainly from liquid deposits on their liabilities. She explained that, on the supply side, the reserve supply curve consisted of a vertical part, where reserves equal net securities, defined as securities minus autonomous factors such as currency and government deposits, and a flat part, where reserves are reduced by facilities such as overnight reverse repurchase (ON RRP). She said that the equilibrium was determined by the intersection of the supply and demand curves. Second, she estimated the reserve demand function for the US since 2009, and found a stable relation once liquid deposit growth is accounted for. Third, she derived the IOR needed to achieve the target effective federal funds rate (EFFR) for a given balance sheet size. She noted that ending QT before a predicted EFFR-IOR spread of 4bps is reached may be preferable in order not to increase interest rate volatility. She also noted that the total of reserves plus ON RRP supply was \$3.6 trillion in March 2025, and that, if it reached the \$2.3 trillion level as a result of QT, reserves would be as tight as they were in September 2019, when money market rates spiked sharply.

As a discussant, **Hibiki Ichiue** (Keio University) made two comments. First, he pointed out the potential for omitted variables in the reserve demand estimation, highlighting that financial regulations, commitment lines, and uninsured deposits were not considered. Second, he noted that the EFFR-IOR spread remained stable between 2022 and 2024, and asked why this regime should not be maintained. He said that maintaining this regime requires large Fed holdings, and holding substantial amounts of long-term bonds potentially affects the term premium. On the other hand, he pointed out that, if large quantities of T-bills are available, holding T-bills might not be problematic and could be preferable to QT. Regarding the BOJ's operations, he said that reserves in Japan had been abundant as the call rates had remained below IOR. He also mentioned that this is the reason why the call rate had been stable even without

5. For details, see Lopez-Salido and Vissing-Jorgensen (2025).

a floor facility. Regarding omitted variables, **Vissing-Jorgensen** replied that she had considered various factors but had not found anything significant. She also noted that, although adding variables would provide a little extra explanatory power, it would be better to keep things simple.

From the floor, **Tuomas Vähimäki** (Bank of Finland) asked what had changed the most in the last 15–20 years regarding reserve management in the US. **Vissing-Jorgensen** replied that, before the GFC, the Fed had adjusted securities to maintain the vertical part of the reserve supply unchanged, taking into account forecasts for autonomous factors such as government deposits. She called this an “active securities” regime and contrasted it with the current “super passive securities” regime, where shifts in supply have minimal impact on call rates. **Andrea Gerali** (Bank of Italy) raised the issue of omitted variables in the reserve demand estimation and asked if incorporating banks’ exposure to non-bank financial institutions (NBFIs) matters. **Vissing-Jorgensen** replied that it could affect reserve demand if the treasury basis trade conducted by NBFIs is financed by banks. **Gourinchas** said that bank deposits were used as an explanatory variable that affects reserve demand in the estimation, but asked if the endogeneity of bank deposits, especially the effect of reserve supply on bank deposits, matters. **Vissing-Jorgensen** replied that she decided not to instrument for bank deposits, as they were included to capture unobservable liquidity demand shocks. **Hauser** asked if differences in the operational framework of supplying reserves, for example between the US and the UK, are important for economic welfare. **Vissing-Jorgensen** replied that rate volatility was lower in the UK so that the differences mattered, but added that the choice of operational framework depended on other factors such as central bank profit risk. **Junko Koeda** (BOJ) asked how, in actual policymaking, central banks can deal with uncertainty arising from the estimation and forecasting of reserve demand. **Vissing-Jorgensen** replied that it was possible to deal with such uncertainty, for example, by using 90% confidence intervals of the estimation.

Himino asked if there had been any deviations from the estimated demand curve during periods of stress, such as the dash for cash in March 2020. **Vissing-Jorgensen** replied that while the reserve demand did increase significantly then, the Fed boosted the reserve supply, preventing a sharp rise in the EFFR. **Shigenori Shiratsuka** (Keio University) noted that the EFFR was currently lower than the IOR, causing financial institutions that are eligible to earn IOR to have no incentive to trade in the Fed funds market. **Vissing-Jorgensen** agreed, adding that the Government Sponsored Enterprises were the main lenders in the market and lent at rates below the IOR, as they were not eligible to earn IOR. **Tsutomu Watanabe** (Nowcast) asked if changing from a semi-log to a log-log specification would affect the results of the estimated reserve demand curve. He also said that some people argued that a large central bank balance sheet was associated with weak fiscal discipline, and asked whether fiscal discipline should be considered when determining the optimal balance sheet size. **Vissing-Jorgensen** explained that a semi-log specification was used because the EFFR-IOR spread is often negative. She also noted that fiscal authorities and a central bank have different objectives. Regarding Hauser’s question, **Williams** commented that differences in economic welfare arising from small variations in overnight rates would be small, and he added that different jurisdictions adopted different operational frameworks based on

their broader objectives, including financial stability and functioning in the interbank lending market, other than interest rate controls.

2. Monetary Policy and Inflation Scares

Erceg developed a dynamic stochastic general equilibrium (DSGE) model to explain the post-COVID inflation surge and provided insights into the conduct of monetary policy in face of such shocks.⁶ He said that inflation had been initially viewed as transient with minimal second-round effects, leading major central banks to largely “look through” the initial rise. He then posed two questions: What were the mechanisms underlying the recent high inflation episode? How should monetary policy be conducted in an economy with more frequent supply shocks that arise, for example, from heightened geopolitical risks and trade uncertainty?

To address these questions, he developed a DSGE model that features: agents’ misperceptions about persistence of supply shocks, an inflation forecast-based Taylor rule, a nonlinear Phillips Curve, and endogenous price/wage indexation. He explained that price/wage indexation rose endogenously if inflation runs persistently above target.

He then presented key results. First, he explained that the transmission of cost shocks was state-dependent: cost shocks can have large, persistent effects on inflation when inflation is initially high, whereas they have only transient effects when inflation is near target. Second, he said that, under a forecast-based rule, cost shocks could temporarily raise output and cause a hump-shaped inflation response if misperceived as transient. He stressed that a standard linearized DSGE model could not reproduce these patterns, and that nonlinearities combined with misperceptions significantly changed the transmission of cost shocks. Regarding policy implications, he suggested that looking through supply shocks was generally reasonable when inflation was near target and the shocks were modest and likely transient. However, he added that such a policy turned problematic with large shocks, especially when persistence was uncertain or inflation had been above target. He also highlighted that when inflation was initially above the target, the probability distribution of inflation became skewed upward, making it more vulnerable to new adverse cost shocks.

As a discussant, **Jae Won Lee** (Bank of Korea) said that the main narrative was that inflation would surge if a large, persistent supply shock hit the economy alongside delayed monetary tightening. He added that indexation then kicked in, and that inflation became higher and more persistent due to the steep, nonlinear Phillips Curve. He then made several comments. First, he pointed out that backward-looking indexation was central to the paper’s results. He then argued that the empirical evidence was mixed. Regarding wage indexation, he said that some studies had shown it to be mostly forward-looking, and that formal wage indexation to inflation had become less prevalent in recent years. He also noted that, according to US studies, firms’ wage posting was predominant, and that firms that post wages had little incentive to change them in response to a “pure” supply shock that raised workers’ cost of living without affecting their productivity. As for price indexation, he mentioned UK studies indicating that mostly state-dependent pricing (SDP) firms increased the frequency of price changes

6. For details, see Erceg, Linde, and Trabandt (2024).

in 2022. He added that SDP firms could explain the fast and large increase in inflation, but that their swift price adjustments could result in lower inflation persistence. In addition, he pointed out that big fiscal stimulus, coupled with central banks' misperceptions about inflationary impact of fiscal stimulus, could also have contributed to the post-pandemic inflation. He then asked how important the supply-side story was relative to the demand side. **Erceg** agreed with his comments and said that the backward-looking indexation parameter had been set below 0.5, which was lower than the estimated persistence in the 1970s. Nevertheless, he noted that the model produced a strong propagation of supply shocks. He added that, although the primary focus of the paper was supply shocks, demand shocks were also important for business cycles.

From the floor, **Ueda** said that the paper fitted well with Japan's experience, where supply shocks seemed to have had persistent effects on inflation. **Erceg** replied that this was a helpful observation for the paper. **Carstens** said that exchange rates often fed back into price formation mechanisms in an emerging market economy, and that it would be interesting to extend the model in this direction. **Erceg** replied that he would like to consider the risks posed by exchange rates and external shocks, which are important for emerging market economies, and added that exchange rate depreciation could have persistent effects on inflation, depending on the state of the economy. **Kose** asked which one of these was the most important for the main results: high inflation, an overheating economy, or persistent shocks. **Williams** said that there was plenty of evidence that prices and wages had adjusted much faster in the US during this period, and that the pass-through of wages to prices was much higher. He then asked which mechanisms were truly important and empirically relevant. **Erceg** replied that persistent shocks were an important element as transient shocks did not lead to the main results. He added that misperceptions about persistence of supply shocks were also crucial because there would be smaller effects if central banks raised rates early and rapidly.

Gerali asked about optimal policy in this specific environment. **Erceg** replied that studying optimal policy was for future work as his co-authors were currently working on this. **Jongrim Ha** (The World Bank Group) asked whether the timing of the policy tightening mattered in light of the nonlinear effects of monetary policy. **Erceg** replied that examining different timings of policy tightening would be interesting. **Ichiiue** asked whether the endogenous indexation is related to higher attention to inflation during a high inflation regime. **Erceg** replied that it was likely related to higher attention, but that it was an open question as to where the tipping point is and when the degree of indexation starts to rise non-linearly.

3. The Causal Effects of Inflation Uncertainty on Households' Beliefs and Actions

Gorodnichenko discussed the effects of inflation uncertainty on household decisions, such as consumption, portfolio choices, labor supply, and mortgages.⁷ He emphasized the importance of studying inflation uncertainty but pointed out several challenges in estimating its causal effects. First, he said that inflation expectations were endogenous. He then pointed out that inflation uncertainty (second moment) was highly correlated

7. For details, see Georgarakos *et al.* (2025).

with inflation levels (first moment), requiring variation in the second moment independent of the first. He also noted that surveys on inflation uncertainty were quite rare, and that, with decades of low and stable inflation before the recent surge in inflation in advanced economies, there had been limited historical variation in inflation uncertainty.

To address these challenges, he conducted a randomized control trial (RCT) using the ECB's Consumer Expectation Survey of September 2023, which was followed by regular monthly surveys until January 2024, to measure households' actual decisions. Households were randomly assigned to a control group and three treatment groups. Treatment group 1 received information on professional forecasters' inflation expectations (first moment); Treatment group 2 received information on the differences in forecasters' expectations (second moment); Treatment group 3 received both pieces of information.

He then presented four main results on the causal effects of higher inflation uncertainty. First, households reduce subsequent durable goods purchases for several months. Second, regarding households' portfolio decisions, households move their funds away from risky assets, such as stocks, and tilt toward safe assets, such as savings accounts. Third, with regard to labor supply, households search more actively for jobs. Fourth, households are more likely to choose a fixed rate mortgage over an adjustable-rate mortgage if they are purchasing a home.

As a discussant, **Taisuke Nakata** (The University of Tokyo) pointed out that monetary policy was often analyzed assuming "Certainty Equivalence (CE)" under which uncertainty does not affect economic agents' decisions. He argued that this assumption, though quite popular, was inconsistent with the evidence presented by the RCT. He discussed how the breakdown of CE changes the implications for monetary policy. He explained that, in an economy with supply shocks, a more aggressive monetary policy reaction created a classic trade-off under CE: lower inflation volatility at the cost of higher output volatility. He continued that, if CE does not hold, lower inflation volatility raises output, but higher output volatility reduces output, creating a trade-off in the level of output. He argued that uncertainty therefore creates an additional layer of trade-off, which could complicate monetary policy analysis, in an economy with supply shocks. He added that supply shocks appeared to be important drivers of the economy, given the experience of the 2020s so far. **Gorodnichenko** replied that the general lesson from this and previous RCT experiments was that people have a strong aversion to macroeconomic volatility and prefer macroeconomic stability.

From the floor, **Kose** asked how important the source of the uncertainty is, whether it is a supply or demand shock, and suggested conducting an RCT to examine the effect of uncertainty in firms' inflation expectations on their decisions. **Erceg** inquired about a potential link between inflation uncertainty and supply shocks. **Gorodnichenko** replied that it was unclear whether people interpret uncertainty as a supply or demand shock, but based on some evidence, households tend to consider supply shocks as a driver of inflation. He added that in his study of firms in New Zealand, higher uncertainty led to less investment, suggesting people have an aversion to macroeconomic uncertainty. **Kosuke Aoki** (The University of Tokyo) asked which of the two interpretations is correct: that households change their behavior while taking the income process as given, or that they change their projections about income and income volatility. **Shioji** asked

whether it is possible to estimate the impact of inflation uncertainty separately from the impact of real economic uncertainty. **Gorodnichenko** replied that, to address these questions, a large-scale RCT would be required that included treatment of GDP expectations and uncertainty. He added that there was no significant change in households' expectations about GDP in the RCT, so uncertainty in GDP was not the main channel for the observed effects.

Ichiiue pointed out that, in a standard New Keynesian model, when inflation expectations increase, a central bank is expected to raise interest rates by more than one-to-one, adding downward pressure on the economy, which contradicts the RCT result that higher inflation expectations lead to a rise in the purchase of durable goods. **Gorodnichenko** said that there was much evidence suggesting that people do not fully understand the model's general equilibrium implications. **Gerali** suggested investigating the effect of multiple, mutually reinforcing information treatments over time. **Gorodnichenko** replied that multiple treatments were possible if budgets allow, noting that some firms in the Bank of Italy's survey were informed about past inflation, and these treatments had a persistent effect on inflation expectations. **Tsutomu Watanabe** said it would be interesting to examine the treatment effect of low-income respondents, who may not react if they have liquidity constraints. He also asked if the result came from changes in inflation expectations or in policy expectations. **Gorodnichenko** replied that the sample size was too small to detect differences among low-income respondents and noted that RCTs provided a very clean result in terms of estimating total effects, but they were not necessarily directly informative about underlying mechanisms. He offered his conjecture that, when inflation uncertainty goes up, households anticipate that their nominal wages may not increase very much, which has a direct negative impact on their purchasing power and thus on purchases of durable goods.

4. Mind the Gap When Exiting Low-for-Long

Ikeda discussed the consequences of low-for-long policy for agents' perceptions and the real economy, both theoretically and empirically.⁸ He said that keeping interest rates low for long supported the economy in a low inflation regime. However, he continued that low-for-long policy might induce agents to believe in lower interest rates for longer than intended by central banks. He therefore argued that this gave rise to a gap between agents' beliefs about monetary policy and the actual monetary policy, the belief gap, and that, when interest rates were raised amid the belief gap, such policy changes could be perceived as surprise tightening. He emphasized that while policies could change quickly, agents' beliefs might not, generating volatility in the economy.

To investigate this potential channel of monetary policy, on the theoretical side, he built a simple New Keynesian model with three features: agents' learning about a monetary policy rule; the effective lower bound (ELB) of the interest rate; and forward guidance with imperfect credibility. He used the model to simulate low-for-long scenarios and studied the mechanisms underlying the evolution of a belief gap. On the empirical side, he estimated a perceived monetary policy rule based on professional forecast data from Japan.

8. For details, see Hagio *et al.* (2025).

He then presented three main findings. First, he said that low-for-long policy could lead to expansion before the exit of the policy, followed by contraction during the exit. Specifically, he explained that as a low interest rate environment was prolonged, agents came to believe that interest rates would remain lower for longer due to their perception that the nominal neutral rate i^* in the monetary policy rule was lower. He continued that this belief stimulated the economy, but during the exit, this belief gap was corrected and perceived as monetary tightening, which caused economic contraction. Second, low credibility about forward guidance exacerbates this ‘boom and bust.’ Finally, he estimated perceived i^* for Japan and reported that its properties were consistent with the model. In particular, he mentioned that the empirical perceived i^* responded to a monetary policy surprise positively, which cannot occur in the model without learning. He argued that this belief gap channel could therefore be relevant in practice.

As a discussant, **Spencer Krane** (Federal Reserve Bank of Chicago) first noted that make-up type policies generally worked well in a setting with full-information and rational expectations. However, he emphasized that the real world was far from that setting, and agents had to learn new policies. He added that the real message from this model was that policy efficacy would be enhanced when markets and the public understood the policy and when they saw it as being credible. He continued that, under the ELB, no short-term policy rate movements were observed, complicating the learning process. He then made two comments. First, he said that it would be interesting to add a time-varying i^* term (which could differ from agents’ perceptions of i^*) to the central bank’s reaction function. Second, he noted that the credibility of forward guidance was exogenous in the model, but it might vary endogenously and thus influence the efficacy of forward guidance. **Ikeda** agreed with the comments while responding that the i^* term was constant and actually zero in the central bank’s reaction function. He continued that the degree of the credibility about forward guidance could be endogenized, but as long as there was an upper limit to the credibility, the main results would continue to hold.

From the floor, **Williams** asked whether introducing a new strategy such as a price-level targeting rule could address the formation of a belief gap. **Ikeda** replied that previous studies indicated slow learning under the ELB, and that a belief gap would probably emerge even with a change to the price-level targeting rule. **Mototsugu Shintani** (The University of Tokyo) asked which factor, imperfect credibility or cognitive discounting, was more important for addressing the so-called forward guidance puzzle, and whether it would be possible to identify and estimate parameters that govern these factors. **Ikeda** replied that imperfect credibility was more important, and that estimating such parameters from data would be difficult. **Orphanides** asked whether reformulating the policy from an overnight rate to a longer-term interest rate would improve the learning in the model. **Ikeda** replied that it was possible to introduce a long-term interest rate rule, but switching from one rule to another would be challenging for households and firms to learn in practice. **Roy** asked how COVID-19 related data were treated in the empirical analysis. **Ikeda** replied the data during the pandemic were treated in the same way as the data outside the pandemic period. **Gorodnichenko** said that credibility about forward guidance was likely to be low in practice by citing his paper on RCTs, which reports that providing forward guidance for more than

a year had no impact on people's beliefs and choices. **Ikeda** replied that the model's calibration could be enhanced by using the RCT evidence on the credibility of forward guidance.

Gerali asked whether relaxing the simplifying assumption of learning would affect the main results. **Ikeda** replied that doing so would be computationally challenging, but it might be worth exploring. **Iwata** asked whether forward guidance in Japan could have widened the belief gap. He also pointed out that the estimated recent perceived i^* was lower than the actual policy rate of 0.5%, and asked whether this implied tight financial conditions. **Ikeda** replied that there might be a belief gap if agents have imperfect beliefs about the central bank's announcement, and that the empirical results alone could not determine whether 0.5% was tight or loose. **Shioji** asked which was more important, the public's perception of the actual r -star, or central banks' perception of it. He also asked whether the model could be extended to include financial frictions. **Ikeda** replied that the combination of r -star and long-term inflation expectations in the monetary policy rule was important in the model, and incorporating central banks' perceptions was beyond the scope of the paper. **Shiratsuka** asked how the model treated long-term inflation expectations. **Ikeda** replied that in the model, long-term inflation expectations were anchored at the target rate of 2%. **Erceg** shared that, in 2015, the Tealbook suggested that there was a modest gap between market expectations and the Fed's internal projections at the time of liftoff.⁹ **Ikeda** expressed his appreciation for the useful information.

VII. Policy Panel Discussion 1

In the Policy Panel Discussion 1, moderated by Hoshi, four panelists, Centeno, Hauser, Kashkari, and Kose, discussed monetary policy challenges in an uncertain economy.

A. Remarks by Moderator and Panelists

Hoshi began by noting that uncertainty surrounding the global economy has always been a close and constant presence, regardless of the era. He then noted that in recent years, uncertainty had had a considerable impact on monetary policy through its effects on price fluctuations. He framed the session as an opportunity to consider how the uncertainty we face today differs from that of the past, and how policymakers should conduct monetary policy in light of these developments. With that, he invited the panelists to share their views.

Centeno began by stating that it is desirable for central banks to make monetary policy decisions based on a simple and consistent framework. At the same time, he noted that when uncertainty surrounding the global economy was high, flexibility was also required—such as updating decisions at each meeting based on the latest information. He cautioned that if policymakers placed too much emphasis on economic uncertainty in their communication, they risked fueling it and being seen as neglecting their responsibilities. Against this backdrop, he pointed to the increasing importance of careful communication with markets. In particular, given the influence of mone-

9. The Tealbook is produced before each meeting of the Federal Open Market Committee.

tary policy signals on consumption and investment decisions, he stressed the critical need to explain both the reasoning behind each policy decision and the degree of confidence policymakers hold in their judgment. He added that sound policy decisions also depended on high-quality data, rich economic knowledge, and preparedness for unexpected developments. In this regard, he emphasized the importance of acquiring new data and conducting analysis from diverse perspectives.

Hauser began by stating that economic uncertainty influences various stages of the conduct of monetary policy, including information collection, forecasting, policy decision-making, and communicating. He said that understanding the relationship between uncertainty and policy decisions was critical for communication. He emphasized that, on that basis, it was important to examine the effects of economic uncertainty on monetary policy in a structured and sequential manner. He noted that while our understanding of how uncertainty affects forecasts had become more refined, uncertainty surrounding supply-side factors—such as global supply chains—had remained poorly understood. Regarding communication, he pointed out that the more frequently policymakers use the term “uncertainty,” the harder it becomes for the general public to interpret their intentions, and he therefore stressed the importance of conveying messages in a clear and accessible manner.

Kashkari reflected on major shocks that have significantly affected the global economy over the past two decades and discussed the lessons learned from those experiences.¹⁰ He began by noting that during periods of major shocks, uncertainty tends to rise both with regard to their effects and with regard to the appropriate course of monetary policy. He emphasized that policymakers had to continue to strengthen their capacity both to analyze the effects of shocks and to make well-reasoned policy judgments. He then argued that in situations where the appropriate policy response was unclear, cautious decision-making could be justified—even if, in hindsight, such a response might appear to have been somewhat delayed. Furthermore, he warned that relying on simple monetary policy rules without taking into account the nature of the shock might result in misguided responses. For this reason, he stressed the importance of maintaining flexibility in policymaking and of basing decisions on the latest available information, rather than depending solely on rigid policy rules.

Kose discussed lessons learned for monetary policy under the conditions of heightened economic uncertainty, referring to studies that analyzed previous episodes of policy rate hikes. He began by noting that the recent tightening phase can be seen as a success, in that it lowered inflation without causing a notable deterioration in unemployment rates. However, he pointed out that the delayed start of rate hikes, followed by rapid increases, had had negative effects both on economies and on financial systems. Specifically, he explained that the delays in initiating rate hikes allowed overall price levels to rise significantly, while the abrupt increases in policy rates had heightened risks to the stability of financial systems. He went on to observe that people tended to respond sensitively to changes in the price level, and that a substantial rise in the price level could undermine the anchoring of inflation expectations. Finally, he concluded his remarks by emphasizing that it is essential for policymakers to consider not just

10. For details, see Kashkari (2025).

inflation rates but also price levels, act pre-emptively to secure financial stability, and maintain the anchoring of inflation expectations through communication with market participants.

B. Discussion between the Moderator, Panelists and Floor Participants

Hoshi, referring to the panelists' remarks, asked about the role of data and information in the conduct of monetary policy under heightened economic uncertainty. He also invited views on how policymakers should address the uncertainty that remains even when abundant data and information are available.

Centeno pointed out that current economic models might not function effectively in situations where the economic structure changed rapidly due to large shocks, such as geopolitical risks. He emphasized that in such cases, it was crucial to monitor changes in the economic situation from multiple perspectives without delay and argued that policymakers should make efforts to collect high-frequency micro-level data in a timely manner. **Kashkari** referred to the case of COVID-19 vaccines, which were developed much more quickly than many medical experts had initially expected. He stated that it would be difficult to clearly identify what kind of data was necessary at the initial stage of new developments. He added that the same would apply to current trade tariffs, arguing that it was extremely difficult at this point to specify what data or information would help reduce the uncertainty surrounding them. **Kose** noted that it was valuable for policymakers to have access to a wide range of data and information, but he emphasized the importance of building expertise in how to use such data and information effectively for monetary policy decisions. He pointed to the possibility that comparing recent data movements with those during past shocks could provide useful insights into the timing of policy responses. **Hauser** agreed that data was useful for policy decisions but cautioned that detailed analysis of large volumes of data did not necessarily lead to good judgment. He argued that policymakers had to think deeply and engage in careful communication with markets and warned that taking too much time for analysis might make it difficult to reach timely decisions. Drawing on his experience at the BOE, he stressed that while preparing action plans in advance to deal with unforeseen developments under high uncertainty was important, it was even more important for policymakers to secure sufficient time and respond flexibly, with thoughtful consideration of the underlying context.

From the floor, **Williams** asked if presenting and elaborating on multiple scenarios regarding inflation outlooks helps inflation expectations become anchored, facilitating consumption and investment decisions by households and firms. **Kashkari** argued that presenting multiple scenarios was useful in helping market participants and central bank professionals understand the reasoning behind monetary policy decisions, but added that for the broader public, a simple message was likely to be more effective. **Centeno** explained that the ECB did not normally present multiple scenarios, but there had been an exception in early 2022 when the ECB used a scenario assuming a prolonged war following Russia's invasion of Ukraine. He stated that this scenario had helped clearly communicate the possibility that the economic and inflation outlook could deviate substantially from the baseline. **Hauser** said that conducting scenario analysis and using the results as a basis for discussion within the policy committee was

useful in enabling flexible policy responses during times of shock. However, he expressed the view that even if multiple scenarios were presented to explain economic uncertainty to non-experts, such efforts were unlikely to change people's behavior. **Kose** stated that central banks had to provide some form of information, not necessarily as scenarios, and argued that when it was difficult to communicate clearly using simple language, presenting scenarios could help market participants and others understand their thinking.

Nakamura commented on the use of scenario analysis by central banks and international institutions as a means of communicating uncertainty. He noted that while he found such analysis to be highly useful for internal discussions within institutions, non-experts tended to focus almost entirely on the main scenario, which made it difficult to use scenario analysis effectively as a tool for external communication. He then asked how scenario analysis could be used more effectively as a means of communication with non-experts. **Centeno** said that scenario analysis could be used to clarify uncertainty and communicate what one could expect if things go a different way. **Hauser** argued that unless each scenario was accompanied by a clear explanation of the corresponding policy response that would be taken if that scenario were to materialize, it would not be useful to the general public. **Waller** commented as he has previously that in situations where multiple scenarios were considered equally probable, people would be highly interested in how policymakers would respond under each of those scenarios, so that communicating such cases would not be particularly difficult.

Orphanides commented that if cautious policymaking under uncertainty means holding the policy rate steady despite fluctuations in the inflation rate, it should not be considered inaction, but rather a deliberate policy decision. **Centeno** also stressed that a “do nothing” response constitutes a clear policy judgment. **Kose** similarly stated that refraining from action should be regarded as a policy decision. He went on to argue that even when a cautious approach was maintained, it was important for policymakers to communicate their thinking, particularly regarding the possible timing of future policy shifts. **Waller** commented as he has previously that it was important to clearly communicate that a cautious approach is not mere inaction, but rather a deliberate effort to avoid risks such as accelerating inflation or rising unemployment.

Erceg raised a question regarding the need for central banks to strengthen efforts toward regulating non-bank financial institutions, citing the recent liquidity crisis faced by UK pension funds that employed liability-driven investment strategies. **Hauser**, reflecting on his experience in addressing the liquidity crisis, noted that it was not possible to have a perfect response for every unexpected event. He emphasized that what matters most was the ability to make flexible decisions in real time.

Gourinchas agreed with Kashkari and voiced concern about policymakers relying on simple monetary policy rules that do not take into account the nature of shocks. He argued that, particularly in recent inflationary episodes—such as during the COVID-19 shock, which differed from previous ones—it was more desirable for policymakers to proceed with caution rather than follow such rules. **Centeno** also contended that monetary policy decisions could not be made appropriately without understanding the nature of shocks. He noted that, for example, in the recent inflationary phase, it was essential to incorporate the impact of government fiscal support measures when making policy

decisions. **Kose** emphasized the importance of fundamental research for understanding the nature of shocks. He pointed out that recent analyses had revealed that the effects of supply shocks tend to be more persistent than previously recognized and suggested that this could warrant earlier policy responses than in the past. **Kashkari** emphasized the importance of medium- to long-term real interest rates in assessing the impact on economic activity, and he noted that policymakers were expected to observe developments carefully over a longer horizon, rather than relying too heavily on day-to-day market movements.

VIII. Policy Panel Discussion 2

In the Policy Panel Discussion 2, moderated by Waller, five panelists, Gourinchas, Laeven, Lombardelli, Remolona, and Uchida, discussed monetary policy in a global economy.

A. Remarks by Panelists

Gourinchas first pointed out the recent global trend of declining goods price inflation, noting that attention should be focused on whether the low inflation can be maintained given the ongoing trade issues among various countries. Next, he expressed concerns about incentives for policy authorities to keep interest rates low, such as reducing fiscal burdens or ensuring financial stability, given high levels of government debt in various countries. He emphasized that under such circumstances, it was extremely important for policy authorities to maintain anchored inflation expectations, carefully evaluate a trade-off between price stability and financial stability, and preserve central bank independence. Finally, he mentioned the importance of capital flows and exchange rate movements in understanding the global economy, noting that while no significant outflows from dollar positions were currently observed, hedging demand had increased and careful monitoring continued to be warranted.

Laeven first stated that globalization had greatly contributed to economic growth and inflation control through various channels over the years. He then pointed out that while a broad reversal of globalization was not currently observed, uncertainty surrounding trade tariffs was creating major demand shocks to the global economy. Next, he mentioned the possibility that increased uncertainty in the global economy could increase dollar funding costs through an increase in risk premiums and could reduce investment globally, noting that policy authorities were becoming increasingly vigilant in monitoring the stability of the financial system. In this context, he argued that it would be important to consider policy responses in the euro area, taking into account the possibility that the landscape of the global financial system, including potential policy measures taken by other jurisdictions in times of stress, may not be the same as before.

Lombardelli stated that globalization had contributed to raising economic growth through productivity improvements over the past several decades, but she pointed out that it had become difficult to forecast the direction of globalization given recent developments in geopolitical risks and trade tariffs. Regarding the UK economy, she

mentioned that while the impact of current tariffs was likely to remain relatively small since UK exports were service-centered, it could become larger than expected if supply chains were constrained. She also noted that the degree of such impact could vary significantly depending on the degree to which large exporters such as China shifted their export from the US to other countries, adding that she was paying close attention to each country's responses. Finally, she argued that past UK experience suggested that prolonged uncertainty would have a negative impact on economic activity, such as suppressed investment, emphasizing that uncertainty was currently high, particularly regarding the impact of geopolitical risks and tariffs.

Remolona discussed the important role of exchange rates while focusing on economic and price developments in emerging economies. First, referring to research that analyzes inflation around the world, he stated that in emerging economies, exchange rates had a larger impact on inflation than commodity prices. He then explained that while the depreciation of domestic currency contributed to an increase in inflation rates and inflation expectations, its appreciation had little impact. Next, citing the characteristics of the Philippines, such as a larger foreign exchange market compared to equity and bond markets, and the substantial amount of remittances from overseas workers, he pointed out that the impact of foreign exchange rates on inflation was extremely large in the Philippines. Finally, based on these points, he argued that when exchange rates continued to depreciate over a long period, inflation rates and inflation expectations would rise significantly, so foreign exchange intervention could be considered as a policy tool in such cases.

Uchida stated that inflation rates in various countries had generally declined under globalization since the early 2000s, and he pointed out that while it was difficult to clearly forecast the direction of globalization at present, if the trend of globalization were to stagnate, inflationary pressures would likely strengthen. Next, reflecting on Japan's situation, he explained that Japan had been more strongly affected by global factors, such as continued increases in foreign direct investment even after the GFC, in contrast to other major economies. He argued that various unconventional monetary policies had been implemented to address deflationary pressures exerted partly by such global factors. He argued that while monetary policy could theoretically offset the effects of global factors, in practice it was difficult to correctly evaluate the magnitude and persistence of the effects, such as those of the effects of supply chain constraints. Finally, referring to the introduction of unconventional monetary policies globally after the GFC, he pointed out their international spillover effects and expressed hope that the advantages and disadvantages of unconventional monetary policies, from the view point of open economies as well as the home economy that initiates such policies, would be widely discussed.

B. Discussion between the Moderator, Panelists and Floor Participants

Waller reflected on Laeven's comment that uncertainty surrounding tariffs was creating demand shocks to the global economy, noting that some market participants viewed tariffs as supply shocks, and asked panelists how tariffs should be characterized. **Gourinchas** responded that tariff policies implemented by the US would generate negative supply shocks for the US and negative demand shocks for other countries. He added

that tariff increases could also yield negative supply shocks for other countries if they affected supply chains. Regarding the uncertainty about tariff policies mentioned by Laeven, he said that this would act as a negative demand shock for all countries including the US. **Laeven** agreed with Gourinchas' views and said that the impact of tariff shocks depended on countermeasures, if any, in response to tariff policies. **Uchida** also agreed with Gourinchas' views and stated that various tariff policies would put downward pressure on economic growth in all countries, including the US. He also said that their effect on inflation would be inflationary in the US, but mixed in other countries, as they would basically put downward pressure on inflation while they might cause supply chain disruptions and increase inflation. **Remolona** stated that the impact of tariff increases would be mitigated if supply chains were optimally reconstructed. **Lombardelli** also agreed with Gourinchas' views and stated that US tariff policies were unlikely to create inflationary pressures in countries other than the US in the short term and would not significantly hinder the conduct of monetary policy. However, she pointed out that from a longer perspective, reversing globalization could potentially push down economic growth and advance inflation.

Waller then asked panelists about the impact on the global economy of the recent increase in goods exports from China to countries other than the US. **Lombardelli** responded that Europe was substituting for US-bound exports, and while this would be a factor for price declines in the short term, it was difficult to evaluate the impact on prices from a longer perspective. **Gourinchas** pointed out that China's export volumes depended heavily on tariff rates. Specifically, he explained that in scenarios where very high tariff rates are imposed only on China, China's export volumes would increase overall as exports to Europe and Asia increased, while in scenarios where high tariff rates are imposed on all countries, China's export volumes would not change much. **Laeven** stated that an increase in exports from China to Europe would lower prices in Europe, and depending on European governments' responses, such downward price pressures could become larger. **Uchida** pointed out the importance of China regarding supply chains and rare metals and argued that it would be difficult for many countries to switch completely from imports from China to imports from other countries.

Next, **Waller** noted that the view that reversing globalization would lower productivity was not necessarily confirmed, as it was unclear whether globalization's progress had improved productivity, and he asked for opinions on the relationship between globalization and productivity. **Lombardelli** stated that a positive relationship could be observed between goods trade and productivity in manufacturing sectors in the long term, while she noted that the share of service sectors had increased, so that the overall effect of globalization on productivity was difficult to measure. **Laeven** stated the need to understand the impact of AI technology on productivity, and he added that one of the priorities for research at the ECB was technology and productivity. **Remolona** mentioned that productivity had been improving in service sectors such as back-office operations, which had been off-shored from developed economies to Asia in recent years, and stated that he was paying attention to whether AI technology would further raise service industry productivity. **Gourinchas** agreed with Remolona's view that service industries would likely drive future productivity growth. He pointed out that geoeconomic fragmentation would push down productivity but said that trade volumes

had not changed significantly so far and the global economy had maintained resilience. **Uchida** pointed out that if global capital were to flow out of the US due to the reversal of globalization, it would have a major negative impact on global economic growth, and he argued that it was important for stable global economic growth not to hinder the flow of global capital.

From the floor, **Koeda** asked to what extent central banks should focus on slow-moving indicators such as long-term inflation expectations in situations of high global economic uncertainty. **Lombardelli** answered that the BOE was considering utilizing scenarios in monetary policy decisions. **Laeven** said that the ECB conducted monetary policy based on medium-term perspectives, and that views were divided over whether to focus on somewhat shorter inflation expectations or utilize scenario analysis as needed.

Masazumi Wakatabe (Waseda University) asked whether central banks had sufficient policy tools to address the next crisis. **Laeven** responded that unconventional monetary policies that had been employed so far would function well as policy tools. **Gourinchas** stated that, regarding crisis policy responses, given the current situation of expanded government debt, there might be less room for fiscal policy rather than monetary policy. **Uchida** shared the view that central banks would be able to devise some policy tools as long as the effects of a crisis were limited to their domestic economies, but close cooperation among central banks would be required in addressing global crises.

Siang Meng Tan (Monetary Authority of Singapore) asked about the role of fiscal policies in mitigating the effects of tariffs. **Gourinchas** said that if the effects became large, a certain degree of fiscal support would be unavoidable. Referring to the recent fiscal support as countermeasures against energy price increases, he pointed out that once fiscal support measures were introduced, it became difficult to remove them, so that it was important to carefully construct policy frameworks. **Uchida** said that while fiscal policy could be an option in responding to demand shortages, it was not clear whether it could be used to address other issues, which called for broad discussions of fiscal policy.

Roy mentioned that core inflation among countries was linked, as shown in Uchida's presentation, and cited trade openness, commodity price movements, and monetary policy coordination as factors that could affect core inflation movements among countries, asking which factors are important. **Uchida** agreed that all the factors pointed out by Roy could affect inflation and said that the impact of fiscal policy could not be ignored.

Kose asked panelists about the idea of providing target ranges to inflation instead of a single target rate, and about the idea of placing emphasis on core inflation rather than headline inflation. **Lombardelli** responded that if central banks changed their inflation targets, it could make people believe that achieving targets was difficult, and it would be particularly undesirable to change inflation targets at the current time, when inflation was above the target. She also mentioned that central banks should place more emphasis on headline inflation since people were highly interested in the prices they actually faced. **Laeven** pointed out that headline inflation was easier for people to understand and had greater merits for central bank communication.

Gorodnichenko asked about room for cooperation among central banks to address global challenges. **Gourinchas** pointed out that many central banks had raised policy rates during the recent inflation period, and that when central banks faced the same shocks in this way, they could cooperate even without pre-arrangements. However, he said that it was not clear whether central banks could cooperate when countries faced different challenges. **Lombardelli** agreed with Gourinchas' views while arguing that there were issues requiring international cooperation, such as climate change and geopolitical problems, which were not necessarily those that should be directly addressed by central banks. **Uchida** replied that central banks could only supply their own currencies, and when foreign currencies including the US dollar were affected, close cooperation among central banks was required. **Laeven** argued that the involvement of key central banks, including the Fed, would be essential for central bank cooperation to function effectively.

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APPENDIX 1: PROGRAM

Tuesday, May 27, 2025

Opening Remarks

Speaker: **Kazuo Ueda**, Bank of Japan

Mayekawa Lecture: Trust and Macroeconomic Stability: a Virtuous Circle

Chairperson: **Seiichi Shimizu**, Bank of Japan

Lecturer: **Agustín Carstens**, Bank for International Settlements

Session 1: Reserve Demand, Interest Rate Control, and Quantitative Tightening

Chairperson: **Tuomas Välimäki**, Bank of Finland

Paper Presenter: **Annette Vissing-Jorgensen**, Federal Reserve Board

Discussant: **Hibiki Ichiue**, Keio University

Keynote Speech: Challenges for Monetary Policy and Its Communication

Chairperson: **Peter Kažimír**, National Bank of Slovakia

Speaker: **Athanasios Orphanides**, Massachusetts Institute of Technology

Session 2: Monetary Policy and Inflation Scares

Chairperson: **Anna Breman**, The Riksbank

Paper Presenter: **Christopher J. Erceg**, International Monetary Fund

Discussant: **Jae Won Lee**, Bank of Korea

Session 3: The Causal Effects of Inflation Uncertainty on Households' Beliefs and Actions

Chairperson: **Rosmarie Schlup**, Swiss National Bank

Paper Presenter: **Yuriy Gorodnichenko**, University of California, Berkeley

Discussant: **Taisuke Nakata**, The University of Tokyo

Policy Panel Discussion 1: Monetary Policy Challenges in an Uncertain Economy

Moderator: **Takeo Hoshi**, The University of Tokyo

Panelists: **Mário Centeno**, Banco de Portugal

Andrew Hauser, Reserve Bank of Australia

Neel Kashkari, Federal Reserve Bank of Minneapolis

M. Ayhan Kose, The World Bank Group

Wednesday, May 28, 2025

Fireside Chat

Moderator: **Ryozo Himino**, Bank of Japan
Guest Speaker: **John Williams**, Federal Reserve Bank of New York

Session 4: Mind the Gap When Exiting Low-for-Long

Chairperson: **Stephen Murchison**, Bank of Canada
Paper Presenter: **Daisuke Ikeda**, Bank of Japan
Discussant: **Spencer Krane**, Federal Reserve Bank of Chicago

Policy Panel Discussion 2: Monetary Policy in a Global Economy

Moderator: **Christopher Waller**, Federal Reserve Board
Panelists: **Pierre-Olivier Gourinchas**, International Monetary Fund
Luc Laeven, European Central Bank
Clare Lombardelli, Bank of England
Eli M. Remolona, Jr., Bangko Sentral ng Pilipinas
Shinichi Uchida, Bank of Japan

APPENDIX 2: LIST OF PARTICIPANTS

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Michael Cheng	Hong Kong Monetary Authority
Christopher J. Erceg	International Monetary Fund
Coletta Frenzel Baudisch	Deutsche Bundesbank
Takuji Fueki	Hitotsubashi University
Rhio D. Fuentes-Nuylan	Bangko Sentral ng Pilipinas
Hiroshi Fujiki	Chuo University
Andrea Gerali	Bank of Italy
Yuriy Gorodnichenko	University of California, Berkeley
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Keiko Harimoto	Bank of Japan
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Ryozo Himino	Bank of Japan
Johannes Hoffmann	Deutsche Bundesbank
Michal Horváth	National Bank of Slovakia
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Kenta Ichikawa	Bank of Japan
Hibiki Ichiue	Keio University
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Shigenori Shiratsuka	Keio University
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Koji Takahashi	Bank of Japan
Sumiko Takaoka	Seikei University
Hajime Takata	Bank of Japan
Naoki Tamura	Bank of Japan
Siang Meng Tan	Monetary Authority of Singapore
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Shinichi Uchida	Bank of Japan
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Shingo Watanabe	Bank of Japan
Toshiaki Watanabe	Hitotsubashi University
Tsutomu Watanabe	Nowcast
John Williams	Federal Reserve Bank of New York
Jonathan (Jon) Willis	Federal Reserve Bank of Atlanta
Mark Wynne	Federal Reserve Bank of Dallas
Tao Zhang	Bank for International Settlements

Opening Remarks

by Kazuo Ueda,
Governor of the Bank of Japan

I. Introduction

We are pleased to welcome all of you, distinguished speakers and guests, to the 2025 BOJ-IMES Conference. Thank you very much for your participation.

The first BOJ-IMES Conference was held in 1983, and while it was held biennially in some cases, this year marks the 30th edition. Since its inception, the conference has brought together participants from central banks, international institutions, and academia, providing a valuable platform for candid and active discussions on central banking in the context of the evolving global landscape.

The theme of this anniversary conference is “New Challenges for Monetary Policy.” I have just returned from the G7 meeting in Canada, where many of my colleagues expressed confidence in the progress made toward fulfilling their mandates, though they also acknowledged new challenges such as heightened trade policy uncertainty and dealing effectively with more frequent supply shocks.

To be honest, I felt slightly left out, though not for the first time, because here in Japan we are still grappling with the longstanding challenge of achieving our 2 percent inflation target in a sustainable manner, while being mindful of the implications of the zero lower bound of policy interest rates.

That said, the nature of our challenge has evolved considerably in recent years. We are now closer to the target than at any time during the last three decades, though we are not quite there. Our recent path has been affected in a unique way by supply shocks.

With that in mind, I would like to take a few minutes to reflect on how our experience has evolved and how it compares with that of other countries. I hope that this perspective will provide some useful background for the discussions to come during the conference.

II. Challenges for the bank’s monetary policy

Inflation rates

Let me begin with the current state of consumer price inflation. Chart 1 shows the headline inflation rates in Japan, the euro area (EA), and the United States (US). Inflation surged sharply in the EA and the US during 2021–2023. As has been widely documented, a significant part of this surge was driven by supply shocks, which, while temporary by nature, proved to have more persistent effects than initially thought. The subsequent decline in inflation in these economies reflects both the unwinding of those shocks and the effects of monetary tightening by the ECB and the Fed.

In contrast, Japan experienced a delayed inflationary response, likely due to infla-

tion expectations having remained anchored at low levels. However, unlike in the EA and the US, inflation in Japan has not moderated significantly since peaking around the start of 2023. As we will see shortly, this period has coincided with a gradual rise in inflation expectations.

More recently, inflation in Japan has picked up again, driven primarily by increases in food prices, most notably rice prices. Over the past 12 months, rice prices have surged by 98 percent, and the price of non-fresh food has risen by 7.0 percent.¹

In sum, Japan has been hit by two substantial adverse supply shocks. As a result, its current inflation rate exceeds that of both the EA and the US.

Policy rates

Turning now to policy rates, as shown in Chart 2, Japan's policy rate remains the lowest among the three economies, at 0.5 percent, markedly lower than in the US, where the rate is above 4 percent.

Chart 3 presents real policy rates, calculated as the nominal rate minus the headline inflation rate. In both the EA and the US, real rates are above zero, reflecting inflation rates above target. In contrast, Japan's real policy rate remains deeply negative, despite a similarly positive inflation gap from the inflation target. These broad features of inflation and interest rates are well known.

The difficult question is: Why has the Bank of Japan maintained such an accommodative stance, even after three years of inflation exceeding 2 percent? The Bank has argued that underlying inflation remains below 2 percent. This naturally leads to the question: What constitutes underlying inflation?

In principle, it refers to inflation excluding temporary factors. But in practice, there is no perfect data series that capture this concept. Instead, it must be judged from the totality of data and information on the economy, making communication with the public challenging. We have often faced harsh criticism for a perceived lack of clarity.

Inflation expectations

One variable we closely monitor to assess underlying inflation is inflation expectations. Although less elusive than the concept of underlying inflation, using inflation expectations also raises questions such as: Whose expectations matter most, and over what horizon?

In Chart 4, I have selected commonly used measures of medium- to long-term inflation expectations for Germany and the US, along with a weighted average of medium- to long-term expectations of various agents in Japan.²

For Germany and the US, inflation expectations have remained remarkably stable within a 2–3 percent range, anchored near the inflation targets, even during the nearly 10 percent inflation episodes of 2022–2023.³ This stability likely reflects the public's confidence in their central banks' ability to maintain price stability.

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1. Non-fresh food accounts for 22.3 percent of the consumption basket.

2. Regarding how the composite index of inflation expectations is constructed, see Osada, M. and T. Nakazawa, "Assessing Measures of Inflation Expectations: A Term Structure and Forecasting Power Perspective," Bank of Japan Review Series, 2024-E-4, 2024.

3. The implications for the US economy of the recent sharp rise in household long-term inflation expectations are yet to be determined.

In contrast, Japan’s medium- to long-term inflation expectations were stuck around 0–1 percent from the late 1990s until 2013, when large-scale monetary easing was introduced. Inflation expectations rose above 1 percent in 2014, but fell back to the earlier range by 2016 and stayed there until 2021. Shorter-horizon expectations remained even closer to zero, reflecting the deeply entrenched nature of Japan’s zero-inflation equilibrium.

Inflation expectations began to rise again in 2022, responding to global inflation dynamics and Japan’s continued monetary easing. They now stand between 1.5–2.0 percent—the highest in 30 years, though still below the 2 percent target. In other words, we have managed to de-anchor expectations from zero, but have yet to re-anchor them at 2 percent. This is why we are still maintaining an accommodative policy stance.⁴

Central bank communications

Communicating this policy stance has been difficult, not only because of the inherent ambiguity in the notion of underlying inflation, but also due to the persistent gap between headline and underlying inflation, as shown in Chart 5. (For the time being, we treat inflation expectations as a proxy for underlying inflation.) The gap corresponds to the direct effects of the supply shocks and other temporary forces affecting headline inflation. While central banks respond primarily to underlying inflation, the public tends to react to headline inflation. This divergence has always existed to some extent, but its recent magnitude and persistence have been particularly problematic in Japan.

Central banks generally adopt a “look-through” approach to supply shocks, so long as supply shocks are not expected to affect underlying inflation. We also largely “looked through” the first round of supply shocks, i.e., the inflation of imported goods in 2022–2023. However, Japan’s recent experience is unique: while headline inflation rose, underlying inflation rose as well. Increases in underlying inflation were driven not only by economic recovery from the pandemic and the tight labor market, but also by the supply shocks, as they fed into domestic prices and wages.

Now we are facing another round of supply shocks in the form of food price increases. Our baseline view is that the effects of food price inflation are expected to wane. However, given that underlying inflation is closer to 2 percent than a few years ago, we need to be careful about how food price inflation will impact underlying inflation.

As supply shocks become more frequent globally, the relationship between headline and underlying inflation will likely remain a major focal point for many central banks.

Way forward

In light of growing uncertainties, particularly those related to trade policy, we have recently revised down our economic and inflation outlook.

However, we continue to expect underlying inflation to gradually move toward 2

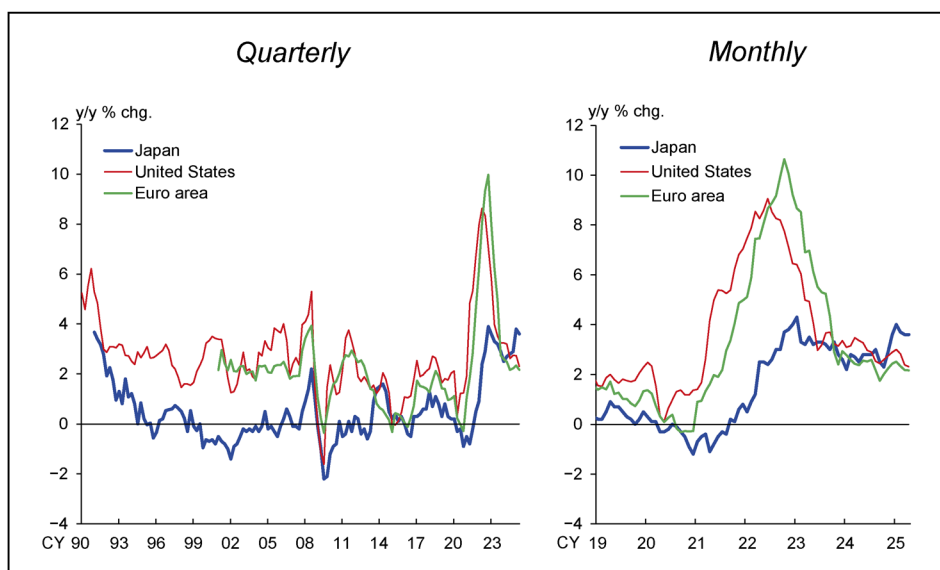
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4. Other proxies of underlying inflation exhibit mixed messages as to what the inflation level is. The rate of increase in base wages is around 3 percent, which is already at a level consistent with 2 percent inflation. Service price inflation has been subdued at 1.3 percent for all services, and at 1.5 percent for general services, as of April 2025.

percent over the second half of our forecast horizon. As discussed in our quarterly *Outlook Report*, there are both upside and downside risks around the baseline scenario, and risks to economic activity and prices are skewed to the downside for fiscal 2025 and 2026. To the extent that incoming data allows us to gain more confidence in the baseline scenario, as economic activity and prices improve, we will adjust the degree of monetary easing as needed to ensure the achievement of the sustainable 2 percent inflation target. Considering the extremely high uncertainties, it is important for us to judge whether the outlook will be realized, without any preconceptions.

III. Concluding Remarks

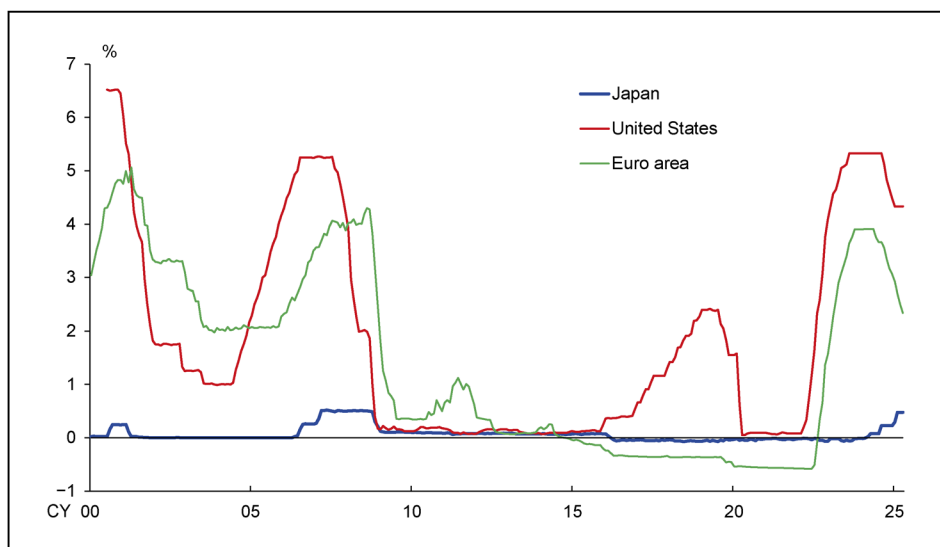
In opening this conference, I have shared some thoughts on the challenges for monetary policy in Japan. While many of these challenges are specific to Japan's unique situation, there are also areas of common concern where we can learn together: the concept and measurement of underlying inflation and inflation expectations, how best to communicate policies anchored in such concepts, and managing monetary policy under frequent supply shocks.

I hope the discussions over the course of this conference will shed light on these critical issues and offer valuable insights for the global central banking community.

Chart 1 Headline Inflation

Note: Figures for Japan are CPI (all items, excluding the effects of the consumption tax hikes). Figures for the United States and the euro area are CPI (all items) and HICP (all items), respectively. Figures for 2025/Q2 are those for April.

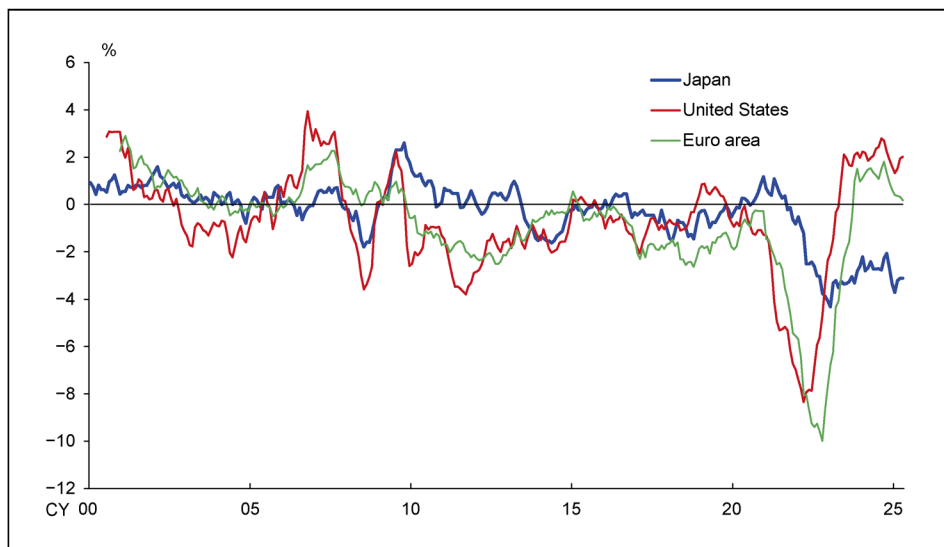
Sources: Ministry of Internal Affairs and Communications; Haver.

Chart 2 Policy Rates

Note: Figures for each economy are as follows: for Japan, the uncollateralized overnight call rate; for the United States, the effective federal funds rate; for the euro area, EONIA before 2020 and ESTR thereafter.

Sources: Bank of Japan; ECB; FRED.

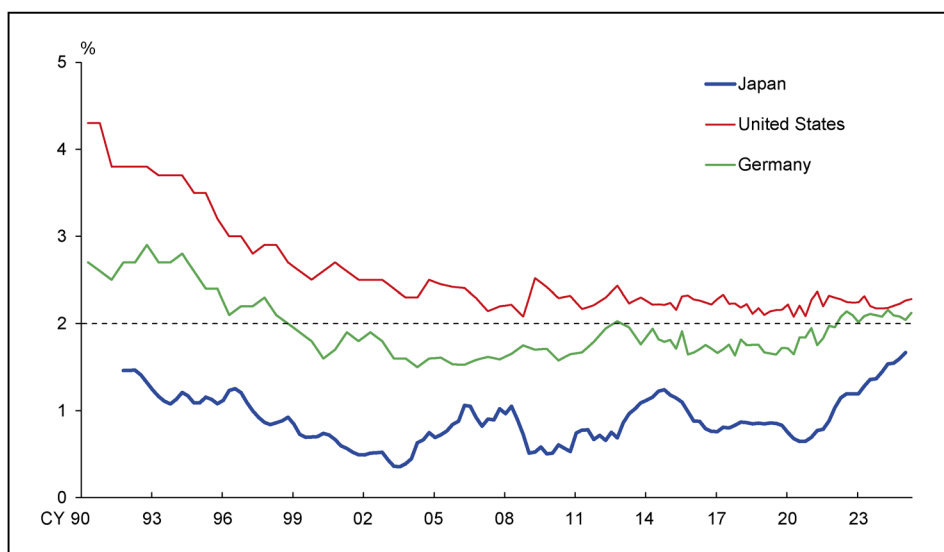
Chart 3 Real Policy Rates



Note: Real policy rates are calculated as nominal policy rates (shown in Chart 2) minus headline inflation (shown in Chart 1).

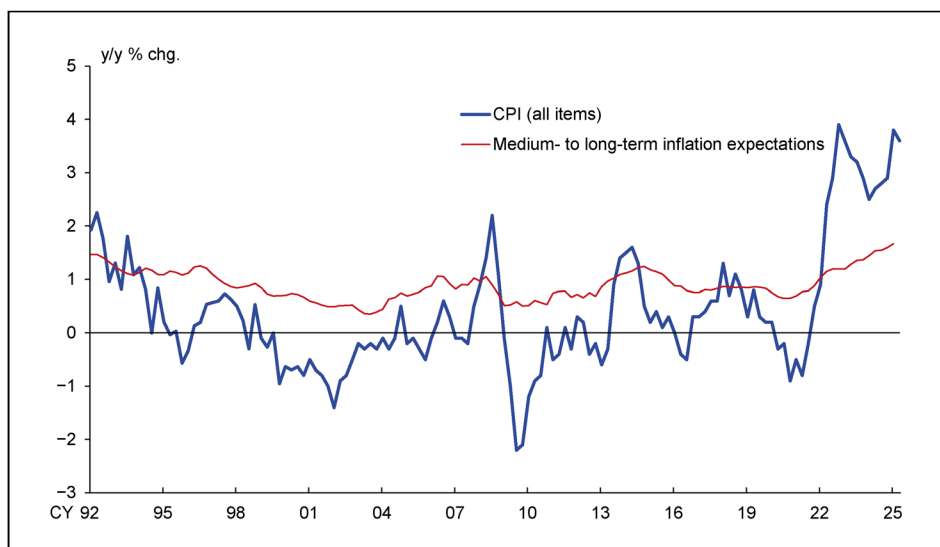
Sources: Bank of Japan; ECB; FRED; Haver; Ministry of Internal Affairs and Communications.

Chart 4 Medium- to Long-term Inflation Expectations



Note: Figures for Japan are the composite index of inflation expectations (staff estimates, 10-year ahead). Figures for the United States and Germany are the forecasts in the Consensus Forecasts (6 to 10 years ahead).

Sources: Bloomberg; Consensus Economics Inc., "Consensus Forecasts"; QUICK, "QUICK Monthly Market Survey (Bonds)"; Bank of Japan.

Chart 5 Japan's Inflation and Inflation Expectations

Note: The blue line represents CPI (all items, excluding the effects of the consumption tax hikes). The red line represents the composite index of inflation expectations (staff estimates, 10-year ahead).
 Sources: Bloomberg; Consensus Economics Inc., "Consensus Forecasts"; QUICK, "QUICK Monthly Market Survey (Bonds)"; Bank of Japan; Ministry of Internal Affairs and Communications.

The Mayekawa Lecture: Trust and Macroeconomic Stability: A Virtuous Circle

by Agustín Carstens

I. Introduction

Good morning.

It is a great honour to have been invited to deliver the Mayekawa Lecture at the Bank of Japan-Institute for Monetary and Economic Studies (IMES) Conference.

The list of past presenters of this lecture includes many influential international policymakers, among them Ben Bernanke, Jean-Claude Trichet, Olivier Blanchard and Raghuram Rajan. These distinguished individuals crafted the intellectual response to many of the key economic and financial challenges of recent times and assumed the immense responsibility of putting their ideas into practice.

It is a privilege to join their company.

For my remarks today, however, I will draw inspiration from an earlier era.

This lecture is named in honour of Governor Haruo Mayekawa. Mayekawa-san was Deputy Governor of the Bank of Japan from 1974 to 1979 and Governor from 1979 to 1984. This put him at the helm of policymaking at a time marked in much of the world by financial instability, large commodity price swings, high inflation and persistently slow productivity growth. The latter years of his tenure also saw rising tensions over global trade imbalances and exchange rate valuations.

Governor Mayekawa's legacy at the Bank of Japan extended beyond monetary policy. Notably, in 1982 he spearheaded the creation of IMES, reflecting the importance he placed on sound research as an input into policymaking. Since then, IMES has served as a bridge between the central bank, academia and the public. It has also been a forum for interaction and exchange between Japanese and international economists, a role that I know Governor Mayekawa deeply valued and championed.

The author is the former General Manager, Bank for International Settlements.

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This paper was prepared as the Mayekawa Lecture at the 2025 BOJ-IMES Conference, Tokyo, Japan, May 27–28, 2025. The views expressed in this text are those of the author and do not necessarily reflect the official views of the Bank of Japan.

Mayekawa-san's links with the Bank for International Settlements (BIS) ran deep. As Governor, he regularly participated in our meetings. Before that, he played a pivotal role in securing the Bank of Japan's re-entry into the BIS in 1970, making monthly visits to our Basel headquarters for several years. Today, the Bank of Japan is one of our most active members, and Governor Ueda serves on our Board of Directors.

The economic challenges Mayekawa-san faced as Governor have renewed salience today. Thanks to his steadfast leadership, Japan navigated them more successfully than many other economies. It is natural to ask whether there are lessons we can glean from that experience.

Towards the end of his tenure, Governor Mayekawa made a speech which was included in the first edition of the IMES in-house journal, *Monetary and Economic Studies*.¹ In it, he laid out what he saw as the main obstacles to global economic growth and proposed measures to address them.

He made four key points:

- First, persistently low growth reflected structural shortcomings. As such, demand management policies were not the answer. The only way to resolve structurally low growth is through structural reforms.
- Second, the best contribution that monetary policy can make to economic and financial stability is to deliver low and stable inflation.
- Third, high public debt and persistent fiscal deficits complicate the task of monetary policy and imperil long-term growth. For many economies, fiscal consolidation was in order.
- Fourth, a well functioning world trading system is fundamental to global economic prosperity. Protectionist measures, particularly those targeting bilateral trade imbalances, hinder long-run economic development.

Governor Mayekawa's policy prescriptions are as relevant today as they were four decades ago. I fully subscribe to them.

I would like to add a fifth point to Governor Mayekawa's list. Namely, that earning and retaining trust is essential for public policy to be effective.

To justify the importance I place on trust, let me first share some lessons learned during my career as a policymaker, which has now spanned more than four decades.

I have had a front row seat during numerous economic and financial crises. Early in my career at the Bank of Mexico, I witnessed the debt crisis that struck many Latin American countries in the early 1980s and the 1994 "Tequila crisis" in Mexico. I was first Mexican Finance Minister and then central bank Governor during the Great Financial Crisis (GFC), which exploded in 2008. The Covid-19 pandemic and its aftermath took place while I was in my current role at the BIS.

These crises were often a catalyst for important changes in policy frameworks. In many emerging market economies, the crises of the 1980s and 1990s led to the adoption of more flexible exchange rate regimes, greater central bank independence and an acceptance of low inflation as the main monetary policy objective. They also led to enhanced fiscal discipline and improved banking sector supervision and regulation.

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1. Mayekawa (1983).

Some jurisdictions also undertook major structural reforms, including the liberalisation of product and labour markets and privatisation of public enterprises.

Similarly, the GFC and the subsequent low-inflation period led to an expansion of central bank policy instruments, particularly in advanced economies. This included the adoption of quantitative easing and forward guidance. The recent inflation surge has prompted further reassessments of policy frameworks.²

Economies have become much more integrated over the course of my career. They trade more with each other. And, due to the emergence of global value chains, they trade more intensively. We felt this intensely in Mexico, particularly after the adoption of the North American Free Trade Agreement (NAFTA) in 1994. Today, I see this international trade integration from the vantage point of a resident of Basel, which lies at the intersection of Switzerland, France and Germany. And it is very evident here in Asia, which is home to the world's most complex and efficient value chains.

More generally, the global economy has become extremely dynamic. Information flows are unfettered, and firms and consumers increasingly sophisticated. Perhaps most importantly, financial markets have become much larger, more integrated and faster-paced than they were when I started my career.

A consequence of all this is that the scope to sustain flawed policy frameworks has shrunk. Global financial markets' immense size and speed discipline policymakers and, at times, force policies to realign.

To be sure, financial markets do not read everything right. They can miss important signals and remain calm in the face of rising vulnerabilities. This can be a serious problem. It is precisely in tranquil times that the seeds of future distress are often sowed.

But when financial markets smell weakness, they can move very quickly. To quote the late Rudiger Dornbusch: "Financial crises take much, much longer to come than you think and then they happen much faster than you would have thought."³ When that happens, policymakers need to react fast, often amidst great uncertainty and with their credibility dented. Unsustainable policies disappear swiftly.

What are the key lessons that I take from my experience?

The first is that crises are costly and best avoided. However, while adopting sensible policy frameworks can make crises less likely, sooner or later they will occur.

The second is that economies and financial markets always evolve. Policy settings and frameworks that seem appropriate today will ultimately need to change, perhaps very quickly.

Thus, it is critical for policymakers to have the nimbleness and flexibility to adapt, both to crises and to evolving economic and financial circumstances.

This takes me to the core issue that I would like to address: the value of trust in policymaking. It is much easier to make the necessary changes in a dynamic and uncertain environment—the theme of today's conference—if the public trusts policymakers and their policies. But the importance of trust goes beyond enabling change. Without trust, public policies cannot succeed.

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2. See, for example, Carstens (2025).

3. Dornbusch and Fischer (2003).

II. Trust in Public Policies

What does “trust” refer to? Essentially, it refers to society’s expectation that public authorities will act predictably in the pursuit of predefined objectives and that they will succeed in their task.

Why is trust so important? If the public trusts authorities’ actions, they will incorporate those actions in their own behaviour. This makes it more likely that the authorities will achieve their objectives. Moreover, if the public trusts public policies, they will be more willing to accept measures that call for short-term costs but deliver long-term benefits. Trust underpins the effectiveness and legitimacy of policies.

Policymakers acquire trust by achieving their objectives over time. Hence the importance of setting clear goals, which provide a benchmark against which to evaluate policies and assess their success. But setting targets alone is not enough. Policymakers must also pursue them decisively, particularly when circumstances change.

There is a positive feedback loop in the dynamics of trust. Effective and legitimate policies make it easier for the authorities to achieve their objectives. This, in turn, builds trust, producing a virtuous circle.

However, this dynamic can also work in the other direction and, at times, very quickly. In the extreme, if trust evaporates, the capacity to make effective public policies disappears. Preserving credibility is a constant challenge. It requires consistency in public policies over time. Institutional arrangements, like independent central banks, can support this purpose.

To establish, preserve and enhance macro-financial stability, it is essential for the public to trust all of the key macro policy dimensions—monetary, financial and fiscal policies—individually and as a group. This requires coherence between them.

Let me elaborate.

I will begin with the most fundamental aspect of central banking: the nature of money. The social convention of money is based on the trust placed in it by the public. As money is the basis for the entire financial system, the system’s stability ultimately rests on that trust.

Fiat money has no intrinsic value. Its worth derives from the social convention that underpins it, and from the institution that allows it to function: the central bank. Money only has value if people expect that others will honour that value, today and in the future. That is why the issuer of money is so powerful. This power comes with great responsibility. Those who abuse their ability to issue currency deprive money of its value and forfeit the trust of the public.

The consequences of losing trust in money can be disastrous. These can range from high inflation and sharp exchange rate depreciations to the substitution of the national currency with a foreign one. In the extreme, for example in hyperinflationary episodes, there could even be a return to barter. Such events typically go hand in hand with financial instability, sharply lower economic growth, widespread job losses and soaring inequality.

Central bank autonomy emerged to prevent such developments. After all, autonomous central banks are institutions within the state vested with a mandate to act in the public interest and preserve the purchasing power of the national currency. Their

autonomy is the social engineering that solidifies society's trust in money.

In recent decades, many central banks have adopted monetary arrangements that allow them to anchor expectations and preserve money's purchasing power. Inflation targeting regimes are the most common framework to ensure this.

But what does inflation targeting consist of?

Central banks do not control inflation directly. But their policy tools can influence it. By adopting an inflation target, a central bank commits to use its tools to achieve that target. If the public trusts the central bank, then the inflation target, rather than current inflation, becomes a key reference point for price and wage decisions. This contributes to low and stable inflation. Inflationary episodes are usually short-lived, reflecting changes in relative prices. Inflation becomes self-equilibrating and ceases to materially influence the behaviour of households or businesses.

That is why the inflation outbreak that followed the Covid pandemic in many countries was so concerning. The trust central banks had gained over many years could have been lost if society had started to doubt their commitment to price stability. Some generations experienced the risk of the economy transitioning to a high-inflation regime for the first time. Once that transition starts, it can be hard to stop.

Faced with this risk, it was necessary and appropriate for central banks to tighten policy forcefully to restore price stability. The value of doing so is reflected in the relatively modest impact on output and employment, compared with the significant costs incurred during the 1970s and 1980s, when many central banks responded slowly to rising inflation and expectations de-anchored.

Let me now turn to my second example.

It is well known that the money issued by the central bank, known as primary money, is not the only money that circulates in a modern economy. Households and businesses rely instead on commercial bank money—in the form of bank deposits and credits—for the bulk of their day-to-day transactions.

It is thus essential that trust in money extends to commercial bank money.

At the same time, primary and commercial bank money are indistinguishable for most people. That is by design.

Over time, institutional arrangements have evolved to extend society's trust in primary money to commercial bank money within a two-tiered monetary system. The cornerstone of that system is that interbank payments ultimately settle on the central bank's balance sheet, through the exchange of primary money between commercial banks. This guarantees the finality of payments and the singleness of commercial bank money. The central bank's ability to create liquidity by lending to the banking system makes ultimate settlement of the banking system at the central bank possible. At times of great instability, the central bank can also provide liquidity through its lender of last resort function. In doing so, it safeguards public trust in the entire monetary system.

The value of the two-tier monetary system is particularly evident when contrasted with recent failed attempts to issue private forms of money through technologies based on decentralised ledgers. These alleged forms of money operate without central bank intervention, a lender of last resort or a robust regulatory and supervisory framework. They have led to the proliferation of so-called cryptocurrencies, which cannot guarantee payment finality, or maintain stable value, and so clearly lack the essential char-

acteristics of money. In addition, the absence of regulation to guard against money laundering or counter terrorist financing means that these assets are widely used for illicit purposes. These developments highlight the critical point that the value of fiat money lies in the institutional framework and social conventions that support it.

The mere existence of a two-tier monetary system is not enough to guarantee trust. The banking system must also remain solvent. Strong, safe and solvent banks help to support the economy. Because banking crises have large social costs, the system requires adequate regulation and supervision. A complement is deposit insurance, which exists to forestall potential bank runs. Together, these layers of protection safeguard the public's savings and foster trust in both primary and commercial bank money.

Banks have become much more resilient since the GFC. Society reaped the benefits in the Covid pandemic, as banks played a vital role in keeping economies and businesses afloat, helping to support jobs. Even during the banking stress of 2023, the post-GFC reforms, combined with authorities' swift deployment of crisis management tools, limited the fallout to only a handful of institutions.

Nonetheless, more should be done to bolster the banking sector's resilience. Make no mistake, the core responsibility lies with banks themselves. There is no substitute for sound business models, strong risk management and effective governance. But, in order to keep them on a sound footing in a more volatile and dynamic financial system, banking supervision must continue to up its game to identify and remedy problems at banks proactively.⁴ And timely, full and consistent implementation of banking reforms and regulations, including Basel III, remains essential.

The non-bank financial system has grown rapidly in recent decades. This sector comprises many activities involving securities, including debt instruments and broader forms of intermediation performed by insurance companies, private credit, investment service companies and hedge funds, among others. In many jurisdictions, non-bank financial intermediation has for some time now accounted for over half of the financial system.

Recent episodes of extreme instability have highlighted the need for greater supervision and regulation of the non-bank sector. One reason is to prevent harmful arbitrage between regulated and unregulated financial activities. Moreover, the sector's links to the traditional banking system and the tendency of non-bank intermediation to generate opaque and excessive leverage and liquidity mismatches can pose systemic risks.

In recent years, some central banks have had to act as "market-makers of last resort" to defuse crises which threatened to spill over into the wider system. In doing so, they upheld trust in the broader financial system. Because such interventions may conflict with measures to preserve price stability, greater regulation and supervision of the non-bank financial sector are called for.

Let me now turn to my third example.

Within the universe of debt instruments, public debt is of particular importance. If used appropriately, public debt allows governments to successfully function. But, from a macro-financial point of view, it is important that any public debt is, and is seen to be, sustainable. Investors must trust the government to meet its financial obligations,

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4. See Carstens (2023).

without resort to central bank financing.

Public debt plays a strategic role. As the instrument with the lowest credit risk, it is essential for grounding the risk of asset portfolios, particularly those of banks. Furthermore, public debt serves as the main reference for valuing other forms of debt, such as corporate debt. Hence, defaults on public debt can destabilise the whole financial system.

They also threaten monetary stability since the central bank, even if it is formally autonomous, may be compelled to finance debt service with primary issuance, leading to fiscal dominance over monetary policy. The result would be rising inflation and sharp exchange rate depreciations.

In the light of these considerations, it is essential for fiscal authorities to curb the relentless rise in public debt. The low interest rate environment that followed the GFC flattered fiscal accounts. Large deficits and high debt seemed sustainable, allowing fiscal authorities to avoid hard choices. But the days of ultra-low rates are over. Fiscal authorities have a narrow window to put their house in order before the public's trust in their commitments starts to fray. Markets are already waking up to the fact that some paths are not sustainable. As I mentioned before, financial markets can remain calm in the face of large imbalances until suddenly, one day, they no longer are.

That is why fiscal consolidation in many economies needs to start now. Muddling through is not enough. In many countries, current policies imply steadily rising public debt in the coming decades. Pressures for more public spending will only increase, not least due to population ageing, climate change and, in many jurisdictions, higher defence spending. Fiscal authorities must provide a transparent and credible path to safeguard fiscal solvency, ideally underpinned by stronger fiscal frameworks. They must then follow through on their commitments. Central banks cannot be the only game in town.

Trust in the various aspects of macroeconomic policy—monetary, financial stability and fiscal—is closely interrelated. Monetary instability imperils financial stability, erodes investors' willingness to hold public debt and hammers public confidence. Financial crises have large fiscal costs. And loss of confidence in public finances compromises the stability of the whole financial system and can undermine price stability. All of this ultimately costs people in terms of lost opportunities, jobs and social and public benefits.

Thus, it is essential to preserve trust in all pillars of a country's macro-financial frameworks, and to ensure consistency between them. This represents a great challenge due to the involvement of multiple authorities and the existence of unavoidable political motivations, particularly in fiscal policy. While this is not an insurmountable issue, it highlights the value of coordination among the various arms of public policy.

Let me add a further reflection on the credibility of fiscal and monetary policy today, one that echoes the prescriptions of Governor Mayekawa four decades ago. Recent experiences should prompt a reflection on the appropriate role of monetary and fiscal policy and greater realism about what they can deliver. Fostering unattainable expectations about policymakers' ability to smooth out every economic pothole will ultimately lower trust in public policies.

For monetary policy, it would be prudent to avoid excessive "fine-tuning." Central

banks should not be expected to stabilise inflation at very short horizons and within narrow ranges. This is particularly important because, as recent events have shown, inflation will partly depend on factors that are not under central banks' control.

Fiscal policy should seek to allocate its scarce resources to measures that can raise future growth. This can include investment in areas such as infrastructure, education and health systems. Nonetheless, we must remember that structural reforms are the best tool to sustainably increase a country's growth potential.

As a final remark, I would like to stress the importance of predictability in building and sustaining public trust. Predictability does not mean inertia. When circumstances change, or when frameworks are clearly flawed, policies must adapt. However, the public has a right to expect a degree of continuity and transparency about basic policy objectives, their development and the procedures for guiding any shifts in course.

III. Conclusion

Let me conclude.

Policymakers have faced frequent and intense challenges in recent decades. In the face of extraordinary strains, they strived to preserve the value of money, and keep their economies and the financial system functioning. Their successes illustrated the importance of maintaining public trust, which was a prerequisite for their decisive actions. And policies worked better when they were each part of a coherent whole.

If the events of the 21st century so far are a guide, we should not expect plain sailing in the coming decades. Building resilience will require policymakers to apply an appropriate policy mix and communicate it effectively.

I would like to leave you with this last thought. Part of preserving trust is to know the limits of what policies can deliver. Expecting policymakers to deploy extraordinary macroeconomic policies to respond to every challenge is a sure way to erode the public trust. Building resilient and robust economies and financial systems is the best way to ensure that policies remain effective, so that they can be deployed when they are needed the most.

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Challenges for Monetary Policy and Its Communication

Athanasios Orphanides

The post-pandemic inflation surge underscores that monetary policy continues to be hampered by two long-standing challenges: the pre-tence of knowledge and the proclivity for discretion. Focusing on the Federal Reserve, this paper demonstrates how simple policy rules, designed to be robust under imperfect knowledge, can mitigate these challenges. The Fed's post-pandemic policy error—maintaining excessive accommodation as inflation pressures mounted—could have been avoided with guidance from a simple natural growth targeting rule that had been included in the Fed's Bluebook/Tealbook starting in 2004, but was not disclosed to the public in real time. Formal adoption and disclosure of such a rule can help discipline discretion and improve both the conduct and communication of monetary policy.

Keywords: Policy discretion; Simple rules; Natural growth targeting;
Inflation surge

JEL Classification: E52, E58, E61

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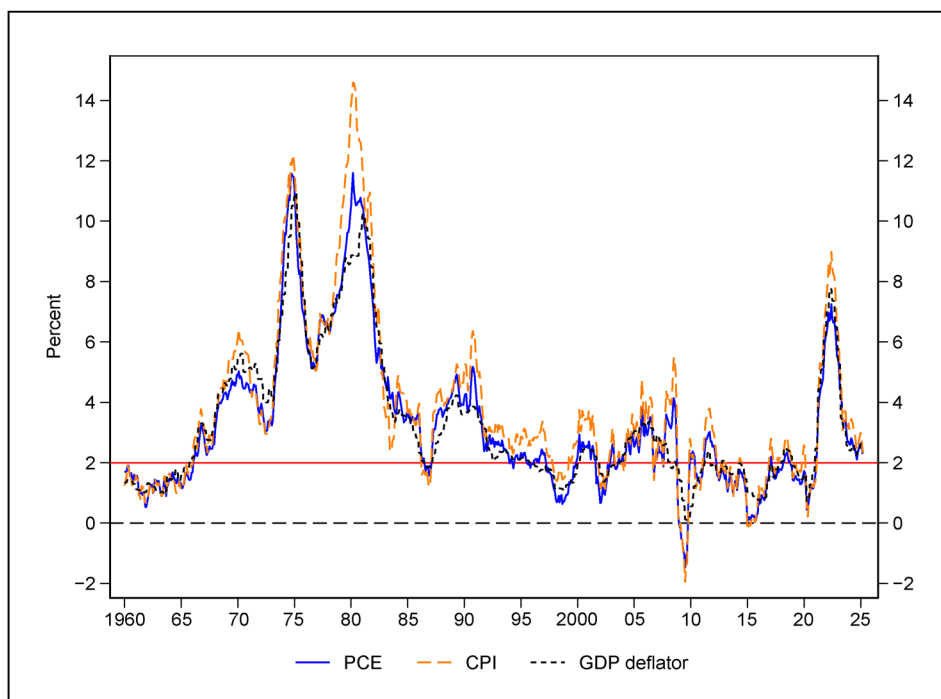
I. Introduction

The post-pandemic surge in inflation around the world revealed underappreciated challenges with the monetary policy strategy and communication pursued by some central banks in recent years. Episodes of high inflation are always unwelcome; Nonetheless they present opportunities to learn, adapt, study how to make monetary policy strategy more resilient in the future. In the United States, the focus of my discussion today, one has to go back to the 1970s to find a period when the Fed faced a similar difficulty in preserving price stability (Figure 1). My plan is to discuss underlying challenges for monetary policy that contributed to this policy miss and demonstrate how simple policy rules, designed to be robust under imperfect knowledge, can mitigate these challenges.

Briefly, I wish to highlight two interrelated challenges for monetary policy and its communication: the pretence of knowledge, and the proclivity for discretion. Monetary policy today continues to be formulated under the implicit assumption of much more knowledge than we can possibly have about the economy and the underlying data in real time. In addition, despite the recognition that systematic policy delivers superior economic outcomes over time, excessive discretion is observed in practice. Too often policymakers cite a vague need for “flexibility” as a justification for unhelpful discretion.

Using real-time data and forecasts for the United States, I discuss how simple policy rules can address these challenges and help improve policy. Simple rules, selected

Figure 1 Inflation in the Unites States



Note: Alternative measures of year-on-year inflation.

with an emphasis on robustness, can protect against imperfect knowledge. Simple rules can discipline discretion and promote systematic policy. The selection and disclosure of a benchmark policy rule to the public, and the communication of associated policy prescriptions in real time, can serve as a constraint on unhelpful discretion. Furthermore, simple rules can facilitate coherent policy communication much better than other forms of forward guidance that attempt to provide information about future policy interest rates without explicitly linking the policy rate to the evolution of the outlook. Indeed, the Fed's post-pandemic policy error—maintaining excessive accommodation as inflation pressures mounted—could have been avoided with guidance from a simple natural growth targeting rule that had been included in the Fed's Bluebook/Tealbook, but not disclosed to the public in real time. A lesson for policy strategy is that the conduct and communication of monetary policy can improve with formal adoption and disclosure of a simple benchmark policy rule.

II. The Pretence of Knowledge and Proclivity for Discretion

The challenges I focus on are not new, they have been discussed in the past. Drawing on policy research and historical experience, monetary policy frameworks can be adapted to better address imperfect knowledge and limit unhelpful discretion. Some progress has been observed over time in this regard. Yet, the recent inflation surge underscores that additional progress is needed to ensure that monetary policy consistently fosters good economic performance.

The focus on the pretence of knowledge is motivated by the previous episode of high inflation in the United States—during the 1970s. Let me remind you of the intellectual environment and monetary policy practice at the time. In retrospect, policy goals were overambitious. Optimal control methods started showing up in policy research. Fine tuning dominated policy, without accounting for how limited our knowledge of the macroeconomy really is. At the Fed, excessive emphasis was placed on delivering the elusive goal of “maximum employment,” without accounting for imperfect knowledge, and largely downplaying the need to defend price stability as a means of fostering good economic performance over time (Orphanides and Williams 2013).

Friedrich von Hayek nicely highlighted the problem in his 1974 Nobel address on the pretence of knowledge:

“It seems to me that this failure of the economists to guide policy more successfully is closely connected with their propensity to imitate as closely as possible the procedures of the brilliantly successful physical sciences—an attempt which in our field may lead to outright error” (Hayek 1974).

For a time, the study of economics became almost like the study of mathematics with excessive emphasis on mathematical methods applied with overly simplistic assumptions and insufficient attention to the human factor, the element that makes economics different from the physical sciences. We are still not able to model in any reasonable way how people form expectations, how they respond to events, how they respond to communication. Our ability to build models like in physical sciences remains

limited.

Hayek continued by pointing out that economic models based on unrealistic assumptions invited policy errors:

“But the effects on policy of the more ambitious constructions have not been very fortunate and I confess that I prefer true but imperfect knowledge, even if it leaves much indetermined and unpredictable, to a pretence of exact knowledge that is likely to be false” (Hayek 1974).

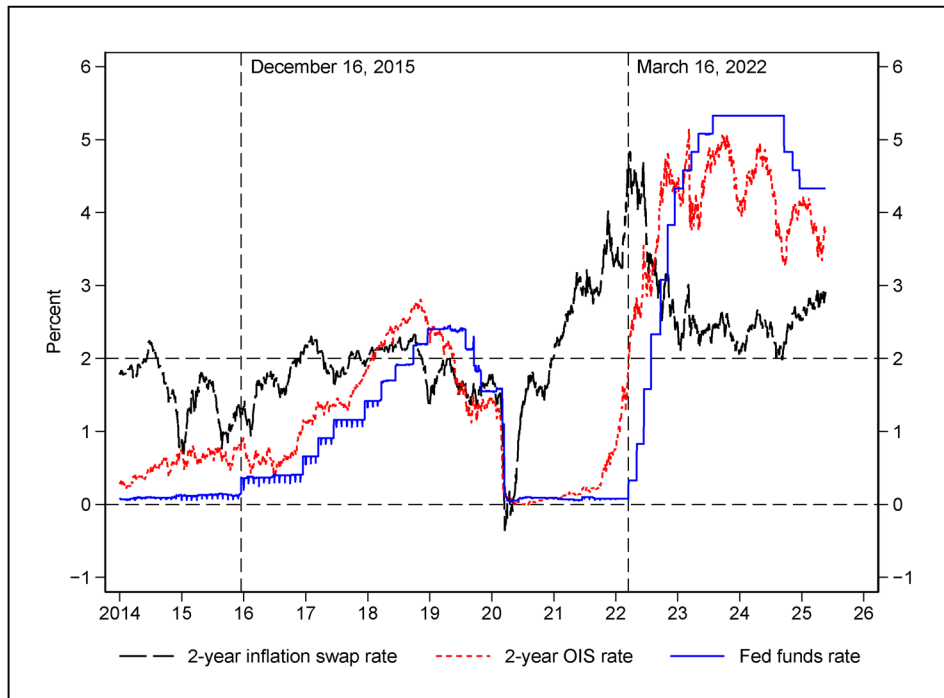
Yet, even today, the sentiment in some policymaking circles is that open admission of lack of knowledge can be read as a sign of weakness and is to be avoided. The methodological issues that so concerned Hayek continue to be present in modelling monetary policy. Optimal control exercises applied to an estimated model of the economy, under the false assumption of perfect knowledge are not uncommon. Indeed, such optimal control exercises can be found in briefing materials informing policy and influencing discretionary decisions.

To be sure, the risks of formulating policy under the presumption of perfect knowledge are sometimes acknowledged in policy circles, and considerable policy research over the past few decades is available that could improve policy design. Yet, insufficient progress has been made in ensuring that monetary policy is formulated in a systematic manner, emphasizing robustness over discretionary fine tuning.

III. Could Simple Rules Have Helped with the Pandemic Policy Challenge?

How did the pretence of knowledge and proclivity for discretion contribute to the post-pandemic inflation surge and how could guidance from simple rules have helped avoid this policy error?

The policy response at the beginning of the pandemic was appropriately forceful, a policy success. The Fed, and other central banks that adopted similar easing policies, helped the economy greatly during 2020, averting worse outcomes that would have likely materialized had the policy response been timid. However, the easing was implemented without sufficient planning for the exit strategy and with the false confidence that this exceptional accommodation was unlikely to trigger notable inflation pressures. To provide additional accommodation at the ZLB, forward guidance was employed, but without proper conditioning on the evolution of the inflation outlook. This proved consequential once the economy started to recover. Stronger than anticipated growth, coupled with supply bottlenecks, exerted greater upward pressure on prices than had been expected. This should have prompted a policy correction during 2021. Rather than adjust policy to account for rising inflation, as a systematic framework would have suggested, the Fed used its discretion to continue to peg the federal funds rate at zero. Figure 2 provides a visual summary: It compares daily data for the federal funds rate, and the two-year OIS rate with the two-year inflation swap rate. As can be seen, by the time policy liftoff was implemented, on March 16, 2022, the two-year inflation swap rate had already exceeded 4%. By comparison, the liftoff from the

Figure 2 The Pandemic Policy Challenge

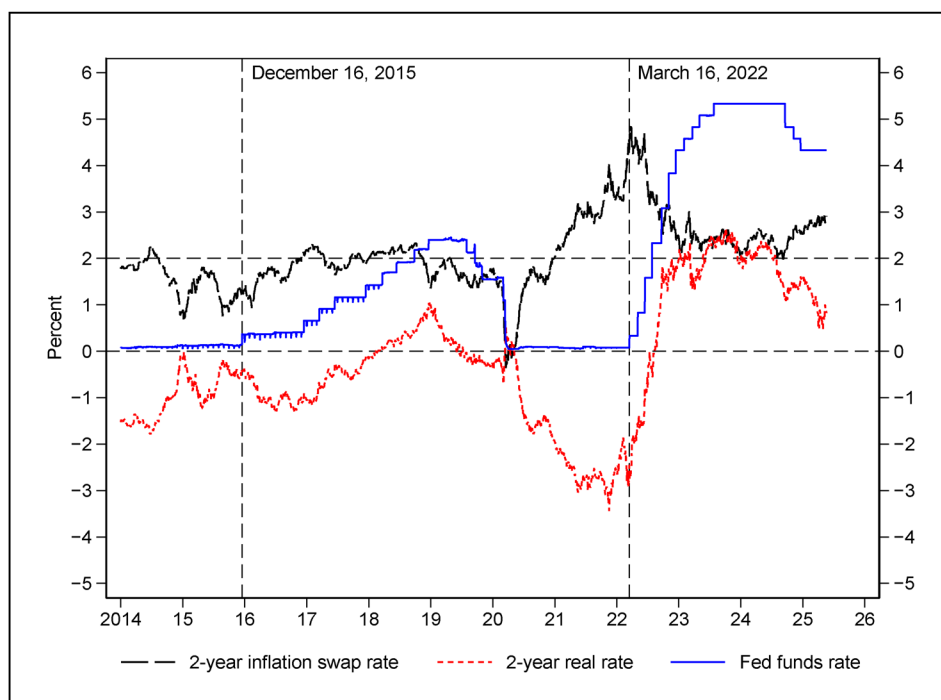
Note: Vertical lines denote liftoff following ZLB episodes.

Fed's earlier encounter with the ZLB on December 16, 2015 was implemented before similar inflation pressures materialized.

To see the Fed's policy error more clearly, it is instructive to focus on the two-year *real* interest rate implied by Fed policy. Figure 3 reproduces the overnight rate and two-year inflation swap rate from Figure 2 but replaces the two-year OIS rate with the corresponding ex ante two-year real interest rate. As can be seen, by maintaining the overnight rate at zero while actual and expected inflation kept rising beyond the Fed's inflation goal, the Fed was pushing real interest rates to even lower and excessively negative levels—adding accommodation instead of removing it. During 2021, the Fed fell into the forward guidance trap (Orphanides 2024).

Figure 4 places the Fed's policy error in this episode in historical perspective. Since comparable swaps data that can be used to construct ex ante real interest rates are not available for the 1970s, we need to resort to proxies. The figure presents a proxy for the real federal funds rate since the late 1960s based on inflation projections from the Survey of Professional Forecasters (SPF). The inflation forecast shown in the figure corresponds to the median year-on-year, three-quarter ahead forecast of inflation for the GNP/GDP deflator. The real rate proxy reflects the difference between the quarter-average federal funds rate and this real-time inflation forecast. As can be seen, the minimum over the sample since the late 1960s was reached in 2022Q1. Compared to the 1970s, the real interest rate was even more negative in late 2021 and early 2022.

Figure 3 The Forward Guidance Trap



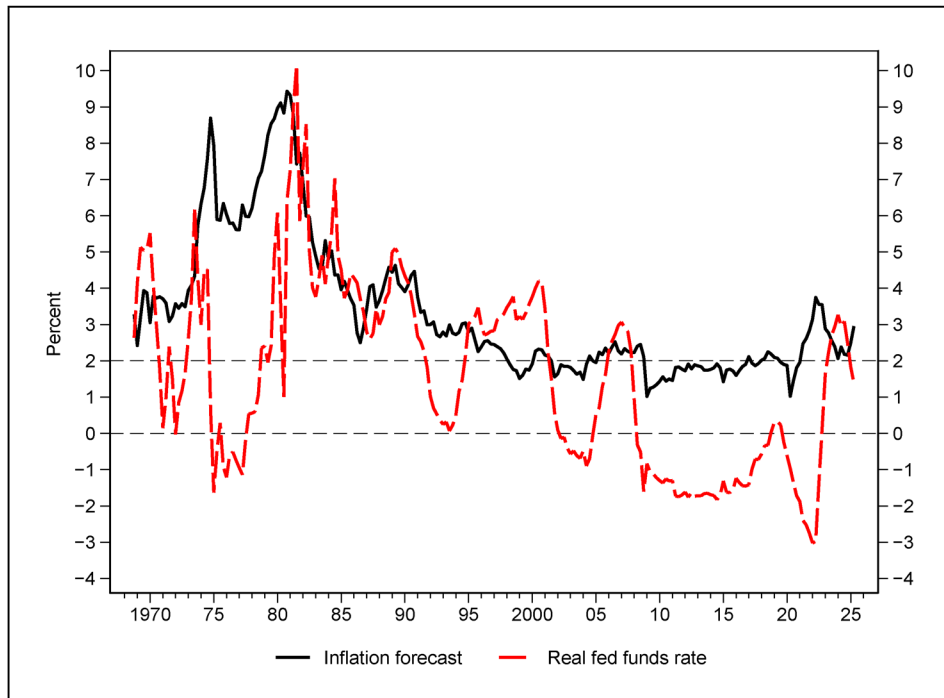
Note: Vertical lines denote liftoff following ZLB episodes. The real interest rate reflects the OIS rate minus the inflation swap rate.

The concerns expressed at the time that the Fed was behind the curve, similar to the experience of the 1970s, were justified. Fortunately, unlike the 1970s, during 2022 the Fed corrected its policy stance more promptly and decisively. Inflation was checked before becoming embedded in longer-term inflation expectations, limiting the cost of the post-pandemic policy error.

A more systematic policy approach would have been better. Guidance from simple and robust policy rules would have helped the Fed avoid this mishap. This is not a new suggestion. Consider the policy advice offered over the years by participants of earlier editions of this conference: Milton Friedman, Allan Meltzer (including his joint influential work with Karl Brunner), Ben McCallum, and John Taylor. The recommendation to strive for systematic policy, guided by simple rules, has been a recurrent theme over the years, most recently at the 2024 edition of this conference, the Mayekawa lecture delivered by John Taylor (Taylor 2024).

In light of the focus on Fed policy, I would note that research staff at the Federal Reserve System has contributed importantly to this research over the years, albeit with insufficient success at convincing policymakers to consistently eschew policy discretion over time.

An early example appeared in 1935, when Carl Snyder, the chief statistician of the Federal Reserve Bank of New York, suggested a version of the simple k-percent rule

Figure 4 The Post-Pandemic Error in Historical Perspective

Note: Real fed funds rate reflects quarter-average rate minus SPF median GNP/GDP deflator inflation forecast, year-on-year, three-quarter ahead.

that was later popularized by Milton Friedman:

“Specifically, it appears that if the growth of trade in our day is at a rate of about four per cent per annum compounded, then the highest attainable degree of general industrial and economic stability will be gained by an expansion of currency and credit, and especially bank credit, at this rate. No more and, what is equally important, no less” (Snyder 1935).

In retrospect, had the Fed followed a monetary rule along these lines, macroeconomic outcomes would have been much better during the 1930s. Unfortunately, the role of monetary policy and significance of money during the Great Depression were not widely understood before Friedman and Schwartz (1963).

In recent decades, with financial innovation making it harder to interpret the relationship between monetary aggregates and nominal income in real time, attention has shifted to simple rules with an interest rate instrument instead of the money supply.¹

Policy rules with a nominal interest rate as the policy instrument cannot be as simple as a $k\%$ money growth rule. At the very least, policy formulated with an interest rate instrument must adjust in a systematic fashion to the inflation outlook. Nonetheless,

1. Fischer (1990), and Taylor and Williams (2010) review the pertinent literature, with the latter focusing on simple and robust rules with an interest rate instrument that became popular following the seminal contribution by Taylor (1993).

policy research over the past several decades suggests that we can formulate simple reactive rules with an interest rate instrument that can deliver better outcomes than policy discretion, can help avoid major policy mistakes, and are superior to policy based on optimal control exercises under the pretence of knowledge.

To be sure, not all simple rules are good rules. The available policy research provides guidance on desirable characteristics of a simple benchmark policy rule that could guide policy in practice. The rule must preserve price stability over time, maintain inflation expectations well-anchored, in line with the Fed's 2% goal; it can be somewhat forward-looking, embracing informational benefits of current analysis, now-casting, short-term projections; it can be somewhat countercyclical, tempering business cycle booms and busts; and it must be robust to imperfect knowledge, protecting against model misspecification and accounting for the pitfalls of relying on unknowable natural rate concepts. In light of changes in the structure of the economy and state of knowledge, a simple rule must be subject to periodic review and adaptation.

IV. A Natural Growth Targeting Rule

Consider a rule that prescribes that the federal funds rate during each quarter be raised (cut) when projected nominal income growth exceeds (falls short) of the economy's natural growth rate.² More precisely, the rule compares the three-quarter ahead projection of year-over-year nominal income growth, n , to the current estimate of the natural growth rate, n^* , and prescribes:

$$\Delta i = \theta (n - n^*).$$

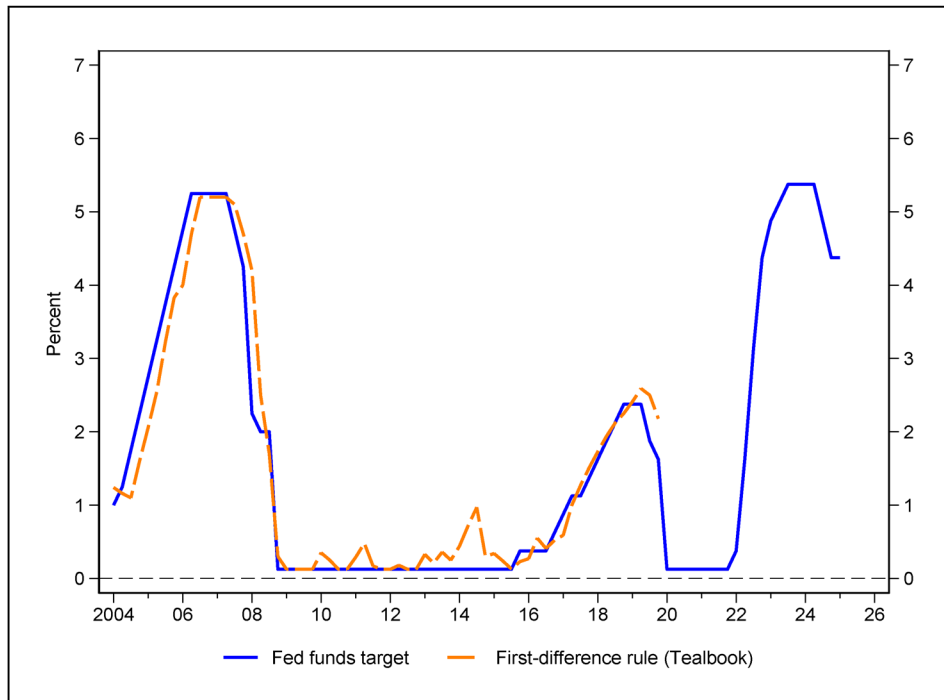
Here Δi is the prescription for the quarterly change of the policy rate from its level one quarter earlier, and θ is a response parameter. The natural growth rate may vary over time, $n^* = \pi^* + g^*$, where π^* is the constant inflation target, and g^* reflects the estimate of potential output growth that may vary over time. In the implementations discussed below, π^* is set to equal the Fed's inflation target, 2%, and the response parameter θ is set to 0.5.

Since 2004, a variant of this simple rule, implemented using Fed staff projections of the economy, has been presented in briefing material prepared by Fed staff for regularly scheduled FOMC meetings (The rule, referred to as the "First-difference rule," was shown in the Bluebook until 2010, and in the Tealbook since then.) Instead of projections of nominal income, the Tealbook variant employs Fed staff projections of three-quarter ahead, year-over-year core PCE inflation, and the difference in the three-quarter ahead projection of the output gap, y , from its estimated value four quarters earlier:

$$\Delta i = \theta (\pi - \pi^*) + \theta \Delta^4 y.$$

This is essentially similar to tracking nominal income growth by using core PCE

2. This follows Orphanides (2025a, b) where additional background information about this rule, its properties, and its implementation is provided.

Figure 5 Bluebook/Tealbook Variant of Natural Growth Rule

Note: Fed funds target (or midpoint of target range) and rule prescriptions constrained by ZLB. Post-2019 Tealbooks not yet available to the public.

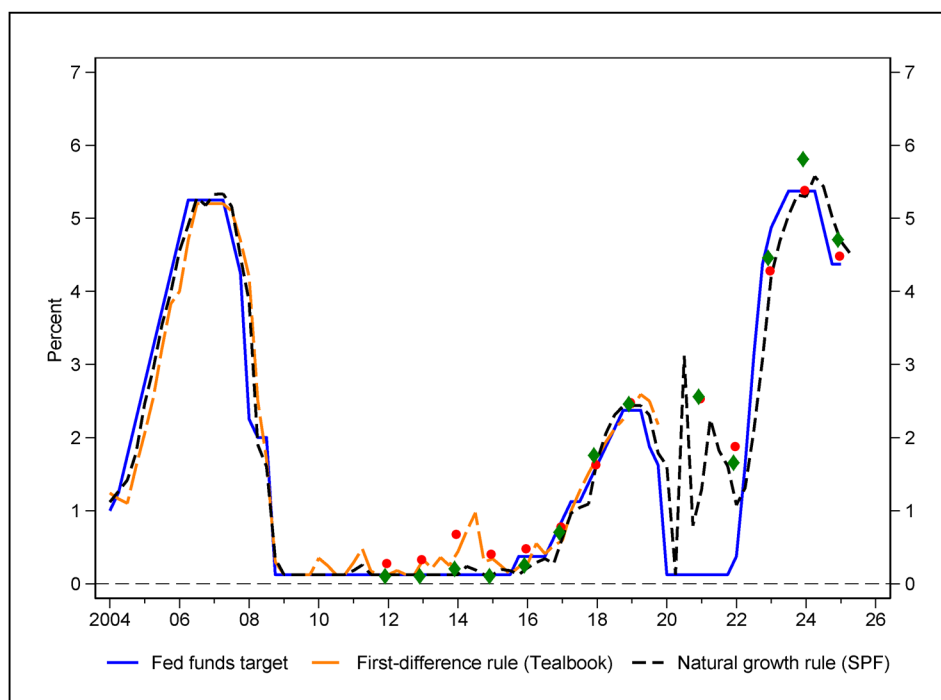
instead of the GDP price deflator for the measurement of inflation (The equivalence stems from the accounting identities: $(n - n^*) = (g - g^*) + (\pi - \pi^*)$, and $(g - g^*) = \Delta^4 y$.)

Figure 5 compares the policy rate to the First-difference rule, as presented in the Tealbook. For the policy rate, the end-quarter target federal funds rate (or midpoint of target range) is shown. For the rule, the prescription shown in the figure in each quarter is the one presented in the first Tealbook of that quarter.³ As can be seen, this rule tracks the contours of actual policy reasonably well from 2004 to 2019. Historical FOMC material is released to the public with a five-year lag so we need to wait until next year in order to examine Fed staff prescriptions for 2020, and until 2027 for 2021.

The natural growth targeting rule can also be implemented using FOMC projections of inflation and real economic activity, as presented in the Summary of Economic Projections (SEP). Two alternatives are presented with bullets and diamonds in Figure 6 starting in 2012, when the FOMC first announced the Fed's 2% inflation goal. Similar to the Tealbook implementation, both alternatives employ the median projections of core PCE inflation, but are based on different measures of economic activity. One alternative, shown in the figure with diamonds, employs projections of real GDP

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 3. All prescriptions shown correspond to the Fed's 2% inflation goal. Early in the sample, the Bluebook presented prescriptions with both a 2% inflation goal for PCE inflation, and 1.5% inflation goal, which was more consistent with a 2% inflation goal for CPI inflation at the time.

Figure 6 Alternative Variants of Natural Growth Rule



Note: Fed funds target (or midpoint of target range) and rule prescriptions constrained by ZLB. Bullets [diamonds] show the inflation-unemployment [real GDP] variants of the natural growth targeting rule based on median SEP projections.

growth:

$$\Delta i = \theta(\pi - \pi^*) + \theta(g - g^*),$$

and is therefore most comparable to the Tealbook variant.⁴ The other alternative, shown in the figure with bullets, employs the difference in three-quarter ahead projection of the unemployment rate, u , from its estimated value four quarters earlier:

$$\Delta i = \theta(\pi - \pi^*) + \theta\kappa\Delta^4 u.$$

This reflects an application of Okun's law, $\Delta^4 y = \kappa\Delta^4 u$, with coefficient $\kappa = -2$. In the figure, prescriptions from the SEP variants are shown only in the first quarter of each year, when the annual projections provided by the FOMC in the SEP correspond to the three-quarter ahead, year-on-year projection in the rule.⁵

4. Since the SEP does not explicitly provide FOMC participants' views regarding potential GDP growth, g^* , the median projection of real GDP growth over the "longer run" is employed as a proxy.

5. No prescriptions are shown for 2020Q1 as the FOMC decided not to publish projections in March 2020. In principle, remaining quarters could be shown using interpolations, but such interpolations can be problematic in periods of high volatility in quarterly projections such as exhibited in 2020–2021.

The natural growth targeting rule could also be tracked based on alternative forecasts and survey data. For comparison, Figure 6 includes an implementation using the median survey responses in the Survey of Professional Forecasters (SPF) that is published quarterly by the Federal Reserve Bank of Philadelphia and is available consistently over the whole sample. In each quarter, median survey responses are used to construct, n , the forecast of nominal income growth over four quarters ending three-quarter ahead. The corresponding estimate of the natural growth rate, n^* , is obtained by adding the Fed's 2% inflation goal to the median response regarding the ten-year annual-average real GDP growth—a proxy for potential output growth.

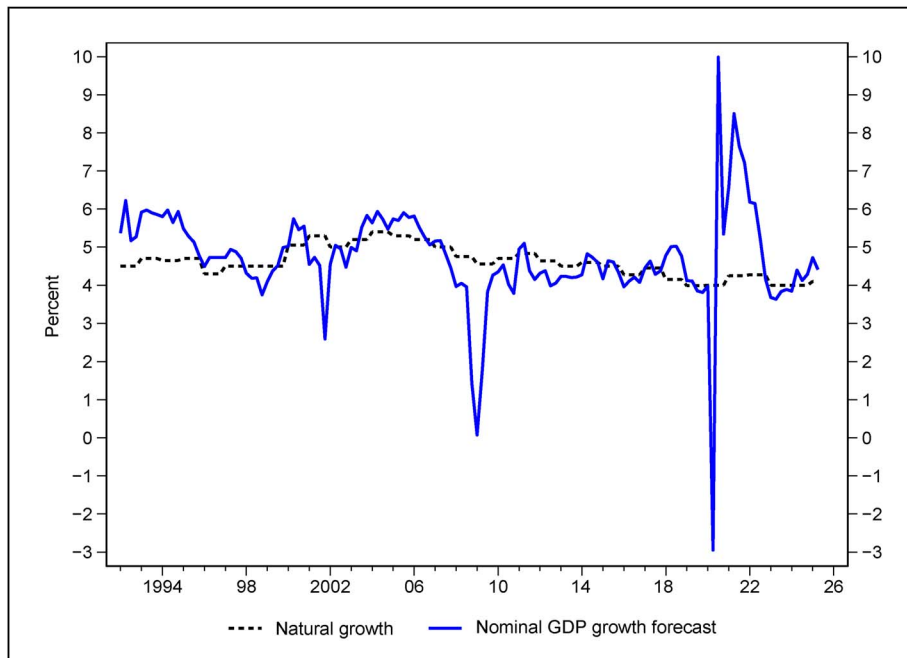
Figure 6 suggests that the alternative variants of the natural growth targeting rule provided broadly similar policy prescriptions over time and, prior to the pandemic, all captured the contours of actual policy reasonably well. The FOMC/SEP and SPF variants show even smaller deviations from actual policy than the Tealbook variant. Fed policy was described reasonably well by this simple, forecast-based policy rule. The figure also highlights one major deviation episode. This coincides with the Fed's post-pandemic policy error. Both the SPF implementation of the natural growth targeting rule and the two variants based on the FOMC/SEP projections called for an earlier liftoff from the ZLB and suggested a much higher policy rate for 2022Q1, when the Fed started the normalization process. Had the Fed adopted this policy rule as a benchmark, and disclosed prescriptions in real time, the post-pandemic policy error would likely have been avoided. The Fed's use of discretion would have been constrained. Considerably tighter policy would have been implemented already in 2021, consistent with the systematic policy that the Fed appears to have adhered to more closely before the pandemic.

Prescriptions from the SPF implementation of natural growth targeting with the Fed's current 2% inflation goal can be constructed since 1992, when the survey first included the question employed to obtain the natural growth rate. To highlight the simplicity of natural growth targeting, Figure 7 plots the two inputs needed for implementation of the rule: The short-term forecast of nominal GDP growth, and the corresponding estimate of the natural growth rate. The (unconstrained) rule prescription for the quarterly change in the target federal funds rate is simply one half the difference between the two series.

The corresponding (unconstrained) prescriptions for the level of the target federal funds rate from 1992 to the present are presented in Figure 8. The figure confirms that the ZLB severely constrained interest rate policy both at the start of the Global Financial Crisis and the beginning of the pandemic. The prescriptions for negative interest rates support the additional accommodation provided with balance sheet expansion in the two episodes.

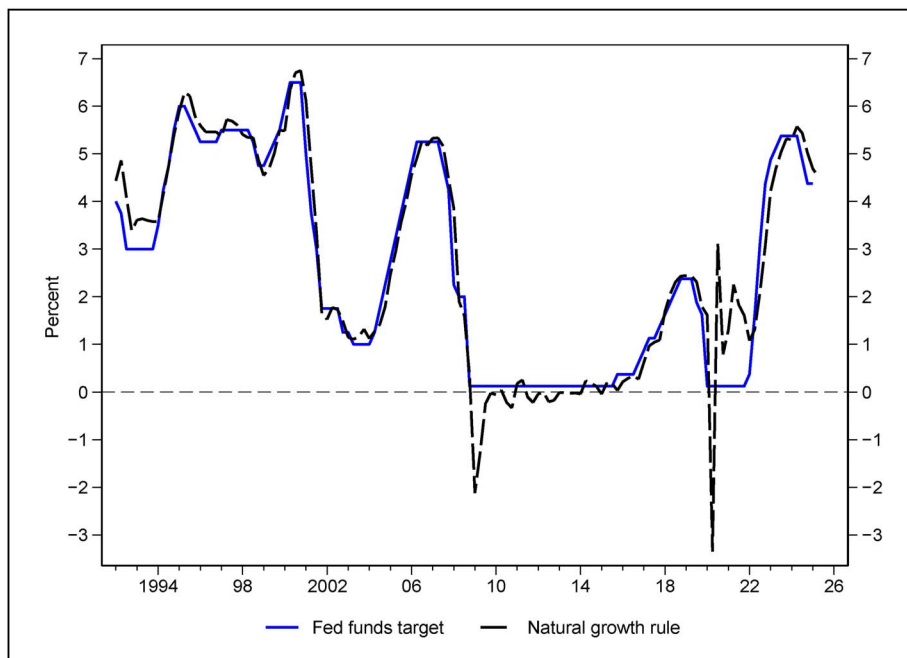
Even though the Fed only announced its 2% inflation goal in 2012, the figure suggests that Fed policy was broadly consistent with this rule since the start of the 1994 tightening cycle, with the notable exception associated with the post-pandemic policy error. Prior to 1994, the rule would have called for tighter policy, unless the Fed's implicit target was higher than 2%. Interestingly, this timing is consistent with the narrative associated with the "opportunistic approach" to disinflation: Prior to the 1990 recession, the Fed tolerated inflation as high as 4%, waiting for an unforeseen reces-

Figure 7 The Simplicity of Natural Growth Targeting



Note: Inputs for SPF-based implementation.

Figure 8 Natural Growth Targeting Rule: 1992–2025



Note: SPF-based implementation, unconstrained rule prescriptions.

sion to complete the disinflation. Only once the 1990 recession delivered the desired reduction in inflation, could Fed policy be described as consistent with a 2% inflation goal. And yet, the deviation observed in 1992 and 1993 was considerably smaller than that associated with the Fed's post-pandemic policy error.

V. Conclusion

Central banks can be more successful over time by embracing critical evaluation of their performance, learning from past errors and continually working to strengthen the resilience of their policy framework. The post-pandemic inflation surge highlights two persistent and interconnected challenges in monetary policymaking: the pretence of knowledge and the proclivity for discretion. These challenges can be better managed with guidance from simple policy rules, grounded in policy research and historical experience.

Focusing on the Federal Reserve, the benefits of formulating policy with guidance from a simple rule can be illustrated by examining a rule that has characterized Fed policy reasonably well since the early 1990s, with the notable exception of the period coinciding with the Fed's post-pandemic policy error. The rule recommends adjusting the federal funds rate each quarter based on whether projected nominal income growth exceeds or falls below the economy's natural growth rate. A version of this simple policy rule has been included in the Fed's Bluebook/Tealbook starting in 2004. Variants of the rule based on the FOMC/SEP projections and the survey forecasts in the SPF, yield similar guidance. Notably, this rule called for considerably tighter policy already in 2021, consistent with the more systematic policy approach that described Fed policy before the pandemic.

A benchmark policy rule, designed to be robust to imperfect knowledge, can protect against major policy errors, and promote systematic policy—key to strengthening public trust in the central bank. As Agustín Carstens emphasized in his Mayekawa lecture, trust is essential for fostering long-term macroeconomic stability (Carstens 2025).

Moreover, a benchmark rule facilitates clear and coherent communication by linking current and future policy decisions explicitly to the evolving economic outlook. This helps avoid pitfalls such as the forward guidance trap that contributed to delay in policy normalization and inflation surge following the pandemic.

Publishing a benchmark policy rule and its real-time prescriptions can constrain unhelpful discretion. No simple rule can address every situation, and adopting a clear benchmark does not preclude occasional discretionary action. Rather, it establishes a standard that requires policymakers to publicly explain any significant deviations, thereby enhancing accountability and ensuring that discretionary choices are well justified.

The implementation and communication of monetary policy can be strengthened through the formal adoption and public disclosure of a simple, robust benchmark rule.

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How Does Climate Change Interact with the Financial System?

Kakuho Furukawa, Hibiki Ichiue,
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We survey the literature on the interaction between climate change, which is associated with the growing intensity and frequency of natural disasters, and the financial system. This paper focuses on three topics. First, we review whether prices of assets, such as real estate, stocks, and green bonds, incorporate climate risks. While many studies show that asset prices reflect climate risks to some extent, many others show that real estate properties, in particular, do not adequately reflect climate risks. Such mispricing may deter efforts to address climate change. Furthermore, investor behavior and asset prices can overreact when risks become more clearly recognized. However, disclosure may help alleviate mispricing and overreaction. Second, we discuss how natural disasters affect bank behavior. Credit demand increases in affected areas. However, credit supply, particularly from non-local banks to young and small firms, is suppressed even in unaffected areas, especially when banks have low capital ratios. Third, we consider the role of insurance and related challenges. Insurance facilitates risk sharing and often complements bank finance. There are, however, at least three challenges: increasing insurance coverage, particularly among low-income households and young and small firms, maintaining insurer solvency, and avoiding moral hazard.

Keywords: Asset pricing; Banking; Insurance; Climate change;
Natural disaster; Financial stability

JEL Classification: G12, G21, G22, G41, Q54, R31

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I. Introduction

Recent years have seen a growing interest in global warming and the associated changes in the climate. Climate science suggests that rising temperatures are likely to be associated with changes in climate patterns, including an increasing intensity and frequency of extreme weather events such as floods and wildfires. With a potential impact of climate change on the financial system, financial institutions and authorities worldwide have taken an interest in climate change. However, research on the relationship between climate change and the financial system has only surged in recent years.¹

This paper aims to provide an extensive survey of the literature on the interaction between climate change and the financial system. With this aim in mind, this survey paper focuses mainly on asset prices, bank behavior, and insurance. Further, our survey covers not only the literature on climate-related natural disasters (such as floods) and environmental performance (such as reductions in greenhouse gas emissions) but also natural disasters and environmental outcomes not directly linked to climate change (such as earthquakes and toxic emissions). This is because they share many similarities and the literature often arrives at similar conclusions. Our survey suggests that climate change and the financial system interact in a fundamental way: climate change threatens financial stability, and at the same time, the financial system has the potential to reduce the cost of climate change and even to slow its progression.²

The structure of this paper is as follows: Section II summarizes channels through which climate change and the financial system affect each other. There have been many discussions on how the real economy and the financial system are affected when climate risks materialize. At the same time, the causal links from the financial system to climate change through the real economy are also important. For instance, financial constraints can increase greenhouse gas emissions by preventing firms from taking action such as investment in green technologies.

Section III reviews whether asset prices factor in climate-related risks. This question is important because, for instance, the misvaluation of climate risks can lead to a misallocation of resources. While many studies show that prices of assets, such as stocks, corporate and municipal bonds, syndicated loans, and weather derivatives, factor in climate-related risks to some extent, many other studies show that asset prices do

1. This development is illustrated by the publication of the special issue on “Climate Finance” of *the Review of Financial Studies* in 2020. Hong, Karolyi, and Scheinkman (2020), who provide an overview of the special issue, observe: “Even though we financial economists are late to the game, we hope that this climate finance issue illustrates that there are many important questions where financial economists are naturally suited given their toolkit and interests.” How rapidly the literature has changed can also be seen from the study by Diaz-Rainey, Robertson, and Wilson (2017), who find that three highly regarded finance journals, including *the Review of Financial Studies*, had not published a single article related to climate finance between January 1998 and June 2015.
2. Since the release of the working paper version of this survey, several survey papers focusing on specific aspects of this literature have been published. For instance, Giglio, Kelly, and Stroebe (2021), Pástor, Stambaugh, and Taylor (2024), de Bandt et al. (2024), and Vyshnevskiy and Sohn (2025) focus on asset pricing of climate risks, the financial effects of sustainable investing, the effects of climate change-related risks on banks, and the role of central banks in supporting climate actions, respectively. This paper complements these surveys by providing an overview of the transmission channels of the interactions between climate change and the financial system and surveying the literature on various aspects of this interaction.

not adequately reflect climate risks. For instance, several studies show that properties exposed to sea level rise risk tend to sell at more discounted prices in areas with a lower percentage of residents who believe in global warming, all else being equal. A number of studies provide evidence that investors can overreact when risks become more clearly recognized due to, for instance, natural disasters occurring in nearby regions. These results suggest that asset prices could fall substantially as climate-related risks materialize. Several studies show that real estate properties tend to be overvalued in areas with insufficient disclosure. Meanwhile, the results for the premium on the yields of green bonds—i.e., bonds issued to support specific climate-related or environmental projects—are mixed.

Section IV discusses bank behavior when natural disasters occur. It has been observed that the banks' solvency deteriorates when the areas in which they operate are affected by a natural disaster. Several studies show that while the demand for credit increases in the affected areas, the supply of loans is suppressed due in part to a lack of bank capital. Some studies suggest that young and small firms are susceptible to borrowing constraints. A number of studies, however, find that local banks in affected areas are more likely than non-local banks to continue lending to households and firms. Many studies find that credit supply also tends to be restricted in unaffected areas. This effect is stronger when banks have a low capital ratio, the unaffected areas are unimportant to banks (for instance, because the areas account for a small share of the banks' business), and the unaffected areas are exposed to a high risk of disasters. Meanwhile, public support for banks has the side effect of distorting resource allocation.

Section V investigates the role of insurance and related challenges. Insurance is important in alleviating damage from disasters and often complements bank finance. There are, however, at least three challenges related to insurance: increasing insurance coverage to provide more protection and improve risk sharing, maintaining the solvency of insurance firms when climate-related risks materialize, and avoiding the problem of moral hazard. The problem of inadequate insurance coverage is particularly prevalent among low-income households and young and small businesses. Some studies suggest that this is partly due to a lack of awareness on the demand side and could be improved with better risk communication. Among other things, the difficulty of diversifying natural disaster risk hinders the supply of insurance. Some studies suggest that natural disasters have deteriorated insurance firms' health, leading to fire sales of assets, higher insurance fees, and reduced underwriting of insurance. Meanwhile, there are concerns that insurance creates moral hazard and slows down efforts to reduce the impact of climate change.

Finally, Section VI concludes this paper. While the studies surveyed in this paper are diverse and wide-ranging, we here focus on three major policy implications.

II. Channels through which Climate Change and the Financial System Affect Each Other

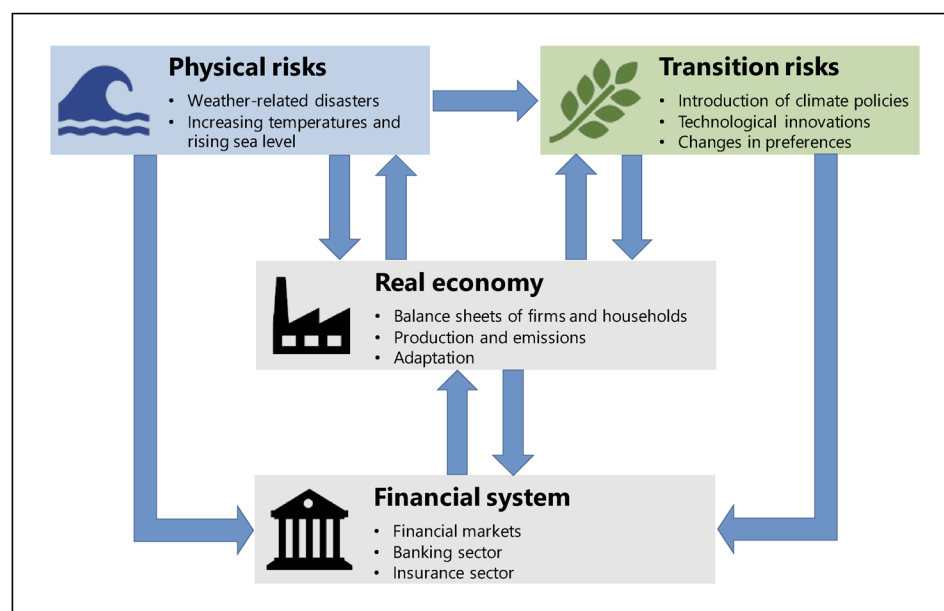
Considerable attention has been paid to the effects of climate change on financial stability, in particular channels through which climate change affects the financial system

(Batten et al. 2016, 2020), as central banks and supervisors have expressed their strong interest in this issue (see, e.g., Carney 2015; Lagarde 2020). At the same time, it is also important to deepen our understanding of how the financial system can affect climate change. Against this background, Figure 1 provides an overview of how climate change and the financial system affect each other.

Climate-related risks can be classified into physical and transition risks. When these risks materialize, the financial system is affected through, broadly speaking, two types of channels: direct channels and indirect channels via the real economy. Furthermore, once the financial system is affected, feedback loops between the real economy and the financial system may start to operate.

Physical risks arise from the physical impacts of climate change and can be further divided into acute physical risks, i.e., risks driven by extreme weather events such as floods and droughts, and chronic physical risks, i.e., risks driven by longer-term shifts in the environment, such as rising sea levels. When physical risks materialize, physical capital, such as factories and houses, is damaged. This leads to a deterioration in firms' and households' creditworthiness and the value of collateral, which in turn affects banks' balance sheets and limits the ability of firms and households to borrow. For these reasons, credit supply from banks is restricted exactly when firms' and households' demand for recovery and liquidity purposes increases. It is also possible that if the losses caused by the materialization of physical risks are covered by insurance, insurers may conduct a fire sale of assets to finance payouts. If payouts are sufficiently large, this can lead to a deterioration in the health of insurance firms. Moreover, if expected losses are revised upward, some physical risks may no longer be insurable, reducing the availability of insurance for firms and households. Financial institutions may also be directly affected by physical destruction in the form of damage to their of-

Figure 1 Interaction between Climate Change and the Financial System



fices, systems infrastructure, and human resources, which can reduce their operational capacity. When physical risks materialize, their impact on the economy is likely to be uncertain for a while, leading to a drop in the prices of risky assets as well as more cautious behavior on the part of firms, households, and financial institutions.

Meanwhile, *transition risks* arise from a transition to a lower-carbon economy. Specific factors that drive such risks include policy changes, technological breakthroughs, and shifts in preferences and social norms. For instance, if a carbon tax is introduced in an attempt to reduce greenhouse gas emissions, firms that emit large amounts of CO₂ could face difficulties in their business. In addition, the market value of fossil fuels such as oil and coal may drop substantially, leaving firms with “stranded assets” that are no longer able to earn an economic return, such as fossil fuels in the ground, production and processing facilities, and distribution infrastructure. As a result, the balance sheets of firms that own those assets may be greatly damaged.³ On the other hand, energy prices overall may rise as cheap fossil fuels are no longer available, which may reduce firms’ profitability. It is also possible that technological changes that spur the transition to a low-carbon economy affect the profitability of certain firms and industries. For instance, technological advances in electric vehicles may make conventional automobile manufacturers obsolete. Further, financial institutions with large exposure to such industries may incur losses as a result of technological changes, even though technological progress benefits the economy in the long run. Lastly, there have already been large shifts in preferences and social norms associated with climate change that are affecting financial markets. The growing awareness of environmental responsibilities can potentially influence asset prices and firm behavior. Note that transition risks may materialize even before an actual transition occurs through the expectations of financial markets or firms.

Physical risks and transition risks are likely to interact with each other. For instance, if physical risks become apparent to all through natural disasters, voters may become more aware of climate change and urge politicians to make policy changes. On the other hand, transition risks may also alter physical risks. For instance, if the introduction of a carbon tax is much slower than warranted, mitigation efforts of firms and households would be insufficient to reduce greenhouse gas emissions, leading to high physical risks.⁴ Financial institutions’ efforts would also be affected. For instance, banks may enable inefficiently large investment in carbon-intensive capital if they do not consider the cost of associated climate change.

There are also transmission channels in the opposite direction through which the financial system influences climate change risks and their impacts on the real economy through people’s mitigation and adaptation efforts. Mitigation focuses on containing

3. The impact of a carbon tax on financial institutions depends on the policies of other countries. For instance, Laeven and Popov (2023) find that the introduction of a carbon tax is associated with a decline in bank lending to coal, oil, and gas companies in domestic markets, but an increase in foreign markets. This form of tax arbitrage is particularly pronounced for banks with large exposures to fossil fuel lending. They also find that banks reallocate a relatively larger share of their fossil loan portfolios to countries with less stringent environmental regulation and bank supervision.

4. There is evidence that lobbying has delayed the transition to a low-carbon economy. Meng and Rode (2019) examine the case of the Waxman-Markey bill, which failed to be enacted, using comprehensive U.S. lobbying records. They find that lobbying by firms expecting losses from the bill was more effective than lobbying by firms expecting gains.

climate change itself, for instance, through the reduction of greenhouse gas emissions, while adaptation reduces the impact of climate change, for instance, through the construction of better flood defenses.

The financial system may impede mitigation and adaptation actions for a variety of reasons. One possible source of this impediment is the mispricing of assets. For instance, if stock markets, in their valuation of firms, do not adequately distinguish between firms with high and low carbon emissions, this can deter efforts to reduce emissions. As discussed by Anderson et al. (2019), if property markets fail to incorporate climate-related risks such as floods and tropical cyclones, they may induce excessive investment in areas that are exposed to high risks, and, at the same time, discourage development of areas that are relatively shielded from these risks. Furthermore, public policy, such as the provision of public disaster insurance at subsidized rates, can induce moral hazard and distort resource allocation. The literature also suggests that there is generally not sufficient public information to accurately assess the value of assets or to optimize decisions with regard to, for instance, stock investment. Mandatory disclosure could be used to address insufficient information.

Another potential source of impediment is financial constraints. Although one might expect that tight financial conditions reduce production and therefore emissions, the literature suggests the opposite: they prevent firms from taking action. For example, using data on 10,776 firms across 22 emerging markets, De Haas et al. (2025) show that credit constraints reduce investment in green technologies, such as more energy-efficient machinery, and increase CO₂ emissions. They also estimate that bank deleveraging due to the global financial crisis increased carbon emissions by 5.6 percent a decade later. Bartram, Hou, and Kim (2022) find that after California introduced its cap-and-trade regulation, financially constrained firms shifted emissions and output to other states, particularly those nearby or with less stringent regulations, and increased their total emissions. This behavior was especially common among firms that had invested less in abatement technologies prior to the regulation. In contrast, this pattern is not observed among unconstrained firms.

The characteristics and behavior of investors can also drive the environmental performance of firms. This is illustrated, for example, by Dyck et al. (2019), who find that institutional ownership improves environmental and social performance when institutional investors come from countries with a strong community belief in the importance of environmental and social issues.⁵ Meanwhile, Shive and Forster (2020) find that, within public firms, greenhouse gas emissions are negatively associated with mutual fund ownership and board size, suggesting that increased oversight may result in firms improving their environmental performance.

Recent studies also examine the roles of equity finance in environmental performance and provide mixed evidence. For instance, using data from 48 countries and 16 industries over the period 1990–2015, De Haas and Popov (2023) find that carbon-intensive industries reduce emissions more rapidly in countries with deeper stock mar-

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5. Although many empirical studies, including Dyck et al. (2019), rely on ESG ratings, ratings from different providers are found to disagree substantially. The divergence in ratings poses a challenge for empirical research, as the choice of data source can alter a study's findings. See Chatterji et al. (2016), Liang and Renneboog (2017), and Berg, Kölbel, and Rigobon (2022) for further discussions.

kets, primarily because stock markets facilitate green innovation in these industries. In contrast, Shive and Forster (2020) find that private firms that are not sponsored by private equity funds are less likely to emit greenhouse gases and incur administrative penalties than comparable public firms, while there are no differences between private sponsor-backed firms and public firms. These findings suggest that short-termist pressure from outside investors for financial performance force public firms to emit more greenhouse gases than private firms.

III. Do Asset Prices Reflect Climate-Related Risks?

Whether prices of assets, such as real estate, stocks, bonds, and loans, reflect climate change risks has significant implications for the stability of the financial system. If they do not, or do so only partially, there is a risk that asset markets will experience significant disturbance when climate change risks materialize, or when people become more aware of the risks. This disturbance, in turn, will have implications for the real economy as households', firms', and financial institutions' balance sheets may be damaged as a result of the abrupt repricing of their assets. Moreover, if these assets are used as collateral, a decline in asset prices may severely impair agents' ability to borrow.

The misevaluation of climate change risks can also lead to misallocation of resources. For instance, if stock markets do not adequately price firms with low carbon emissions relative to those with high emissions, this can deter efforts to reduce emissions. Similarly, if real estate property prices do not reflect the risk of floods or sea level rise, this may encourage excessive development in risky areas, which poses an immense threat to housing, infrastructure, and people's lives.

Against this background, in the present section, we review the literature investigating whether—and to what extent—prices of a wide range of assets incorporate climate change risks. We start with the market for real estate, on which there is a rich literature on the association with climate change risks and which provides a good illustration of what factors encourage (or hinder) the incorporation of climate change risks into prices (Section III.A). We then review the literature on stocks (Section III.B), green bonds (Section III.C) and other types of financial assets such as corporate and municipal bonds, syndicated loans, and weather derivatives (Section III.D). Finally, we briefly summarize this section (Section III.E).

A. Real Estate Property

Many studies—most using data from the United States—find that property prices do not adequately reflect the physical risks of climate change, such as sea level rise and floods. For instance, Bernstein, Gustafson, and Lewis (2019) find that, on average, homes exposed to sea level rise sell at a discount relative to unexposed properties, but the price discount is concentrated in the non-owner-occupied segment of the market, in which buyers tend to be more sophisticated.⁶ They also find that although the prices

6. The authors find that descriptive statistics are consistent with the idea that non-owner occupiers are more sophisticated, as they tend to originate from zip codes with higher education and income levels. Further, owner-occupier to non-owner occupier sales earn higher returns than non-owner occupier to owner-occupier sales.

of owner-occupied properties are not significantly related to sea level rise exposure on average, such exposure does affect prices when residents are sufficiently worried about sea level rise, which suggests that “unsophisticated” buyers are susceptible to local beliefs.⁷

Another study examining whether house prices reflect different beliefs about climate change is that by Baldauf, Garlappi, and Yannelis (2020), who use comprehensive transaction data to relate prices to flood projections of individual homes and measures of beliefs about global warming in each county in the United States. They find that houses projected to be underwater due to sea level rise in believer neighborhoods (i.e., counties with a relatively large share of people believing in global warming) sell at a discount compared to houses in denier neighborhoods. As a placebo test, they also examine commercial properties, for which differences in local beliefs are likely less important because the participants in those transactions tend to be more sophisticated than those in residential real estate transactions. Additionally, firm headquarters may be located somewhere else and decisions by corporations may therefore be made in a different geography from where the real estate is located, which is not the case in residential housing transactions. Consistent with this intuition, the authors find that differences in beliefs about climate change do not appear to affect the price of commercial real estate.

Meanwhile, using two decades of sales data covering the universe of homes in the United States, Hino and Burke (2021) find little evidence that the discounts on properties located in floodplains reflect the expected damage. Their findings indicate that floodplain homes are currently overvalued by US\$44 billion in total. They also find that the home price discount is larger for commercial buyers, who are regarded as a group likely to have more experience purchasing real estate and greater resources to seek out flood-related information than individuals and households. Furthermore, a large discount tends to be observed in states where sellers must disclose information about flood risk to potential buyers. This result suggests that policies to enhance disclosure could improve the functioning of the market. That a lack of information disclosure leads to the overpricing of houses is also shown by Giglio et al. (2021). They perform a systematic textual analysis of for-sale listings to measure the frequency with which climate-related text (e.g., mentions of flood zones) appears in the written description of the listed properties. They show that when the fraction of property listings with climate-related text doubles, there is a 2–3 percent relative decrease in the prices of properties in a flood zone compared to comparable properties.

While the studies mentioned so far suggest that house prices partially reflect sea level rise risk, Murfin and Spiegel (2020) consistently find no evidence for effects of sea level rise exposure on real estate prices in a variety of specifications and test settings. They highlight the identification problem that arises from the presence of correlation between amenity and risk exposure. In particular, while the literature often uses

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7. Bernstein, Gustafson, and Lewis (2019), as well as many others, such as Baldauf, Garlappi, and Yannelis (2020) and Murfin and Spiegel (2020), use data from the Yale Climate Opinion Survey (Howe et al. 2015). This survey provides answers of respondents in the United States at the county level to questions such as (i) whether they think that global warming is happening, (ii) whether they will be personally harmed by global warming, and (iii) how worried they are about global warming.

data on housing elevation (i.e., the elevation above sea level) and assumes that this is negatively associated with sea level rise exposure, housing elevation is also correlated with housing amenity, such as scenic views. Thus, even if house prices are found to be higher for higher elevations, we cannot identify whether this is due to less sea level rise exposure or greater amenity. To address this identification challenge, Murfin and Spiegel (2020) exploit cross-sectional differences in trends in vertical land motion due to land subsidence and land rebound, which provide variation in the expected time to flood due to sea level rise for properties of similar elevation.⁸

The importance of heterogeneity in risk perceptions as a source of overpricing in housing markets is highlighted by Bakkensen and Barrage (2022). Constructing a theoretical model with heterogeneity, they argue that the impact of risks on property prices may be suppressed since optimistic people move to high-risk regions in place of non-optimistic people when the risks increase. Conducting their survey, they indeed find significant heterogeneity in flood risk perceptions and amenity values. Using this survey result, they calibrate their theoretical model and find that house prices exceed fundamentals by around 10 percent.

In sum, the literature finds that property prices do not adequately reflect climate change risks. In particular, properties tend to be overpriced when buyers are unsophisticated, they do not believe in global warming, or information disclosure is insufficient. These results suggest that property prices may drop significantly once people become aware of the risks. In fact, several studies find that when natural disasters happen, property prices decline even in areas that are not directly affected or damaged. For instance, Hallstrom and Smith (2005) find that although Hurricane Andrew did not hit Lee County, Florida, in 1992 and the storm was a “near-miss,” home values in high-risk flood areas of the county declined by at least 19 percent relative to those in low-risk areas of the county. This suggests that the large hurricane conveyed risk information to homeowners in the county. Further evidence in this regard is provided by Ortega and Taspinar (2018), who use Hurricane Sandy in 2012 as a natural experiment. They show that Sandy persistently reduced house prices in New York City’s flood zone relative to similar properties in the rest of the city, even if the hurricane did not damage the properties: a price penalty among non-damaged properties in the flood zone has gradually emerged, reaching 8 percent in 2017 and showing no signs of disappearing. Examining several hypotheses to explain their findings, such as out-migration or damaged neighbors (residential properties, businesses, and infrastructure), they conclude that updated perceptions of flood risk likely drove the persistent price decline.

While this subsection focused on the market prices of real estate properties, financial institutions’ valuations of property as collateral also matter. Overvaluation of collateral can lead to distortions in the allocation of resources, and a downward adjustment in the prices of collateral can threaten financial stability. For instance, Garbarino and Guin (2021) find that after a severe flood event in England in 2013–14, market prices of properties declined but lenders did not adjust interest rates or loan amounts

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8. Relatedly, while being close to the waterfront increases the exposure to sea level rise and flood risks, it also improves amenity by providing scenic views and access to water activities. To disentangle the effects of flood hazard and ocean view on coastal house prices, Bin et al. (2008) construct a three-dimensional measure of ocean view.

because their valuations of properties (used for mortgage refinancing) did not mark-to-market against the market price declines in neighborhoods. Their result implies that the lenders may have effectively provided subsidies for borrowers to invest in high-risk areas. Nguyen et al. (2022) show that lenders charge higher interest rates on mortgages for properties exposed to greater sea level rise risk. However, this risk premium is smaller in areas with a higher share of climate change deniers, which is consistent with the housing price literature showing that beliefs influence market outcomes.

B. Stocks

While the literature on real estate focuses on physical risks such as floods and sea level rise, many studies on stocks focus on transition risks faced by firms. Typical examples of firms with high transition risks are those that emit large amounts of CO₂. If policy measures are taken to penalize CO₂ emissions, such firms could face difficulties in their business. If a firm is more exposed to climate change risks than others, investors should demand higher returns, or carbon premia, from its stock in compensation, all else being equal. Some studies show that firms more exposed to climate change risk indeed provide higher returns, which suggests that stock prices, to some extent, incorporate some types of climate change risk. However, other studies find opposite results. In what follows, we first survey studies on the relationship between risk exposures and stock prices and then discuss the potential problems arising from mispricing and the usefulness of disclosures.

Using firm-level carbon emissions estimated by a data vendor, Bolton and Kacperczyk (2021) find evidence of a positive carbon premium in the United States; that is, stock returns are higher for companies with higher carbon emissions. Further, in a separate study, Bolton and Kacperczyk (2023) estimate the carbon premium for over 14,400 firms in 77 countries and find a widespread carbon premium in all sectors.

However, Aswani, Raghunandan, and Rajgopal (2024) find that the positive associations between carbon emissions and stock returns reported in previous studies, including Bolton and Kacperczyk (2021), disappear when using firms' self-disclosed emissions rather than vendor-estimated emissions. Bauer et al. (2022) show that green stocks across G7 countries generally outperformed brown stocks over the almost entire period from 2010 to 2021. While they intensively check the robustness of results, they find positive carbon premia only when using vendor-estimated emissions. Zhang (2025) points out that emissions are closely tied to sales and are known to investors only with substantial delay. After accounting for the data release lag, she finds that carbon returns turn negative in the United States and insignificant globally. She concludes that the positive carbon premia documented in previous studies reflect forward-looking information about firm performance contained in emissions data, rather than a true risk premium in *ex ante* expected returns.

Pástor, Stambaugh, and Taylor (2022) attribute high returns of green assets to unexpectedly strong increases in climate-related concerns. Supporting this view, Ardia et al.'s (2023) index of climate change concerns, which is constructed from news published by major U.S. newspapers and newswires, exhibits an upward trend. Ardia et al. (2023) show that, on days with unexpected increases in climate concerns, the green stock prices tend to rise whereas brown stock prices fall. This pattern holds for both

transition and physical risks. These results suggest that high returns of green assets may be driven by shifts in investors' risk perception, rather than negative carbon premia, and highlight the challenges of estimating premia from ex-post returns when unexpected changes in risk factors play an important role.

Recent studies quantify firm-level climate-related exposures using textual analysis of quarterly earning call transcripts. Sautner et al. (2023) define exposures to opportunity, physical, and regulatory shocks associated with climate change as the percentage of conversation in a transcript devoted to each topic. Using data on over 10,000 firms from 34 countries between 2002 and 2020, they find that the exposures are reflected in stock and option prices. In options, the relationship is particularly strong in the tails and for opportunity exposures. Li et al. (2024) measure exposures to physical and transition risks and identify firms that proactively respond to climate risks. They show that firms facing high transition risk have been valued at a discount, particularly after 2010, only when they do not actively manage their transition risk.

A widely used approach in the literature to examine the causal impact of climate risks on asset pricing is the event study. Some studies, for instance, use announcements of the issuance of green bonds as the event. For example, Flammer (2020) documents that stock market investors respond positively to the announcement of the issuance of green bonds, and that the responses are stronger for first-time issuers and bonds certified by third parties. The stronger response for first-time issuers than seasoned issuers suggests that initial issues convey substantial new information about the firm's commitment to green projects, while subsequent issues provide relatively less information. She also finds that, after the announcement, issuers' environmental rating improves, their CO₂ emissions fall, and they experience an increase in ownership by long-term and green investors. Along similar lines, Tang and Zhang (2020) examine the announcement returns in 28 countries and document that stock prices positively respond to green bond issuance. They also show that institutional ownership increases and stock liquidity improves after a firm issues green bonds.

Another strand of the literature focuses on political events. Since the likelihood of introducing climate change policies depends heavily on the political environment, transition risks may evolve discontinuously in the wake of political events, as exemplified by the adoption of the Paris Agreement in 2015 and the election of U.S. President Trump in 2016.⁹ If the Paris Agreement helped strengthen markets' expectations of transition to a lower-carbon economy, asset prices may have started to reflect transition risks to a greater extent. On the other hand, the election of President Trump, a climate skeptic, potentially lowered expectations of climate change policies. In fact, there are quite a number of studies focusing on the election of President Trump. Ramelli et al. (2021), for example, find that firms with high current carbon emissions enjoyed relatively high abnormal returns after Donald Trump was elected president in 2016. Hsu, Li, and Tsou (2023) suggest that 3-day window returns around this event for firms with higher toxic emission intensity are higher. Ilhan, Sautner, and Vilkov (2020) show that

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9. The Paris Agreement set the goal of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change." The agreement requires all parties to report regularly on their emissions and on their implementation efforts.

the cost of option protection against downside tail risks of carbon-intensive firms decreased after the election of President Trump. They also find that the cost rises when public attention to climate change spikes, as measured by increases in Google search volume data for the topic “climate change” and Engle et al.’s (2020) negative climate change news index, which captures the share of news articles that are about “climate change” and have been assigned to a “negative sentiment” category.

Many papers, except for those estimating carbon premia from ex-post returns, suggest that stocks, to some extent, price in some climate change risks. However, the literature also finds evidence for mispricing. For instance, examining the stock prices of food companies, which rely on water and hence are sensitive to drought risk, in 31 countries, and data on droughts since 1900, Hong, Li, and Xu (2019) find that a stronger long-term trend toward droughts in a particular country predicts lower profit growth and stock returns of food companies in that country. This predictability of returns indicates that the stocks of food companies are mispriced.

One concern that arises from the mispricing of climate-related risks is potential sudden changes in risk perceptions, which could lead to a shift away from risky assets, a plunge in stock prices, and severe financial instability. In fact, the literature indicates that events that raise the awareness of risks, such as abnormal weather events, lead to a larger decline in stock prices of firms with greater climate-related risks. For instance, using temperature data from 74 cities around the world where stock exchanges are located, Choi, Gao, and Jiang (2020) find that the number of Google searches on global warming-related topics in those cities increases significantly when they experience abnormally warm temperatures, implying that beliefs about climate change of individual investors are revised upward. They also find that stocks of carbon-intensive firms underperform those of firms with low carbon emissions in abnormally warm weather. In addition, retail investors (not institutional investors) sell off carbon-intensive firms in such weather, which is consistent with the conjecture that retail investors tend to be influenced by notable events. Moreover, stock returns are affected by extreme temperatures regardless of whether the firms are domestic or international or whether firms belong to specific industries, such as utilities and leisure, whose earnings are likely to be directly affected by rising temperatures. These results suggest that changes in returns are due to changes in investor perceptions rather than changes in firms’ fundamentals or future cash flows. The authors, therefore, argue that, as investors become more aware of climate risk, they seem to avoid holding stocks of high-emission firms similarly to “sin” stocks (stocks of alcohol, tobacco, and gaming companies).¹⁰

Another important issue is that investors may not only suddenly price in climate change risks when facing climate risk-related events but also overreact to them due to a salience bias, the tendency to overestimate the risk of events based on their vividness, proximity, or emotional impact. For instance, Alok, Kumar, and Wermers (2020) find that professional money managers within a major disaster region underweight disaster

10. Hong and Kacperczyk (2009) hypothesize that there is a societal norm against funding operations that promote vice and that some investors pay a financial cost in abstaining from these stocks. Consistent with this hypothesis, they find that sin stocks are less held by norm-constrained institutions such as pension plans as compared to mutual or hedge funds that are natural arbitrageurs, and sin stocks receive less coverage from analysts than stocks with otherwise comparable characteristics. The authors also show that sin stocks have higher expected returns than otherwise comparable stocks.

zone stocks much more than distant managers. They argue that this aversion to disaster zone stocks is related to a salience bias rather than superior information held by managers nearby, citing the following evidence. First, the post-disaster change in the return on assets or sales growth of firms in the disaster zone relative to firms close to the disaster zone is statistically indistinguishable from zero. Second, disaster zone stocks that are most underweighted by disaster zone funds subsequently outperform stocks that are overweighted by those funds, indicating a potential price pressure effect due to the misjudgment and overreaction of the funds. Huynh and Xia (2023) quantify firms' exposure to physical risk using establishment-level data on subsidiaries, branches, and plants, combined with disaster damage data in the United States. They find that, when firms are exposed to disasters, both corporate bond and stock prices tend to overreact, leading to higher ex-post returns. This effect is more pronounced for firms with weaker environmental profiles and higher levels of institutional ownership.

Finally, many studies examine the impact of climate-related disclosure in the stock market. Using a survey on institutional investors, Ilhan et al. (2023) find that many institutional investors consider climate risk reporting to be at least as important as financial reporting. Several studies on voluntary disclosures suggest that stocks tend to be undervalued in the absence of disclosure. Matsumura, Prakash, and Vera-Muñoz (2014), for example, find that firm value decreases as carbon emissions increase using carbon emissions data voluntarily disclosed by S&P 500 firms. They also find that the median value of firms that disclose their carbon emissions is higher than that of comparable non-disclosing firms. This result indicates that a penalty is imposed on firms that do not disclose. Further, Flammer, Toffel, and Viswanathan (2021) document that firms voluntarily disclosing climate risks in response to environmental shareholder activism experience valuation increases.

However, establishing causality between firms' disclosure activities and stock price reactions is inherently challenging. For instance, firms with favorable private information may be more inclined to disclose voluntarily, leading to potential self-selection bias. Although the studies mentioned above apply bias correction methods, they do not necessarily solve the issue. One solution to mitigate self-selection bias is examining the impact of mandatory disclosure requirements. Given the global trend toward enhancing mandatory climate disclosure based on advanced frameworks such as the Task Force on Climate-related Financial Disclosures (TCFD), the literature increasingly exploits such opportunities.¹¹ However, Matsumura, Prakash, and Vera-Muñoz (2024) suggest that mandatory disclosure is not necessarily a panacea. In the United States, while firm managers are required to disclose material climate risks, their disclosure decisions are confounded by the lack of consensus on materiality and by uncertainty surrounding the enforcement of disclosure regulations. The authors find that the cost of equity is lower for disclosing firms than for non-disclosing firms, particularly in industries where climate risks are deemed material. This result suggests that markets use information of industry-level materiality to evaluate the credibility of managers' disclosure decisions.

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11. See, for example, Ichiue (2025).

C. Green Bonds

Another type of asset on which much research has focused is green bonds and many studies estimate the premium—or “greenium”—on such bonds. Many of these studies focus on municipal green bonds in the United States. As highlighted by Larcker and Watts (2020), U.S. green municipal bonds are identical to ordinary municipal bonds in all ways except that the use of proceeds is allocated to environmentally friendly projects. They argue that any differences in security pricing are attributable to investor preferences for non-monetary security features, rather than differences in expectations about future cash flows or risk. Even if their argument is correct, it is still important for us to understand this growing market related to climate change risks.

The empirical results on the greenium are mixed. Using data on secondary market yields, Karpf and Mandel (2018), for example, find that green bonds display a positive premium. However, their result is questioned by Baker et al. (2022), who observe that Karpf and Mandel (2018) compare taxable and non-taxable securities, although pricing in the U.S. municipals market is highly sensitive to tax features. To address this problem, Baker et al. (2022) focus on after-tax yields. They find a minus 5–9 basis points premium. Meanwhile, focusing on the period from 2013 to 2017, Zerbib (2019) uses observations for green bonds traded in the secondary market and for which the counterfactual yields of ordinary bonds with the same characteristics, such as the issuer and the currency, can be estimated. He finds a statistically significant green bond premium of minus 2 basis points after controlling for the difference in liquidity between green and ordinary bonds using bid-ask spreads. Moreover, negative premiums are larger in absolute terms for financial and lower-rated bonds.¹² Pástor, Stambaugh, and Taylor (2022) examine German government’s green bonds and find that these bonds trade at lower yields than virtually identical non-green bonds.

In contrast, other studies find little evidence of a greenium. For instance, comparing green securities to nearly identical securities issued for non-green purposes by the same issuers on the same day, Larcker and Watts (2020) find essentially no premium on municipal green bonds. Moreover, using the certification by the Climate Bonds Initiative, which ensures that issuers of green bonds are actually using the financing proceeds for environmentally friendly purposes, they also show that the lack of an observed premium is unlikely to be driven by the presence of greenwashing (the practice of trying to make people believe that an entity is doing more for sustainability than it really is). Since investment banks appear generally to charge fees to issue green bonds in part due to the cost associated with certification processes, the authors argue that their results suggest that the borrowing costs of municipalities increase if they issue green bonds. Another study that finds little—or at best mixed—evidence on a greenium is that by Tang and Zhang (2020). Examining green bonds issued by firms in 28 countries, they do not find a consistently significant premium for green bonds.

D. Other Assets

We now turn to the literature on other asset classes: corporate and municipal bonds, syndicated loans, and weather derivatives.

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12. The author argues that these findings can be linked with the literature on the liquidity premium, which shows that the liquidity premium is higher for financial bonds and lower-rated bonds.

Several studies examine corporate bonds. For example, Huynh and Xia (2021) use Engle et al.'s (2020) negative climate change news index and estimate the beta of bond returns with respect to the index. They find that bonds with a higher climate change news beta earn lower future returns, consistent with the idea that investors are willing to pay a premium to hedge climate risk. The effect is more pronounced for longer-term bonds, suggesting higher concern about the longer-term risk.

Further, studies suggest that municipal bond markets also reflect climate change risks. For instance, Painter (2020) finds that U.S. counties with greater exposure to sea level rise pay higher underwriting fees and initial yields to issue long-term municipal bonds, although no such relationship is observed for short-term bonds. He also finds that the effect of sea level rise risk on issuance costs is driven by bonds with low credit ratings, which suggests that lower rated counties are more likely to be susceptible to climate change risks, as they generally have weaker infrastructure and smaller fiscal capacity. Meanwhile, Goldsmith-Pinkham et al. (2023) obtain somewhat different results from Painter (2020). Discussing potential reasons behind the difference in results, they highlight that they measure sea level rise exposure at the school district level, while Painter (2020) uses a measure of climate risks for 17 major metropolitan areas that does not differentiate among coastal and inland municipalities in the same region. Goldsmith-Pinkham et al. (2023) find that municipal bond markets began pricing sea level rise exposure in 2013, coinciding with upward revisions to worst-case sea level rise projections. The effect is larger for long-maturity bonds, suggesting that the premium is primarily attributable to the long-term risk of gradually rising oceans, rather than the near-term risk of flooding from increased storm frequency and intensity.

The literature also examines syndicated loans. Ehlers, Packer, and de Greiff (2022) find a significant “carbon premium” across a wide range of industries since the Paris Agreement in December 2015. However, they argue that the premium appears to be low given a plausible estimate of a future carbon tax. In addition, only Scope 1 carbon emissions (i.e., emissions directly produced by the firm) are priced. Furthermore, the authors find no evidence that syndicated loans arranged by green banks, which are defined as those participating in the United Nations Environmental Programme Finance Initiative or adhering to the Equator Principles, factor in more climate risk than loans arranged by other banks.

Turning to studies on weather derivatives, Schlenker and Taylor (2021) argue that the market for weather futures is accurately anticipating rising temperatures in line with scientific predictions. Weather futures are products whose prices are determined by how much average daily temperatures fall below or above a certain benchmark in a month. Weather futures have been traded on the Chicago Mercantile Exchange since 2001, and there are products for eight different cities across the United States. Schlenker and Taylor (2021) show that weather futures prices indicate that the market is anticipating an increasing number of hot days in the summer and a decreasing number of cold days in the winter. Moreover, the authors find that this price trend approximates the projections of scientific models and is not influenced by year-to-year temperature fluctuations. This result suggests that market participants fully internalize the scientific forecasts and do not myopically update their predictions based on short-term weather outcomes.

E. Key Takeaways of Section III

While many studies show that prices of assets, such as stocks and bonds, factor in climate-related risks to some extent, many other studies show that real estate prices in particular do not adequately reflect such risks. Several studies provide evidence that investor behavior and asset prices have changed due to revised perceptions of risks as a result of disasters or local signs of the impact of climate change. Consequently, there are concerns that asset prices could fall substantially as climate-related risks materialize. When asset prices do not adequately factor in risks, they can hinder adaptation and mitigation actions, for instance, through excessive lending to high-risk areas and deterring financing by companies with low carbon emissions. Many studies demonstrate the effects of information disclosure, for example, by providing evidence that property prices do not sufficiently factor in climate risks in the absence of adequate information disclosure. Meanwhile, the empirical findings on green bond premiums remain mixed.

IV. Natural Disasters and Bank Behavior

We now turn to the literature on how banks are affected by and respond to natural disasters. In particular, we focus on whether the banking sector is sufficiently resilient to supply credit to satisfy liquidity needs and aid in the recovery after a severe disaster. In the conventional banking literature, natural disasters are often used as a natural experiment, where the disaster is regarded as an exogenous shock. As climate change advances and concerns over the growing frequency and intensity of natural disasters rise, these studies are becoming increasingly relevant in understanding the threats that natural disasters pose to the financial system. Furthermore, an increasing number of studies investigate the relationship between banks and natural disasters with specific reference to climate change. Our survey finds that banks' solvency and their role as credit suppliers are adversely affected by natural disasters (Section IV.A). We also review the rich literature on how the geographical expansion of banks leads to the transmission of adverse shocks to distant, unaffected regions (Section IV.B). We next investigate the heterogeneous responses of banks, areas, and loan types to natural disasters (Section IV.C). We then consider the benefits and side effects of public support related to the banking sector (Section IV.D). Finally, we summarize this section (Section IV.E).

A. Damage to Banks and Credit Constraints

Natural disasters affect banks' solvency through various channels: disasters can lead to a deterioration in the balance sheets of affected lenders, reduce the value of collateral, and directly damage banks' assets, such as their offices and system infrastructure. For instance, in a cross-country analysis covering more than 160 countries, Klomp (2014) finds that large-scale natural disasters adversely affect commercial banks' z-score (a measure of bank soundness or, more accurately, the inverse distance to default). Gramlich et al. (2023) examine data on 9,928 banks across 149 countries and find that natural disasters have a negative impact on banks' capital ratios. Similarly, using county-level data on natural disasters such as thunderstorms, hurricanes, floods, wildfires, and tornadoes in the United States, Noth and Schüwer (2023) show that property damages from weather-related natural disasters significantly weaken the stability of banks as reflected

in lower z-scores, higher non-performing asset ratios, higher foreclosure rates, lower returns on assets, and lower bank capital ratios. Meanwhile, Schüwer, Lambert, and Noth (2019) find that the z-scores of banks affected by three hurricanes that hit the U.S. Gulf Coast decreased and that these banks became significantly riskier than banks that were not affected. Further, Koetter, Noth, and Rehbein (2020) examine the effects of a major flood in Germany in 2013. Their main analysis disregards banks in flooded counties to avoid confounding loan supply and credit demand responses in those counties. They compare exposed banks, which are defined as banks with a critical share of corporate borrowers located in flooded counties, with unexposed banks. They find evidence for a relative increase in the share of non-performing loans for exposed banks that are not part of geographically diversified banking groups.

The literature also examines the impact of natural disasters on financial outcomes for borrowers. For example, Gallagher and Hartley (2017) find that following Hurricane Katrina, overall delinquency rates on credit cards increased, and credit scores decreased for the most flooded residents, although these changes were modest in size and short-lived. Using loan-level data from Mexico, Aguilar-Gomez et al. (2024) find that unusually hot days (with maximum temperatures above 35°C) lead to higher firm delinquency rates, especially in the agricultural sector, but also in nonagricultural industries that rely heavily on local demand. Ho et al. (2023) investigate the impact of the 2016 Fort McMurray Wildfire in Canada and find that it led to increased mortgage arrears in severely affected areas.

When natural disasters strike, affected firms' and households' credit demand often increases because they need to rebuild destroyed or damaged physical capital, bridge financing gaps until they receive monetary support from the government or payments from insurance firms, or secure their liquidity positions. The increase in credit demand is illustrated in several studies. For instance, Brown, Gustafson, and Ivanov (2020) show that firms, particularly solvent small firms, draw on their credit lines and increase the size of credit lines in response to a significant cash flow decline after unexpectedly severe snow cover in the United States. Meanwhile, Collier et al. (2019) find that, one year after Hurricane Sandy, negatively affected firms in New York were more likely to report that they had applied for credit than other firms. Similarly, in their study on the 2013 flood in Germany mentioned earlier, Koetter, Noth, and Rehbein (2020) find evidence that credit demand increased. Using data on lending to micro, small, and medium-sized enterprises in Ecuador, Berg and Schrader (2012) find that the number of loan applications increased after volcanic eruptions. Dessaint and Matray (2017) show that after hurricane events in the United States, unaffected firms located in the neighborhood of the disaster area substantially increased cash holdings, and their managers expressed greater concern about hurricane risk. The authors also find that the amount of cash increases during the first four quarters following the disaster and then reverts to pre-hurricane levels over the year. Based on such findings, they argue that firm reaction is consistent with a salience bias.

Whether banks can meet the heightened credit demand after a natural disaster is critical for the affected economies. The literature indicates that natural disasters limit both banks' ability to lend and firms' ability to borrow. For example, using data from a survey conducted for several years after the Great East Japan (Tohoku) Earthquake

in Japan in 2011, Uesugi et al. (2025) find that both damage to firms' tangible assets and to the net worth of their primary bank increased the probability that firms faced borrowing constraints after the disaster, providing evidence of the existence of both a so-called collateral and a bank lending channel. They also show that firms that faced a tighter credit constraint after the earthquake saw a fall in the level of production and sales activities. Meanwhile, in their study on Ecuador, Berg and Schrader (2012) show that volcanic activity restricts access to credit. Other studies find that natural disasters, such as hurricanes, snow, and high temperatures, increase credit constraints through higher interest rates and less borrower-friendly revisions of non-price loan terms, such as shorter maturity, flexible interest rates, and requirements to secure loans (Collier et al., 2019; Brown, Gustafson, and Ivanov, 2020; Aguilar-Gomez et al., 2024).

B. Reduction in Credit Supply in Unaffected Areas

As reviewed in the previous subsection, natural disasters lead not only to higher lending demand from firms and households but also to restrictions in the lending supply by banks. Clearly, this is bad news because firms may not be able to access credit when they need it the most. We next take a more granular look at banks' credit supply and review how banks propagate the impact of natural disasters to distant regions (we will refer to this propagation as "network effects" hereafter). Several studies suggest that the geographical expansion of banks has both harmful aspects, such as the propagation of adverse shocks, and beneficial aspects, such as risk sharing and new business creation (Demyanyk, Ostergaard, and Sørensen 2007; Morgan, Rime, and Strahan 2004; Black and Strahan 2002). Our survey shows that these findings in the literature are also relevant in the context of natural disasters.

Several studies find that banks reduce credit supply in unaffected regions after a natural disaster. For instance, like Koetter, Noth, and Rehbein (2020), Rehbein and Ongena (2022) examine the effects of the 2013 flooding in Germany. While Koetter, Noth, and Rehbein (2020) focus on lending within the affected region after the flood, Rehbein and Ongena (2022) examine the impact on unaffected regions. To this end, they define disaster-exposed banks as banks that provided credit to corporate borrowers in flooded counties to a large extent. They then find evidence that firms in non-disaster areas but connected to disaster-exposed banks reduced total borrowing, employment, and tangible assets. They also show that in a non-flooded area, the more firms were connected to disaster-exposed banks, the greater the reduction in GDP was. A similar result is provided by research on an earthquake in Japan. Hosono et al. (2016) examine the impact of the Great Hanshin-Awaji Earthquake in 1995 on firms located outside of the affected area. They find that the investment ratio (investment per capital stock) of firms whose main banks were inside the area was lower than that of firms whose main banks were outside of the area. Further, using U.S. disaster data, Cortés and Strahan (2017) find that mortgages in unaffected but connected markets decline by a little less than 50 cents per dollar of additional mortgage lending in affected areas after properties in these areas are damaged due to natural disasters. As for the reason why banks propagate the shocks of natural disasters to unaffected areas, Garbarino and Guin (2021) argue that the reallocation of lending from unaffected areas to affected areas may be due to a failure to mark-to-market property collateral against declining

market prices, preventing a tightening of credit supply in the affected areas.

While so far, we have focused on natural disasters—i.e., physical risks—as sources of network effects, transition risks, for example, through regulatory and technological changes, can also have network effects. For instance, if a carbon tax is introduced, the market value of fossil fuels may drop significantly as they become unusable, rendering them stranded assets. Consequently, the balance sheets of firms that own those assets may be greatly damaged, adversely influencing the lending capacity of branch networks of banks exposed to those firms. In this regard, Gilje, Loutskina, and Strahan (2016) examine the impact of an unexpected technological breakthrough that made vast amounts of shale oil and natural gas economically profitable in the United States. They find evidence that the resulting increase in deposit supply leads to higher growth in mortgages. Hence, it is plausible that a drop in the market value of fossil fuels could have the opposite effect—i.e., result in a significant decline in the supply of loans.

C. Heterogeneity

There is likely to be considerable heterogeneity in the impact of a natural disaster, depending on a range of circumstances. The literature identifies several factors that affect the size of the adverse impacts following natural disasters, such as capital regulation and supervision, bank-borrower relationships, age and size of firms, and alternative funding sources. For instance, Klomp's (2014) country-level analysis finds that the impact of a natural disaster is negatively associated with the stringency of capital regulation and supervision, in addition to the level of financial and economic development. Studies also find that the presence of bank-borrower relationships prior to natural disasters reduces credit constraints. In their study using Ecuadorian data, Berg and Schrader (2012) find that repeat clients already known to the financial institution are about equally likely to receive loans after volcanic eruptions as before, while new clients face difficulty in receiving financing. The importance of relationship banking is also highlighted by Koetter, Noth, and Rehbein (2020), who find that after the 2013 flood in Germany, firms located in flooded counties on average increased their borrowing if they were connected to banks in unaffected counties. Another source of heterogeneity is firm characteristics. Collier et al. (2019) show that younger and smaller firms were less likely to receive all of the credit financing that they requested after Hurricane Sandy. Aguilar-Gomez et al. (2024) find that the increase in delinquency rates on unusually hot days is concentrated among small and medium-sized firms. A further source of heterogeneity is access to non-bank credit. For instance, using zip-code level data for California, Morse (2011) finds that foreclosures increase after a natural disaster but access to high-interest credit (payday loans) mitigates the impact when disasters are not covered by homeowner insurance.

Several studies examine the impact of natural disasters, focusing on differences between local and non-local banks. Theoretically, local banks in affected areas should be more vulnerable to the shock and potentially tighten credit supply to a larger extent. On the other hand, local banks may also be more willing to continue lending after a natural disaster because borrowers in the disaster area are more important to them than to non-local banks or because local lenders face lower costs of monitoring borrowers in the reconstruction phase. In fact, the literature suggests that local banks have a com-

parative advantage in accessing soft information about borrowers (Berger et al. 2005; Agarwal and Hauswald 2010).

Empirical studies generally find that local banks in affected areas are more likely to continue lending than non-local banks. Gallagher and Hartley (2017) find that after Hurricane Katrina hit New Orleans, mortgage reductions were larger in areas where homeowners were likely to have a home loan originated by non-local lenders. Furthermore, two years after Katrina, local banks' lending returned to the pre-Katrina level, while a large share of non-local banks exited from the market. Schüwer, Lambert, and Noth (2019) find similar results and further show that affected counties with a relatively large share of local banks and relatively high average bank capital ratios show higher growth in total personal income and employment than other affected counties following Hurricane Katrina. Meanwhile, Chavaz (2016) examines the effects of hurricanes in the United States in 2005 including Katrina. He finds that compared to geographically diversified banks, local banks originated a higher share of new mortgage and small business loans in affected areas while cutting lending to unaffected counties and selling a higher share of the new mortgages into the secondary market. These results indicate that local banks have special abilities or incentives to seize opportunities in a distressed market, while loans in affected areas are increasingly transferred to agents that can better support the associated risk. On the other hand, he finds that local banks did not accept more loans in an affected area in which they owned a higher share of outstanding mortgages, suggesting that local banks did not aim to influence local house prices and economic activity.

Other factors that create heterogeneity in the impact of a natural disaster include bank, area, and loan characteristics. In particular, many studies show that bank characteristics are an essential determinant of the network effects. As mentioned above, Schüwer, Lambert, and Noth (2019) find that local banks increase new lending in the local market only when they are highly capitalized. Bank capitalization is an important determinant of network effects, too. For example, Rehbein and Ongena (2022) find that low bank capital amplifies network effects. They show that the impact of the 2013 flood in Germany was transmitted to firms in non-disaster areas via their banks: firms connected to banks with high exposure to the flood and ranking into the bottom quartile in terms of their capitalization experienced a significant decline in borrowing, employment, and tangible assets relative to similar firms connected to a well-capitalized bank. Meanwhile, Cortés and Strahan (2017) suggest that bank size is another factor determining the network effects. Specifically, they find that exogenous shocks to credit demand are transmitted to distant regions through the reallocation of funds only in the case of small banks but not large banks. Hosono et al. (2016) find that the network effects differ depending on whether main banks' headquarters or branches are damaged. While the impact of damage to main banks' headquarters emerged immediately after the Great Hanshin-Awaji earthquake, the impact of damage to main banks' branches emerged only with a one-year lag.

Turning to studies on area characteristics as a determinant of the strength of bank network effects, Cortés and Strahan (2017) find that a reduction in lending is mainly observed outside banks' core markets in which they own branches. Somewhat in contrast, the study by Gilje, Loutskina, and Strahan (2016) on shale boom windfalls finds

that banks exposed to the shale boom grew mortgages faster than similar non-exposed banks only in counties where the banks had branches. This suggests that if those wind-falls disappear, banks may shrink their lending again in counties where they had increased their mortgage lending due to the shale boom. Meanwhile, Rehbein and Ongena (2022) find that, following a disaster, banks reduce their exposure to areas that, although currently unaffected, are generally disaster-prone.

Finally, studies examining the role of loan characteristics suggest that whether loans are easy or difficult to securitize matters. For instance, Gilje, Loutskina, and Strahan (2016) show that banks exposed to the shale boom expanded lending more in segments that were less likely to be securitized. This suggests that if banks were to experience a tightening in liquidity constraints due to, for example, a natural disaster, they might find it more difficult to extend loans that are hard to securitize.

D. Benefits and Side Effects of Public Support

Many governments provide direct or indirect public support for banks, firms, and individuals in the event of a disaster. While such support can have positive effects on lending and the economic conditions of firms and individuals, it can potentially also have adverse side effects by distorting the behavior of banks and borrowers.

In this context, several studies examine the positive and negative effects of public support from government-sponsored enterprises (GSEs) in the United States. For instance, Cortés and Strahan (2017) find that after natural disasters, banks originate more small loans that can be sold to the GSEs. This result suggests that GSEs meet the legislative goal of promoting access to mortgage credit for low- and moderate-income households.

Meanwhile, in a study on the Tohoku earthquake in Japan, Uchida et al. (2015) show that the injection of public capital into damaged banks appears to have distorted resource allocation. To extract the impact of purely exogenous financial shocks on bankruptcy, they focus on firms located outside the affected area but transacting with banks located inside the area. They obtain some evidence that the capital injection reduced the probability of firm bankruptcy and weakened the natural selection mechanism, whereby less efficient firms are more likely to go bankrupt.

Some studies examine the impact of public support on individuals after natural disasters. Gallagher, Hartley, and Rohlin (2023) find evidence that federal disaster assistance ameliorates the negative impact of devastating tornadoes on household finance, businesses survival, and employment. The effects on business survival and employment are concentrated among small non-manufacturing establishments that rely on local demand. On the other hand, Bleemer and van der Klaauw (2019) show that public support distorts resource allocation. They find that, ten years after Hurricane Katrina, credit scores and homeownership among flooded residents of New Orleans are lower than among their non-flooded neighbors. They also find, however, that residents of areas surrounding New Orleans, who were eligible for various federal programs like residents of New Orleans, had higher rates of consumption, credit scores, and homeownership and lower rates of bankruptcy and foreclosure than residents outside the area

a decade later.¹³

E. Key Takeaways of Section IV

The review of the literature presented here suggests that when the area in which banks operate is affected by a natural disaster, banks' health deteriorates, and the demand for borrowing increases while the supply of loans, especially to young and small businesses, falls. The supply of bank credit also declines in unaffected areas. Further, there is considerable heterogeneity in the impact of natural disasters, with factors determining this impact including bank, area, and loan characteristics. For instance, local banks in affected areas are more likely to continue lending, and the effects are less severe when banks have high capital ratios. Finally, while public support mitigates the impact of a disaster, it has the negative side effect of distorting resource allocation.

V. The Role of Insurance and Related Challenges

Another essential part of the financial system that is significantly relevant to climate change is the insurance sector. On the one hand, insurance (and economically equivalent public support) serves as a means for policyholders to mitigate the impact of negative shocks caused by climate change: if losses caused by weather-related natural disasters are covered by insurance, the payouts provide an important source of funding for recovery. On the other hand, the insurance sector may become a source of financial instability if large payouts impair insurers' solvency or lead to fire sales of assets. Furthermore, insurance can introduce moral hazard, potentially delaying adaptations to reduce the costs of climate change. In this section, we start with the role of insurance in mitigating disaster risk and complementing bank finance (Section V.A). We then consider three challenges related to insurance: increasing the coverage of insurance (Section V.B), maintaining the solvency of insurance firms when climate-related risks materialize (Section V.C), and avoiding the problem of moral hazard (Section V.D). Finally, we sum up the key takeaways (Section V.E).

A. The Role of Insurance

Insurance can mitigate the adverse effects of natural disasters on economies. According to a survey by Kousky (2019) focusing on catastrophe insurance for housing in advanced economies, the literature indicates that insurance speeds up post-disaster recovery at both the household- or small business-level and the level of the economy as a whole, although she cautions that rigorous empirical work on these topics is limited. Billings, Gallagher, and Ricketts (2022) investigate the impact of flooding caused by Hurricane Harvey, which struck Houston in August 2017. They find that credit-constrained homeowners experienced increases in bankruptcies and in the share of debt in severe delinquency in flooded blocks outside the flood plain, relative to non-flooded

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13. Relatedly, Deryugina (2017) shows that U.S. hurricanes lead to substantial increases in non-disaster government transfers, such as unemployment insurance and public medical payments, in affected counties in the decade after a hurricane. The present value of this increase significantly exceeds that of direct disaster aid. This implies that without counting this increase, the fiscal costs of natural disasters are significantly underestimated.

areas. In contrast, this pattern was not observed inside the floodplain, where households were required to insure against flood risk. This result suggests that flood insurance mitigates the financial impact of flooding.

Insurance also influences the availability of, repayments on, and demand for bank credit. As we saw in Section IV, the literature finds that following natural disasters, borrowing constraints tighten, delinquency rates rise, and credit demand increases. Insurance can alleviate these impacts to some extent. For instance, Uesugi et al. (2025), using the Tohoku Earthquake in 2011 as a natural experiment, find that earthquake insurance payouts and government subsidies for recovery investment alleviated firms' borrowing constraints or reduced the probability that firms were unable to obtain the desired amount of loans following the disaster. Meanwhile, Gallagher and Hartley (2017) find that after Hurricane Katrina hit New Orleans in 2005, the greater the flood damage households experienced the larger was the reduction in their total debt because they used flood insurance to repay their mortgages rather than to rebuild. Collier et al. (2019) find that after Hurricane Sandy, businesses that suffered large losses and were not covered by insurance were significantly more likely to apply for credit than businesses that experienced large losses that were fully covered by insurance. In addition, Morse (2011), in her study on natural disasters in California, finds that access to payday loans reduces foreclosures after natural disasters only when disasters are not covered by homeowner insurance.

While the studies mentioned so far examine the effect of insurance on credit *after* a disaster has struck, insurance can also influence credit provision even *before* a disaster occurs. Garmaise and Moskowitz (2009) find that insurance market imperfections can restrict credit supply in particular to non-wealthy individuals, who rely on credit to purchase a property. They theorize that with a perfect insurance market, there should be no link between earthquake risk and loan provision since insurance can cover all of the risk. Their empirical analysis on earthquake and hurricane risks in the United States, however, indicates that properties with higher earthquake risk were less likely to be financed with bank debt, suggesting that the insurance markets are imperfect.

B. Insurance Coverage

The preceding section discussed the important role insurers play in cushioning the financial impact of natural disasters on households, firms, and the economy overall. Given this crucial role, an important question is the current level of insurance coverage. Extensive coverage would imply that more people and firms enjoy protection against natural disasters and hence the economy would be more resilient to the adverse effects of such disasters. However, existing evidence suggests that insurance coverage is low. According to Swiss Re, worldwide, more than 70 percent of natural disaster losses are not covered by insurance, and this ratio is particularly high for floods and earthquakes (Holzheu and Turner 2018).

Even if a household or firm has insurance of some kind, the loss may not be covered by that insurance. Collier et al. (2019) find that while Hurricane Sandy damaged firms' assets and disrupted their operations (e.g., through utility outages and customer relocation), 29 percent of the negatively affected firms had no insurance of any kind. Moreover, even insured businesses often did not have coverage for the kinds of losses

that Sandy created: 74 percent of businesses with property insurance, 72 percent with business interruption insurance, and 52 percent of businesses with flood insurance reported that none of their losses from the event had been covered by their policies. The low level of insurance payments is likely because the types of losses created by the hurricane differ from the types of losses that are protected by the most common forms of insurance. For instance, flood insurance from the National Flood Insurance Program (NFIP) protects against flood-related property losses but does not cover flood-related business interruptions. On the other hand, all the businesses with flood insurance that did not receive any insurance payments reported that they did not have property damage. These facts suggest that the insurance policies poorly match the losses stemming from customer and utility disruptions commonly reported by negatively affected firms.

Moreover, existing studies also show that there is heterogeneity in coverage and indicate that insurance fails to cover those who need it the most. For instance, Botzen, Kunreuther, and Michel-Kerjan (2019) find evidence that homeowners with lower incomes were less likely to buy flood insurance than those with higher incomes due to affordability concerns. Collier et al. (2019) find that younger and smaller firms were significantly less likely to be insured. These results suggest that the most vulnerable groups—low-income homeowners as well as younger and smaller firms—were least likely to be covered by insurance.

The literature also finds that international risk-sharing through reinsurance is low. Ito and McCauley (2022) find that international sharing of disaster losses is generally very limited. For example, they document that earthquake insurance covered only 16 percent of Japan's direct losses from the Tohoku earthquake, and less than a quarter of this 16 percent was reinsured internationally, implying that only 3.6 percent of total losses were ultimately shared with the rest of the world. Using data on cross-border reinsurance payments for 93 disasters across 44 economies from 1982 to 2017, they show that this limited international risk-sharing stems from both low participation in primary insurance and the limited use of reinsurance. Moreover, they find that those most in need of risk-sharing receive the least support: countries with lower levels of economic or financial development tend to insure a smaller share of disaster losses, and among advanced economies, less fiscal space is associated with lower levels of international risk-sharing.

The literature suggests that both demand and supply factors are responsible for the low insurance coverage. Several studies find that there is heterogeneity in the demand for insurance. For instance, Gallagher (2014) suggests that demand for flood insurance is positively related to the flooding experience. Using U.S. data, he finds that the take-up of insurance spikes in the year following a flood and then steadily declines back to the pre-disaster level over the next decade, indicating that the infrequent nature of natural disasters may be one reason for the low demand for insurance, and raising awareness of risks may help increase insurance demand. Botzen and van den Bergh (2012) use data from a survey among homeowners in the Dutch river delta. The survey asks whether respondents would be willing to purchase flood insurance and how much they would be willing to pay (WTP) under the current flood probability of 1 in 1,250 years and under higher probabilities as a result of climate change. The survey is hypothetical in the sense that flood insurance was not available in the Netherlands at that

time. The authors find that even when the flood probability increased to 1 in 400 years, at most around 50 percent of respondents would purchase flood insurance. On the other hand, the WTP of those who would purchase is on average considerably higher than the expected value of the flood risk they face. The authors also find evidence that risk communication increases risk awareness of respondents.

Another reason why insurance coverage is low is supply constraints. Supply of catastrophe insurance may be constrained for several reasons, such as information asymmetries (and adverse selection resulting from such asymmetries) and limited availability of reinsurance. A defining characteristic of disasters is that large numbers of people, properties, and businesses are impacted simultaneously, meaning that the law of large numbers does not work well. Under these circumstances, insurance firms build up reserves, purchase reinsurance, or issue catastrophe bonds. However, the literature shows that such steps by insurers make disaster insurance more expensive. For instance, Froot (2001) documents that although theory suggests that risk sharing against severe, low-probability events is most valuable, most insurers do not purchase reinsurance against such events, and that reinsurance premiums are high relative to expected losses. He argues that the most compelling explanation is supply restrictions associated with capital market imperfection facing reinsurers and market power enjoyed by the relatively small number of reinsurers.

C. Insurance Firm Losses and Their Implications

It is important to note that insurance firms themselves may be made vulnerable by climate change risks. If they underestimate natural disaster risks *ex ante*, collected premiums may not be sufficient to pay out for covered damages *ex post*. A deterioration in the financial health of insurers may result in a fire sale of assets, higher insurance fees, and a reduced supply of insurance.

The solvency of insurance firms has indeed been affected by large disasters. For instance, following Hurricane Andrew, which landed on the eastern coast of the United States in 1992, a number of insurance firms became insolvent. Even if insurance firms remain solvent, they may conduct a fire sale of assets to meet insurance claims, which could undermine financial stability. The effects of insurers' fire-sales on financial markets are illustrated by Massa and Zhang (2021), who examine the impact of the liquidation of corporate bond holdings by (re)insurance firms in the wake of Hurricane Katrina. They find that property insurance firms with large exposure to Katrina reduced their corporate bond holdings by 14 percent, while other property insurers reduced theirs by only 1 percent. The authors further show that, as a result, firms whose bonds were held by Katrina-exposed property insurers faced a larger decline in their risk-adjusted bond returns. Moreover, these affected firms shifted from bond financing to bank loans at least for three years after Katrina.

Another concern is that insurers may raise premiums to cover expected losses, likely resulting in lower participation. Indeed, Froot (2001) shows that reinsurance of catastrophic event risks became considerably more expensive following Hurricane Andrew, which led to a decline in reinsurance purchases. He further shows that the amount of reinsurance purchased fell by more, and the premium paid rose by more for insurers with large exposure to hurricanes.

It is also possible that insurers consider the costs of natural disasters too large to insure and consequently stop providing insurance. Existing evidence finds that this has indeed happened in the past. For example, following the 1994 Northridge earthquake in California, insurers paid more in claims than they had collected in earthquake premiums over the preceding 30 years. Consequently, many insurers began to withdraw from offering homeowners insurance coverage, since California state law requires insurers providing homeowners coverage to also offer earthquake coverage. This retreat of insurers triggered a housing market crisis in California (Insurance Information Institute 2025).

D. Moral Hazard

Another critical issue in the context of insurance is moral hazard. Insurance may cause the policyholders to engage in risk-taking activities because they know that they will be compensated for a loss by the insurance. In the context of climate change, insurance may discourage policyholders from taking measures that reduce the costs of climate change and natural disasters. As a result, it is possible, at least in theory, that the social costs of induced risk-taking activities exceed the benefits brought about by insurance. In addition, moral hazard could lead to higher premiums and lower insurance supply.

Existing empirical studies find some evidence of moral hazard induced by public insurance. For instance, Annan and Schlenker (2015) examine the impact of the Federal Crop Insurance Program in the United States on the incentive to adapt to extreme heat using county-level data. They find that insured corn and soybean yields decline more significantly than uninsured yields when exposed to extreme heat, implying that public insurance acts as a disincentive for farmers to engage in adaptation strategies to cope with extreme heat. Relatedly, Bakkensen and Barrage (2022), referencing a report by the U.S. Government Accountability Office, point out that the NFIP, the dominant public flood insurer, is fiscally unsustainable, suggesting that it fails to provide households with sufficient incentives to fully internalize flood risk.

Moral hazard may pose a problem, but theory suggests that well-designed insurance programs can reduce it. For instance, many insurance policies involve deductibles, based on the expectation that if the insureds must bear part of the losses, they will be encouraged to engage in risk-reducing activities. Moreover, insurance can play a critical role in improving resilience to natural disasters not only by supporting recovery but also by providing incentives for climate adaptation or investment in hazard alleviation.

While studies often find a positive correlation between having disaster insurance coverage and investing in hazard alleviation among individuals, Kousky (2019) cautions that the correlation may be driven by common underlying factors, such as high risk aversion and high risk perceptions. She concludes that rigorous empirical evidence on this topic remains limited. The correlation could also reflect adverse selection: individuals who are more exposed to disaster risk tend to purchase more insurance coverage.¹⁴ However, she argues that for many disasters, insurers possess more accurate risk information than policyholders, which may mitigate concerns about adverse selection.

Botzen, Kunreuther, and Michel-Kerjan (2019) find conflicting evidence on moral

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14. See Cohen and Siegelman (2010) for a survey on the empirical literature on adverse selection in insurance markets, including methods for distinguishing between moral hazard or adverse selection.

hazards. The authors survey more than 1,000 homeowners in New York City after they experienced Hurricane Sandy. On the one hand, those who had purchased insurance were more likely to undertake loss reduction measures, such as installing water-resistant walls, before the disasters. On the other hand, however, those people were less likely to undertake emergency loss reduction measures, such as moving contents to higher floors to avoid them suffering flood damage.

E. Key Takeaways of Section V

Insurance mitigates the negative impact of natural disasters and also influences the availability and repayment of, and demand for, bank lending. However, several challenges remain. Insurance coverage is particularly low among low-income households and young and small businesses, with some studies pointing to both supply and demand factors as underlying reasons, suggesting that risk communication could help expand insurance coverage. Natural disasters can lead to a deterioration in the financial health of insurers, potentially triggering fire sales of assets, higher insurance fees, and a reduced supply of insurance. While there is some evidence that public insurance programs have resulted in moral hazard, there is a lack of rigorous empirical studies that show whether private insurance mitigates or induces moral hazard.

VI. Conclusion

This paper attempted to provide a comprehensive literature survey on the interaction between climate change and the financial system. While our survey covered a broad range of issues, we conclude by highlighting three policy implications of the findings in the literature.

First, our survey finds that asset prices, particularly real estate properties, do not adequately price in climate risks. It also finds that investors update their risk perceptions when they experience the impacts of climate change. These findings indicate that asset prices may decline significantly as climate change risks materialize. Moreover, mispricing can distort incentives for financial institutions, households, and firms to take mitigating and adapting actions against climate change. Meanwhile, many studies provide evidence that disclosure of climate change risks helps alleviate these problems. While these findings do not immediately warrant stricter regulations on disclosure since there are associated costs and limits on market participants' ability to process information, they nonetheless provide useful guidance for policymakers seeking to encourage asset markets to price in more climate change risks.

Second, natural disasters restrict credit supply from affected banks, adversely affecting the real economy, even in unaffected areas. Public support can unintentionally distort resource allocation. On the other hand, some studies argue that the impact of a natural disaster on banks—and hence credit supply and the economy overall—is less severe for banks with a higher capital ratio and located in countries with stricter financial regulations and supervision. These results imply that regulatory frameworks, including capital requirements, which were originally intended to maintain the resilience of banks and the financial system against non-climate shocks, are also effective with regard to climate change risks.

Third, while insurance plays a critical role in mitigating the adverse effects of climate change, the literature also highlights several challenges: increasing coverage, maintaining insurers' solvency when climate change risks materialize, and avoiding the problem of moral hazard. Policymakers need to be aware of the benefits and challenges when designing monitoring and supervisory frameworks for the insurance sector as climate risks grow.

Our survey highlights that the literature on the interaction between climate change and the financial system has grown rapidly in recent years. While our understanding of this subject has advanced considerably as a result, significant research is still needed to fill the gaps in our knowledge. Moreover, it is essential to ensure that future policy discussions are evidence-based and incorporate the growing body of research findings in this area.

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Advance in Security Proofs of Quantum Key Distribution and Its Challenges towards Practical Implementation

Kazutoshi Kan and Toshihiko Sasaki

This paper provides an overview of advancements in the security proof of quantum key distribution (QKD) while discussing the rationale and challenges of its practical implementation. QKD ensures information-theoretic security, meaning even eavesdroppers with unlimited computational power cannot decipher the transmitted data. As a result, it is resilient against various attacks, including eavesdropping and harvest-now-decrypt-later attacks. QKD encompasses a range of methodologies, each supported by corresponding security proofs. Since the introduction of the first QKD protocol, BB84, theoretical progress has been made to address evolving technologies and counter implementation attacks that exploit device imperfections. In 2020, the first security proof for continuous-variable QKD (CV-QKD) was established. This method offers greater compatibility with existing optical fiber networks. Despite its advantages, QKD requires specialized devices, resulting in high costs for network construction. Currently, QKD is primarily suitable for transmitting highly confidential information across multiple hubs. To encourage its adoption, several challenges must be addressed, including advancing quantum relay technologies, enhancing performance, establishing protocol standards, and creating institutional frameworks for verifying and certifying device security.

Keywords: QKD; CV-QKD; Implementation attack

JEL Classification: L86, L96, O36

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I. Introduction

Quantum key distribution (QKD) is a communication protocol that encodes cryptographic key information into quantum bits (qubits), represented by the states of photons. The quantum-mechanical properties of these qubits ensure the secure protection of this information. Currently, widely used cryptographic algorithms on the Internet, such as RSA and elliptic curve cryptography (ECC), are theoretically known to be efficiently breakable by quantum computers with sufficient computational power.¹ QKD is considered one of the cryptographic techniques secure against the threat posed by quantum computers. It stands as a potential alternative alongside **post-quantum cryptography (PQC)**, which does not rely on quantum-mechanical properties. Demonstration experiments using QKD for encrypted communication are being conducted worldwide.² Encrypted communication with QKD works by first performing QKD between two parties to share a random key. This shared key, in combination with classical cryptography (such as a one-time pad [OTP]), is then used to securely transmit any arbitrary message. The following discussion focuses on QKD.

A key advantage of QKD is its ability to guarantee both the absence of eavesdropping and **information-theoretic security**. Information-theoretic security is a robust property that ensures confidentiality even if an attacker possesses unlimited computational power or employs any eavesdropping techniques permitted by the laws of physics. Unlike computational security, information-theoretic security remains unaffected by future advancements in computational power, cryptanalysis algorithms, or eavesdropping techniques, thereby ensuring the confidentiality of communications indefinitely. This property makes QKD secure against the threat of cryptanalysis by ideal quantum computers. Notably, QKD is resistant to **harvest-now-decrypt-later (HNDL) attacks**, where ciphertext is stored for future decryption once computational power becomes sufficiently advanced. This is a significant advantage that PQC does not offer. Cryptosystems like PQC and RSA rely on **computational security**, meaning their security depends on the attacker's computational resources and the efficiency of cryptanalysis algorithms. Consequently, they cannot guarantee protection against unexpected future increases in computational power or breakthroughs in algorithms, making them inherently vulnerable to HNDL attacks.

However, there are variations in QKD protocols, and while each is supported by mathematical security proofs, the security of certain implementations remains uncertain. To ensure that a QKD system achieves the same level of security as its theoretical model, the following three conditions must be met.

(a) The communication protocol used must be supported by a corresponding security

1. The security of RSA and elliptic curve cryptography is based on the assumption that the integer factorization problem and the elliptic curve discrete logarithm problem, respectively, cannot be efficiently solved. Theoretically, it is known that quantum computers can solve these problems efficiently (in polynomial time) using Shor's algorithm. However, the required specifications for quantum computers capable of cryptanalysis are extremely high, and their realization remains out of reach.
2. In Japan, the Tokyo QKD Network (Fujiwara [2023]) has been demonstrated. In Europe, the SECOQC (Secure Communication based on Quantum Cryptography) network and the EuroQCI (European Quantum Communication Infrastructure) network, which involves all 27 EU member states, have been implemented. In China, a QKD network spanning 4,600 kilometers between Shanghai and Beijing has also been demonstrated.

proof.

- (b) The **device models** assumed in the security proof must be realistic.
- (c) The implemented devices must operate in accordance with the device models assumed in the security proof mentioned in (a).

Condition (a) is necessary because not all proposed communication methods and protocols classified as QKD have been provided with complete security proofs. In 2021, for the first time, an information-theoretic security proof was established for a method called continuous-variable QKD (CV-QKD, see Section III.C.2. for more details), which is highly compatible with existing optical communication technologies (Matsuura *et al.* [2021]).

Condition (b) requires that security proofs be based on practical assumptions regarding communication devices. Security proven under theoretically convenient assumptions is not necessarily guaranteed in real-world communication. This is because such assumptions may be violated due to noise within the communication devices themselves, or sensitive information could be stolen through implementation attacks (see Section IV.A.3. for details), where an attacker directly exploits vulnerabilities in the devices. As a result, recent advancements in security proof theory have shifted toward accommodating realistic properties, including inherent imperfections.

Condition (c) requires that communication devices comply with security specifications. Since it is impractical for user companies to directly verify compliance with these specifications, establishing an institutional framework to evaluate and certify the performance and security of communication devices is essential for the widespread adoption of QKD.

While research and development efforts for the practical implementation of QKD are actively underway, achieving both sufficient performance and compliance with the aforementioned conditions should require more time. Additionally, implementing QKD on a large scale would involve significant network infrastructure costs. As a result, current concrete measures to counter the threat posed by quantum computers primarily focus on PQC, with increasing momentum to transition from contemporary cryptographic methods to PQC. The National Institute of Standards and Technology (NIST) is advancing the standardization of PQC, inviting public submissions for candidate encryption schemes and conducting evaluations. In its Round 3 evaluation report (NIST [2022]), NIST announced the selection of CRYSTALS-KYBER as the standard key encapsulation mechanism for key exchange, while indicating that further evaluations of other candidates would continue in Round 4. The motivation behind this cryptographic transition is to prepare for the emergence of an ideal quantum computer and to address threats posed by HNDL attacks. Moving forward, a shift to stronger cryptographic methods is anticipated, regardless of the timeline for the realization of quantum computers. Even as PQC gains traction, understanding the relative characteristics of QKD and PQC will be valuable for evaluating the potential adoption of QKD and identifying optimal use cases for each approach.

The transition to PQC may take over ten years if it requires updating hardware with integrated encryption modules. Similarly, the deployment of QKD should require an extended preparation period due to the need for building new network infrastructure.

Therefore, early planning is essential when considering the future landscape of cryptographic usage. For financial institutions, where stringent information management is critical, a comprehensive understanding of QKD's security, applicability, and the challenges associated with its practical implementation is vital for developing a long-term cryptographic strategy.

On the basis of the aforementioned information, Section II. outlines the positioning of QKD, Section III. provides an overview of the fundamentals of QKD, Section IV. reviews the security proofs associated with QKD, and Section V. examines the challenges related to the broader adoption of QKD.

II. The Positioning of Cryptographic Communication Using QKD

In Section II.A., we first explain the threat posed by quantum computers to public-key cryptography. Next, in Sections II.B. and II.C., we outline the principles of PQC and QKD, respectively. On the basis of these discussions, Section II.D. organizes the relative strengths and weaknesses of QKD.

A. Public-Key Cryptography and the Threat of Quantum Computers

In classical communication, cryptographic methods are categorized into symmetric-key encryption and public-key encryption. **Symmetric key encryption** enables fast encrypted communication, as it relies on the assumption that the sender and receiver have pre-shared a secret key. **Public-key encryption**, on the other hand, does not require a pre-shared key but generally operates more slowly. Practical communication systems leverage the strengths of both: bulk data is securely transmitted using symmetric key encryption, while the symmetric encryption key is exchanged via public-key encryption.

The predominant forms of public-key cryptography today are RSA encryption and elliptic curve cryptography. The security of these methods is based on the assumption that problems such as large integer factorization and the elliptic curve discrete logarithm problem cannot be solved within a practical timeframe. Security based on the assumed difficulty of specific computational problems is termed **computational security**. This type of security diminishes over time due to advances in computational power and algorithmic breakthroughs, rendering it time-limited. Consequently, cryptographic key lengths are progressively extended to maintain security. Cryptographic schemes relying on computational security are inherently vulnerable to HNDL attacks, posing a realistic threat to entities requiring long-term data protection. In particular, RSA and elliptic curve cryptography are theoretically vulnerable to efficient decryption by quantum computers. If such quantum computers become viable, they could decrypt accumulated ciphertexts.

B. Comparison with PQC

In this section, we provide an overview of PQC, which is often compared with QKD. One approach to addressing the threat of quantum computers is to replace current cryptographic schemes with stronger ones. Schemes that maintain security against quantum

computers are referred to as PQC.

The security of PQC relies on the difficulty of certain computational problems considered intractable even for quantum and classical computers. These problems are closely related to the class of computational problems known as NP-hard³ in computational complexity theory.⁴ However, this theoretical assurance is based on analyzing the asymptotic behavior of computational complexity as the input size grows indefinitely. Crucially, PQC does not guarantee that finite-sized problems with practical key lengths and security parameters are unsolvable within realistic time frames.

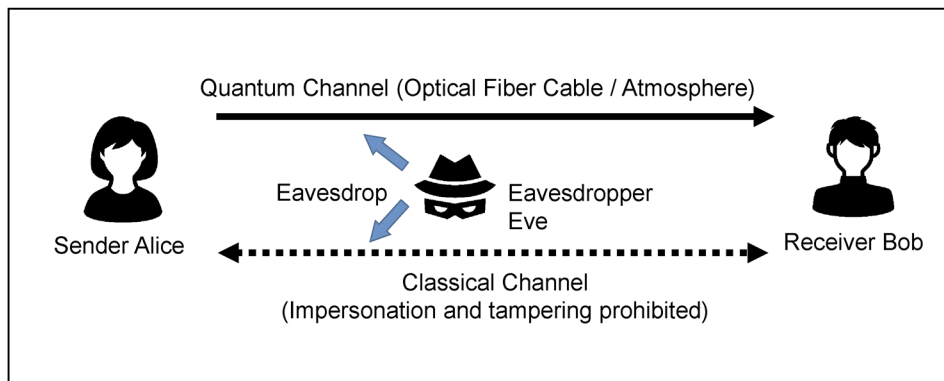
The assessment that encryption cannot be broken within practical time frames is based on projections of future advancements in decryption algorithms and computational power. Consequently, it is anticipated that PQC, like RSA encryption, will require operational measures such as increasing key lengths over time. However, significant uncertainty remains in these projections. Notably, many experts emphasize that while the probability of realizing a quantum computer capable of efficient cryptanalysis is extremely low, its impact would be catastrophic, classifying it as a difficult-to-predict tail risk. Computational security cannot fully eliminate such risks.

While experimental demonstrations of PQC are progressing, establishing trust in its resistance to implementation attacks and algorithmic security will take time. In contrast, RSA encryption benefits from over two decades of deployment and accumulated implementation expertise. For this reason, a **hybrid mode** combining elliptic curve cryptography and PQC for dual encryption is being standardized by the Internet Engineering Task Force (IETF). Additionally, since PQC encompasses diverse cryptographic algorithms, achieving **crypto-agility**—the ability to flexibly select appropriate algorithms—remains a key challenge. For recent discussions on hybrid modes and crypto-agility, see Une (2023a, b) and Kanno (2023).

Unlike QKD, PQC cannot inherently detect eavesdropping because classical bits⁵ can be duplicated without altering the original information. Attackers can thus replicate classical bits transmitted over communication channels without leaving traces, rendering PQC vulnerable to HNDL attacks. In contrast, QKD enables post-transmission eavesdropping detection by statistically estimating its presence, as detailed in Section II.C., enabling compromised information to be discarded and secure key sharing without eavesdropping risks. This advantage, rooted in quantum-mechanical properties, is unattainable in classical cryptography, including PQC.

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3. Intuitively, NP-hard refers to a class of computational problems that are difficult to solve efficiently but for which a candidate solution, if provided, can be efficiently verified. More precisely, NP-hard denotes a class of problems that are at least as difficult as the hardest problems in NP (nondeterministic polynomial time). NP is the class of computational problems that can be solved by a nondeterministic polynomial-time algorithm.
 4. The computational difficulty of these problems depends on the distribution of their parameters. Furthermore, the interpretation of cryptographic security assessments varies depending on whether they are based on the average computational cost across various parameter settings or the worst-case computational cost. In cryptographic security evaluations, the average computational cost is generally preferred. The lattice-based PQC scheme CRYSTALS-KYBER, selected by NIST as a standard for public-key cryptography, provides a security proof based on the average computational cost under random parameter settings.
 5. A classical bit represents a state of either “0” or “1.” A device that performs computations using only classical bits is called a “classical computer.” Cryptography in which plaintext and ciphertext are represented as sequences of classical bits is known as “classical cryptography.”

Figure 1 Overview of QKD Communication



C. Principles of QKD

Another countermeasure against the threat of cryptographic decryption by quantum computers is QKD. QKD leverages quantum-mechanical properties and carefully designed protocols to achieve information-theoretic security. In this section, we explain the principles of QKD.

In QKD, two channels are utilized: a quantum channel for transmitting quantum bits and a classical channel for transmitting classical bits (see Figure 1). The quantum channel provides a low-noise environment essential for the delicate transmission of quantum bits, but it is costly, making it inefficient for sending classical bits. Thus, to efficiently share deterministic information (i.e., keys), the classical channel is typically used in conjunction with the quantum channel. For the classical channel, it is assumed that an attacker can eavesdrop on the communication but cannot impersonate the participants or alter the transmitted content. To satisfy this assumption, the ability to authenticate both participants and messages is necessary. These authentication mechanisms are crucial in evaluating the overall security of QKD protocols. However, for simplicity, we assume that secure authentication is possible here. Issues related to authentication are discussed in detail in Section V.B.

A quantum bit, or qubit, can take a state that is a combination of both “0” and “1,” known as a **superposition**. Furthermore, the state of any unknown qubit cannot be copied—a property derived from quantum mechanics called the **no-cloning theorem**. This is a characteristic unique to qubits. In other words, the information contained in a qubit cannot be read without affecting its state.

When extracting information from a qubit, an operation called **measurement** is performed. Generally, an observer cannot fully extract the information of an unknown qubit; instead, the observer can probabilistically obtain partial information through measurement. However, if a qubit is known to be in one of several specific states (though which one is unknown), specific measurement methods can definitively de-

termine the state.^{6,7}

For example, consider a situation where an observer performs a measurement on a qubit to distinguish between the “0” and “1” states. If the qubit is in the state “0” or “1,” the observer can deterministically identify it. However, if the qubit is in a superposition of these states, the measurement outcome will yield “0” or “1” probabilistically, on the basis of the degree of superposition.

QKD leverages the inherent properties of qubits in a protocol to *retrospectively* estimate the presence or absence of eavesdropping and discard information from suspected qubits, thereby enabling the secure sharing of a random number sequence. Since it is unknown in advance which qubits might be intercepted, QKD cannot be used to directly send an encrypted message. This limitation confines QKD to sharing only random number sequences. Additionally, QKD cannot distinguish between the effects of eavesdropping and environmental noise, making it impossible to definitively confirm eavesdropping. Eavesdropping involves extracting information from a qubit, which alters its state. By following a well-designed QKD protocol, the sender and receiver can detect changes in the quantum state caused by noise or potential eavesdropping, though they cannot determine the exact cause. Thus, in the security analysis of QKD, any change in quantum state is conservatively attributed to eavesdropping, providing a security framework that ensures safety regardless of the cause of state alteration.

Once a random number sequence has been securely shared, any message can be sent securely by the OTP, a classical encryption method that is information-theoretically secure. If the length of the message matches the length of the shared sequence, the message retains information-theoretic security.⁸

D. Positioning of QKD

QKD is frequently compared with PQC as a countermeasure against the threat of quantum computers. As introduced in Section V.A., numerous national white papers and position papers offer negative assessments of QKD from this perspective. However, note that these assessments primarily focus on QKD within the context of broadly applicable Internet encryption schemes. In the following section, we compare QKD with other key-sharing methods, including modern cryptography (RSA encryption and elliptic curve cryptography), PQC, and human-based random number transportation.

As shown in the Table 1, at the current technological level, the most comparable method to QKD in terms of application scenarios is human-based transportation, or the **Trusted Courier** approach, which is primarily suited for one-to-one communication. While it can be used for one-to-many communication if random numbers are transported to multiple locations, it remains poorly suited for many-to-many communication.

6. When known states are mutually orthogonal, they can be determined with certainty. In quantum state measurement, the observer must select an appropriate measurement method (measurement basis) depending on the quantum states they wish to distinguish. The details of quantum state orthogonality and basis selection are beyond the scope of this paper. For more information, refer to foundational texts on quantum computing, such as Nielsen and Chuang (2010).

7. QKD does not utilize orthogonal states to prevent eavesdropping.

8. For example, let the securely shared random number sequence be $x = 010111$ and the message be $y = 111000$. The ciphertext using the OTP is defined as the bitwise exclusive OR $z = x \oplus y = 101111$. In this case, if the random number sequence x is entirely unknown to the attacker, no information about the message y can be inferred from the ciphertext z , ensuring information-theoretic security.

Table 1 Comparison among Encrypted Communication Schemes

	RSA, ECC	PQC	QKD	Trusted Courier
Methodology	Public Key Encryption	Public Key Encryption	Quantum Cryptography	Delivered by Human
Security	Computational Security	Computational Security	Information Theoretic Security	—
Principle of Security	Computational Difficulty of Prime Factorization	Computational Difficulty of NP-Hard Problems ¹	Quantum Mechanics (Laws of Nature)	Closed Channel, Trustworthiness of Courier
Quantum Safe	×	△	○	○
Eavesdropping detection	×	×	○	× (difficult for eavesdropping)
Resistance against Implementation Attacks	Reliable	Not Sufficiently Reliable. Used in Hybrid Mode Recommended	Seems to Sufficiently Consider the Risks. Need to Develop Verification and Certification Frameworks	Reliable
Specialized Devices	Not Required	Not Required for Internet (Implemented as Software) Some Cases Require Replacement of Cryptographic Modules	DV-QKD Requires Dedicated Networks CV-QKD Can Coexist with Existing Optical Networks	Not Required
Network Topology	from N to N	from N to N	from N to N	1 to N
Secured Area	End-to-End	End-to-End	Between Specialized Devices Need to Trust Relay Nodes ²	End-to-End
Authentication	○	○	PQC Signature Offers Computational Security Wegman-Carter Authentication Requires Small Pre-Shared Key	Certification of the Courier

Notes: 1. There are several PQC encryption schemes with corresponding computational problems of which difficulties guarantee their security.

2. The trust to relay nodes will be less required if quantum relay will be realized.

tion. This limitation stems from the significant time required for key (random number sequence) transportation and the burden of securely managing keys equal in length to the total message volume communicated over a period. In contrast, QKD, as long as a communication path is available, is better suited for many-to-many communication between nodes and enables rapid key sharing per communication instance.

As noted earlier, QKD's primary advantage is its information-theoretic security. It is well-suited for communications involving a limited number of nodes, even in many-to-many configurations, where long-term confidentiality or highly sensitive information is critical. Examples include genetic information managed by life insurance companies and certain financial institutions' credit information. However, if only the main communication line between sender and receiver buildings is protected by QKD, securing the "last mile" of communication, from the QKD receiver device to individual user terminals on the receiver's side, may still require alternative methods. Additionally, since **quantum relay**⁹ technology remains underdeveloped, implementations must rely on trusted conventional relay devices.

Conversely, for information requiring confidentiality for approximately 10 years, PQC is likely more cost-effective. Similarly, if the security of the shared random number sequence can be ensured through other means—such as a one-time password generator used by financial institutions—QKD's advantage diminishes. Furthermore, QKD does not authenticate participant identities, necessitating supplementary authentication methods as discussed in Section V.B. Given these significant differences in security guarantees, applications, and assumptions between QKD and PQC, careful selection and complementary deployment of these technologies are essential.

III. Fundamentals of QKD

A. Embedding Quantum Bits in Light

In QKD, light serves as the medium for carrying qubits due to its stability at room temperature and its ability to propagate at the fastest possible speed. One example of a qubit utilizes a property of light called **polarization**. As an electromagnetic wave, light naturally oscillates in various directions of electric and magnetic fields. When passed through a polarizing filter, light with oscillations restricted to a specific angle is extracted, a state referred to as polarization. Digital information can be encoded in these oscillation angles.¹⁰ Polarization may take the form of **linear polarization**, where the oscillation angle remains constant (typically represented by four states: 0°, 45°, 90°, and 135°) or **circular polarization**, where the oscillation angle rotates (either clockwise or counterclockwise) as light propagates. In addition to polarization, qubits can also be encoded using two phase-controlled light pulses with defined **phase differences**. All these encoding methods—linear polarization, circular polarization, and phase-controlled pulses—are theoretically equivalent for realizing qubits.

QKD protocols that treat single photons as qubits benefit from theoretically straightforward security proofs. However, practical implementations face challenges in achieving precise control over single-photon generation. For this reason, weak light pulses—short laser bursts attenuated to approximately the single-photon level—are commonly used in practice.

9. Quantum relay refers to a relay method in which the relay device receives quantum bits and forwards them to the next relay device without converting them into classical bits.

10. In classical communication, information is transmitted by associating the on-off states of light with the bits "0" and "1."

B. Communication Channels and Relays in QKD

Quantum channels consist of optical fiber cables for terrestrial communication or the atmosphere for satellite-to-ground communication, resembling conventional optical or satellite communication systems. However, in quantum channels, the optical signal's intensity is extremely weak, necessitating exceptionally low-noise tolerance. In several QKD implementations, signals are handled at the single-photon level, making long-distance communication challenging due to increased noise. Thus, establishing reliable relay points is crucial, often referred to as **trusted nodes** or **trusted points**, at regular intervals along the communication route.

In general, increasing the distance between relay points reduces the cost of building a network. However, this comes at the expense of slower key generation rates due to the attenuation of light in the communication channel. As of February 2024, in the most commonly implemented QKD protocol—the decoy-state BB84 protocol¹¹ (Hwang [2003]; Lo, Ma, and Chen [2005]; Wang [2005])—the key generation rate decreases tenfold for every additional 50 kilometers of optical fiber distance. At a distance of 50 kilometers, the transmission speed is at most approximately 1 megabit per second. Consequently, the distance between relay points is constrained by the required speed of key generation.

Relay methods in QKD can be categorized into classical relays and quantum relays. In **classical relays**, qubits are read at each relay device, converted into classical bits, and then re-encoded into qubits for transmission to the next relay device. To prevent information leakage from stored data within each relay device, safeguarding the devices is essential.

Quantum relays eliminate the effects of light attenuation in the channel. Since the relays avoid conversion into classical bits, stringent protection of the relay devices is not required. However, as of now, quantum relays have yet to be established.

C. Classification of QKD Protocols

While the decoy-state BB84 protocol is the most commonly employed in demonstrations and commercialization, many other protocols have also been proposed. These protocols are classified on the basis of communication schemes, the type of optical detectors, and device reliability.

1. Classification by communication schemes

QKD protocols can be categorized into the following three types on the basis of the communication schemes between the two parties:

- **Prepare-and-Measure QKD (PM-QKD):** One party transmits light while the other measures it. Examples include the BB84 protocol and the decoy-state BB84 protocol.
- **Measurement-Device-Independent QKD (MDI-QKD; Lo, Curty, and Qi [2012]):** Both parties send light to a device at an intermediate point. At the

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11. For details on the BB84 protocol, refer to Section III.D. The decoy-state BB84 protocol is a variant of the BB84 protocol that uses weak laser pulses (light pulses), which are cost-effective and easier to handle, instead of single photons. The sender randomly selects the intensity of the laser pulses from a predefined set of values and transmits them. This approach ensures performance equivalent to that of the single-photon-based protocol.

device, the incoming lights are interfered with and measured. The outcomes are then disclosed. A notable example is the Twin-Field protocol (Lucamarini *et al.* [2018]).

- **Entanglement-Based QKD (EB-QKD):** The device at an intermediate point generates pairs of correlated photons (quantum entangled¹² photon pairs). One photon from the pair is sent to the sender and the other to the receiver. Each then independently measures the photons they receive. Examples include the BBM92 protocol (Bennett, Brassard, and Mermin [1992]) and the E91 protocol (Ekert [1991]).

The characteristics of the protocols are as follows: **PM-QKD** is the simplest type and has already been widely commercialized. **MDI-QKD** requires a measurement device placed at an intermediate point in the channel. This method offers an advantage: even if the measurement device is entirely under the control of an eavesdropper, any eavesdropping attempts can still be detected as errors. Moreover, the protocol's security is guaranteed regardless of whether the outcomes at the measurement device can be trusted. Additionally, depending on the specific protocol, MDI-QKD can significantly reduce the impact of performance degradation caused by distance. Compared with PM-QKD, MDI-QKD can effectively double the communication distance before encountering similar levels of performance degradation. Furthermore, MDI-QKD is considered robust against **implementation attacks**, which often target receiver devices. This robustness stems from the fact that both parties use transmitter devices in MDI-QKD. In contrast, receiver devices are generally more vulnerable to such attacks, as they must accept signals from the communication channel, which is exposed to potential manipulation by eavesdroppers. For a detailed discussion on implementation attacks, refer to Section IV.

In **EB-QKD**, the use of specialized light sources capable of generating entangled photon pairs typically results in higher costs and complexity, making it less common in practice. However, EB-QKD offers certain advantages, such as reducing the need for random number generators. Additionally, it is considered useful for **frequency-division multiplexed communication** (Wengerowsky *et al.* [2018]), though it requires specific optical fibers for optimal performance.

2. Classification by optical detectors and the advantages of CV-QKD

QKD protocols can be categorized into two types on the basis of the optical detectors: **Discrete-Variable QKD (DV-QKD)** and **Continuous-Variable QKD (CV-QKD)**. The terms "DV" and "CV" originally referred to whether the transmitted information was discrete or continuous. However, in modern implementations, even CV-QKD can transmit discrete information. Thus, the prefixes "DV" and "CV" are now used primarily to distinguish the types of detectors employed in the protocols.

- **DV-QKD:** This approach employs **photon detectors** to identify the presence or absence of individual photons. For example, by placing a photon detector behind a polarization filter (or a polarization beam splitter), the polarization angle of

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12. The measurement outcomes of particles in quantum entangled states are correlated regardless of the distance between them. Quantum entanglement is a fundamental quantum mechanical property in quantum computing but is not essential for QKD.

the photon can be determined. All QKD protocols discussed so far fall into this category.

- **CV-QKD:** This approach uses **optical detectors**, employing techniques like homodyne detection or heterodyne detection (dual-homodyne detection),¹³ to measure the amplitude of light. In this case, the sender encodes information in the amplitude of the light. Historically, the GG02 protocol (Grosshans *et al.* [2003]) is a well-known example. However, many modern protocols do not have specific names.

Photon detectors are devices designed to detect the presence or absence of extremely weak light, such as single photons. In practice, most photon detectors distinguish between 0 photons and 1 or more photons, a process referred to as on-off photon detection. DV-QKD, which leverages the properties of single photons, enables simpler descriptions of quantum states, making security proofs more straightforward. However, it has limitations: DV-QKD is susceptible to interference from strong light signals used in classical communication operating at similar frequencies. Additionally, photon detectors are expensive, making cost-effective implementation of DV-QKD challenging.

Optical detectors measure the intensity of light but cannot detect light as weak as single photons. To overcome this limitation, homodyne and heterodyne detection amplify weak single-photon-level light by interfering it with laser light before measurement by the optical detector. CV-QKD has a cost advantage over DV-QKD, as optical detectors are inexpensive.

Another advantage of CV-QKD is its ability to share optical fiber networks with classical communication. In optical communication, signals can be multiplexed on a single optical fiber by encoding them on light pulses of different wavelengths, thereby increasing communication capacity. This technology is known as **wavelength-division multiplexing (WDM)**. CV-QKD's light measurement benefits from wavelength filters, which selectively isolate the desired wavelength of light. Thus, CV-QKD is less affected by signals at other wavelengths, making it more robust than DV-QKD. By assigning a dedicated wavelength to CV-QKD within a WDM system, it becomes possible to coexist with classical optical communication systems without requiring new optical fiber installations.

According to Pirandola *et al.* (2017), CV-QKD has the potential to surpass DV-QKD in communication speed, provided that theories and implementation technologies continue to advance. However, establishing security proofs for CV-QKD is not straightforward. The first security proof for a practically implementable discrete-modulated CV-QKD protocol was provided by Matsuura *et al.* (2021). As of February 2024, existing CV-QKD protocols with established security proofs still exhibit inferior performance compared with DV-QKD. Thus, future improvements in CV-QKD performance depend on advancements in protocols, device implementation, and theories for security

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13. This is a detection technique for measuring weak optical signals, characterized by its resistance to noise from light with different frequencies. In homodyne detection, the target optical signal is combined with a reference light, amplified, and then converted into an electrical signal by a detector. In this process, the target and reference lights must have the same frequency. Heterodyne (or dual-homodyne) detection, on the other hand, splits the input light into two parts and performs homodyne detection on each, using reference lights with a phase difference of one-quarter wavelength.

proofs.

3. Classification by device reliability

QKD protocols can also be classified on the basis of assumptions regarding the reliability of the devices. These assumptions affect both the security proofs and the design of the communication protocols.

- **Device-Dependent QKD (DD-QKD):** This approach assumes that the devices function consistently with their specified models, and security is guaranteed under this assumption. All the QKD protocols discussed earlier fall under this category.
- **Device-Independent QKD (DI-QKD):** In this approach, security is guaranteed under minimal assumptions about the devices. Specifically, it assumes that the devices do not leak information intended for the sender or receiver to an eavesdropper, that they can generate genuine random numbers, and that they do not possess internal memory storage (Barrett, Colbeck, and Kent [2013]). An example is the E91 protocol.

DI-QKD adopts a security-proof approach that does not rely on specific device models. Due to the limited assumptions available for security proofs, developing protocols with security proofs is highly challenging. However, because DI-QKD does not assume particular device models, the number of testing criteria for verifying device properties is smaller compared with DD-QKD.

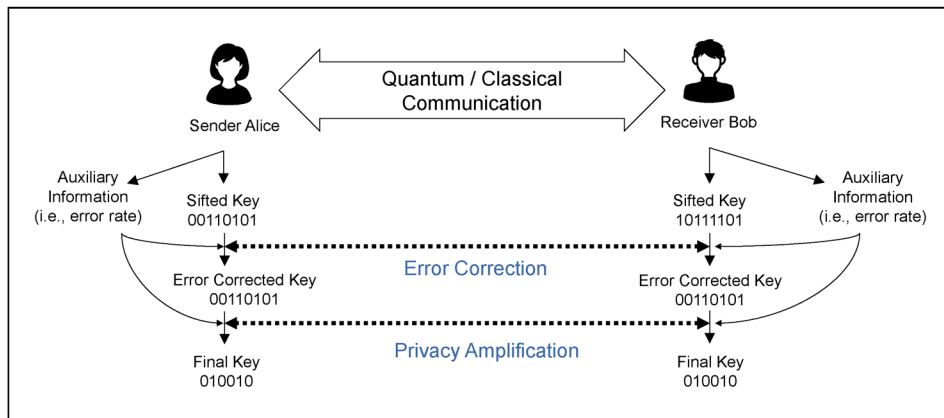
When considering the differences between DI-QKD and DD-QKD, the following two points should be noted. First, it is sometimes misunderstood that DI-QKD does not require device verification since it avoids assuming specific device models. However, it is necessary to verify that the devices satisfy fundamental theoretical assumptions. These assumptions are not about specific device models but are universal and fundamental from a quantum-mechanical perspective, as required by Bell experiments. Second, in both types of QKD, ensuring that devices do not leak information intended for the sender or receiver to an eavesdropper is essential. This requirement remains critical for addressing implementation attacks, leaving little difference between the two types of QKD. Given this point, the fundamental differences between DI-QKD and DD-QKD remain subject to debate.

From a performance standpoint, however, DI-QKD has drawbacks. Without advanced components such as **quantum memory** for preserving qubits, its performance is drastically inferior to DD-QKD. Furthermore, long-term retention of qubits poses considerable technical challenges. Several experts estimate that the practical implementation of DI-QKD may require over 20 years of further development. Thus, unless otherwise specified, the following discussion assumes DD-QKD.

D. Basic Structure of the Protocol

A representative QKD protocol is the BB84 protocol (Bennett and Brassard [1984]). BB84 was introduced by Charles Bennett and Gilles Brassard in 1984 and was named after the initials of its proposers and the year of its proposal. Experimental demonstrations of QKD conducted across various countries are mostly based on the BB84 protocol. For details of this protocol, excellent resources are already available in the

Figure 2 Three Broad Steps of the QKD Protocol



literature. Readers are encouraged to refer to Koashi and Koshiba (2008), Goto (2009), and Nielsen and Chuang (2010).

This section outlines an overview of QKD protocols (see Figure 2). Most QKD protocols, including the BB84 protocol, are executed in three broad steps. In Step 1, an incomplete random number sequence, known as the **sifted key**, is shared. In Steps 2 and 3, the secure portions of the sifted key are extracted, and the **final key** is obtained. Each step is described in the following.

Step 1 involves sharing the sifted key. A random number sequence is shared, and the states of the quantum and classical channels are monitored. Specifically, in PM-QKD, the sender transmits a sequence of qubits through the quantum channel, while the receiver measures the qubits. During this process, the sender probabilistically switches between types of quantum states, and the receiver also switches between types of measurement methods (**measurement bases**; see Footnote 6). These choices are later communicated and reconciled between the sender and receiver via the classical channel. The random number sequence shared during this step is not perfectly identical between the sender and receiver due to noise.¹⁴ Moreover, there is a possibility that parts of this sequence have been intercepted by an eavesdropper. This imperfect sequence is referred to as the **sifted key**.

Step 2 involves **error correction**. By communicating partial information about the sifted key (e.g., **syndromes** in error-correcting codes) through the classical channel,¹⁵ the sender and receiver identify discrepancies in their keys and correct one party's key to match the other's. This procedure is analogous to error correction in a noisy classical channel. The proportion of discrepancies is referred to as the **error rate**, and the length of the obtained key increases as the error rate decreases.

Step 3 involves **privacy amplification**. A random number sequence independent of the key is shared via the public classical channel. Using a predetermined algorithm,

14. For example, noise in the communication channel, eavesdropping by an attacker, and quantum mechanical fluctuations in measurement outcomes.

15. In some protocols, it is necessary to encrypt and transmit information using a pre-shared key. In such cases, the key generation rate of the protocol is defined as the total amount of keys generated minus that of the pre-shared keys used during this step.

the key is shortened to eliminate any partial information that may have leaked to a potential eavesdropper. The more information suspected to have leaked, the shorter the key must be adjusted. As a result of this process, the sender and receiver can share a highly secure and identical key with an extremely high level of certainty.

IV. Theory of Security Proof in QKD

A. Security Criteria and Assumptions for Security Proofs

The components of a QKD security proof include the security criteria that define the level of security to be proven, the device model that mathematically represents the properties of the communication devices, and the QKD protocol itself.

1. Security criteria

The security criteria, which serve as the goal of a security proof, are based on information-theoretic security. A protocol is considered secure if the key shared by a real-world protocol P_{real} is indistinguishable from the key shared by an ideal protocol P_{ideal} , where the ideal protocol assumes no noise or eavesdropping in the channel and achieves perfect secrecy.¹⁶ This indistinguishability is referred to as ϵ -indistinguishability, defined as follows.

Given a positive constant ϵ , a real-world protocol P_{real} and an ideal protocol P_{ideal} are **ϵ -indistinguishable** if, for any distinguisher, the following condition

$$|\Pr[B = 1|P_{\text{real}}] - \Pr[B = 1|P_{\text{ideal}}]| \leq \epsilon,$$

holds. Here, a **distinguisher** is a virtual entity that attempts to differentiate between the two protocols. On the basis of its evaluation, the distinguisher outputs an estimate B . If the distinguisher identifies the protocol as ideal, it outputs $B = 1$; if it identifies it as real, it outputs $B = 0$. The probability of obtaining an estimate B under a given protocol P is denoted as $\Pr[B|P]$. Satisfying ϵ -indistinguishability for all possible distinguishers ensures security against all possible eavesdropping attempts, forming the basis for the protocol's information-theoretic security.

A protocol that ensures the shared key satisfies this property is referred to as **ϵ -secure**. The positive constant ϵ , which can be set to any desired value by the QKD user, intuitively represents the maximum probability that the real protocol's outcome deviates from that of an ideal protocol.

2. Assumptions for security proofs

The proof of QKD's information-theoretic security (or **unconditional security**¹⁷) relies on a set of mathematical assumptions about the abilities of the sender, receiver, and eavesdropper, as well as the device models and the QKD protocol itself. These assumptions include the following.

- (a) On the quantum channel, the attacker can perform any attack including interception and eavesdropping.

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16. This security criterion ensures closeness in terms of the trace distance between the ideal and real states.

17. The term "unconditional" in this context has a limited meaning, indicating that no specific conditions are imposed on the quantum communication channel.

- (b) On the classical channel, the attacker can eavesdrop but cannot impersonate either party or tamper with the transmitted data.
- (c) Both the sender and receiver can generate genuine random numbers.
- (d) The devices function precisely in accordance with the device models.
- (e) The eavesdropper has no direct access to the internal components of the devices.

Assumption (a) considers extreme attacks, such as denial of service (DoS) attacks in which the attacker observes all qubits or completely severs the channel. In such cases, the length of the shared key becomes zero. This highlights a fundamental characteristic of QKD: while its security is always guaranteed, the ability to share a key is not.

Assumption (b) indicates that authentication of the parties and messages is securely conducted. Although authentication methods are established for classical communication, it is essential to recognize that the security of authentication is encompassed within the overall security of the QKD protocol. For further details, see Section V.B.

Assumption (c) presumes that the sender and receiver possess secure physical random number generators. These generators can be based on quantum or classical pseudorandom methods, but the associated risk profiles differ. Classical pseudorandom generators are susceptible to backdoor attacks and inherently carry a risk of random number prediction. Quantum random number generators (QRNGs) are believed to have a lower risk of backdoor attacks, but they still have a risk stemming from other types of attacks.¹⁸

Assumption (d) defines the device model as an abstraction of real-world devices, mathematically described within the framework of quantum mechanics.

Assumption (e) presumes that the attacker cannot directly steal the classical bits of random number sequences stored inside the devices. It is notable that this assumption does not rule out the possibility of remote extraction attacks. Additionally, regarding implementation attacks, the associated risks are inherently tied to the assumptions of the device model.

Under these assumptions, the security of the QKD protocol is established.

3. Relationship between assumptions for security proofs and the threat of implementation attacks

The security of QKD is proven based on the assumption that devices operate in accordance with their device models. However, discrepancies between real-world devices and their theoretical models may be exploited by attackers, enabling eavesdropping or tampering. Such risks pose significant threats of implementation attacks to QKD.

Implementation attacks encompass any attacks that break cryptographic security without relying on design flaws in the protocol or cryptographic weaknesses.¹⁹ In QKD,

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18. For example, it is necessary to consider the risk of attacks that replicate random numbers output by a random number generator through some means.

19. For details on implementation attacks, see, for example, Suzuki, Sugawara, and Suzuki (2015). In classical cryptography, implementation attacks are classified into invasive attacks, which involve direct physical access to the internal components of a device, and non-invasive attacks, which do not require such access. Non-invasive attacks can be further divided into side-channel attacks, where the normal operation of a device is passively observed, and fault-injection attacks, where errors are actively induced in the device to observe

these are defined as attacks that compromise the assumptions of the device model. Importantly, such attacks invalidate the security guarantees provided by mathematical proofs.

One example of an implementation attack in QKD involves exploiting vulnerabilities in the photon detectors on the receiving side. If a detector is exposed to extremely intense light, it may become damaged, rendering it unresponsive to light below a certain intensity. An attacker could exploit this phenomenon by ensuring that the receiver detects signals only on specific measurement bases chosen by the attacker. This enables eavesdropping without introducing detectable errors, thereby bypassing the QKD protocol's error-checking mechanisms.

To mitigate such risks, countermeasures can be employed, such as introducing MDI-QKD as described in Section III.C.1., or by actively monitoring the intensity of incoming light to the receiver to detect potential attacks.

In general, however, anticipating and mitigating unknown implementation attacks in advance is challenging. Thus, countermeasures against implementation attacks typically focus on addressing known attack methods. Over the nearly 40-year history of QKD, particularly in the past two decades, knowledge has been accumulated regarding device models tailored to real-world devices and countermeasures against implementation attacks.

In theoretical research, efforts have been made to redesign QKD protocols—especially the processes for privacy amplification—by incorporating device imperfections as assumptions. Such redesign efforts have helped extend security proofs to account for potential risks posed by these imperfections, effectively nullifying certain vulnerabilities.

In practice, verifying whether devices operate in accordance with their theoretical models requires experimental testing of actual devices. This highlights the need for developing standards for device specifications and establishing institutional frameworks for verification and certification. For further details on this topic, see Section V.C.

Finally, even in QKD, once information is converted into classical bits, the devices become vulnerable to implementation attacks as classical systems. Thus, standard countermeasures used in classical systems must also be applied to QKD devices.

B. Advances in QKD Security Proofs

Section IV.B provides an overview of the evolution of research on QKD, focusing on the **security criteria** and the **device imperfections**.

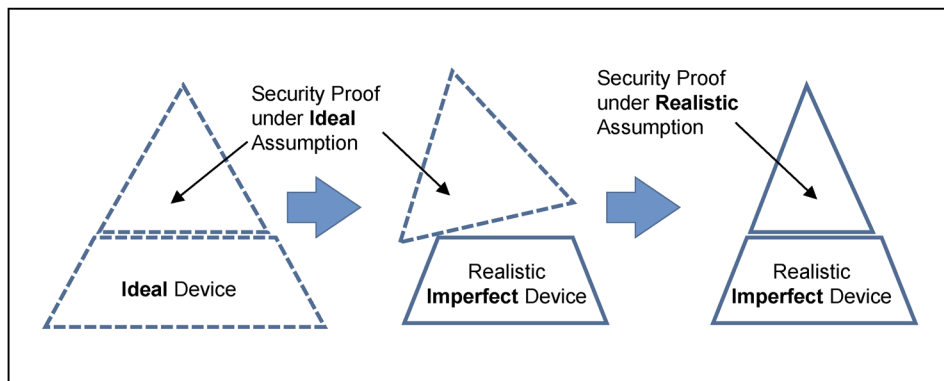
Since the proposal of the BB84 protocol, the theory for proving QKD security has continuously evolved. Typically, QKD security proofs begin by adopting idealized assumptions that are conducive to mathematical analysis. These studies have driven advancements in research on security criteria for QKD protocols.

abnormal behavior.

An example of a side-channel attack includes methods that extract information about plaintext by observing electromagnetic emissions or power consumption from a processing device during encryption or decryption operations.

In the case of QKD, a classification of implementation attacks similar to those for classical cryptography has not been well-established. Furthermore, implementation attacks are sometimes referred to as side-channel attacks, so caution should be taken with the use of terminology.

Figure 3 Device Imperfection and Security Proof



However, a key challenge has been the gap between the assumptions required for theoretical security proofs and the practical constraints of real-world devices. To address this, researchers have developed improved proofs that incorporate device imperfections as explicit assumptions. These advances enable security proofs that preserve QKD performance while accounting for risks posed by implementation attacks and other practical limitations (Figure 3).

The following subsections discuss these two research streams. Section IV.B.1. explains the research on security criteria. Section IV.B.2. explains the research on security proofs incorporating device imperfections.

1. Advances in research on security criteria

The first QKD protocol was the BB84 protocol, in which the sender generates ideal single photons and encodes their polarization in one of four states (0° , 45° , 90° , 135°) before sending them to the receiver. The receiver, using photon detectors, measures the polarization of the photons. The original paper by Bennett and Brassard (1984) claimed that the protocol was information-theoretically secure over an idealized noiseless channel. However, this claim faced criticism, as real-world channels inevitably contain noise, rendering the original security proof incomplete.

In response to these criticisms, Mayers (1996) extended the security proof for the BB84 protocol to account for noisy channels and imperfect measurement devices. This work advanced the field, establishing a broader consensus among researchers that QKD could indeed achieve information-theoretic security. However, the security criterion used in Mayers' proof was fundamentally based on **mutual information**.²⁰

Subsequent research by Müller-Quade and Renner (2009) revealed that mutual information was insufficient as a security criterion. Their findings raised the consensus among researchers that ϵ -security, an information-theoretic security criterion, should be adopted (see the definition of ϵ -security in Section IV.A.1.). Today, ϵ -security is the

20. Mutual information is a metric that represents the degree of dependency between two random variables and can be interpreted as the amount of information about one random variable obtained from the other. Intuitively, if the information about the secret key that can be derived from the quantum information processing system executing a QKD protocol (i.e., the values of certain random variables) is small, the protocol could be considered secure.

On the basis of this intuition, a security criterion using mutual information was developed. However, counterexamples have demonstrated that a protocol is not necessarily secure despite this intuitive reasoning.

de facto standard security criterion for QKD protocols.²¹

2. Advances in research incorporating device imperfections

Even when ϵ -security is guaranteed, the significance of the security heavily depends on the underlying assumptions. For device models, several critical aspects must be considered, including the feasibility of procuring devices that meet the model's requirements, the extent of losses and noises in the devices, the accuracy of performance metrics, and the methods for verifying these metrics.

One challenge involves the light source used in the BB84 protocol. The original security proof assumed the availability of an ideal single-photon source. However, realizing such an ideal source is technically difficult, so practical implementations typically use laser sources with average photon intensities reduced to the single-photon level.

Nonetheless, laser sources inherently emit **multiple photons** with a certain probability, violating the assumptions of the original security proof. This discrepancy introduces vulnerabilities that can be exploited by attackers. For instance, when multiple photons with identical quantum states are emitted, an eavesdropper could intercept one photon while forwarding the remaining photons to the receiver. Since the eavesdropper leaves no trace of their interference, the attack compromises the security of the protocol without introducing detectable errors. Thus, regardless of analysis, it is fundamentally impossible to derive a secure key from signals containing multiple photons under the BB84 protocol.

Furthermore, laser light in reality exists as a **superposition of single-photon and multi-photon states**, creating additional risks of efficient eavesdropping via implementation attacks. To mitigate these risks, countermeasures involving phase randomization of the laser light have been developed. This randomization—achieved using laser oscillation instability or phase modulators—transforms the laser light into a probabilistic mixture of classical states corresponding to various photon numbers, neutralizing attacks that exploit its quantum superposition nature.

The methodology for proving security under such conditions was established by Gottesman *et al.* (2004). However, this approach introduced a drawback: long-distance communication performance was substantially lower compared with systems using ideal single-photon sources.

To address the performance decline, **decoy-state QKD** (Hwang [2003], Lo, Ma, and Chen [2005], Wang [2005]) was proposed. In this protocol, the sender probabilistically varies the intensity of laser pulses, and the receiver analyzes the corresponding detection rates. If an attacker selectively targets multi-photon states, changes in detection rate ratios reveal the attack's presence.

Decoy-state QKD offers the following benefits. First, the average key generation rate per pulse improves to levels comparable with those achievable with ideal single-photon sources, even over long distances. Second, laser sources with high pulse repetition rates outperform single-photon sources in average key generation rate per unit time.

Decoy-state QKD exemplifies advancements in QKD protocols and security proofs addressing device imperfections, as illustrated in Figure 3. Beyond this study, Sajeed *et*

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21. For the approach in security proofs based on ϵ -security, please refer to the appendix.

al. (2021) provide a comprehensive survey of other device imperfections.²² For many known implementation attacks exploiting such imperfections, basic countermeasures have been devised. For unknown implementation attacks and device imperfections with unclear security implications, Pereira *et al.* (2020) proposed a methodology to handle discrepancies between adopted device models and idealized models. Their framework quantifies these differences using fidelity-like metrics, ensuring QKD system security if discrepancies remain sufficiently small.

Many frameworks addressing device imperfections include provisions for verifying noise levels in devices as part of their security guarantees. Thus, simplifying device property testing and ensuring high QKD protocol performance remain key challenges in the field.

V. Discussion

This section examines the challenges toward the widespread adoption of QKD.

Section V.A. reviews position papers on QKD published by national information security organizations and agencies. Section V.B. discusses authentication in QKD. Section V.C. summarizes the standardization of QKD protocols and technologies. Finally, Section V.D. explores the key challenges toward the adoption of QKD, on the basis of the preceding discussions.

A. International Assessments of QKD

Information security agencies and related authorities from various countries have published documents evaluating QKD. Many of these assessments express skepticism regarding the practicality and cost-effectiveness of QKD. However, note that these evaluations often assume a comparative context with PQC, specifically focusing on general-purpose encryption used in Internet communications.

Reviewing these documents, QKD is not currently viewed as a viable alternative to PQC in terms of performance and cost. Its primary advantage lies in its information-theoretic security, which is particularly beneficial for scenarios requiring ultra-long-term confidentiality or for addressing risks such as the secret compromise of PQC or the threat of HNDL attacks. Thus, the value of QKD depends on its application context.

As discussed in Section II.D., QKD is best suited for the transmission of highly confidential information with restricted applications. Thus, its most appropriate comparison is likely with trusted courier systems rather than PQC. In any case, constructive discussions about the appropriate use cases for QKD and its differentiation from PQC should consider evaluations from cryptographic experts.

The following provides a summary of the evaluations of QKD by national authorities.

The U.S. National Security Agency (2021) has stated that it does not recommend the use of QKD in National Security Systems unless the following technical limitations are addressed.

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22. For example, the uncertainty in the sender's ability to perfectly prepare qubits in the desired states is taken into consideration.

- (a) QKD does not provide authentication mechanisms equivalent to digital signatures.
- (b) QKD requires dedicated communication devices.
- (c) QKD relies on trusted relays, which increases infrastructure costs.
- (d) The actual security guaranteed by QKD depends on the implementation of the communication devices.

The authors consider these constraints, highlighted in the discussions by the NSA and other nations, as follows.²³ Limitation (a) does not significantly undermine the utility of QKD. For further details, please refer to Section V.B. Limitations (b) and (c) primarily relate to the issue of initial implementation costs. In scenarios requiring ultra-long-term confidentiality, QKD remains a promising option even with such costs. Additionally, studies have proposed cost-effective approaches that integrate existing communication lines with QKD-based systems, providing further support for its adoption. Regarding limitation (d), similar constraints apply to classical cryptographic systems, including PQC. Nevertheless, for QKD, the establishment of institutional frameworks to certify device security remains a challenge. For further discussion, see Section V.C.

The United Kingdom's National Cyber Security Centre (NCSC) also expressed its position on QKD in a white paper on cryptographic transition published in November 2020 (National Cyber Security Centre [2020b]). Citing reasons similar to the aforementioned limitations (a) and (b), the NCSC recommended against the use of QKD in all government and military institutions. Further details on these reasons were elaborated in another white paper on QKD and quantum random number generation, released in March of the same year (National Cyber Security Centre [2020a]).

The Netherlands National Communications Security Agency (2022) has similarly criticized QKD, citing limitation (a) as a vulnerability to man-in-the-middle attacks. A man-in-the-middle attack occurs when an attacker intercepts and manipulates communication between a sender and receiver, who mistakenly believe they are directly communicating with each other, thereby enabling an attacker to eavesdrop or alter the transmitted information. To address this vulnerability, the use of PQC for authentication has been proposed; however, doing so would undermine the relative advantages of QKD to PQC. Additionally, the agency noted that the security proofs for QKD are incomplete because they fail to account for the entire application environment in which QKD is implemented. Many of the assumptions regarding the devices are unrealistic. Moreover, QKD suffers from limitations in communication distance, the necessity of numerous trusted points, and poor scalability. On the basis of these considerations, the agency concluded that QKD cannot serve as a viable substitute for PQC.

A position paper ANSSI (2023) published by France's National Agency for the Security of Information Systems (Agence Nationale de la Sécurité des Systèmes d'Information: ANSSI) highlighted the challenges of large-scale deployment of QKD, emphasizing that the risks posed by universal quantum computers are already

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23. Additionally, Renner and Wolf (2023) have reviewed and countered the NSA's evaluation. Their paper concludes that many of the issues raised by the NSA regarding QKD will be resolved in the medium- to long-term future. Here, the medium-term future refers to an era when affordable optical devices and quantum repeaters become available, while the long-term future refers to a time when quantum computers are interconnected via quantum networks.

addressed within PQC. While the paper acknowledged the potential niche applications of QKD, such as secure communication between critical sites, it also pointed out that QKD fails to meet many of the functional requirements demanded by modern communication systems, including scalability, high transmission speed, and end-to-end encryption. Thus, the agency concluded that PQC is a more suitable option for long-term data protection.

In a joint position paper released by the information security authorities of France, Germany, the Netherlands, and Sweden (ANSSI *et al.* [2024]), additional limitations of QKD, as outlined by the U.S. NSA, were reiterated. The paper notes that QKD's constraints on transmission speed preclude its use for encrypting data payloads. Instead, the data must be encrypted using symmetric cryptography rather than OTPs, meaning that QKD cannot guarantee information-theoretic security for the data itself. Moreover, it is argued that the theoretical security assurances of QKD are not directly applicable to its practical implementations in real-world devices. On the basis of these considerations, the paper concluded that QKD remains an immature technology and, for the time being, is limited to niche applications.

However, in the authors' view, QKD holds the potential to be effectively combined with OTPs by continuously running the QKD protocol to accumulate keys even during periods of non-use. This approach enables the practical encryption of data payloads using OTPs. Furthermore, as discussed in Section IV., security proofs now increasingly account for device imperfections, thereby narrowing the gap between theoretical guarantees and practical implementations.

B. Discussion on Authentication

As noted in Section V.A. with reference to the evaluation of the U.S. NSA, QKD has been criticized for not providing an inherent authentication mechanism. Without mutual authentication, QKD becomes vulnerable to man-in-the-middle attacks. However, since QKD utilizes both quantum and classical channels, integrating any desired authentication mechanism is feasible through the classical channel. Ideally, mutual authentication should be conducted before initiating key sharing to verify the legitimacy of the communication partner.

This section discusses how the choice of authentication mechanism integrated with QKD impacts the assumptions and security evaluations of the entire QKD protocol, including authentication. In particular, as explained later, even if the authentication mechanism is based on computational security, this does not necessarily undermine the overall utility of QKD.

Many QKD protocols aim to achieve information-theoretic security not only for the key distribution process but also for authentication. To this end, they often incorporate the **Wegman-Carter authentication** scheme (Wegman and Carter [1981]), designed to ensure information-theoretic security. This scheme assumes that the sender and receiver share a small number of secure random numbers in advance—no more than the logarithmic scale of the classical communication volume. Under the use of Wegman-Carter authentication, QKD should more accurately be described as “key growing” rather than “key distribution.” In this sense, QKD can be viewed as a mechanism for prolonging the secure random number sequence pre-shared for Wegman-Carter authen-

tication.

If information-theoretic security is not required for mutual authentication, computationally secure authentication may also be employed. For instance, digital signatures based on elliptic curve cryptography can be used. However, because it does not guarantee security against quantum computers, there remains a risk of impersonation.

Digital signatures based on PQC provide security against quantum computers. In this case, as discussed in Section II.D., this leads to criticisms that QKD offers little relative advantage over PQC. Nonetheless, the importance of information-theoretic security for authentication is generally lower than that for data confidentiality.

In authentication, it is sufficient to ensure the authenticity of the communication partner only during the limited timeframe in which message exchange occurs. Even if the authentication mechanism is based on computational security and could potentially be compromised in the future, impersonation of the partner would have no practical impact once the exchange is completed. Thus, in practice, as long as computationally secure authentication mechanisms cannot be broken within the short timeframe, the utility of QKD in ensuring the confidentiality of the data payload remains largely intact.

C. Standardization of QKD

A challenge of QKD is to establish an institutional framework to verify and certify the security of its communication devices. Toward this goal, international standardization is being promoted. Such frameworks are expected to promote the adoption of QKD by providing formal certification of cryptographic products' security on the basis of international standards.

To provide context, the following provides an overview of the institutional frameworks for classical cryptographic products. Institutional frameworks for third-party evaluation and certification have been established and are currently in operation. In Japan, the **Japan Information Technology Security Evaluation and Certification Scheme (JISEC)**²⁴ provides a framework under which the security functions of products and systems are defined and assessed on the basis of the Common Criteria (CC) established by the International Organization for Standardization (ISO/IEC 15408). These assessments certify whether the security functions are appropriately implemented. Additionally, the **Japan Cryptographic Module Validation Program (JCMVP)**²⁵ provides a framework to test and certify cryptographic modules on the basis of standards such as the U.S. Federal Information Processing Standards (FIPS 140-3) or its international equivalent, ISO/IEC 19790. Cryptographic modules implementing algorithms listed in the **e-Government Recommended Ciphers List**²⁶ are tested and certified by third-party organizations under Japan's national standard, JIS X 19790, which aligns with ISO/IEC 19790. The historical context of these frameworks is thoroughly discussed in Tamura and Une (2008).

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24. For an overview of JISEC, please refer to the following webpage provided by the Information-technology Promotion Agency (IPA) (<https://www.ipa.go.jp/security/jisec/about/index.html>).

25. For an overview of JCMVP, please refer to the following IPA webpage (<https://www.ipa.go.jp/security/jcmvp/index.html>).

26. Cryptography Research and Evaluation Committees (CRYPTREC) has established a list of recommended cryptographic algorithms for procurement in e-government systems, commonly referred to as the CRYPTREC Cryptographic List.

For QKD, the standardization of cryptographic protocols as well as the institutional frameworks for evaluation and certification of QKD products will be essential for its broader adoption. Specifically, for the deployment of QKD products, security evaluation standards certified by a third-party organization for compliance with international standards and implemented using methods recommended by public authorities will serve as critical benchmarks for decision-making.

In recent years, the development of security evaluation standards for QKD has been progressing in Europe and other regions. In Europe, the European Telecommunication Standards Institute (ETSI) published a Protection Profile (ETSI GS QKD 016) in April 2023. This document defines security requirements for CC-based evaluations, with contributions from Japan's National Institute of Information and Communications Technology (NICT).²⁷

Furthermore, significant advances have been made in the international standardization of security evaluation criteria. The **ITU-T Recommendations**,²⁸ which are international standards for telecommunications, already include numerous standards for QKD within the Y.3800 series. As of the time of writing (February 2024), 20 standards ranging from Y.3800 to Y.3819 have been established. ITU-T Recommendations are recognized as one of the enforceable *de jure* standards²⁹ under the WTO/TBT Agreement.³⁰ Additionally, the Agreement on Government Procurement within the WTO agreements mandates that technical specifications in government procurement be based on international standards wherever appropriate, giving ITU-T Recommendations significant influence over public procurement.

In the field of information security, **ISO/IEC JTC 1/SC 27** is also working on standards related to QKD security. For example, the draft standard ISO/IEC CD 23837-1/2 defines security requirements and specifies testing and evaluation methods for QKD. Similarly, an Industry Specification Group (ISG) under ETSI has advanced the standardization of QKD. Japanese researchers have significantly contributed their expertise to the development of these standards. For the effective implementation of these standards after their establishment, it is also crucial to cultivate domestic testing and certification bodies.

D. Challenges for the Adoption of QKD

The adoption of QKD faces four key challenges as follows.

The **first challenge** lies in improving communication performance by advancing

27. For further details, refer to the NICT webpage (<https://www2.nict.go.jp/qictcc/social/standard.html>).
28. The International Telecommunication Union (ITU) is a specialized agency of the United Nations responsible for developing international standards for telecommunications. Among the three sectors of the ITU, the ITU-T (ITU Telecommunication Standardization Sector) focuses on telecommunication standardization. The international standards developed by ITU-T are published as ITU-T Recommendations.
29. The TBT Agreement, included in the WTO Agreement, establishes principles to ensure that national standards for industrial products and their conformity assessment procedures do not create unnecessary obstacles to international trade (Technical Barriers to Trade). It emphasizes the development of standards on the basis of international norms.
30. A **de jure standard** refers to an official standard that has been formally documented and developed through publicly available procedures by a standardization body. In contrast, a **forum standard** is a standard established through the consensus of companies and experts interested in standardization within a specific field. A **de facto standard** refers to a standard created by an individual company or other entity that has become dominant in the market through selection and competition.

the theory of protocols and their security proofs, as well as communication devices. These elements are not independent; instead, there is a reciprocal relationship where improvements to protocols and devices necessitate corresponding updates to security proofs.

The **second challenge** involves developing institutional frameworks for evaluating and certifying the security of QKD devices. For QKD systems manufactured by various vendors to operate seamlessly on the same network, it is essential to standardize protocol specifications. Additionally, accumulating and validating expertise in implementation practices is crucial to prevent implementation attacks.

In Japan, it would be worth considering the option of including QKD-related cryptographic technologies in the e-Government Recommended Ciphers List, which provides guidelines for government procurement.

The **third challenge** is the development of quantum relay technology. In QKD systems that rely on classical relays, trust in the relay devices is a prerequisite, which significantly diminishes the inherent value of QKD. As of February 2024, there have been no successful demonstrations of quantum relays. However, the realization of quantum relay technology is a critical milestone for maintaining QKD's relative advantage over other encryption schemes. For detailed discussions on proposed approaches and challenges related to quantum relays, refer to Azuma *et al.* (2023).

The **fourth challenge** involves lowering the costs associated with deploying and operating QKD systems. The need for specialized devices makes the initial setup expensive, making it impractical for individual companies to establish proprietary QKD networks. Thus, public initiatives to develop and support communication infrastructure are essential. In this regard, Japan's efforts—led by NICT to demonstrate QKD networks—are a step in the right direction. Additionally, advancements in technologies that integrate QKD with existing networks could further reduce operational costs, enhancing its feasibility for broader adoption.

VI. Concluding Remarks

While progresses have been made in QKD demonstration experiments across major countries and regions, QKD remains a developing technology. Its societal utility heavily depends on uncertain future technological advancements. At present, QKD is not a replacement for the general-purpose encryption schemes used in Internet communications. Instead, it is best suited for transmitting highly confidential information between limited, secure endpoints.

The unique strength of QKD lies in its information-theoretic security, a robust property that cannot be guaranteed by PQC. For transmitting highly confidential information with exceptionally long retention periods, QKD could become a valuable option. Moreover, the advent of quantum computers capable of breaking conventional cryptography and the potential development of new cryptanalysis algorithms targeting PQC are unpredictable. Considering these tail risks, QKD provides a societally valuable option.

Beyond the scope of this paper, QKD could contribute to future innovations such as **quantum-secure clouds**, enabling the information-theoretically secure distribution

and storage of data by combining QKD networks with existing cryptographic technologies (e.g., secret sharing). Additionally, the development of a **quantum Internet**, which could interconnect quantum information processing devices on a global scale, might emerge in the distant future. The research and development of QKD are likely to proceed with these societal implications and potential applications.

For now, it is crucial for the financial sector requiring high-security solutions to gain a precise understanding of the technical capabilities of QKD, the security services it provides, and the level of security it guarantees.

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APPENDIX: APPROACHES TO PROVING ϵ -SECURITY

There are two major approaches to proving ϵ -security.

The first approach employs the quantum version of the leftover hash lemma (Renner [2005], Tomamichel *et al.* [2011]). The hash values of the sifted key are compared between the sender and the receiver. For legitimate senders and receivers, who share an identical sifted key, the hash values will match. However, for an eavesdropper who possesses only partial information about the sifted key, the presence of unknown elements prevents the hash values from matching. If the hash values are sufficiently consistent between the sender and receiver, the final key can be considered secure.

The second approach involves virtual error correction (Lo and Chau [1999], Shor and Preskill [2000], Koashi [2009]). This approach treats the changes in the key caused by eavesdropping as errors induced by the eavesdropper obtaining key information. It then verifies whether these errors can be corrected. If correction is possible, it indicates that the eavesdropper does not possess sufficient information about the key, and the final key is secure. This technique is termed virtual error correction because it determines the correctability of errors theoretically from the error rate, without performing the experimentally challenging quantum error correction.

Following these proofs, further discussions have developed to evaluate more rigorously the characteristic quantities (e.g., min-entropy, phase error rate) that demonstrate the security of the final key in protocols guaranteeing ϵ -security.

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