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Essays in Financial Intermediation

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Publication Date
2015

Peer reviewed|Thesis/dissertation
Essays in Financial Intermediation

by

Jiakai Chen

A dissertation submitted in partial satisfaction of the requirements for the degree of

Doctor of Philosophy

in

Business Administration

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Nancy Wallace, Co-chair
Professor Christine Parlour, Co-chair
Professor Dwight Jaffee
Professor Robert Bartlett

Spring 2015
Essays in Financial Intermediation

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Jiakai Chen
Abstract

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Professor Nancy Wallace, Co-chair

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This dissertation consists of two chapters that concern financial intermediation. Many shadow banks rely heavily on bank-sponsored private credit and liquidity support instead of government guarantees. Bank capital regulation cannot be effective without explicitly considering these facilities. In the first chapter of the dissertation, I use a continuous time model with maturity mismatch and bank moral hazard to study the impact of credit and liquidity guarantees on bank capital structure. I focus on a particular type of shadow banking called asset-backed commercial paper (ABCP). When banks provide credit guarantees to ABCP conduits, assuming that the validity of the guarantees is ensured by rating agencies, the commercial paper becomes risk free and is always priced at par. Rolling over the commercial paper is thus costless, so that frequently rolling over the short term ABCP to fund long term assets—a maturity mismatch—has no impact on bank value. Regulators can eliminate a bank’s moral hazard by imposing a simple capital ratio requirement. However, the capital ratio requirement is no longer valid if banks use liquidity guarantees in their ABCP conduit funding because the funding maturity becomes important. Moreover, a liquidity guarantee becomes as costly as a credit guarantee when the maturity shortens. Using Moody’s ABCP conduit data, I confirm that shorter ABCP maturity causes the bank’s return to be more sensitive to the conduit credit loss. Thus, when banks have significant exposure to a liquidity guarantee, the search for a single appropriate risk weight is futile. More sophisticated tests, such as model-based tests are not only necessary but also have to be carried out under stressed scenarios.

The second chapter studies the current London Interbank Offered Rate (LIBOR). Recent investigation reveals banks might have manipulated the London Interbank Offer Rate (LIBOR). With banks concern about derivative position, net interest income and signaling effect, the equilibrium reporting strategy is a monotonic non-linear function of borrowing cost. Current trimming mechanism cannot block tacit collusion: when banks benefit from lower LIBOR, tacit collusion leads to downward biased LIBOR quotes. Signaling effect causes further depressed LIBOR. Equilibrium submissions do cluster together, as people
have observed from the data. Comparative statics suggest LIBOR bias spikes during the crisis, due to more dispersed borrowing costs and consumers’ less confidence in banks. I propose a direct and *ex ante* budget balanced LIBOR fixing mechanism. Finally, by calibrating the model to the ratio of dispersion among banks’ LIBOR submissions to their CDS spreads, I come up with an initial estimation, which matches practitioner’s opinions back in 2008, about LIBOR bias during the recent crisis.
To Lauren and Kevin
Contents

1 Off-Balance Sheet Financing and Bank Capital Regulation: Lessons from Asset-Backed Commercial Paper 1
   1.1 Introduction ................................................. 1
   1.2 Institutional Details of ABCP Conduits ......................... 4
   1.3 The Model ................................................ 10
   1.4 Empirical Analysis ............................................. 27
   1.5 Conclusion ................................................. 43

2 LIBOR’s Poker: Discover Interbank Borrowing Costs Amid Banks’ Strategic Behavior 46
   2.1 Introduction and literature review .................................. 46
   2.2 The model ................................................ 51
   2.3 Signaling ................................................ 62
   2.4 Mechanism design ............................................. 66
   2.5 Economic implications ........................................... 69
   2.6 Empirical study ............................................... 72
   2.7 Conclusion ................................................. 77

Bibliography ................................................ 79

A Off-Balance Sheet Financing and Bank Capital Regulation: Lessons from Asset-Backed Commercial Paper 82

B LIBOR’s Poker: Discover Interbank Borrowing Costs Amid Banks’ Strategic Behavior 93
## List of Figures

1.1 **Total ABCP outstanding vs commercial bank liability**  The left y-axis is for total ABCP outstanding, and the right y-axis (scaled 10 times) is for commercial bank liabilities. In early 2000s, the total ABCP outstanding is about 10% the size of total commercial bank liability in U.S. The left dashed line marks the confirmation of ABCP exclusion in risk capital calculation. The ABCP market size picked up rapidly then, reaching 1.21 Trillion USD in July 2007. The ABCP market experienced a rapid drop in size in the summer of 2007, and never recovered since. The ABCP exclusion was dropped in March 2010, as the second dashed line marks. .......................................................... 8

1.2 **Issuance percentage of USD ABCP with overnight maturity**  During the financial crisis, the percentage of newly issued ABCP with overnight maturity jumped from 60% to 70%. This percentage peaked at 80% around September 2009 when Lehman Brother failed. .................................................. 9

1.3 **Capital structure of bank using ABCP conduit funding with a credit guarantee.**  The assets in the conduit are booked as pledged assets on bank’s balance sheet, and the ABCP is booked as debt. Therefore, both the assets and commercial paper in the conduit remain on the sponsoring bank’s balance sheet. 12

1.4 **Capital structure of bank using ABCP conduit funding with a liquidity guarantee.**  The transfer of assets from the balance sheet to the conduit is booked as sales, and the proceeds of the originating ABCP are booked as sales revenue. Therefore neither the assets nor the commercial paper exist on bank’s balance sheet. The liquidity guarantee obligation is booked on the balance sheet using the fair value at origination. .......................................................... 13

1.5 **Timeline.**  There are multiple events of deposits (ABCP) maturity. The distance between two maturities follows an exponential distribution with intensity $m$. The event of bank shirking may happen before or after the ABCP wind-down, or may not happen at all. .......................................................... 15
1.6 **Equity value functions with exogenous default.** A shirking region exists. The lines plot the values of equity at varying cashflow levels, under monitoring and shirking. The exogenous default cashflow level is 0.285. A shirking region exists. The risk-free interest rate $r = 0.05$, the drift and volatility under monitoring are $\mu_m = 0.03$ and $\sigma_m = 0.3$, the drift and volatility without monitoring are $\mu_s = 0.02$ and $\sigma_s = 0.7$, corporate tax rate is 20 percent ($\tau = 0.2$), liquidation costs are 20 percent ($\alpha = 0.2$). The bank moves $S = 10\%$ of the assets to the ABCP conduit and provides a credit guarantee. The bank raises deposits $P_a = 27$, ABCP outstanding $P_d = 3$.

1.7 **Equity value functions under REE with social planner imposed equilibrium default barrier** $y^*_b$ that eliminates the shirking region. The lines plot the values of equity at varying cashflow levels, under monitoring and shirking. The risk-free interest rate $r = 0.05$, the drift and volatility under monitoring are $\mu_m = 0.03$ and $\sigma_m = 0.3$, the drift and volatility without monitoring are $\mu_s = 0.02$ and $\sigma_s = 0.7$, corporate tax rate is 20 percent ($\tau = 0.2$), liquidation costs are 20 percent ($\alpha = 0.2$). The bank moves $S = 10\%$ of the assets to the ABCP conduit and provides credit guarantee. Bank raises deposits $P_a = 27$, ABCP outstanding $P_d = 3$. The REE default threshold is $y^*_b = 0.386$.

1.8 **Social planner’s best response** $y^*_b(P_a, P_d)$ and bank’s total value under various amounts of deposits and commercial paper under as $y^*_b(P_a, P_d)$.

The risk-free interest rate $r = 0.05$, the drift and volatility under monitoring are $\mu_m = 0.03$ and $\sigma_m = 0.3$, the drift and volatility without monitoring are $\mu_s = 0.02$ and $\sigma_s = 0.7$, corporate tax rate is 20 percent ($\tau = 0.2$), liquidation costs are 20 percent ($\alpha = 0.2$).

1.9 **Value functions by ABCP maturity and guarantee** The risk-free interest rate $r = 0.05$, the drift and volatility under monitoring are $\mu_m = 0.03$ and $\sigma_m = 0.3$, the drift and volatility without monitoring are $\mu_s = 0.02$ and $\sigma_s = 0.7$, corporate tax rate is 20 percent ($\tau = 0.2$), liquidation costs are 20 percent ($\alpha = 0.2$).

1.10 **Bounded rational expectation equilibrium capital structure:** Amount of deposits and ABCP under various conversion factor $\rho$ This figure shows under the Bounded rational expectation equilibrium, in which the social planner sets the capital requirement without valuing the liquidity guarantee but through a conversion factor $\rho$, the bank have incentive to use large leverage through ABCP financing.

1.11 **Subprime ARM 2/28 60+ day delinquency ratio** The delinquency status of 30-year adjustable-rate subprime mortgages with a fixed rate for the first two years. I aggregate the monthly current balance of over 60 day delinquent subprime ARM 2/28 loans, and normalize it with the monthly total current balance of subprime ARM 2/28 loans. The delinquency rate was stable before mid 2006, then started to pick up as the U.S. housing market softened. By the end of 2009, about 50\% of the subprime ARM 2/28 borrowers are over 60 day delinquent.
1.12 **USD CP maturing overnight** The outstanding ABCP and non-financial commercial paper on a daily basis. The maturity of ABCP shortened during the 2007 ABCP market freeze, while the maturity of non-financial commercial paper shortened during the 2006 downgrade of General Motors.

1.13 **Model specification: the value of a liquidity guarantee as a function of the ABCP maturity and the cashflow of conduit assets.** The value of a liquidity guarantee is not a linear function of the ABCP maturity and the conduit cashflow. The non-linearity suggests that, in addition to the effect of the change in ABCP maturity and the effect of change in conduit cashflow, the interaction between these two changes may also be important to explain the change in the value of the liquidity guarantee.

1.14 **Identification strategy.** Simultaneity exists between the maturity of ABCP and the sponsoring bank’s abnormal return. Hence the ABCP maturity is an endogenous regressor. Meanwhile, the investor’s maturity preference drives the maturities of both ABCP and non-financial commercial paper. Since the abnormal return of non-financial firms are by construction orthogonal to that of the financial firms, the simultaneity issue between the non-financial firms and the maturity of their commercial paper is irrelevant. I therefore use the maturity change of non-financial commercial paper as an instrumental variable, even a similar simultaneity issue exists between the non-financial firms and the maturity of their commercial paper.

2.1 **Strictly increasing equilibrium strategy** The properties of equilibrium strategy when LIBOR panel is formed by \( N = 16 \) banks with i.i.d. normally distributed true borrowing cost. The first subplot is equilibrium strategy \( \beta^* (s) \) as a function of borrowing cost \( s \). The second and the third subplot show the CDF and PDF of borrowing cost as well as submissions in equilibrium. Under tacit collusion, the submissions of banks cluster around the lower half of the distribution.

2.2 **Determining the bunching level** The bunching level is between \( b_{\text{max}} \) and \( b_{\text{min}} \).

2.3 **Equilibrium strategy with binding monotonicity constraint** The properties of equilibrium strategy when LIBOR panel is formed by \( N = 16 \) banks with i.i.d. normally distributed true borrowing cost. The first subplot is equilibrium strategy \( \beta^* (s) \) as a function of borrowing cost \( s \). The second and the third subplot show the CDF and PDF of borrowing cost as well as submissions in equilibrium. It shows the bunching level is around the lowest quartile of the distribution.
2.4 **Strictly increasing equilibrium strategy with signaling** The properties of equilibrium strategy when LIBOR panel with signaling. The panel contains $N = 16$ banks with i.i.d. normally distributed true borrowing cost. The first subplot is equilibrium strategy $\beta^*(s)$ as a function of borrowing cost $s$. The second and the third subplot show the CDF and PDF of borrowing cost as well as submissions in equilibrium.

2.5 **Equilibrium strategy with binding monotonicity constraint with signaling** The properties of equilibrium strategy when LIBOR panel with signaling. The panel contains $N = 16$ banks with i.i.d. normally distributed true borrowing cost. The first subplot is equilibrium strategy $\beta^*(s)$ as a function of borrowing cost $s$. The second and the third subplot show the CDF and PDF of borrowing cost as well as submissions in equilibrium.

2.6 **Panel banks’ LIBOR quote-OIS spreads vs. CDS par spreads 2008-2010** The cross-sectional dispersions among CDS spreads and LIBOR quote-OIS spreads are different by order of magnitude: the variance ratio of LIBOR quote-OIS spread over CDS spread is less than 0.1.

2.7 **1Yr USD LIBOR adjustment during 2008-2010**
List of Tables

1.1 Summary statistics ................................................................. 32

1.2 Effect of ABP maturity on abnormal returns (OLS) This table reports
the OLS betas of the model presented in section 1.4. The dependent variable,
\( r_{it}^{a} \), is the holding period equity abnormal return of bank \( i \) at period \( t \). For
the explanatory variables, \( \%OVN_{t} \) measures outstanding ABP during period
\( t \), so \( \Delta \%OVN_{t} \) measures the change in the ratio of ABP outstanding matures
overnight from period \( t - 1 \) to \( t \). \( \Delta \text{Conduit Risk}_{i,t} \) is the product of subprime
mortgage delinquency rate change between period \( t-1 \) and \( t \), multiplies the bank’s
exposure to ABP liquidity guarantee aforementioned, which is the principal of
ABP relative to the bank’s book value. The regression controls for bank fixed
effect, bank balance sheet variables, and macroeconomic variables, as discussed
in the section 1.4. Standard errors are clustered at the bank level as well as at
the year level. ............................................................................. 38

1.3 Effect of ABP maturity on stock abnormal returns (IV) This table
reports the IV betas of the model presented in section 1.4. The dependent vari-
able, \( r_{it}^{a} \), is the holding period equity abnormal return of bank \( i \) at period \( t \). For
the explanatory variables, \( \%OVN_{t} \) measures outstanding ABP during period
\( t \), so \( \Delta \%OVN_{t} \) measures the change in the ratio of ABP outstanding matures
overnight from period \( t - 1 \) to \( t \). \( \Delta \text{Conduit Risk}_{i,t} \) is the product of subprime
mortgage delinquency rate change between period \( t - 1 \) and \( t \), multiplies the
bank’s exposure to ABP liquidity guarantee aforementioned, which is the prin-
cipal of ABP relative to the bank’s book value. The regression controls for
bank fixed effect, bank balance sheet variables, and macroeconomic variables, as
discussed in the section 1.4. Standard errors are clustered at the bank level as
well as at the year level. ..................................................................... 40
1.4 Effect of ABCP maturity on stock abnormal returns (IV: First-stage)

This table reports the first stage of the IV regression presented in section 1.4. ∆%OVN_t measures the change in the ratio of ABCP outstanding matures overnight from period t−1 to t. Similarly, the instrumental variable ∆%OVN Non-financial_t measures the change in the ratio of Non-financial CP outstanding matures overnight from period t − 1 to t. ∆Conduit Risk_i,t is the product of subprime mortgage delinquency rate change between period t − 1 and t, multiplies the bank’s exposure to ABCP liquidity guarantee aforementioned, which is the principal of ABCP relative to the bank’s book value. The regression controls for bank fixed effect, bank balance sheet variables, and macroeconomic variables, as discussed in the section 1.4. Standard errors are clustered at the bank level as well as at the year level.

1.5 Robustness I: Effect of ABCP maturity on excess returns (OLS)

This table reports the OLS betas of the model presented in section 1.4. The dependent variable, excess return r_i,t − r^m_t, is the holding period excess return of bank i at period t. For the explanatory variables, r^m_t is the CRSP value-weighted index return with distribution as the market return at the same period. %OVN_t measures outstanding ABCP during period t, so ∆%OVN_t measures the change in the ratio of ABCP outstanding matures overnight from period t−1 to t. ∆Conduit Risk_i,t is the product of subprime mortgage delinquency rate change between period t − 1 and t, multiplies the bank’s exposure to ABCP liquidity guarantee aforementioned, which is the principal of ABCP relative to the bank’s book value. The regression controls for bank fixed effect, bank balance sheet variables, and macroeconomic variables, as discussed in the section 1.4. Standard errors are clustered at the bank level as well as at the year level.

1.6 Robustness II: Effect of alternative ABCP maturity on stock abnormal returns (IV)

This table reports the IV betas of the model presented in section 1.4. The dependent variable, excess return r^a_i,t, is the holding period abnormal return of bank i at period t. For the explanatory variables, %OVN Issuance_t measures the ratio of newly issued overnight ABCP at day t to the total ABCP outstanding in the previous day. So ∆%OVN Issuance_t measures the change in the ratio from period t−1 to t. ∆Conduit Risk_i,t is the product of subprime mortgage delinquency rate change between period t−1 and t, multiplies the bank’s exposure to ABCP liquidity guarantee aforementioned, which is the principal of ABCP relative to the bank’s book value. The regression controls for bank fixed effect, bank balance sheet variables, and macroeconomic variables, as discussed in the section 1.4. Standard errors are clustered at the bank level.
1.7 **Robustness II: Effect of alternative ABCP maturity on stock abnormal returns (IV: First-stage)** This table reports the first stage of the IV regression presented in section 1.4. \( \% \text{OVN Issuance} \) measures the change in the ratio of newly issued overnight ABCP at day \( t \) to the total ABCP outstanding in the previous day. Similarly, the instrumental variable \( \Delta \% \text{OVN Issuance Non-financial} \) measures the change in the ratio of newly issued overnight non-financial CP at day \( t \) to the total non-financial CP outstanding in the last day. \( \Delta \text{Conduit Risk}_{i,t} \) is the product of subprime mortgage delinquency rate change between period \( t-1 \) and \( t \), multiplies the bank’s exposure to ABCP liquidity guarantee aforementioned, which is the principal of ABCP relative to the bank’s book value. The regression controls for bank fixed effect, bank balance sheet variables, and macroeconomic variables, as discussed in the section 1.4. Standard errors are clustered at the bank level.

2.1 **BofA’s non-trading interest income sensitivity to yield curve shift, in million USD.** Source: BofA 10-K, 10-Q

2.2 **Citi’s non-trading interest income sensitivity to yield curve shift, in million USD.** Source: Citi 10-K, 10-Q

2.3 **Summary statistics of panel banks’ 1Yr CDS spreads and 1Yr USD LIBOR quote-OIS spreads 2008-2010**

2.4 **Test for equal dispersions between 1Yr CDS spreads and 1Yr USD LIBOR quote-OIS spreads 2008-2010** The dispersions are significantly different

2.5 **K-S test for 1Yr CDS spread**

2.6 **1Yr USD LIBOR bias and adjustment during 2008-2010**
Acknowledgments

I want to thank the many without whose help the thesis could never have been realized.

I would like to thank my wife Xiaoyan Su for her great support and unbounded patience at all times. I thank my parents Huayu Chen and Pingzhong Zhong for their love and support throughout my life. I also acknowledge the support from my parents-in-law Juli Su and Wenlong Liu.

I am deeply indebted to my dissertation committee members Nancy Wallace, Christine Parlour, Dwight Jaffee, and Robert Bartlett for their invaluable intellectual influence, unconditional encouragement, and unlimited patience. They are all exceptional advisors and their help was way above their duties. Nancy has always been supportive of my research ideas, and has provided me grant support. I highly appreciate the countless hours you put in while I was going through my job market. Christine has shared with me her great insights about the literature and the promising future research areas. She has also carefully read and commented on my papers with exceptional patience. Dwight has offered great insights and overview to the field of financial intermediation, and has challenged me with difficult questions that have been asked multiple times in my job interviews. Robert has offered invaluable perspectives, challenged a widely adopted assumption with empirical evidence.

I am also grateful for deep discussions and admirable advice from Willie Fuchs, Nicolae Garleanu, Brett Green, Amir Kermani, Hayne Leland, Gustavo Manso, Christopher Palmer, Demian Pouzo, Richard Stanton, and Alexei Tchisty. I have been blessed with fellow PhD students who have taught me much: Javed Ahmed, Boris Albul, Anna Amirdjanova, Carlos Avenancio, Brian Ayash, Aya Bellicha, Fernando Comiran, Nathan George, Isaac Hacamo, Barney Hartman-Glaesar, Farshad Haghpanah, Albert Hu, Paulo Issler, Sanket Korgaonkar, Nirupama Kulkarni, Chris Lako, Raymond Leung, Haoyang Liu, Ryan Liu, So-Eun Park, Pratish Patel, Narhari Phatak, Michael Weber, Sean Wilkoff, Calvin Zhang, Dayin Zhang, and Ying Zhu. Thanks are also due to Thomas Chapplear, Kim Guilfoyle, Melissa Hacker, Bradley Jong, and June Wong for their amazing administrative assistance over the past six years.

I greatly acknowledge the financial support of Fisher Center of Real Estate and Urban Economics and the Institute of Business and Economic Research.

Thank you all.
Chapter 1

Off-Balance Sheet Financing and Bank Capital Regulation: Lessons from Asset-Backed Commercial Paper

1.1 Introduction

Shadow banks carry out traditional banking activities—financing long-term illiquid assets with short-term liquid debt—outside the regulated banking sector. With less restrictive regulatory control, shadow banks usually have little access to traditional government sponsorship such as the central bank discount window or deposit insurance. Instead, shadow banks rely more on bank-sponsored private credit and liquidity facilities, which are often both complex and opaque. The recent financial crisis proved that the collapse of shadow banking can lead to large-scale bank failure. Thus, the regulation of these private credit and liquidity facilities has become an important, challenging, and controversial topic in the debate on post-crisis regulatory reform. In this paper, I analyze bank-sponsored credit and liquidity facilities in the asset-backed commercial paper (ABCP) program. I show that credit and liquidity facilities have different interactions with the maturity transformation, which can lead to ineffective regulation.

Asset-backed commercial paper or ABCP was an important part of the U.S. shadow-banking system. The ABCP market appeared in the mid-1980s and then grew rapidly, peaking in 2007 when it reached 1.21 trillion USD, about 12.3% the size of total U.S. commercial bank liability\footnote{Source: Federal Reserve Bank St. Louis}. Many researchers believe the growth of ABCP was mainly driven by regulatory arbitrage (see Adrian and Ashcraft (2012), Acharya et al. (2012), Pozsar et al. (2010), Gorton et al. (2010), and Ordonez (2013)). Specifically, regulators imposed capital requirements to curb the moral hazard encouraged by deposit insurance (see Decamps et al. (2004)). Such capital requirements increased banks’ funding costs, so banks turned to...
CHAPTER 1. OFF-BALANCE SHEET FINANCING AND BANK CAPITAL REGULATION: LESSONS FROM ASSET-BACKED COMMERCIAL PAPER

cheaper off-balance sheet funding channels, such as ABCP conduits. Briefly, a bank sponsoring such a conduit transfers assets to a separate trust, which funds the acquisition by issuing short-term commercial paper backed by the assets. Moving assets off-balance sheet reduces banks’ capital charge. To obtain cheap funding for the move, the sponsoring bank usually promises credit or liquidity guarantees to the commercial paper investors. On paper, the credit guarantee transmits the conduit’s credit risk to the bank, while under a liquidity guarantee the ABCP investors retain the credit risk.

Liquidity guaranteed ABCP conduits experienced three different regimes of accounting standards and capital regulations in the 2000s. The first regime started in 2001, when Financial Accounting Standards (FAS) 140 was the prevailing accounting rule. FAS 140 effectively allowed banks to treat the asset transfer to a conduit as a true sale. Hence, there was no risk-capital requirement for using ABCP funding. However, after the Enron scandal, the Federal Accounting Standard Board (FASB) proposed a consolidation of conduits to balance sheets. The proposition raised concerns about ABCP conduit financing, and slowed down the growth of the ABCP market. The second regime started in 2004, when FASB issued Interpretation 46 (FIN 46) that required conduit assets to be consolidated onto banks’ balance sheets. However, the financial regulators amended the risk-based capital standards by allowing ABCP conduits to enjoy an “ABCP exclusion”, so that the conduit assets could be excluded from banks’ risk-weighted assets base after consolidation. As a result the ABCP market expanded rapidly, then shrank drastically following concerns about the housing market slow-down. The third regime started in 2010, when FAS 166 and 167 required banks to prepare allowance for loan and lease losses, which is included in tier 2 risk capital. The financial regulators also dropped the ABCP exclusion. A benefit to banks of using an ABCP conduit is the reduced capital charge it has to hold against risky assets. Yet the benefit to a bank depends on whether investors view the assets as guaranteed and are willing to finance them at low rates. Given the complex relationship between off-balance sheet financing, investor behavior and bank moral hazard, can regulation of on-balance sheet activities curb banks’ moral hazard? How do investors value bank guarantees versus government guarantees? How do the various types of bank guarantees and commitments interact with prudential regulation?

To answer these questions, I present a dynamic framework in which a bank chooses

Section 1.2 contains an introduction to the institutional details of the ABCP program, credit guarantees, and liquidity guarantees.


its optimal capital structure by using ABCP funding in addition to traditional deposits.\footnote{The dynamic capital structure model literature includes Leland (1994b), Leland and Toft (1996), Leland (1994a), and Decamps et al. (2004). The fair value of deposit insurance is related to Merton (1977) and Merton (1978), which studies the pricing of insurance under dynamic settings.} The regulator, who also provides deposit insurance, tries to eliminate the moral hazard by setting capital ratio requirements. I show that when banks rely on deposits or ABCP funding with credit guarantees, perfect insurance of credit loss not only protects the investors, but also eliminates the bank’s rollover risk. Without the rollover risk, banks’ riskiness does not change with deposit maturity. Since the regulator demands banks that provide credit guarantees to prepare risk capital for 100\% of the outstanding ABCP, risk-based capital ratio requirements are effective regulatory measures to control the moral hazard of banks using credit guaranteed ABCP conduit financing.

However, when banks use ABCP funding and provide liquidity guarantees to the commercial paper investors, they face rollover risk when they need to reissue new paper to replace the maturing paper. Rollover risk goes up when the maturity of the commercial paper becomes shorter. As a result, it is impossible to set an ‘appropriate’ risk capital requirement \textit{ex ante}, without taking maturity mismatch into consideration.\footnote{Regulators also carry out liquidity coverage tests, which check whether the bank has enough cash (or equivalent short-term assets with good liquidity) to cover the short-term payment obligations. My model suggests there is actual credit loss on rolling over short-term commercial paper, in addition to the cashflow liquidity pressure.} This result calls for more comprehensive model-based bank regulatory tests, as proposed in Bartlett III (2012).

Furthermore, when the maturity of ABCP becomes short, the value of liquidity guarantees converges to that of credit guarantees.\footnote{ABCP in the United States has maturity ranging from overnight to 270 days, while in Europe the maturity usually ranges from overnight to 180 days.} By allowing banks that provide liquidity guarantees to prepare risk capital for a fixed 10\% of the outstanding ABCP, the regulator ignores the effect of ABCP maturity to the risk transfer between banks’ balance sheets and ABCP conduits. This helps to explain why some large U.S. financial institutions that failed during the financial crisis had core capital ratios well in excess of the regulatory minimum of 8\%.

As Brunnermeier (2008) and Krishnamurthy (2009) point out, the excessive use of short-term debt financing is a major factor behind the notable collapse of large U.S. banks such as Bear Stearns. My result complements this literature by showing that the shortening of debt maturity not only adds to the liquidity pressure on the bank, but also imposes direct credit loss that the regulations failed to capture in the mid-2000s. My paper also extends several recent studies on rollover risk. Martin et al. (2014) study the fragility of short-term secured funding markets by investigating whether a run can occur as a result of changing market expectations. Acharya et al. (2011) show that high rollover frequency can lead to a market freeze, therefore lowers the maximum amount that can be borrowed using good collateral.
He and Xiong (2012b) study how deteriorating market liquidity leads to an increase in credit risk, originating from the firm’s debt rollover. In contrast, my paper focuses on the banking sector and studies the impact of rollover risk on the effectiveness of capital ratio regulation. Using a proprietary dataset from Moody’s Investor Service, I verify that the maturity on the off-balance sheet ABCP conduits significantly affects banks’ equity value. Specifically, I analyze the relationship between banks’ returns and the size of the liquidity guarantees they provide to ABCP conduits, and the change in the commercial paper’s maturity. Using an instrumental variable that corrects for the simultaneity between banks’ returns and the maturity of ABCP conduits, I find that the interaction between the change in ABCP conduit maturity and the change in the underlying conduit riskiness measure significantly impacts banks’ equity returns. When subprime 2/28 adjustable-rate mortgage delinquency rate goes up by one standard deviation, about 3.3 basis points, for a bank with average obligation of liquidity guarantee to ABCP conduit, about 3.6% of its book value, and the fraction of outstanding ABCP maturing overnight raise by one standard error, about 1.137%, the U.S. banks experience about 7.5 to 11.3 basis points negative abnormal return. Both the theoretical and empirical results suggest that the capital regulation before 2009 did not correctly capture the riskiness of ABCP conduit liquidity guarantor.

The rest of the article is organized as follows. Section 2 describes the institutional details of ABCP conduits. I set up a benchmark model that describes the ABCP conduit with credit guarantees, as well as a model for the ABCP conduit with liquidity guarantees in section 3. I analyze the rational expectation equilibrium in the benchmark model, and the bounded rational equilibrium motivated by the capital regulation practice for ABCP with liquidity guarantees. I then test the key theoretical implication in section 4, showing that the change in ABCP maturity has a clear effect on the risk transfer from the conduit to the bank. Section 5 concludes the paper, and all technical proofs are given in the Appendix.

### 1.2 Institutional Details of ABCP Conduits

An ABCP conduit is a special purpose entity (SPE), established to fund a portfolio of long-term financial assets with commercial paper. A sponsoring bank creates an ABCP conduit, then transfers assets, such as Mortgage Backed Securities (MBS), from its balance sheet to the conduit. When the long-term underlying assets of the conduit are paid off, the bank replaces them by moving new assets to the conduit. The conduit funds any such purchases by issuing ABCP collateralized by the underlying assets. The conduit has a default

Bartlett III (2010) shows that there is little evidence show that the investors of some financial institutions, monoline insurers in particular, uses the firm’s derivative disclosure to estimate its exposure to credit risk: the complexity of CDOs impeded informational efficiency. However, the ABCP conduit usually only contains the commercial paper tranche and a residual tranche. The much simpler deal structure allows the investors to assess the credit risk with less difficulty.
threshold: when the underlying assets deteriorate such that the default threshold is crossed, the sponsoring bank has to wind down the ABCP conduit and pay off the ABCP investors.

Typically, ABCP is structured as short-term, senior secured debt. This is done to attract investment from money market funds. Under SEC Rule 2a-7, a money market fund may only hold the highest rated debt (a Prime-1 rating), which matures in under 13 months and must maintain an overall portfolio weighted average maturity of 60 days or less. This source of investment is large: Aggregate assets in money market funds were up to 2.69 trillion USD by the end of year 2008. The large size of money market funds leads to lower transaction costs of ABCP in the secondary market than those of equity or longer-term debt.

Credit vs. Liquidity Guarantees

For ABCP to obtain the desired Prime-1 rating, banks typically provide explicit guarantees to the ABCP investor upon the conduit default. There are two types of guarantees that banks can offer: credit guarantees or liquidity guarantees. Credit guarantees completely mitigate the ABCP investors’ credit loss upon conduit default, by paying the ABCP investor the full principal amount. It is thus akin to private deposit insurance offered by the sponsoring bank.

A liquidity guarantee, unlike a credit guarantee, does not cover the loss inflicted by the already defaulted assets when the ABCP conduit winds-down. Although the conduits usually have some credit enhancement measures, such as a subordinate or overcollateralization tranche as the first group to absorb the loss of the defaulted assets, the ABCP investors are still subject to credit risk once the credit enhancement is depleted. Specifically, if a conduit with a liquidity guarantee defaults, its ABCP investors will only recover the remaining collateral value of the underlying assets.

Rollover support The sponsoring bank also helps the rollover of commercial paper when the investors with maturing ABCP no longer want to reinvest. In this case, the sponsoring bank pays the commercial paper’s principal amount back to the ABCP investors, therefore making sure that the ABCP investor can always recover their principal when the conduit has not reached the default threshold. The bank then reissues ABCP, usually at a discounted price. The short maturity of ABCP allows the ABCP investors to liquidate their investment by not rolling over maturing paper if they believe the underlying assets are deteriorating.

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10 The size of program credit enhancement is small, usually covers less than 10% of the conduit assets.
Conduit wind down  The use of off-balance sheet funding is critical to modern banks’ business model. If a sponsoring bank ever allows the ABCP investors to fire-sale the commercial paper upon the default of the conduit, it would lack the credibility to continue placing assets in any other conduits. Hence, it is in the bank’s interest to promise to consolidate a conduit back into its balance sheet when the conduit’s underlying assets deteriorate towards the wind-down trigger, though the bank may not keep the consolidation promise *ex post*, if fulfilling this promise would lead to bankruptcy. Furthermore, at the origination of the conduit, the rating agencies carefully study the health of the bank and the structure of the conduit to make sure the banks can make good upon their guarantees. During the crisis, banks suffered sizable fire-sale losses of conduit assets, when they consolidated conduit assets back onto their balance sheets.

Risk-Based Capital Requirements

ABCP conduits structured with credit guarantees cause the sponsoring banks, instead of the commercial paper investors, to carry the credit risk of conduit assets. Therefore, a bank that transfers assets from its balance sheet to an ABCP conduit and provides a credit guarantee cannot treat the assets transfer as a true sale, and the bank still has to prepare 100% of risk capital for the ABCP.

ABCP conduits structured with liquidity guarantees allow banks to enjoy “regulatory arbitrage”, because the bank can reduce the amount of regulatory risk capital it needs to keep by transferring assets off the balance sheet. Whether the bank needs to hold risk capital against the risky assets moved to the conduit is determined by both the Financial Accounting Standards Board (FASB), and financial regulators such as the Federal Reserve, FDIC, and Department of the Treasury. The changes in accounting standards and capital regulation in the 2000s impacted banks’ risk capital requirements when they used ABCP funding.

In September 2000, FASB introduced the Financial Accounting Standards (FAS) 140, which grants a conduit ‘qualifying SPE’ status, if the bank moves its assets to the conduit and satisfies the following conditions:

1. The financial assets are isolated from the bank after the transfer;
2. The limited activities of the conduit are entirely specified in the legal documents;
3. The conduit holds only passive financial assets that were transferred in, guarantees, and servicing rights;
4. Sale or disposal of the conduit assets must be specified in the legal documents, and exercised by a party that put that holders’ beneficial interest back to the SPE.
FAS 140 allowed a bank to transfer its assets to a “qualified SPE”, and book the trans-
action as a “true sale”. This means that the bank can remove the assets from its balance 
sheet and can book the proceedings raised from the commercial paper issuance as cash. This 
allows the bank to avoid the costly risk capital requirement completely.

However, FASB Interpretation 46(R), effective December 2003, required banks to consol-
idate the SPE assets to its balance sheet. In response to the FASB Interpretation 46(R), the 
Office of the Comptroller of the Currency (OCC), Board of Governors of the Federal Reserve 
System, Federal Deposit Insurance Corporation (FDIC), and Office of Thrift Supervision 
(OTS) collectively permitted the sponsoring banks to exclude from their risk-weight asset 
base those assets in ABCP programs that were consolidated as a result of FASB Interpreta-
tion 46(R).

Instead, the financial regulators required the banks to hold risk capital against 
10% of the size of ABCP liquidity facilities. The favorable risk capital treatment, also re-
ferred as the “ABCP exclusion”, allowed the banks to save risk capital even the conduit 
assets were booked in the banks’ balance sheets. Unlike the liquidity guarantee, the credit 
guarantee consistently had capital requirements similar to on-balance sheet loans, since it 
voids the “true sales” condition.

Over time, especially since 2004 when financial regulators permitted the ABCP exclusion, 
conduits with liquidity guarantee gained popularity. As in Acharya et al. (2012), before the 
2007 market freeze, the “liquidity guarantee” was the most popular form of conduit guarantee 
provided by sponsoring banks. As a result, the banking industry became increasingly reliant 
upon the smooth functioning of the ABCP market. In addition, banks moved more and 
more risky and complex assets, such as mortgage-backed securities (MBS) and collateralized 
debt obligations (CDO) to conduits. Finally, the deterioration of the underlying risky assets 
caused the ABCP market to freeze abruptly in 2007. The collapse of the ABCP market as a 
major funding source limited the capability of the U.S. banking sector to raise capital, and 
became an important reason for the subsequent crisis.

The financial crisis motivated a series of reforms in shadow banking regulation. In January 
28, 2010, the aforementioned financial regulators collectively decided to eliminate the 
ABCP exclusion, effective March 29, 2010. As a result, nowadays banks not only need to 
consolidate the conduit onto their balance sheets, but also need to have risk capital for the 
full balance of the conduit. In other words, the new regulation assumes the bank retains the 
credit risk for 100% of the conduit assets on its balance sheet.

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11Risk-Based Capital Guidelines; Capital Adequacy Guidelines; Capital Maintenance: Consolidation of 
Asset-Backed Commercial Paper Programs and Other Issues, 69 Fed. Reg. 44,908 (July 28, 2004), (to be 

12This change is inline with the essence of FAS 166 and FAS 167 issued by FASB in June 2009. FAS 166 
and FAS 167 required banks to prepare allowance for loan and lease losses (ALLL) for consolidated conduit 
assets. The ALLL is included in the tier 2 capital calculation.
Figure 1.1: **Total ABCP outstanding vs commercial bank liability** The left y-axis is for total ABCP outstanding, and the right y-axis (scaled 10 times) is for commercial bank liabilities. In early 2000s, the total ABCP outstanding is about 10% the size of total commercial bank liability in U.S. The left dashed line marks the confirmation of ABCP exclusion in risk capital calculation. The ABCP market size picked up rapidly then, reaching 1.21 Trillion USD in July 2007. The ABCP market experienced a rapid drop in size in the summer of 2007, and never recovered since. The ABCP exclusion was dropped in March 2010, as the second dashed line marks.

The regulatory changes drove the ABCP market growth in the 2000s. Figure 1.1 shows that the total outstanding ABCP was about 10% the size of total commercial bank liability in the early 2000s. After the introduction of the “ABCP exclusion”, the market grew rapidly until the ABCP market froze. The ABCP market has remained at a small size after the favorable risk capital treatment was dropped in 2010.
Figure 1.2: **Issuance percentage of USD ABCP with overnight maturity** During the financial crisis, the percentage of newly issued ABCP with overnight maturity jumped from 60% to 70%. This percentage peaked at 80% around September 2009 when Lehman Brothers failed.

### Maturity of ABCP during the Financial Crisis

The ABCP market freeze witnessed not only the collapse of the amount of ABCP outstanding, but also a rapid drop in ABCP maturity. Figure 1.2 shows the percentage of overnight ABCP among all the newly issued ABCP. During the financial crisis, the percentage of newly issued ABCP with overnight maturity jumped to 70% from a pre-crisis level of 40–60%. This percentage peaked at 80% around September 2009 when Lehman Brothers failed. The drastic change in ABCP maturity had a profound impact on the sponsoring banks, as I will show in the latter part of the paper.
1.3 The Model

Setup

Consider the following continuous time risk neutral economy with a bank that can move assets off balance sheet. The economy consists of a social planner, a continuum of one measure of risk neutral investors, and a bank controlled by its equity holder.

There is one risky project that pays one unit of cashflow at origination. The project requires an initial investment to start. The project also benefits from the monitoring performed by the bank. If monitored, the project generates pre-tax cashflow that follows a geometric Brownian motion

\[ dy_t = \mu_m y_t dt + \sigma_m y_t dW_t, \]

where \( W_t \) is a standard Brownian motion. Once the monitoring is withdrawn, the project deteriorates irreversibly and generates pre-tax cashflow that follows geometric Brownian motion

\[ dy_t = \mu_s y_t dt + \sigma_s y_t dW_t, \]

with \( \mu_s < \mu_m \), and \( \sigma_s > \sigma_m \), and \( y_0 = 1 \).

Both the bank equity holder and the risk neutral investors have capital, but only the equity holder knows how to initiate the project. This assumption captures the idea that bank capital is special. The equity holder can operate the bank and raise funding for the project from three sources. He can either collect deposits with face amount \( P_d \) from the risk neutral investors, or invest in the equity claim himself. The equity holder can also raise capital by setting up an ABCP conduit by moving \( S \) fraction of the project to the conduit. The bank then raises capital from the conduit by selling commercial paper with face amount \( P_a \) to investors. The ABCP pays coupon \( k \) for each dollar of its face value. The ABCP coupon \( k \) is fixed upon origination such that the ABCP is originated at par. Once the bank has raised capital, it makes the initial investment and starts the project. The bank also commits to a conduit wind-down trigger at origination.

The bank pays a one-time deposit insurance premium to the social planner upon the deposit origination. The deposit insurance agency will cover the depositor’s loss when the

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\(^{13}\)Since the project generates risky cashflow, I can also treat it as a risky asset. For purposes of the following discussion, the terms “asset” and “project” are used interchangeably.

\(^{14}\)The one-time irreversible option to drop the monitoring has a realistic motivation. For example, if a bank monitors its mortgage borrower and follows up with those who just became delinquent, it will be easier for the borrower to make up the missing payments. If the bank does not monitor the loans and lets the delinquency build up, the borrowers are more likely to stay behind the payments, and catching up becomes increasingly difficult. In business operations, once a company has experienced bad management, it can be hard to turn it around.

\(^{15}\)In U.S., the deposit insurance premium usually does not change much with the bank’s earning and profits as long as the bank stays in the same risk category. Therefore I model the deposit insurance premium as an one-time payment, as in [Decamps et al. (2004)].
bank defaults, such that depositors receive their full principal if the project gets liquidated. Hence, the deposits are risk-free. Similarly, the bank provides on-going credit or liquidity guarantee to the ABCP investors until the conduit winds-down.

The social planner collects the corporate income tax, receives the deposit insurance premium from the bank at origination, and pays the depositors the bankruptcy loss upon project liquidation. He also oversees the operation of banks and imposes an exogenous default barrier \( y_b \): once \( y \) hits \( y_b \), the social planner seizes the bank, at which point, the bank equity holder loses his stake. As in [Allen and Gale (2004)], the social planner then spawns a new bank, which takes over the old bank’s assets at a discounted price that equals to \( 1 - \alpha \) fraction of the project’s liquidation value. He maximizes the total value in the economy, which is the sum of the values to all agents.

The constant riskless interest rate is \( r \), and the corporate tax rate is \( \tau \). The project has an intrinsic value as the risk-neutral expectation of pre-tax cashflow, so under monitoring \( V_m(y) = y / (r - \mu_m) \), and without monitoring the project value becomes \( V_s(y) = y / (r - \mu_s) \). The initial investment to set up the project equals to \( V_m(y_0) \). The liquidation value of the project, given it occurred when \( y = y_b \), is \( V_m(y_b) \) if the project is monitored, or \( V_s(y_b) \) otherwise.

I also assume that the bank maintains a stationary debt structure in both ABCP and regular debt issuance, as in [Leland and Toft (1996), He and Xiong (2012a), and He and Xiong (2012b)]. Once the coupon rate and maturity are decided at origination, later origination of deposits as well as ABCP at \( t > 0 \) all have the identical coupon rates. The maturities of the deposits and the ABCP are random, and follow the same exponential distribution with intensity \( m \) as the setup in [Leland (1994a) and He and Xiong (2012a)], hence the average maturity of the ABCP is \( 1/m \).

The ABCP Conduit

When the commercial paper matures, the investor can choose whether to rollover the ABCP. No transaction happens if he chooses to rollover: he just holds the paper and waits for the next maturity event. If he chooses not to rollover, the sponsoring bank steps in and pays the ABCP investor the face value of the paper. The sponsoring bank then reissues the commercial paper at the market price \( A(y) \). Without loss of generality, I assume that the bank sells the new paper to the same ABCP investor since the paper is fairly priced. The ABCP investor only chooses to rollover his paper when its market price \( A(y) \) is no less than the face value \( P_a \). Hence, the rollover support is costly to the sponsoring bank. I denote the rollover support cost in the credit guarantee as \( K_r(y) \), and that in the liquidity guarantee \( L_r(y) \).

\[16\] This is the same as the pre-tax abandonment value in [Hackbarth et al. (2006)].
The ABCP conduit winds down when the conduit assets’ cashflow \( y \) drops below a threshold \( y_a \). As described in the introduction, there are two ways in which banks reduce the credit risk of ABCP so that it attracts money market mutual funds: credit guarantees or liquidity guarantees. I denote the value function for the bank’s credit guarantee obligation as \( K(y) \), and the value function for the bank’s liquidity guarantee obligation as \( L(y) \). Under a credit guarantee, the sponsoring bank takes the conduit assets back and pay the ABCP investors its principal amount upon conduit wind-down: so the net transfer to the bank is \( -P_a + SV_m(y_a) \). I write the bank’s value function of this payment as \( K_w(y_a) \), so \( K_w(y_a) = -P_a + SV_m(y_a) \). Figure 1.3 summarizes the capital structure of a bank structuring ABCP conduit with a credit guarantee.

Figure 1.3: **Capital structure of bank using ABCP conduit funding with a credit guarantee.** The assets in the conduit are booked as pledged assets on bank’s balance sheet, and the ABCP is booked as debt. Therefore, both the assets and commercial paper in the conduit remain on the sponsoring bank’s balance sheet.

Under liquidity guarantee, when the ABCP conduit winds down, the sponsoring bank pays the ABCP investor the fair value of the assets \( SV_m(y_a) \), rather than the full principal
amount. So the wind-down payoff function of liquidity guarantee \( L_w(y_a) = -SV_m(y_a) + SV_m(y_a) \geq 0 \). The ABCP investors are still subject to credit risk since the fair value of the assets under \( y_a \) may be lower than the par value of ABCP. Figure 1.4 summarizes the capital structure of a bank structuring ABCP conduit with a credit guarantee.

Figure 1.4: **Capital structure of bank using ABCP conduit funding with a liquidity guarantee.** The transfer of assets from the balance sheet to the conduit is booked as sales, and the proceeds of the originating ABCP are booked as sales revenue. Therefore neither the assets nor the commercial paper exist on bank’s balance sheet. The liquidity guarantee obligation is booked on the balance sheet using the fair value at origination.

The high credit rating of ABCP relies on the credit or liquidity guarantee offered by the bank. Therefore, when the sponsoring bank defaults, the ABCP conduit has to be wound-down. In my model, the ABCP conduit is constructed such that \( y_a \geq y_b \), so the conduit

\[17\] The existence of a wind-down trigger upon the sponsoring bank default does not conflict with the bankruptcy remoteness of the ABCP conduit as an special purpose entity. The ABCP conduit is still bankruptcy remote from the sponsoring bank since the creditors of the bank do not have claim to the assets in the conduit.
CHAPTER 1. OFF-BALANCE SHEET FINANCING AND BANK CAPITAL REGULATION: LESSONS FROM ASSET-BACKED COMMERCIAL PAPER

no longer exists when the sponsoring bank defaults. In addition, I assume that when the conduit winds down and bank default happens at the same time, the residual of bank assets is always used to fulfill the bank’s credit or liquidity guarantee obligation before paying off the depositors. This is reasonable since the bank can always set the ABCP default barrier such that \( y_a = y_b + \varepsilon \) so that the bank has to deliver the credit or liquidity guarantee before it pays its depositors.

Finally, the bank may not issue the full amount of underlying assets in the conduit as ABCP. Instead, the bank can only issue ABCP using a fraction of the assets, and holding the residual claim of the asset’s cashflow after the coupon of ABCP gets paid. When the cashflow from the underlying asset \( S_y_t \) is lower than the ABCP coupon payment \( kP_a \), the residual tranche needs to cover the cashflow shortfall. In addition, when the ABCP conduit gets wound down, the remaining value of the underlying asset is used to pay ABCP investors only: the residual piece does not get any claim on the underlying assets. I assume that the sponsoring bank holds the residual on its balance sheet too.

Timeline

Figure 1.5 shows the timing of the events in my model:

At \( t = 0 \), the bank collects deposits and issues equity by determining the principal amount \( P_d \) and interest rate \( c \), such that the deposit is priced at par. The bank also uses ABCP funding. So the balance sheet contains \( 1 - S \) fraction of the assets, and the bank moves \( S \) fraction of the assets into an ABCP conduit. The conduit sells asset-backed commercial paper with a principal amount \( P_a \) and a coupon \( k \) to the investors. The bank equity holder invests in the residual claim, and offers a credit or liquidity guarantee to the conduit. The bank then uses the capital to originate the project. The social planner evaluates the risk of the deposits and charges the bank a one-time deposit insurance premium. The social planner decides the default threshold \( y_b \). The project then starts to operate.

At \( t > 0 \), the following events may take place:

- The incumbent deposit or ABCP may mature: the bank (if still solvent) needs to pay off the principal amount of the debt, and then reissues new debt under the cashflow \( y_t \) with the same amount of principal. Since the cashflow \( y_t \) may not be as high as \( y_0 \), the new debt may be issued at a discount since the investor may demand a higher return. In this case, the bank equity holder has to post the margin and will suffer a loss.

- The bank may exercise its one-time option to drop the monitoring on the project, and change the cashflow dynamic.
Figure 1.5: **Timeline.** There are multiple events of deposits (ABCP) maturity. The distance between two maturities follows an exponential distribution with intensity $m$. The event of bank shirking may happen before or after the ABCP wind-down, or may not happen at all.
• When the cashflow in the ABCP conduit hits the pre-specified barrier $y_a$, the ABCP conduit winds down and the bank delivers its credit or liquidity guarantee to the commercial paper investor. The bank then liquidates the assets in the conduit.

• The social planner seizes the bank when the project cashflow hits the default barrier $y_b$. The social planner then creates a new bank that takes over the project the old bank’s assets at a discounted price that equals to $1 - \alpha$ fraction of the project’s liquidation value. The investors get the liquidation value, as well as a reimbursement from the social planner for the loss of capital. The new bank then issues new sets of debts, and operates the project. Since the initial cashflow is $y_b$, the new economy operates in a smaller scale $y_b/y_0$.

**Benchmark Model with a Credit Guarantee**

I first work on a benchmark case where the bank offers a credit guarantee to the ABCP. Since the social planner has no control over the bank’s shirking decision, the bank may choose to shirk from monitoring when it is in the bank’s best interest to do so. Suppose the optimal shirking strategy is to shirk at time $\theta$ when the cashflow first hits the barrier $y_\theta$, so $\theta = \inf \{ t : y_t < y_\theta \}$. Then the shirking will happen before the bank defaults if $y_\theta > y_b$. I denote the value function for depositor as $D(y)$, and the value function for bank equity holder as $E(y)$. The value function of the social planner $S(y)$ is the sum of the deposit insurance obligation $I(y)$ and the tax income value $T(y)$. Proposition 1 specifies the value functions in the benchmark model, assuming that $y_a = y_b$.

**Proposition 1.** Under the shirking barrier $y_\theta$ such that the bank will shirk at time $\theta = \inf \{ t : y_t < y_\theta \}$, the value function for deposit is

$$D(y) = P_d,$$

the value function for the ABCP is

$$A(y) = P_a,$$

and the value function for the bank equity holder is

$$E(y) = (1 - \tau) \left[ (1 - \phi_m(y; y_\theta)) V_m(y) + \phi_m(y; y_\theta) V_s(y) - P \right]$$

$$+ (1 - \tau) (P - V_s(y_b)) \phi_m(y; y_\theta) \phi_s(y_\theta; y_b),$$

where $P = P_a + P_d$.

The value function of the social planner $S(y)$ is the sum of the deposit insurance obligation

$$I(y) = [-P + (1 - \alpha) V_s(y_b)] \phi_m(y; y_\theta) \phi_s(y_\theta; y_b),$$

the present value of the corporate income tax payment to the social planner is

$$T(y) = \tau \left[ (1 - \phi_m(y; y_\theta)) V_m(y) + \phi_m(y; y_\theta) V_s(y) - P \right]$$

$$+ \tau (P - V_m(y_b)) \phi_m(y; y_\theta) \phi_s(y_\theta; y_b),$$
where \( \phi_i(y, y') \) is the state price of a unit payoff at the moment when \( y \) first becomes smaller than \( y' \), when the project is under state \( i \in \{m, s\} \). Specifically,

\[
\phi_i(y, y') = \begin{cases} 
1 & y' \geq y \\
\left( \frac{y'}{y} \right)^{H_i} & y' \in (y, y'] \\
0 & y' < y_b
\end{cases},
\]

where \( y' \) can either be \( y_b \) or \( y_\theta \), and

\[
H_i = \frac{1}{2} - \frac{\mu_i}{\sigma_i^2} - \sqrt{\left( \frac{1}{2} - \frac{\mu_i}{\sigma_i^2} \right)^2 + \frac{2r}{\sigma_i^2}} < 0.
\]

Figure 1.6: **Equity value functions with exogenous default.** A shirking region exists. The lines plot the values of equity at varying cashflow levels, under monitoring and shirking. The exogenous default cashflow level is 0.285. A shirking region exists. The risk-free interest rate \( r = 0.05 \), the drift and volatility under monitoring are \( \mu_m = 0.03 \) and \( \sigma_m = 0.3 \), the drift and volatility without monitoring are \( \mu_s = 0.02 \) and \( \sigma_s = 0.7 \), corporate tax rate is 20 percent \( (\tau = 0.2) \), liquidation costs are 20 percent \( (\alpha = 0.2) \). The bank moves \( S = 10\% \) of the assets to the ABCP conduit and provides a credit guarantee. The bank raises deposits \( P_a = 27 \), ABCP outstanding \( P_d = 3 \).
which shirking leads to a higher equity value, the equity holder will switch to shirking. In
the following analysis, I assume the combination of model parameters ensures that \( y_0 \leq y_b \):
in other words, the bank do not have incentive to shirk immediately after the project starts.

I denote the total value in the economy as \( \Sigma(y) \). The total value in the economy not
only contains the value of the social planner \( S(y) \), the debt holders \( D(y) \) and \( A(y) \), and the
current bank equity holder \( E(y) \), but also the future total value of economy after the newly
formed bank takes over the current one. Hence,

\[
\Sigma (y) = \begin{cases} 
D(y) + A(y) + E(y) + S(y) + [\Sigma (y_b) - (1 - \alpha)V_m(y_b)]\phi_m (y; y_\theta) \phi_s (y_\theta; y_b) & y_\theta > y_b \\
D(y) + A(y) + E(y) + S(y) + [\Sigma (y_b) - (1 - \alpha)V_m(y_b)]\phi_m (y; y_\theta) & y_\theta \leq y_b 
\end{cases}
\]

Intuitively, since the monitoring keeps the value of project higher, the shirking option
may introduce a moral hazard problem. Proposition 2 shows the total value function \( \Sigma(y) \),
and the loss of total value introduced by the moral hazard.

**Proposition 2.** The total value in the economy is

\[
\Sigma (y) = \begin{cases} 
V_m (y) - \phi_m (y; y_\theta) [V_m (y) - V_s (y_\theta)] & y_\theta > y_b \\
V_m (y) & y_\theta \leq y_b 
\end{cases}
\]

therefore the one-time option of shirking, which will be exercised by the bank in case \( y_\theta > y_b \),
causes a loss of total value in the economy \( \phi_m (y; y_\theta) [V_m (y) - V_s (y_\theta)] \). So the bank’s shirking
option does introduce a moral hazard.

The moral hazard in the economy motivates a rational expectation equilibrium (REE), in
which the social planner offers a continuous “menu” of the default barrier, given the amount
of the bank’s deposit \( P_d \) and ABCP \( P_a \).

**Definition.** The rational expectation equilibrium is an equilibrium in which:

- The social planner commits to a default barrier of the bank \( y_b \), given the amount of
deposit \( P_d \) and the amount of ABCP \( P_a \), issued by the bank. The social planner chooses the
optimal default barrier \( y_b^* (P_a, P_d) \) to maximize the total value in the economy \( \Sigma(y) \).
Among all the choices of \( y_b \) that maximize the total value of economy, the social planner
will pick the \( y_b \) that maximizes the bank’s total value at origination.

- The bank chooses the capital structure by deciding the amount of deposit issuance \( P_d \)
and ABCP issuance \( P_a \), together with the default barrier of the ABCP conduit \( y_a \), to
maximize the total origination value \( v(y_b) = D(y_b) + A(y_b) + E(y_b) \), given the social
planner’s optimal default barrier \( y_b^* (P_a, P_d) \).

\[
\{P_a^*, P_d^*, y_a^*\} = \arg \max_{P_a, P_d, y_a} v(y_b; P_a, P_d, y_a, y_b^* (P_a, P_d)),
\]

since the ABCP conduit will lose the P-1 rating once the guarantee becomes invalid, the bank is subject to a constraint
\[ y^*_a \geq y^*_b (P_a, P_d). \]

The following proposition shows that there exists a minimum exogenous default barrier, which varies with the bank’s debt, such that we can completely eliminate shirking by setting the default barrier strategically. Since sponsoring banks do not enjoy the “ABCP exclusion” when they provide credit guarantees to ABCP conduits, they have to prepare risk capital for the full balance of ABCP. This allows the social planner to implement the default barrier by enforcing a minimum level of capital ratio, when the capital ratio \( \kappa \) is defined as the book value of equity over the book value of assets
\[ \kappa = \frac{V_i(y) - P_a - P_d}{V_i(y)}. \]

**Proposition 3.** In the rational expectation equilibrium, there exists an optimal default barrier \( y^*_b \) such that the bank does not shirk:
\[ y^*_b = \frac{P (H_m - H_s)}{(1 - H_s) / (r - \mu_s) - (1 - H_m) / (r - \mu_m)}, \]
where \( P = P_a + P_d \). The social planner can implement the optimal default barrier by enforcing a minimum capital ratio
\[ \kappa^* = \frac{(1 - H_s) (\mu_m - \mu_s)}{(H_m - H_s) (r - \mu_s)}. \]

The total bank debt under the REE \( P^* = P_a + P_d \) is
\[ P^* = \frac{1 - \kappa^*}{r - \mu_m} \left( \frac{(1 - \kappa^*) \tau}{(1 - H_m) (\alpha - \kappa^* \tau)} \right)^{-\frac{1}{H_m}}, \]
and the bank choose \( y^*_a = y^*_b \).

Proposition 3 shows that although the social planner cannot interfere with the bank’s shirking decision directly, it can still solve the moral hazard problem by forcing an exogenous default barrier \( y^*_b \), or equivalently a minimum capital ratio \( \kappa \). Figure 1.7 plots the equity value functions under the minimum exogenous default barrier case \( y_b = y^*_b \): the shirking region has been removed.

Figure 1.8a shows the social planner’s best response \( y^*_b \) to the bank’s outstanding deposits and commercial paper under REE. The linearity of the default barrier \( y^*_b \) shows that the barrier can be implemented by a minimum capital ratio \( \kappa^* \). Figure 1.8b shows how the bank’s total value changes with the amount of deposits and commercial paper, given the social planner’s menu of \( y^*_b \).
CHAPTER 1. OFF-BALANCE SHEET FINANCING AND BANK CAPITAL REGULATION: LESSONS FROM ASSET-BACKED COMMERCIAL PAPER

Figure 1.7: Equity value functions under REE with social planner imposed equilibrium default barrier $y^*_b$ that eliminates the shirking region. The lines plot the values of equity at varying cashflow levels, under monitoring and shirking. The risk-free interest rate $r = 0.05$, the drift and volatility under monitoring are $\mu_m = 0.03$ and $\sigma_m = 0.3$, the drift and volatility without monitoring are $\mu_s = 0.02$ and $\sigma_s = 0.7$, corporate tax rate is 20 percent ($\tau = 0.2$), liquidation costs are 20 percent ($\alpha = 0.2$). The bank moves $S = 10\%$ of the assets to the ABCP conduit and provides credit guarantee. Bank raises deposits $P_a = 27$, ABCP outstanding $P_d = 3$. The REE default threshold is $y^*_b = 0.386$.

Two more results follow from the value functions and equilibrium default barrier. The value functions for the bank using deposit and equity only shows that the maturities of deposits and ABCP do not matter.

**Corollary 4.** The agents’ value functions remain invariant when the maturity $m$ changes. Subsequently, the REE equilibrium capital structure does not change with $m$ either.

Deposit insurance makes the deposit riskless. Therefore, when the investors withdraw their deposits, the bank can always rollover the old deposit using new deposits priced at face value, even if the cashflow $y_t$ maybe lower than before. The credit guarantee to the ABCP plays a similar role and allows the bank to rollover the maturing ABCP without risk. The riskless rollover saves the bank equity holder from worrying about the maturity of debts since the equity value no longer changes with the maturity. Subsequently, the social planner, who tries to prevent the bank from shirking, does not need to consider the maturity when
Figure 1.8: Social planner’s best response $y^*_b(P_a, P_d)$ and bank’s total value under various amounts of deposits and commercial paper under as $y^*_b(P_a, P_d)$. The risk-free interest rate $r = 0.05$, the drift and volatility under monitoring are $\mu_m = 0.03$ and $\sigma_m = 0.3$, the drift and volatility without monitoring are $\mu_s = 0.02$ and $\sigma_s = 0.7$, corporate tax rate is 20 percent ($\tau = 0.2$), liquidation costs are 20 percent ($\alpha = 0.2$).
he is trying to set up the equilibrium default barrier. A maturity invariant default barrier also means the credit risk of the bank does not change with maturity. Therefore, the value of deposit insurance does not change with maturity as well.

The maturities of deposits and ABCP do not affect the equilibrium capital structure. Since all the agent’s value functions in the economy do not change with the maturity \( 1/m \), the equilibrium does not move with the maturity.

**Corollary 5.** As long as the total amount of debt \( P = P_a + P_d \) is fixed, the value functions of the equity holder and the social planner, as well as the default barrier \( y_b \), remain invariant when the bank substitutes deposits with ABCP, or vice versa.

**Model with a Liquidity Guarantee**

Instead of using an ABCP conduit with a credit guarantee, the bank can also provide a liquidity guarantee to the ABCP conduit. Figure 1.4 shows the capital structure of a bank with a liquidity guaranteed ABCP conduit. The value functions are:

**Proposition 6.** The value function of ABCP is

\[
A_H (y) = \frac{k}{r} P_a + C_H \phi_m (y; y_a).
\]

\[
A_L (y) = \frac{k + m}{m + r} P_a (1 - \psi_m (y; y_a))
+ SV_m (y_a) \psi_m (y; y_a) - C_L (\psi_m (y; y_a) - \bar{\psi}_m (y; y_a)).
\]

where

\[
\psi_m (y; y_a) = \left( \frac{y}{y_a} \right)^{G_m},
\]

\[
\bar{\psi}_m (y; y_a) = \left( \frac{y}{y_a} \right)^{\bar{G}_m}.
\]

The coefficients \( H_i, i \in \{s, m\} \), is defined in Proposition 7.

\[
G_i = \frac{1}{2} - \frac{\mu_i}{\sigma_i^2} - \sqrt{\left( \frac{1}{2} - \frac{\mu_i}{\sigma_i^2} \right)^2 + \frac{2 (r + m)}{\sigma_i^2}} < 0,
\]

\[
\bar{G}_i = \frac{1}{2} - \frac{\mu_i}{\sigma_i^2} + \sqrt{\left( \frac{1}{2} - \frac{\mu_i}{\sigma_i^2} \right)^2 + \frac{2 (r + m)}{\sigma_i^2}} > 0.
\]
Finally, the $C_H, C_L$ satisfies

\[
A_H (y_0) = A_L (y_0),
A_H' (y_0) = A_L' (y_0).
\]

The value function of the residual tranche investor is

\[
R (y) = (1 - \tau) \left[ SV_m (y) - \frac{k}{r} P_a (1 - \phi_m (y; y_a)) - SV_m (y_a) \phi_m (y; y_a) \right].
\]

The value functions in Proposition 6 tell us that when the bank uses a ABCP conduit with a liquidity guarantee as a funding source, a change in maturity $1/m$ does change the value functions of the ABCP and the bank equity holder. In other words, the model shows that the maturity invariance property in the credit supported ABCP conduits no longer holds for the liquidity supported ABCP conduit. Figure 1.9a shows how the value of ABCP varies with its maturity, when ABCP receives a liquidity guarantee from the sponsoring bank. This motivates a careful study of the effect of maturity.

**ABCP maturity $1/m$** Figure 1.9b shows that when the maturity of ABCP becomes shorter than a week, the credit guarantee and liquidity guarantee value functions are very close except for those cases with assets value close to the ABCP conduit consolidation threshold. In addition, even in the case when $y$ is close to $y_a$, a shorter maturity means more risk remains on bank’s balance sheet.

Furthermore, the following proposition shows that when the maturity approaches zero, the liquidity support converges to credit support.

**Proposition 7.** When the ABCP maturity decreases, the liquidity support value function converges to the credit support value function. When the maturity intensity $m \to \infty$, $L_r (y) = K_w (y)$ for all $y \in (y_a, +\infty)$.

The banking capital regulations before 2009 treated credit guarantees and liquidity guarantees differently. When the bank provides a credit guarantee, it had to have risk capital corresponding to 100% of the ABCP principal amount. The risk capital requirement for the bank that provides a liquidity guarantee, on the contrary, is only 10% of the ABCP principal amount. The ignorance of the intrinsic similarity of the credit guarantee and the liquidity guarantee for short-term ABCP gives us the false sense that the latter is much safer than the former. During the recent financial crisis, many banks that relied on ABCP as a funding source were forced to swallow huge credit losses that exceeds their risk capital. This finding also provides a theoretical support to the empirical finding in Acharya et al. (2012), which states that the ABCP sponsor bank kept the risk to themselves.
Figure 1.9: **Value functions by ABCP maturity and guarantee** The risk-free interest rate $r = 0.05$, the drift and volatility under monitoring are $\mu_m = 0.03$ and $\sigma_m = 0.3$, the drift and volatility without monitoring are $\mu_s = 0.02$ and $\sigma_s = 0.7$, corporate tax rate is 20 percent ($\tau = 0.2$), liquidation costs are 20 percent ($\alpha = 0.2$).
The value of a liquidity guarantee cannot be correctly measured without considering the ABCP maturity. The risk transferred out of the balance sheet will be higher during normal “nice” times. However, once the cashflow deteriorates, the risk transfer becomes ineffective. Hence, the effort of determining a correct risk weight without considering the maturity is futile. More importantly, the capital regulation decision based on the risk transfer during regular times gives the banking industry false sense of security, as the next proposition shows.

**Equilibrium** What is the equilibrium capital structure when the social planner, under bounded rationality, imposes minimum risk capital ratio based on a conversion factor, which was 10% before the financial crisis, for the outstanding ABCP? I define the equilibrium as follows:

**Definition.** *The bounded rational expectation equilibrium is an equilibrium in which:*

- The social planner chooses the $y_b$ as in Proposition 3 by assuming a conversion factor $\rho$ for ABCP outstanding $P_a$, so

$$y_b^+ (P_a, P_d, \rho) = \frac{P (H_m - H_s)}{(1 - H_s) / (r - \mu_s) - (1 - H_m) / (r - \mu_m)},$$

where $P = P_d + \rho P_a$.

- The bank then chooses the capital structure by deciding the amount of deposit issuance $P_d$ and ABCP issuance $P_a$, together with the default barrier of the ABCP conduit $y_a$, to maximize the total origination value $v(y_0)$, given the social planner’s optimal default barrier $y_b^+ (P_a, P_d)$,

$$\{P_a^+, P_d^+, y_a^+\} = \arg \max_{P_a, P_d, y_a} v(y_0; P_a, P_d, y_a, y_b^+ (P_a, P_d)),$$

since the ABCP conduit will have lost the P-1 rating once the guarantee becomes invalid, the bank is subject to a constraint

$$y_a^+ \geq y_b^+ (P_a, P_d).$$

Intuitively, the social planner sets the default barrier $y_b^+$ for the bank, according to a belief that the bank only keeps a $\rho$ fraction of the risk for the underlying assets, instead of the full amount of risk as in a credit guarantee.

The capital structure under the bounded rational expectation equilibrium is different from the capital structure under the rational expectation equilibrium. Figure 1.10 shows the various principal amounts of ABCP and deposits under different values of conversion factor $\rho$, when the ABCP conduit is selling 90 day paper. When $\rho$ becomes smaller, the bank uses...
Figure 1.10: **Bounded rational expectation equilibrium capital structure: Amount of deposits and ABCP under various conversion factor** $\rho$ This figure shows under the Bounded rational expectation equilibrium, in which the social planner sets the capital requirement without valuing the liquidity guarantee but through a conversion factor $\rho$, the bank have incentive to use large leverage through ABCP financing.

more ABCP funding. This result is due to the existence of conversion factor $\rho$ that did not fully capture the riskiness of ABCP, therefore allows the bank to use high leverage and shift the insurance burden to the social planner. Under the bounded rational expectation equilibrium, the equilibrium face amount of ABCP

$$\frac{P^+_a}{S} > \frac{P^+_d}{1 - S^+},$$

when $\rho$ is significantly smaller than 1, the equilibrium $P^+_d$ is close to zero. In reality, banks usually move only the AA rated assets to the ABCP conduit for the rating purpose. Therefore, the actual capital structure decision between deposit funding and ABCP funding does not lead to a very small deposit funding. However, the intuition that the conversion factor incorrectly estimates the riskiness in ABCP funding and causes a distortion in capital structure, remains valid.

More importantly, when the maturity of ABCP changes after the capital structure has been fixed at $t = 0$, the bank may default endogenously before $y$ hits the default barrier imposed by the minimum capital ratio.

**Proposition 8.** When the maturity of ABCP $m$ becomes very short after $t = 0$, then the default barrier $y_b^+$ will not be binding. In other words, the bank equity holder will endogenously
default when \( y \) hits some \( \hat{y}_b^+ > y_b^+ \), a.k.a. before the bank reaches the minimum capital requirement.

The proof is in the Appendix. The intuition is that, since the value function of the liquidity guarantee converges to the full credit loss amount when \( y \to y_b \), while at the point \( y_b \) the bank is only responsible for the liquidation cost of non-defaulted assets. Therefore, the bank equity value function is discontinuous at \( y_b \), and there exists some \( \varepsilon \) such that \( E(y) < E(y_b^+, y_b^+ + \varepsilon) \). The equity holder will choose to endogenously default before the cashflow hits the social planner imposed barrier \( y_b^+ \). This helps to explain why the major U.S. financial institutions with Tier-1 capital ratio way above the minimum requirement experienced sharp drops in share prices, and eventually shut down. Since the liquidity guarantee value function can have a large negative rollover loss even before the ABCP conduit wind-down, the bank default can happen when the bank still has a higher than minimum capital ratio, and the ABCP conduit is still functioning. Thus seemingly healthy bank may collapse, causing big disruption in the economy.

1.4 Empirical Analysis

The theory section suggests that when the underlying asset deteriorates together with a decreasing ABCP maturity, the bank equity holder suffers more deficit by supporting the ABCP rollover. To test this hypothesis, I study how the ABCP maturity and the underlying conduit risk, as well as their interactions, drive the returns of banks that provide liquidity guarantees to the ABCP conduits.

Data and Summary Statistics

I focus on banks’ abnormal returns under different ABCP maturities and conduit exposures from April 2001, when FAS 140 became effective, to the end of 2009, when the “ABCP exclusion” was dropped. I use a variety of data sources to construct the sample used. The sample consists of data about the ABCP conduits and their guarantor banks, the credit information about mortgage loans, financial market conditions, regulatory policy dummies, and macroeconomic variables.

ABCP Conduit: Sponsoring Banks  I collect the ABCP conduit information from Moody’s Investors Service, who publishes quarterly spreadsheets that summarize the basic information on most of the ABCP conduits. These spreadsheets contain the outstanding amount of commercial paper, the rating of the commercial paper, whether the conduit has a credit or a liquidity guarantee, and the guarantor institution, for each ABCP conduit at each quarter end. Most of the guarantors are banks. Other types of institutions, such as asset management firms and automotive manufacturers, also provide supports to ABCP conduits:
so I remove the entries for these conduits. Some mortgage lenders use ABCP conduits as mortgage warehouses to fund the newly originated mortgage loans that have not been moved into a mortgage pool for securitization yet. ABCP conduits provide the working capital for these mortgage lenders: so I exclude these mortgage lenders. I also focus on the U.S. banks only. This leads to 18 guarantor banks in my sample.

Among the ABCP conduits, some of the them are CDOs that sell senior tranches as ABCP, while some others are Asset-Backed Securities whose senior tranches are commercial paper. I drop both types. Furthermore, some ABCP conduits have full credit guarantees as a repurchase agreement or a total return swap, which covers 100% of the ABCP balance, with a counter party other than the sponsoring bank. I drop these records since it is the total return swap protection seller that carries the credit risk.

I measure each bank’s quarterly absolute exposure to liquidity guarantees by aggregating the principal amount of outstanding ABCP across all the conduits supported by the bank in each quarter. I then normalize the exposure using the book value of the sponsoring bank’s balance sheet in the same quarter. In other words, the exposure for each bank $i$ at period $t$ is:

\[
\text{Exposure}_{i,t} = \frac{\text{Total outstanding of ABCP that receives the guarantee}}{\text{Book value}_{i,t}}
\]

The measure of exposure corresponds to the parameter $S$ in my model. I repeat the same process to calculate each bank’s quarterly relative exposure to credit guarantee. The quarterly call reports also provides other balance sheet and income statement information, such as the tier-1 capital ratio, cash ratio, book value and earnings, which I use as control variables.

Daily returns of the commercial banks are from CRSP, which is also the source of the daily riskless rate and value-weighted index return with dividends. I dropped the records for the banks that have daily return lower than $-20\%$ or higher than $20\%$. I merge the daily returns of banks with the latest quarterly ABCP conduit outstanding information as well as banks’ call reports before the return date.

**ABCP Conduit: Underlying Assets** It is difficult to obtain complete information about the assets in ABCP conduits, due to the nature of off-balance sheet financing. Nevertheless, Moody’s Investors Service does release, on an irregular basis, the mix of underlying assets for a few large ABCP conduits. In these conduits, a large fraction of the underlying assets are residential mortgage backed securities. Therefore, I collect the subprime mortgage delinquency information from ABSNet as a proxy of the expected future credit loss in ABCP conduit assets. Specifically, I focus on the delinquency status of 30-year adjustable-rate subprime mortgages with a fixed rate for the first two years. Adjustable-rate subprime mortgages allowed the borrowers to enjoy a low teaser rate at the beginning, which initially made the mortgage loan more affordable than fixed-rate subprime mortgages. When
the growth of home price began to soften in 2007, the subprime adjustable-rate Mortgage (ARM) borrowers started to show increasing level of delinquency. Since the borrowers with low credit quality usually do not recover once they are over 60 days delinquent, the mortgage delinquency rate is a closely watched indicator of the healthiness of mortgage loans. I aggregate the monthly current balance of over 60 day delinquent subprime ARM 2/28 loans, and normalize it with the monthly total current balance of subprime ARM 2/28 loans. Figure 1.11 shows the change in subprime ARM 2/28 delinquency ratio during the study period.

\[
Mortgage \text{ Delinquency}_t = \left[ \frac{\text{Balance of 60+ day delinquent subprime ARM 2/28 loans}}{\text{Balance of subprime ARM 2/28 loans}} \right]_t.
\]

The risk exposure of the sponsoring bank to ABCP conduits is the product of relative conduit exposure and the percentage of over 60 day subprime ARM 2/28 delinquent ratios:

\[
\text{Conduit Risk}_{i,t} = \text{Exposure}_{i,t} \times \text{Mortgage Delinquency}_t.
\]

**Commercial Paper Maturity** I obtain both the Federal Reserve's Asset-backed Commercial Paper and non-financial Commercial Paper market data for commercial paper maturity. The dataset includes the daily maturity distribution for newly issued ABCP and non-financial Commercial Paper. By summing up the issuance balance of the commercial paper with different maturities, I obtain the distribution of maturity dates for the outstanding commercial paper.

I the use the ratio of the outstanding amount of ABCP maturing overnight to the total outstanding of ABCP with all maturities at the same period as a measurement for the overall maturity of ABCP:

\[
\%\text{OVN}_t = \left[ \frac{\text{Outstanding of ABCPs that are maturing overnight}}{\text{Total ABCP outstanding}} \right]_t.
\]

A higher overnight share at day \( t \) corresponds to a shorter ABCP maturity, and also means the bank needs to deliver a large liquidity guarantee at that day. Since the parameter \( m \) in the model measures how fast the outstanding commercial paper hitting their maturity date, the share of ABCP maturing overnight is equivalent to the parameter \( m \).

Figures 1.12a and 1.12b shows the daily fraction of ABCP and non-financial commercial paper maturing overnight. The maturity of ABCP shortened during the 2007 ABCP market.

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18 There are two standard approaches to calculate days in delinquency: the Office of Thrift Supervision (OTS) standard, and the Mortgage Banker’s Association (MBA) standard. A mortgage loan that is 30 days delinquent in OTS standard is usually 60 days delinquent in MBA standard. Similarly, a 60 days delinquent loan in OTS standard means it is 90 days delinquent in MBA standard, and so on. The OTS standard has wider acceptance for subprime mortgage products. I follow the OTS standard in this paper.

19 The term 2/28 means the borrower will enjoy a low fixed teaser mortgage rate for the first two years, then a floating rate after that. The total term of the mortgage is 30 years.
Figure 1.11: **Subprime ARM 2/28 60+ day delinquency ratio** The delinquency status of 30-year adjustable-rate subprime mortgages with a fixed rate for the first two years. I aggregate the monthly current balance of over 60 day delinquent subprime ARM 2/28 loans, and normalize it with the monthly total current balance of subprime ARM 2/28 loans. The delinquency rate was stable before mid 2006, then started to pick up as the U.S. housing market softened. By the end of 2009, about 50% of the subprime ARM 2/28 borrowers are over 60 day delinquent.

freeze, while the maturity of non-financial commercial paper shortened during the 2006 downgrade of General Motors.

**Other Macroeconomic and Financial Market Conditions** I collect the macroeconomic data such as the monthly U.S. GDP and the magnitude of quantitative easing (QE). The GDP data is from Macroeconomic Advisers LLC, and the QE data is from the weekly mortgage backed security purchase amount published by the Federal Reserve. I also obtain general financial market conditions, including the market volatility from CBOE Dow Jones Volatility Index, the slope of treasury yield curve as the difference between 10-year and 3-month treasury constant maturity rate, and the spread between the Moody’s Seasoned Baa Corporate Bond Yield and 10-Year Treasury Constant Maturity Rate, all from the Federal Reserve Bank of St. Louis. Table 1.1 shows the summary statistics.
Figure 1.12: **USD CP maturing overnight** The outstanding ABCP and non-financial commercial paper on a daily basis. The maturity of ABCP shortened during the 2007 ABCP market freeze, while the maturity of non-financial commercial paper shortened during the 2006 downgrade of General Motors.
Table 1.1: **Summary statistics**

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<th>min</th>
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<td>Return (%)</td>
<td>0.028</td>
<td>3.503</td>
<td>-81.600</td>
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<td>Market Return (%)</td>
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<td>1.339</td>
<td>-8.976</td>
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<td><strong>Maturity of ABCP</strong></td>
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<td></td>
</tr>
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<td>%OVN</td>
<td>7.390</td>
<td>2.148</td>
<td>1.632</td>
<td>21.681</td>
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<td>Δ %OVN</td>
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<td>-7.200</td>
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<tr>
<td><strong>Maturity of non-financial CP</strong></td>
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<td></td>
<td></td>
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<td>%OVN Non-financial</td>
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<td>4.425</td>
<td>1.330</td>
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<td>Δ %OVN Non-financial</td>
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<td>2.815</td>
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<td><strong>Exposure to ABCP conduit</strong></td>
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<td>Liquidity Guarantee Exposure (%)</td>
<td>3.636</td>
<td>3.962</td>
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<td>Δ Mortgage Delq. (%)</td>
<td>0.019</td>
<td>0.033</td>
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<td><strong>Bank balance sheet</strong></td>
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<td>Total Assets (USD Bil.)</td>
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<td>613.474</td>
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<td>BPS (Dollars)</td>
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<td>EPS (Dollars)</td>
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<td>Cash Ratio (%)</td>
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<td>7.510</td>
<td>0.471</td>
<td>40.870</td>
<td>880</td>
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<td>Fed fund purchase(%)</td>
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<td>7.230</td>
<td>0.044</td>
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<td>Fed fund sold(%)</td>
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<td>7.701</td>
<td>0.000</td>
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<td>Tier 1 ratio (%)</td>
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<td>20.480</td>
<td>880</td>
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<td><strong>Macro</strong></td>
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<td>Monthly GDP Growth(%)</td>
<td>0.131</td>
<td>0.597</td>
<td>-1.688</td>
<td>1.580</td>
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<td>Fed QE (USD in Bil.)</td>
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<td>2.690</td>
<td>-0.982</td>
<td>33.506</td>
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<td><strong>Financial market</strong></td>
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<td>1.294</td>
<td>-0.640</td>
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<td>Δ Treasury yield slope (%)</td>
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<td>0.080</td>
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<tr>
<td>Baa - 10yr spread (%)</td>
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<td>1.023</td>
<td>1.480</td>
<td>6.160</td>
<td>2264</td>
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<td>Δ Baa - 10yr spread (%)</td>
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<td>0.034</td>
<td>-0.140</td>
<td>0.380</td>
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Empirical Strategy

OLS Specification

My theoretical model suggests that the change in ABCP maturity impacts the risk transfer between the ABCP conduit and its liquidity guarantee providing bank. In other words, the interaction between the change in ABCP maturity and the change in ABCP conduit asset credit loss would change the sponsoring bank’s value. I estimate the effect of the interaction on the sponsoring bank’s abnormal return, a proxy of the change in bank equity value. As Figure 1.13 shows, a shorten ABCP maturity together with a drop in conduit value may cause the equity value to drop more.

Hence, my model implies the following specification:

\[ r_{i,t}^a = \beta_0 + \beta_1 \times \Delta \%\text{OVN}_t \times \Delta \text{Conduit Risk}_{i,t} \\
+ \beta_2 \times \Delta \text{Conduit Risk}_{i,t} \\
+ \beta_3 \times \Delta \%\text{OVN}_t \\
+ \beta_4 \times X_{i,t} + \beta_5 \times Y_t + \alpha_i + \varepsilon_{i,t}. \]

Here \( r_{i,t}^a \) is the holding period equity abnormal return of bank \( i \) at period \( t \). For the explanatory variables, \( \%\text{OVN}_t \) measures outstanding ABCP during period \( t \), so \( \Delta \%\text{OVN}_t \) measures the change in the ratio of ABCP outstanding matures overnight from period \( t - 1 \) to \( t \). \( \Delta \text{Conduit Risk}_{i,t} \) is the product of subprime mortgage delinquency rate change between period \( t - 1 \) and \( t \), multiplies the bank’s exposure to ABCP liquidity guarantee aforementioned, which is the principal of ABCP relative to the bank’s book value. The regression includes bank fixed effect \( \alpha_i \) to account for unobserved heterogeneity at the bank level that may be correlated with the explanatory variables. In addition, I control for bank balance sheet variables \( X_{i,t} \), and macroeconomic variables \( Y_t \), both are discussed in the section 1.4. Finally, \( \varepsilon_{i,t} \) is a bank-specific error term. Standard errors are clustered at the bank level as well as at the year level to account for heteroscedasticity and serial correlation of errors as in Petersen (2009). My model suggests that \( \beta_1 < 0 \) given the fact that the ABCP maturity modulates the risk transfer.

\[ \text{Acharya et al.} \ (2012) \] study the risk transfer in ABCP securitization using the following baseline specification:

\[ r_i = \alpha + \beta \times \text{Conduit Exposure}_i + \gamma \times X_i + \varepsilon_i \]

where \( r_i \) is the cumulative equity return of bank \( i \) computed over the 3-day period from August 8 to 10, 2007, and \( \text{Conduit Exposure}_i \) is bank \( i \)'s conduit exposure relative to total assets at time \( t \). They find that, for those banks that providing liquidity guarantees to ABCP conduits, a larger ABCP conduit exposure was associated with more negative stock returns during the short period of the ABCP market freeze. \[ \text{Acharya et al.} \ (2012) \] challenge the belief that by transferring assets to an ABCP conduit and providing liquidity guarantee, a bank unloads the credit risk of those assets from its balance sheet.
Figure 1.13: **Model specification: the value of a liquidity guarantee as a function of the ABCP maturity and the cashflow of conduit assets.** The value of a liquidity guarantee is not a linear function of the ABCP maturity and the conduit cashflow. The non-linearity suggests that, in addition to the effect of the change in ABCP maturity and the effect of change in conduit cashflow, the interaction between these two changes may also be important to explain the change in the value of the liquidity guarantee.

Control for balance sheet, macroeconomic, and market variables

Banks can hold the same type of assets on their balance sheet as well as on the sponsored conduits. As a result, when the assets deteriorate, the bank return becomes lower even if the bank has completely transferred the conduit assets risk out to the investors. To control for this, I introduced the balance sheet information such as earnings per share as control variables to capture the losses on the balance sheet. Furthermore, other balance sheet variables, such as the cash ratio and the tier-1 capital ratio, may also varies with the bank’s exposure to ABCP conduit. Therefore I include them in the control variables as well. Finally, I also control for the bank’s exposure to credit guarantee. Bank specific controls are in the \( X_{i,t} \) vector.

Macroeconomic and general market conditions can also change banks’ returns as well as the investor’s appetite to ABCP. Therefore, I control for the magnitude of the Federal Reserve’s quantitative easing during the financial crisis by using the weekly mortgage backed security purchase amount. I also include the investor’s perceived volatility, a.k.a. the “fear index”, to control for the flight to safe assets during market turmoil. I also include the
Ch. 1: Off-Balance Sheet Financing and Bank Capital Regulation: Lessons from Asset-Backed Commercial Paper

Treasury yield slope to capture the difference between the short-term and long-term riskless rates. I control for the spread between Baa corporate bond and 10-Year treasury yield to capture the market’s changing risk appetite. I also control for the GDP growth as an indicator of general economy. The financial accounting standards for off-balance sheet funding channels have undergone changes in the 2000s: I have also included time dummies for FIN 46, and FAS 166/167. \( Y_t \) contains these macroeconomic variables at period \( t \), as well as time dummies that account for different financial accounting standards.

Identifications and IV Specifications

The maturity of the ABCP conduit in the OLS specification is an endogenous regressor. The ABCP investor may choose to run or rollover to shorter term ABCP because the bank’s creditworthiness deteriorates, which is usually accompanied by a low excess or abnormal equity return of the bank. To see this, suppose the ABCP investors have time-varying intrinsic preferred maturity \( \text{IntrinsicMaturity}_t \). They also adjust their maturity preference when investing in ABCP according to the bank’s current abnormal return. Then the change in the ABCP maturity for each bank \( i \) becomes

\[
\Delta \%\text{OVN}_{i,t} = \rho_0 + \rho_1 \times \Delta \text{Intrinsic maturity preference}_t + \rho_2 \times r_{i,t}^{a} + u_t,
\]

which shows that \( \Delta \%\text{OVN}_{i,t} \) is correlated with \( \varepsilon_{i,t} \), therefore the estimated \( \hat{\beta}_0 \) and \( \hat{\beta}_2 \) are inconsistent.

I use the following two identification strategies to tackle the endogeneity problem aforementioned. First, the maturity of ABCP conduit may reflect the investor’s belief about the credit worthiness of the specific sponsoring bank. Using the average maturity of ABCP partly resolves this problem, since the idiosyncratic risk components among the banks can cancel out each other.

Second, I use the maturity of non-financial commercial paper as an instrumental variable. Many large non-financial firms issue commercial paper directly. These commercial paper have similar credit and liquidity profile as the ABCP, therefore, are usually sold to the same group of investors such as the money market mutual funds. The maturity of non-financial commercial paper correlates with the maturity of ABCP, since both of them are driven by the intrinsic maturity preference of investors. Similar to the ABCP, the non-financial commercial paper may also experience runs when the abnormal returns of the issuing firms are low. Therefore,

\[
\Delta \%\text{OVN Non-financial}_{i,t} = \theta_0 + \theta_1 \times \Delta \text{Intrinsic maturity preference}_t + \theta_2 \times r_{i,t}^{NF,a} + u_t^{NF},
\]
where %OVN Non-financial_{i,t} is the maturity of non-financial commercial paper issued by firm i at period t, and the r_{i,t}^{NF} here refers to the abnormal return of the non-financial firm. However, the abnormal return of non-financial firms and the abnormal return of banks are orthogonal by construction. Therefore, I can use the maturity of non-financial commercial paper maturity as an instrumental variable, since the abnormal return of non-financial firms will not interfere with the estimation due to orthogonality. Figure 1.14 illustrates the identification strategy.

Following the identification strategies, I use a two stage least squares estimation (2SLS), with the change in average maturity of non-financial commercial paper as the instrumental variable. In the first stage, I estimate:

$$\Delta\%OVN_t = \gamma_0 + \gamma_1 \times \Delta\%OVN\text{ Non-financial}_t \times \Delta\text{Conduit Risk}_{i,t}$$

$$+ \gamma_2 \times \Delta\text{Conduit Risk}_{i,t}$$

$$+ \gamma_3 \times \Delta\%OVN\text{ Non-financial}_t$$

$$+ \gamma_4 \times X_{i,t} + \gamma_5 \times Y_t + \alpha_i + v_t,$$

as well as the interaction term $\Delta\%OVN_t \times \Delta\text{Conduit Risk}_{i,t}$ as the left-hand side variable in the same first-stage setup.

In the second stage, I estimate:

$$r_{i,t}^{a} = \beta_0 + \beta_1 \times \Delta\%OVN_t \times \Delta\text{Conduit Risk}_{i,t}$$

$$+ \beta_2 \times \Delta\text{Conduit Risk}_{i,t}$$

$$+ \beta_3 \times \Delta\%OVN_t$$

$$+ \beta_4 \times X_{i,t} + \beta_5 \times Y_t + \alpha_i + \varepsilon_{i,t},$$

where $\Delta\%OVN_t$ and $\Delta\%OVN_t \times \Delta\text{Conduit Risk}_{i,t}$ are estimated from the first stage regressions. I control for bank fixed effect. I also control for bank balance sheet variables $X_{i,t}$ and macroeconomic variables $Y_t$, as in section 1.4, in both the first and second stage regressions.

**Results**

**OLS regression results**

Table 1.2 shows the OLS regression result. Although the riskiness of conduits, approximated by the product of conduit exposure and subprime delinquencies, do not affect the bank’s excess return significantly, the interaction between maturity and the riskiness of the conduit significantly moves the sponsoring banks’ abnormal returns.
Figure 1.14: **Identification strategy.** Simultaneity exists between the maturity of ABCP and the sponsoring bank’s abnormal return. Hence the ABCP maturity is an endogenous regressor. Meanwhile, the investor’s maturity preference drives the maturities of both ABCP and non-financial commercial paper. Since the abnormal return of non-financial firms are by construction orthogonal to that of the financial firms, the simultaneity issue between the non-financial firms and the maturity of their commercial paper is irrelevant. I therefore use the maturity change of non-financial commercial paper as an instrumental variable, even a similar simultaneity issue exists between the non-financial firms and the maturity of their commercial paper.
Table 1.2: **Effect of ABCP maturity on abnormal returns (OLS)** This table reports the OLS betas of the model presented in section 1.4. The dependent variable, $r^{a}_{i,t}$, is the holding period equity abnormal return of bank $i$ at period $t$. For the explanatory variables, $\%OVN_t$ measures outstanding ABCP during period $t$, so $\Delta \%OVN_t$ measures the change in the ratio of ABCP outstanding matures overnight from period $t-1$ to $t$. $\Delta$Conduit Risk$_{i,t}$ is the product of subprime mortgage delinquency rate change between period $t-1$ and $t$, multiplies the bank’s exposure to ABCP liquidity guarantee aforementioned, which is the principal of ABCP relative to the bank’s book value. The regression controls for bank fixed effect, bank balance sheet variables, and macroeconomic variables, as discussed in the section 1.4. Standard errors are clustered at the bank level as well as at the year level.

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<th>(3)</th>
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<tr>
<td>$\Delta %OVN \times \Delta$ Conduit Risk</td>
<td>-0.137***</td>
<td>-0.135***</td>
<td>-0.139***</td>
</tr>
<tr>
<td></td>
<td>(0.0500)</td>
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<td>$\Delta %OVN$</td>
<td>0.0139</td>
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<td>0.0148</td>
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<td>(0.0480)</td>
<td>(0.0478)</td>
<td>(0.0492)</td>
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<td>$\Delta$ Conduit Risk</td>
<td>-0.0985</td>
<td>-0.0973</td>
<td>-0.0964</td>
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<td>(0.113)</td>
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<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Balance Sheet Controls</td>
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<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Macro Controls</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
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<tr>
<td>Observations</td>
<td>24347</td>
<td>24347</td>
<td>24347</td>
</tr>
<tr>
<td>N. of Bank Clusters</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>N. of Time Clusters</td>
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<td>9</td>
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<tr>
<td>Overall F-Statistics</td>
<td>5.917</td>
<td>6.517</td>
<td>0.286</td>
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</table>

Standard errors in parentheses

*p < 0.10, ** p < 0.05, *** p < 0.01
IV regression results

Table 1.3 shows the IV betas of the model presented in section 1.4. The result shows that the maturity of ABCP plays an important role. Although the maturity of ABCP, does not affect the bank’s return significantly, the interaction between maturity and the riskiness of conduit does move the return significantly.

Table 1.4 shows the first stage result. The relationship between the maturities of ABCP and non-financial commercial paper is strongly positive with \( p\)-value < 0.01: when investors start to prefer shorter (longer) term non-financial commercial paper, they also start to prefer shorter (longer) term ABCP. The relationship is robust to the inclusion of bank fixed effect, macroeconomics control variable, and bank balance sheet control variables.

For instance, compare two banks, A and B, with identical conduit exposure at the average level 3.636% and both provide liquidity guarantee to a conduit with mortgage delinquency rate increases by 3.3 basis points, which is one standard deviation change. The empirical estimation result in Table 1.3 suggests that, suppose the percentage of outstanding ABCP with overnight maturity guaranteed by bank A is one standard deviation higher, i.e. 1.137% higher, than the percentage of similar outstanding ABCP guaranteed by bank B, the equity return of bank A will be 7.5 to 11.3 basis points lower than that of bank B. Therefore, regulators should consider the ABCP maturity as a critical factor when evaluating the riskiness of the ABCP conduit.

Robustness Test I: Excess Returns

To check the robustness of my regression result, I use bank excess return as an alternative measure of the sponsoring bank’s value. The OLS specification then becomes:

\[
    r_{i,t} - r_f^t = \beta_0 + \beta_1 \times (r_m^t - r_f^t) \\
    + \beta_2 \times \Delta\%OVN_t \times \Delta\text{Conduit Risk}_{i,t} \\
    + \beta_3 \times \Delta\text{Conduit Risk}_{i,t} \\
    + \beta_4 \times \Delta\%OVN_t \\
    + \beta_5 \times X_{i,t} + \beta_6 \times Y_t + \alpha_i + \varepsilon_{i,t}. 
\]

Here \( r_f^t \) is the riskless rate; \( r_{i,t} \) is the holding period equity return of bank \( i \) at period \( t \) and \( r_m^t \) is the market return at the same period, both calculated using the difference in the closing prices between period \( t \) and \( t - 1 \). In particular, \( r_m^t \) is the CRSP value-weighted index return with distribution as the market return. Other explanatory variables and controls are the same as in section 1.4. My model suggests that \( \beta_2 < 0 \) given the fact that the ABCP maturity modulates the risk transfer. Table 1.5 shows the OLS regression result. The regression coefficients confirm that the \( \beta_2 \) is significantly negative, and the magnitude is close to the results obtained using abnormal returns.
Table 1.3: Effect of ABCP maturity on stock abnormal returns (IV) This table reports the IV betas of the model presented in section 1.4. The dependent variable, $r_{it}^a$, is the holding period equity abnormal return of bank $i$ at period $t$. For the explanatory variables, $\%OVN_t$ measures outstanding ABCP during period $t$, so $\Delta \%OVN_t$ measures the change in the ratio of ABCP outstanding matures overnight from period $t - 1$ to $t$. $\Delta Conduit Risk_{it}$ is the product of subprime mortgage delinquency rate change between period $t - 1$ and $t$, multiplies the bank’s exposure to ABCP liquidity guarantee aforementioned, which is the principal of ABCP relative to the bank’s book value. The regression controls for bank fixed effect, bank balance sheet variables, and macroeconomic variables, as discussed in the section 1.4. Standard errors are clustered at the bank level as well as at the year level.

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<th></th>
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<tbody>
<tr>
<td>$r_{it}^a$ (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta %OVN \times \Delta Conduit Risk$</td>
<td>-0.765***</td>
<td>-0.757***</td>
<td>-0.690***</td>
</tr>
<tr>
<td></td>
<td>(0.131)</td>
<td>(0.125)</td>
<td>(0.149)</td>
</tr>
<tr>
<td>$\Delta %OVN$</td>
<td>-0.0629</td>
<td>-0.0627</td>
<td>-0.0723</td>
</tr>
<tr>
<td></td>
<td>(0.0453)</td>
<td>(0.0454)</td>
<td>(0.0469)</td>
</tr>
<tr>
<td>$\Delta Conduit Risk$</td>
<td>-0.0957</td>
<td>-0.0984</td>
<td>-0.0981</td>
</tr>
<tr>
<td></td>
<td>(0.120)</td>
<td>(0.116)</td>
<td>(0.0955)</td>
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- Bank Fixed Effects: Yes, Yes, Yes
- Balance Sheet Controls: No, Yes, Yes
- Macro Controls: No, No, Yes
- Observations: 24347, 24347, 24347
- N. of Bank Clusters: 18, 18, 18
- N. of Time Clusters: 9, 9, 9
- Overall F-Statistics: 22.13, 11.63, 14.03

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
Table 1.4: Effect of ABCP maturity on stock abnormal returns (IV: First-stage)
This table reports the first stage of the IV regression presented in section 1.4. ∆%OVN_t measures the change in the ratio of ABCP outstanding matures overnight from period t − 1 to t. Similarly, the instrumental variable ∆%OVN Non-financial_t measures the change in the ratio of Non-financial CP outstanding matures overnight from period t − 1 to t. ∆Conduit Risk_{i,t} is the product of subprime mortgage delinquency rate change between period t − 1 and t, multiplies the bank’s exposure to ABCP liquidity guarantee aforementioned, which is the principal of ABCP relative to the bank’s book value. The regression controls for bank fixed effect, bank balance sheet variables, and macroeconomic variables, as discussed in the section 1.4. Standard errors are clustered at the bank level as well as at the year level.

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<tbody>
<tr>
<td>∆ %OVN Non-financial</td>
<td>0.126**</td>
<td>-0.009968</td>
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<tr>
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<td>(0.0437)</td>
<td>(0.00108)</td>
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<tr>
<td>∆ %OVN Non-financial × ∆ Conduit Risk</td>
<td>-0.0832</td>
<td>0.0895***</td>
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<tr>
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<td>(0.0801)</td>
<td>(0.0220)</td>
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<td>∆ Conduit Risk</td>
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<td>0.00273</td>
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<tr>
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<td>(0.0316)</td>
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<td>19.50</td>
<td>144.8</td>
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Standard errors in parentheses
* p < 0.10, ** p < 0.05, *** p < 0.01

Robustness Test II: Maturity of Newly Issued ABCP
Testing the model using alternative measures of ABCP maturity further validates my empirical design and results. The ABCP conduit issues new commercial paper each day to replace the matured paper. It issues more short-term paper when the investors demand shorter maturity. Hence an alternative measure is to compare the amount of overnight ABCP—with 1 day maturity—with the total outstanding of ABCP as of the previous day:

\[
\text{%OVN Issuance}_t = \left[ \frac{\text{Daily new issuance of ABCP with overnight maturity}}{\text{Total ABCP outstanding as of the previous day}} \right]_t,
\]

and the %OVN Issuance Non-financial_t is defined similarly for non-financial commercial paper.

The overnight fraction of newly issued ABCP also subjects to the same endogeneity problem as in section 1.4 and the similar identification strategy suggests a two stage least squares estimation (2SLS), with the change in overnight fraction of newly issued non-financial com-
Table 1.5: Robustness I: Effect of ABCP maturity on excess returns (OLS) This table reports the OLS betas of the model presented in section 1.4. The dependent variable, excess return \( r_{i,t} - r_f \), is the holding period excess return of bank \( i \) at period \( t \). For the explanatory variables, \( r_m^t \) is the CRSP value-weighted index return with distribution as the market return at the same period, \( \%\text{OVN}_t \) measures outstanding ABCP during period \( t \), so \( \Delta \%\text{OVN}_t \) measures the change in the ratio of ABCP outstanding matures overnight from period \( t - 1 \) to \( t \). \( \Delta \text{Conduit Risk}_{i,t} \) is the product of subprime mortgage delinquency rate change between period \( t - 1 \) and \( t \), multiplies the bank’s exposure to ABCP liquidity guarantee aforementioned, which is the principal of ABCP relative to the bank’s book value. The regression controls for bank fixed effect, bank balance sheet variables, and macroeconomic variables, as discussed in the section 1.4. Standard errors are clustered at the bank level as well as at the year level.

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<tr>
<td>( \Delta %\text{OVN} \times \Delta \text{Conduit Risk} )</td>
<td>-0.133***</td>
<td>-0.130***</td>
<td>-0.131***</td>
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<tr>
<td></td>
<td>(0.0607)</td>
<td>(0.0601)</td>
<td>(0.0511)</td>
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<td>( \Delta %\text{OVN} )</td>
<td>0.0187</td>
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<td>(0.0471)</td>
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<td>(0.111)</td>
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<td>Macro Controls</td>
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<td>No</td>
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<td>24347</td>
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<td>N. of Bank Clusters</td>
<td>18</td>
<td>18</td>
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<td>N. of Time Clusters</td>
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<tr>
<td>Overall F-Statistics</td>
<td>26.34</td>
<td>25.88</td>
<td>17.08</td>
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</table>

Standard errors in parentheses

* \( p < 0.10 \), ** \( p < 0.05 \), *** \( p < 0.01 \)
mmercial paper as the instrumental variable. In the first stage, I estimate:

\[ \Delta\%\text{OVN Issuance}_t = \gamma_0 + \gamma_1 \times \Delta\%\text{OVN Issuance Non-financial}_t \times \Delta\text{Conduit Risk}_i,t \\
+ \gamma_2 \times \Delta\text{Conduit Risk}_i,t \\
+ \gamma_3 \times \Delta\%\text{OVN Issuance Non-financial}_t \\
+ \gamma_4 \times X_{i,t} + \gamma_5 \times Y_t + \alpha_i + \nu_t, \]

as well as the interaction term \( \Delta\%\text{OVN Issuance}_t \times \Delta\text{Conduit Risk}_i,t \) as the left-hand side variable in the same first-stage setup.

In the second stage, I estimate:

\[ r_{i,t}^{a} = \beta_0 + \beta_1 \times \Delta\%\text{OVN Issuance}_t \times \Delta\text{Conduit Risk}_i,t \\
+ \beta_2 \times \Delta\text{Conduit Risk}_i,t \\
+ \beta_3 \times \Delta\%\text{OVN Issuance}_t \\
+ \beta_4 \times X_{i,t} + \beta_5 \times Y_t + \alpha_i + \varepsilon_{i,t}, \]

where \( \Delta\%\text{OVN Issuance}_t \) and \( \Delta\%\text{OVN Issuance}_t \times \Delta\text{Conduit Risk}_i,t \) are estimated from the first stage regressions. I control for bank fixed effect, bank balance sheet variables \( X_{i,t} \), and macroeconomic variables \( Y_t \), as in section 1.4, in both the first and second stage regressions.

Table 1.6 shows the IV regression result, using the alternative ABCP maturity measure \( \Delta\%\text{OVN Issuance}_t \). Again, the regression results are in line with the IV regression in Table 1.3. Table 1.7 shows the first stage regression results.

1.5 Conclusion

The recent financial crisis challenged the effectiveness of conventional micro-prudential regulation. The adoption of various forms of shadow banking introduced complex risk transfers between a bank’s balance sheet and off-balance sheet entities. A careful study of these risk transfers is vital to the success of on-going regulation reform.

This paper studies the interaction between maturity transformation and moral hazard, under the context of banks financing through the off-balance sheet ABCP conduit. The deposit insurance isolates the maturity mismatch to the value function of depository institution equity holders, as well as the deposits, commercial papers, and the deposit insurance itself. Therefore, regulators can eliminate the moral hazard problem by imposing a simple minimum capital ratio requirement. For ABCP conduits with a liquidity guarantee, a change in the maturity of ABCP does affect the value function of the sponsoring bank. Therefore, the simple capital ratio rule without considering maturity mismatch is inadequate to solve the moral hazard problem. This result calls for more comprehensive model-based bank regulatory tests, especially stress tests that check the health of banks in adverse situations.
Table 1.6: **Robustness II: Effect of alternative ABCP maturity on stock abnormal returns (IV)** This table reports the IV betas of the model presented in section 1.4. The dependent variable, excess return $r_{i,t}$, is the holding period abnormal return of bank $i$ at period $t$. For the explanatory variables, %OVN Issuance$_t$ measures the ratio of newly issued overnight ABCP at day $t$ to the total ABCP outstanding in the previous day. So $\Delta$%OVN Issuance$_t$ measures the change in the ratio from period $t-1$ to $t$. $\Delta$Conduit Risk$_{i,t}$ is the product of subprime mortgage delinquency rate change between period $t-1$ and $t$, multiplies the bank’s exposure to ABCP liquidity guarantee aforementioned, which is the principal of ABCP relative to the bank’s book value. The regression controls for bank fixed effect, bank balance sheet variables, and macroeconomic variables, as discussed in the section 1.4. Standard errors are clustered at the bank level.

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<th>(1)</th>
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<tbody>
<tr>
<td>$r_{i,t}$ (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta$ %OVN Issuance $\times \Delta$ Conduit Risk</td>
<td>-0.384**</td>
<td>-0.367**</td>
<td>-0.390**</td>
</tr>
<tr>
<td></td>
<td>(0.180)</td>
<td>(0.178)</td>
<td>(0.175)</td>
</tr>
<tr>
<td>$\Delta$ %OVN Issuance</td>
<td>-0.00416</td>
<td>-0.00361</td>
<td>-0.0132</td>
</tr>
<tr>
<td></td>
<td>(0.0528)</td>
<td>(0.0532)</td>
<td>(0.0547)</td>
</tr>
<tr>
<td>$\Delta$ Conduit Risk</td>
<td>-0.102</td>
<td>-0.104</td>
<td>-0.103</td>
</tr>
<tr>
<td></td>
<td>(0.116)</td>
<td>(0.127)</td>
<td>(0.120)</td>
</tr>
</tbody>
</table>

Bank Fixed Effects | Yes | Yes | Yes |
Balance Sheet Controls | No | Yes | Yes |
Macro Controls | No | No | Yes |
Observations | 24332 | 24332 | 24332 |
N. of Bank Clusters | 18 | 18 | 18 |
Overall F-Statistics | 1.625 | 1.536 | 1.681 |

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
Table 1.7: Robustness II: Effect of alternative ABCP maturity on stock abnormal returns (IV: First-stage) This table reports the first stage of the IV regression presented in section 1.4. %OVN Issuance_t measures the change in the ratio of newly issued overnight ABCP at day t to the total ABCP outstanding in the previous day. Similarly, the instrumental variable ∆%OVN Issuance Non-financial_t measures the change in the ratio of newly issued overnight non-financial CP at day t to the total non-financial CP outstanding in the last day. ∆Conduit Risk_{i,t} is the product of subprime mortgage delinquency rate change between period t − 1 and t, multiplies the bank’s exposure to ABCP liquidity guarantee aforementioned, which is the principal of ABCP relative to the bank’s book value. The regression controls for bank fixed effect, bank balance sheet variables, and macroeconomic variables, as discussed in the section 1.4. Standard errors are clustered at the bank level.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>∆ %OVN Issuance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-financial</td>
<td>0.131***</td>
<td>0.000235</td>
</tr>
<tr>
<td></td>
<td>(0.00608)</td>
<td>(0.000422)</td>
</tr>
<tr>
<td>∆ %OVN Issuance Non-financial × ∆ Conduit Risk</td>
<td>-0.0219*</td>
<td>0.103***</td>
</tr>
<tr>
<td></td>
<td>(0.0123)</td>
<td>(0.0111)</td>
</tr>
<tr>
<td>∆ Conduit Risk</td>
<td>-0.0402***</td>
<td>-0.000952</td>
</tr>
<tr>
<td></td>
<td>(0.0132)</td>
<td>(0.0108)</td>
</tr>
<tr>
<td>Observations</td>
<td>24332</td>
<td>24332</td>
</tr>
<tr>
<td>Overall F-Statistics</td>
<td>314.6</td>
<td>1606.9</td>
</tr>
</tbody>
</table>

Standard errors in parentheses

* p < 0.10, ** p < 0.05, *** p < 0.01
Chapter 2

LIBOR’s Poker: Discover Interbank Borrowing Costs Amid Banks’ Strategic Behavior

2.1 Introduction and literature review

Background

The London Interbank Offered Rate (LIBOR) measures the average interest rate at which major banks can borrow short-term unsecured funds from other banks in the London interbank lending market. British Banker’s Association (BBA) oversees the daily LIBOR fixing process. LIBOR reflects the rate at which most creditworthy banks are able to borrow. Rates for less creditworthy borrowers, such as corporations and home buyers, may also base on this benchmark. Therefore, the influence of LIBOR extends far beyond interbank lending. Central banks closely watch the TED spread in order to gauge how well the banking sector are functioning. LIBOR also nurtures a spectrum of financial derivatives, such as FRAs and Eurodollars. According to BBA, 350 trillions of dollars of corporate bond, residential mortgages, and other financial contracts are quoted as spreads over LIBOR.

Currently, LIBOR is produced on a daily basis for ten currencies, each with 15 maturities ranging from overnight to 12 months. Notably, LIBOR is not based on interbank lending transactions, but on a daily survey, in which members of the LIBOR panel banks submit their borrowing costs. According to BBA website:

1

Every contributor bank is asked to base their bbalibor submissions on the following question: “At what rate could you borrow funds, were you to do so by asking for and then accepting inter-bank offers in a reasonable market size just prior to 11 am?” Therefore, submissions

1http://www.bbalibor.com/.
CHAPTER 2. LIBOR’S POKER: DISCOVER INTERBANK BORROWING COSTS AMID BANKS’ STRATEGIC BEHAVIOR

are based upon the lowest perceived rate that a bank on a certain currency panel could go into the inter-bank money market and obtain sizable funding, for a given maturity.

It is a member of the staff with responsibility for management of the bank’s cash, instead of the bank’s derivative desk, who submits the bank’s rates for the day to Thomson Reuters, the BBA designated calculation agent. Banks cannot see each other’s rates as they submit. Once Thomson Reuters receives each contributor’s submissions, it ranks them in descending order and then drops the top and bottom quartiles. The LIBOR rate is the arithmetic average of the rest of the quotes. Thomson Reuters then releases the LIBOR rate, together with the submissions from all panel banks.

The LIBOR fixing is not transaction based, since it is unlikely that all panel banks borrow from interbank lending market in each of the currencies and maturities everyday. In addition, although panel bank’s CDS spread reflects its credit risk, which is an important component of bank’s borrowing cost, the liquidity in CDS market and in interbank lending market are quite different: so the average level of CDS spreads cannot be used directly to measure interbank lending cost. As a result, the panel bank’s submission of borrowing cost is not based on actual transactions, but on the perceived cost of funds.

During the recent financial crisis, some bankers suspected that their rivals behaved strategically by claiming suppressed borrowing costs. On April 16th, 2008, a WSJ article questioned the veracity of LIBOR by saying "LIBOR fixings had been lower than actual traded interbank rates through the period of stress." A subsequent report cites Credit Suisse strategist William Porter, who believes the 3 month LIBOR is 40 basis points too low; and Scott Peng from Citigroup, who believes the LIBOR is 30 basis points too low. Besides the level of LIBOR, the cross-sectional variance of daily LIBOR submissions among panel banks is also unreasonably low. The cross-sectional variance of submissions is consistently less than 10% of the variance among panel banks’ senior CDS spread.

In response to the challenges, in 2008 the BBA nonetheless affirmed that LIBOR was still reliable. A WSJ report cited Ms. Knight, the BBA chief, who insisted that there was no need to replace the current LIBOR fixing process: “I see no reason suddenly to up sticks and change a process that has actually served the financial community worldwide extremely well for a very considerable number of years.” In addition, at the Bank for International Settlements (BIS) found that while LIBOR did diverge from other key reference rates to “an unusual extent” during the relevant period, the divergence could be explained by a “deterioration in market liquidity, an increase in

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interest rate volatility and differences in the composition of the contributor panels.” They concluded that “if there were any attempts to manipulate fixings during the recent turbulence, trimming procedures appear to have minimized their impact.”

However, the controversy about LIBOR did not rest. In 2011, Charles Schwab Corp files lawsuits accusing 11 major banks of conspiring to manipulate Libor. At the mean time, the U.S. and British regulators started to investigate possible LIBOR manipulation. According to an Financial Times article of February 2012 the probe ”has widened with more than a dozen traders fired at banks including UBS, Royal Bank of Scotland, Deutsche Bank, J. P. Morgan Chase and Citigroup in connection with the investigation.” In June 2012, Barclays has been fined for 450 million USD for LIBOR rigging, which led to the departure of its CEO and Chairman a month later. On August 15, 2012, Barclays, HSBC, RBS, Citigroup, Deutsche Bank, UBS and JP Morgan are subpoenaed in America over LIBOR manipulation.

Incentive of LIBOR manipulation

Banks have strong incentives to manipulate LIBOR: First, as Barclay’s case suggests, LIBOR-linked derivative trading positions, such as swaps and Euro Dollar futures, give derivative traders incentive to interfere with LIBOR fixing. Barclay’s case is not unique: Japanese Securities and Exchange Surveillance Commission (SESC) also sought sanctions against Citi and UBS, on the ground that a former employee of UBS made repeated requests to change rate quotes in order to benefit their own positions in derivative trades since 2007. The trader left UBS and joined Citi in December 2009 and continued his rate-influencing practice.

Besides, net interest income, a significant component of a bank’s net income, is also directly related to LIBOR. Table 2.1 and table 2.2 shows how much (in million USD) Bank of America and Citigroup’s projected net interest income from non-trading activities changes when yield curve shifts by ±100 bps in the next 12 months. From 2004 to 2008, lower short-term rate helped the financial performance of banks in general.

The last but not the least reason for interfering with LIBOR fixing is the potential signaling effect of a bank’s risk of failure. By revealing high interbank borrowing cost, a bank sends off a negative signal of weak balance sheet. The negative signal may damage its reputation and invite bank-run. During the financial crisis, the signaling became a critical concern among LIBOR panel banks.

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Table 2.1: BofA’s non-trading interest income sensitivity to yield curve shift, in million USD. Source: BofA 10-K, 10-Q

<table>
<thead>
<tr>
<th>Steepens</th>
<th>2008/12</th>
<th>2007/12</th>
<th>2006/12</th>
<th>2005/12</th>
<th>2004/12</th>
</tr>
</thead>
<tbody>
<tr>
<td>-100 bps short end</td>
<td>453</td>
<td>1255</td>
<td>971</td>
<td>536</td>
<td>766</td>
</tr>
<tr>
<td>100 bps long end</td>
<td>698</td>
<td>181</td>
<td>138</td>
<td>163</td>
<td>875</td>
</tr>
</tbody>
</table>

Table 2.2: Citi’s non-trading interest income sensitivity to yield curve shift, in million USD. Source: Citi 10-K, 10-Q

<table>
<thead>
<tr>
<th>Steepens</th>
<th>2008Q3</th>
<th>2008Q2</th>
<th>2008Q1</th>
<th>2007Q4</th>
<th>2007Q3</th>
<th>2007Q2</th>
<th>2007Q1</th>
</tr>
</thead>
<tbody>
<tr>
<td>-100 bps O/N</td>
<td>518</td>
<td>484</td>
<td>629</td>
<td>486</td>
<td>409</td>
<td>511</td>
<td>383</td>
</tr>
</tbody>
</table>

Overview

A number of academic researchers and practitioners have looked into LIBOR manipulation from an empirical perspective. Hartheiser and Spieser (2010) looked at panel banks’ submissions, and estimated the clustering of LIBOR submissions by running a cluster analysis. Snider and Youle (2010) studied the relationship between LIBOR submissions and banks’ CDS spread, in various currencies. Abrantes-Metz et al. (2011) compared individual bank quotes to CDS spreads and market capitalization data during three periods spanning from early 2007 to mid-2008, and found the data is inconsistent with a material manipulation of US dollar 1-month LIBOR rate, though anomalies in individual quotes do exist. Kuo et al. (2010) provides a more solid evidence by finding out that banks are willing to borrow from Fed with collateral requirement with a higher interest rate than what they have reported in Libor fixing process during the financial crisis.

This paper studies the LIBOR fixing mechanism from a theoretic perspective. Firstly the paper answers what is the equilibrium submission strategy for panel banks, and does LIBOR still reflect the true average borrowing cost in the equilibrium. I find that when banks’ borrowing costs are identical, the trimming mechanism in the LIBOR fixing leads to a truth revealing equilibrium. When banks’ borrowing costs are not identical and banks benefit from low LIBOR rates, banks will collude tacitly and the equilibrium submissions are lower than their true borrowing costs. During normal time when signaling is not a concern, banks with average borrowing cost will report most biased number. The signaling effect affects the banks with high borrowing cost the most by depressing their the LIBOR
CHAPTER 2. LIBOR’S POKER: DISCOVER INTERBANK BORROWING COSTS AMID BANKS’ STRATEGIC BEHAVIOR

quotes as well. As a result, the trimming mechanism itself is not enough to block strategic behaviors, and the LIBOR understates banks’ borrowing costs.

I then propose a direct, efficient and ex ante budget balanced AGV mechanism for LIBOR fixing. By associating banks’ LIBOR submission with a transfer between banks and the BBA, banks’ equilibrium reporting strategy is to reveal their true borrowing costs. At the mean time, the sum of banks’ expected transfer to to BBA is budget balanced.

Policy wise, the paper suggests LIBOR does not reliably reflects the solidness of major banks. More worrisome is that it becomes less reliable especially during the financial crisis, exactly when the measure of solidness matters the most. The more dispersed banks’ borrowing costs are, the more tacit collusion lowers LIBOR. In addition, when consumers doubt a bank’s financial solidness, the bank will have a much bigger incentive to misreport: again. Therefore, a better mechanism for LIBOR is much needed.

The application for the analysis for equilibrium strategy goes beyond LIBOR fixing process. For a lot of financial contracts without liquid market, prices are usually determined by a trimmed average of player’s quote. For instance, the daily closing price of many derivatives traded in the over-the-counter market, such as ABX, is formed in a similar manner. Baltic Dry Index is another example. This paper extends the theory literature by studying these price fixing practice. A large body of closely related literature is about price formation in common value auction theory. Klemperer (2000) and Krishna (2009) provide summary of major critical literature in auction theory. More specifically, Wilson (1977) studies the price formation in competitive bidding. Milgrom (1979) offers a more detailed description about the signal structures that will cause convergence in competitive bidding. Pesendorfer and Swinkels (1997), which coins the term full information aggregation for the property that price converges in probability to value, focuses on information aggregation in common value auctions. I have showed that in general, the trimmed average of all bids will not achieve full information aggregation, even with a penalty for misreporting. Full information aggregation, however, can be achieved through a direct and budget balanced mechanism.

Furthermore, this study links to the the growing market microstructure literature about how prices are discovered in financial markets. Several papers investigate the price discovery process in the equity market, including Madhavan and Panchapagesan (2000) study New York Stock Exchange single-price opening auction. They find the opening mechanisms play a crucial role in information aggregation following the overnight nontrading period. Biais et al. (1999) and Cao et al. (2000) analyze the price discovery in Paris Bourse and NASDAQ. This paper extends the literature by studying the price discovery in interbank lending market.

This paper also carries out an initial empirical analysis to calibrate by how much LIBOR was manipulated. By using the equilibrium in the paper, I estimate the LIBOR bias during the recent financial crisis.
CHAPTER 2. LIBOR’S POKER: DISCOVER INTERBANK BORROWING COSTS AMID BANKS’ STRATEGIC BEHAVIOR

The remainder of the paper is organized as follows: Section 2 first presents two illustrative examples, then a formal model that describes banks’ optimal response. I also extend the model to contain the effect of signaling. Section 3 proposes the direct, efficient and ex ante budget balanced LIBOR fixing mechanism. Section 4 discusses the policy and economic implication of the banks’ equilibrium strategy. Section 5 presents the empirical result of the model. Concluding remarks appear in section 6. Lengthy proofs are relegated to the appendix.

2.2 The model

Two illustrative cases

Before I start formulating the model, it is helpful to study two illustrative cases. In the first case, all banks have the same borrowing costs. While in the second case LIBOR panel contains only four banks, so it is easier to analyze banks’ best response.

Case I: Banks with identical borrowing costs

Consider an economy with \( N \) risk neutral banks that participate in the LIBOR fixing. Bank \( i \)'s true borrowing cost is \( r \text{ } + s_i \), where \( s_i \) is the spread between its true borrowing cost and riskless rate. The level of riskless rate \( r \text{ } + s \) is public information. For brevity’s sake I focus on the spread \( s \) and refer to it as a bank’s borrowing cost, rather than spread of borrowing cost over riskless rate, in the rest of the paper.

In this illustrative case, banks are homogeneous: so \((\forall i), \text{ } s_i = s\). The value of \( s \) is public information among banks, but is unknown to regulators and investors. There is also public knowledge about \( S \), the upper limit of borrowing cost. Therefore \( s_i \in \Theta = [0, S] \subset \mathbb{R}^+ \). Since \( s_i \) corresponds to the type of banks, \( \Theta \) is the type space.

Note that instead of having banks report claimed borrowing cost, each bank could equivalently submits \( b_i \geq 0 \), which is the spread of its claimed borrowing cost over \( r_f \). Bank’s submission \( b_i \) corresponds to the ’bid’ in the auction literature. From the perspective of bank \( i \) that submits \( b_i \), given other banks report \( b_{-i} = \{b_j\}_{j \neq i} \), the function of LIBOR rate \( L: \Theta^N \rightarrow [r_f, r_f + S] \) is calculated by truncating the lowest and highest \( n \) quotes, \( N > 2n \), and taking average of the rest. So

\[
L(b_i, b_{-i}) = r_f + \frac{1}{N - 2n} \sum_{j=n+1}^{N-n} b_j^{(N)}
\]

where \( b_j^{(N)} \) is the \( j^{th} \) order statistic of \( \{b_1, b_2, ..., b_N\} = \{b_i, b_{-i}\} \). It is trivial to see that \( L(b_i, b_{-i}) \) is increasing in \( b_i \) since \( \forall b_i \leq b_i' \) we have \( L(b_i, b_{-i}) \leq L(b_i', b_{-i}) \). In addition,
$L (b_i, b_{-i})$ is also continuous in $b_i$. The net interest income of banks as well as the signaling factor both suggest banks benefit from a lower LIBOR, and so do I assume.

A bank faces penalty once it is caught misreporting its borrowing cost. The BBA mentions that it may withdraw a dishonest bank from the panel. The SEC may also step in to probe the veracity of a bank’s LIBOR submission, and impose fine to banks that misreport. Let function $K: \mathbb{R} \rightarrow \mathbb{R}^+$ measures the expected penalty, and the function takes the difference between the true cost and bank’s report $s_i - b_i$ as input. Bank faces no penalty when it truthfully reports $b_i = s_i$, and faces positive expected penalty when $b_i \neq s_i$. It is trivial to see a bank should not report anything higher than its true borrowing cost, since doing so will bring in penalty and at the same time may raise LIBOR.

Given the symmetric settings, I focus on symmetric pure strategy profile $(b_1, b_2, ..., b_N)$, in which $b_1 = b_2 = ... = b_N$, and pure strategy nash equilibrium (PSNE). A PSNE is defined as a symmetric pure strategy profile such that for any bank $i$ reporting $b_i$, its payoff is not lower than the payoff when it reports $b'_i \neq b_i$ and other bank $j$ follows PSNE $b_j$.

In this case the symmetric PSNE is to report true borrowing cost. Suppose banks’ symmetric PSNE strategy is to report $b < s$. If one of the panel bank deviates and submits $s$ instead, its submission will be discarded due to the truncation mechanism. Therefore, LIBOR rate is still $L = r_f + \frac{1}{N-2n} \sum_{i=n+1}^{N-n} b^{(i)} = r_f + b$. However, the deviating bank now faces zero instead of positive penalty, hence a higher payoff. Therefore banks will deviate from the level $b$, unless the current $b$ equals to banks’ borrowing cost $s$.

Case II: A minimized LIBOR panel

In reality, banks’ borrowing costs are quite different due to many practical reasons such as capital structure and business cycle. In this example, I allow bank borrowing costs to be i.i.d. random, and assume the existence of symmetric Bayesian Nash equilibrium.

Suppose a minimized LIBOR panel with only $N = 4$ banks and $n = 1$. LIBOR is the average of two submissions in the middle, and the highest and lowest quotes get trimmed. Without loss of generality, suppose we focus on bank 1, who tries to set the optimal $b_1$ to maximize its payoff $P(L, K)$.

Should bank 1 report the lowest $b_1$ possible, for $L (b_1, \{b_2, b_3, b_4\})$ is continuous and increasing in $b_1$? Without loss of generality, I assume the submissions from other banks satisfies $b_2 < b_3 < b_4$. Apparently, $b_3$ enters the calculation anyway: so what matters is the relationship among $b_1$, $b_2$, and $b_4$. When $b_1 \in [b_2, b_4]$, a 1% drop in $b_1$ will lead to $\frac{1}{N-2n} \times 1\% = 0.5\%$ drop in LIBOR. When $b_1$ is too low or too high such that $b_1 \notin [b_2, b_4]$, $b_1$ will be thrown out: but bank 1 still faces possible penalty. Therefore it is unwise for bank 1 to simply report lowest possible value.
CHAPTER 2. LIBOR’S POKER: DISCOVER INTERBANK BORROWING COSTS AMID BANKS’ STRATEGIC BEHAVIOR

Being unaware of other bank’s borrowing cost, bank 1 worries about the probability of \( b_1 \) falls into \([b_2, b_4]\). When \( s_1 \) is closer to the median of other banks’ costs, the symmetric equilibrium suggests bank 1 should feel confident that \( b_1 \in [b_2, b_4] \). Therefore it will understate its borrowing cost more aggressively. On the other hand, when \( s_1 \) is closer to the low end or high end, the symmetric strategy also suggests that it is ineffective for bank 1 to lower \( b_1 \), for \( b_1 \) is unlikely to fall into \([b_2, b_4]\). In this case, \( b_1 \) will be closer to \( s_1 \) due to penalty. In summary, the closer a bank’s realized borrowing cost \( s \) towards the median of the distribution, the more the bank should understate its \( b \) with regard to \( s \).

Does this suggest when bank 1’s borrowing cost raises up from 0 towards the median, at some point the incentive of manipulating LIBOR is high enough such that \( b_1 \) actually goes down when \( s_1 \) goes up? In the formal model, I will show that under supermodularity condition, regardless of how sensitive banks are to the LIBOR rate, their equilibrium submission are always non-decreasing.

Model

Consider an economy with \( N \) risk neutral banks. A bank \( j \)’s ex ante true borrowing cost is \( S_j \) over riskless rate \( r_f \), where \( S_j \) is now a random variable independently and identically distributed on type space \( \Theta \equiv [0, \bar{S}] \). The cumulative density function \( F(\cdot) \) for \( S_j \) is absolute continuous, while the PDF function is \( f(\cdot) \). If all the banks report honestly, then LIBOR, as the trimmed average of bank’s borrowing cost \( S \), is a robust L-estimator as in Huber Peter (2004). The unconditional expectation of LIBOR in this case is

\[
\bar{S} = \frac{N}{N-2n} \int_{n/N}^{1-n/N} F^{-1}(t) \, dt
\]

where \( F^{-1}(t) \) is the inverse of CDF function.

In reality, bank observes its own realized borrowing cost and decides its submission, without knowing other banks’ borrowing costs and submissions. Therefore the information set of bank \( i \) is \( \mathcal{I}_i = \{s_i, b_i\} \). Write the quotes from banks other than \( i \) as \( B_{-i} = \{B_j\}_{j \neq i} \notin \mathcal{I}_i \), while \( B^{(N-1)}_j \) is the \( j \)th order statistic among \( B_{-i} \). Similarly \( S^{(N)}_j \) refers to the \( j \)th order statistic of \( S_1, S_2, ..., S_N \). From bank \( i \)’s perspective, the LIBOR rate after banks’ report \( \{b_i, B_{-i}\} \) is a random number

\[
L(b_i, B_{-i}) = r_f + \begin{cases} 
\frac{1}{N-2n} \sum_{j=n}^{N-1-n} B_j^{(N-1)} & b_i \leq B^{(N-1)}_n \\
\frac{1}{N-2n} \left[ b_i + \sum_{j=n+1}^{N-1-n} B_j^{(N-1)} \right] & B^{(N-1)}_n < b_i < B^{(N-1)}_{N-1-n} \\
\frac{1}{N-2n} \sum_{j=n+1}^{N-n} B_j^{(N-1)} & B^{(N-1)}_{N-1-n} \leq b_i
\end{cases}
\]
The expectation conditional on bank $i$’s information set is
\[ \mathbb{E} \left[ L \left( b_i, B_{-i} \right) \mid \mathcal{I}_i \right] = \int_{\Theta^{N-1}} L \left( b_i, B_{-i} \right) dF \left( B_{-i} \right) \]
where $F \left( B_{-i} \right)$ is the CDF of $B_{-i}$. $\mathbb{E} \left[ L \left( b_i, B_{-i} \right) \mid \mathcal{I}_i \right]$ is continuous and increasing in $b_i$ since $L \left( b_i, B_{-i} \right)$, as defined in (2.1), is uniformly continuous and increasing in $b_i$ given any realization of $B_{-i}$.

I define bank’s payoff function $\Pi : \Theta \times \Theta \times \Theta^{N-1} \to \mathbb{R}$ as $\Pi \left( s_i, b_i, B_{-i} \right)$: the functional form is the same across banks. Since bank $i$’s payoff depends on $B_{-i} / \in \mathcal{I}_i$, it is a random number with expected value $\mathbb{E} \left[ \Pi \left( s_i, b_i, B_{-i} \right) \mid \mathcal{I}_i \right]$ defined as
\[ \mathbb{E} \left[ \Pi \left( s_i, b_i, B_{-i} \right) \mid \mathcal{I}_i \right] = \int_{\Theta^{N-1}} \Pi \left( s_i, b_i, B_{-i} \right) dF \left( B_{-i} \right) \]

Define the symmetric pure strategy Bayesian Nash equilibrium as well as value function as:

**Definition.** A symmetric pure strategy Bayesian Nash equilibrium is a $N$-tuple
\[ \left( \beta \left( S_1 \right), \beta \left( S_2 \right), ..., \beta \left( S_N \right) \right), \]
in which $\beta : \Theta \Rightarrow \Theta$ is a bank’s best response correspondence for LIBOR submission, given private realized borrowing cost. So that for any other $\beta' : \Theta \Rightarrow \Theta$, bank $i$’s submission $b_i^* \in \beta \left( s_i \right)$, and $b_i' \in \beta' \left( s_i \right),
\[ \mathbb{E} \left[ \Pi \left( s_i, b_i, B_{-i}^* \right) \mid \mathcal{I}_i \right] \geq \mathbb{E} \left[ \Pi \left( s_i, b_i', B_{-i}^* \right) \mid \mathcal{I}_i \right] \]
Bank $j$’s quote is $B_j^* \notin \mathcal{I}_i$. Given best response correspondence $\beta$, we have $B_j^* \in \beta \left( S_j \right)$, $B_{-i}^* = \left\{ B_j^* \right\}_{j \neq i}$.

**Corollary 9.** Since the PDF $f \left( s_i \right)$ is positive over the domain $\Theta$, $\mathbb{E} \left[ \Pi \left( s_i, b_i, B_{-i}^* \right) \mid \mathcal{I}_i \right] \geq \mathbb{E} \left[ \Pi \left( s_i, b_i', B_{-i}^* \right) \mid \mathcal{I}_i \right]$ is equivalent to
\[ \int_0^s \mathbb{E} \left[ \Pi \left( s_i, b_i, B_{-i}^* \right) \mid \mathcal{I}_i \right] f \left( s_i \right) ds_i \geq \int_0^s \mathbb{E} \left[ \Pi \left( s_i, b_i', B_{-i}^* \right) \mid \mathcal{I}_i \right] f \left( s_i \right) ds_i \]

**Definition.** The value function is
\[ V \left( s_i \right) = \mathbb{E} \left[ \Pi \left( s_i, b_i^*, B_{-i}^* \right) \mid \mathcal{I}_i \right] \]
where $b_i^* \in \beta \left( s_i \right)$ which is defined above.

In the rest of the paper I focus on the symmetric strategies only.
CHAPTER 2. LIBOR’S POKER: DISCOVER INTERBANK BORROWING COSTS AMID BANKS’ STRATEGIC BEHAVIOR

Existence and Monotonicity

I introduce an extra assumption about the payoff function \( \Pi (s_i, b_i, B_{-i}) \) satisfies supermodularity or strictly increasing difference, in the sense of Edlin and Shannon (1998). Given \( s_i < s'_i \) and \( b_i < b'_i \),

\[
\Pi (s'_i, b'_i, B^*_{-i}) - \Pi (s'_i, b_i, B^*_{-i}) > \Pi (s_i, b'_i, B^*_{-i}) - \Pi (s_i, b_i, B^*_{-i})
\]

The supermodularity in \( \Pi (s_i, b_i, B_{-i}) \) guarantees the existence and monotonicity of pure strategy Bayesian Nash equilibrium.

**Proposition 10.** There exists a pure strategy symmetric Bayesian Nash equilibrium in the economy defined above.

The proof, which could be referred to Athey (2001) and Reny (2011), is in the appendix.

**Proposition 11.** The symmetric best response correspondence \( \beta (s) \) is non-decreasing: so for \( \forall s_i < s'_i \) and \( \forall b_i \in \beta (s_i) \), \( b'_i \in \beta (s'_i) \), we have \( b_i \leq b'_i \).

The proof is in the appendix. One way to intuitively think why best response correspondence is monotone: If all the other banks except bank \( i \) have non-monotone best response \( \beta_{-i} \), bank \( i \)’s best response \( \beta^*_i \) is still monotone. So we cannot have non-monotone best response correspondence.

**Remark.** Notice we do not need to know the functional form of \( L (b) \) to show the best response correspondence \( \beta (s) \) is non-decreasing in \( s \). Specifically, we do not require \( L (b) \in \mathbb{C}^2 \).

Payoff function with quadratic penalty

To solve for the equilibrium I need specific functional form for payoff function. I assume the penalty \( K \propto (s_i - b_i)^2 \) for the following reasons. First, misreporting will invite audit from agencies with a small probability \( p (b_i) \), which increases when the difference between \( s_i \) and \( b_i \) goes up. In case the audit does happen, and confirms that a bank has submitted \( b_i \neq s_i \), then a fine proportional to the deviation from the true borrowing cost will be imposed to the bank. Aggregating these two factors, bank’s cost of submitting \( b_i \) can be measured as a positive linear function of \( (s_i - b_i)^2 \).
Furthermore I assume LIBOR fluctuation is small enough such that I can approximate the effect of LIBOR locally using a linear function of LIBOR rate, which leads to a specific form of bank’s payoff function

\[
\Pi (s_i, b_i, B_{-i}) = \delta \left[ \bar{S} - L (b_i, B_{-i}) \right] - \gamma (s_i - b_i)^2
\]

The value \( \gamma > 0 \) is the coefficient that measures the severity of penalty, and \( \delta > 0 \) measures the payoff increase given the bank has manipulated LIBOR downwards, both \( \delta \) and \( \gamma \) are the same across panel banks. In addition, scale the payoff \( \Pi \) by \( \delta \) does not change the preference order, I can focus on the penalty ratio \( \gamma / \delta \) instead. Since the penalty coefficient \( \gamma \) is not observed, \( \gamma / \delta \) can also be treated as the implied penalty coefficient, which is used by banks to estimate the penalty when they submitting LIBOR quotes.

Since \( \Pi (s_i, b_i, B_{-i}) \) is uniformly continuous in \( s_i \in \Theta \) and \( b_i \in \Theta \), \( E [\Pi (s_i, b_i, B_{-i}) | I_i] \) is continuous in \( s_i \) and \( b_i \).

When the monotonicity constraint is not binding, \( \beta (s) \) is strictly increasing and we have a one-to-one mapping \( \beta^* (s) \) between bank’s borrowing cost \( s \) and LIBOR quotes \( b \). I discuss this case first, then the case in which monotonicity constraint is binding.

**Strictly increasing optimal LIBOR submissions**

Before solving for equilibrium strategy \( \beta^* (s) \), it is helpful to check the expected value of LIBOR \( E [L (b_i, B_{-i}) | I_i] \) more closely.

**Lemma 12.** With the assumption of strict monotonicity in \( \beta (s) \), the expected value of LIBOR \( E [L (b_i, B_{-i}) | I_i] \), is twice differentiable in \( b_i \).

The proof is in the appendix. I can then solve \( \beta^* (s) \).

**Theorem 13.** Under i.i.d. borrowing cost, and the pdf of distribution of \( n \)th and \( N - n \)th order statistics satisfies the condition

\[
\max_{s \in \Theta} \left[ f^{(N-1)}_n (s) - f^{(N-1)}_{N-n} (s) \right] < 2\gamma (N - 2n)
\]

, the strictly increasing equilibrium strategy \( \beta^* : \Theta \rightarrow \Theta \) for bank with realized borrowing cost \( s \) is

\[
\beta^* (s) = s - \frac{\delta}{2\gamma (N - 2n)} \frac{\Gamma (N)}{\Gamma (n) \Gamma (N - n)} \int_0^{F(s)} \frac{(1 - y)^{N-2n} - y^{N-2n}}{[y (1 - y)]^{1-n}} dy
\]

where the CDF and PDF of \( n \)th order statistics of \( S \) is \( F^{(N-1)}_n (s) \) and \( f^{(N-1)}_n (s) \) respectively.
CHAPTER 2. LIBOR’S POKER: DISCOVER INTERBANK BORROWING COSTS AMID BANKS’ STRATEGIC BEHAVIOR

The proof is in the appendix. For $\forall s \in (0, \bar{S})$, $F_n^{(N-1)}(s) - F_{N-n}^{(N-1)}(s) > 0$ since the PDF $f(s)$ is continuous and positive on $(0, \bar{S})$. Together with the fact that $\gamma, \delta > 0$, $\beta^*(s) < s$. In addition, $\beta^*(0) = 0$, $\beta^*(\bar{S}) = \bar{S}$.

Figure 2.1 shows the properties of equilibrium strategy when LIBOR panel is formed by $N = 16$ banks with i.i.d. normally distributed true borrowing cost. The mean borrowing cost $\mu = 5\%$ and standard deviation $\sigma = 1.5\%$. The penalty ratio $\gamma/\delta = 0.05$. The first subplot is equilibrium strategy $\beta^*(s)$ as a function of borrowing cost $s$. The second and the third subplot show the CDF and PDF of borrowing cost as well as submissions in equilibrium. Under tacit collusion, the submissions of banks cluster around the lower half of the distribution.

Criteria of Binding Monotonicity Constraint

Under which condition is the equilibrium strategy strictly increasing? The first order derivative of $\beta^*(s)$ with regard to $s$

$$\frac{\partial}{\partial s} \beta^*(s) = 1 - \frac{\delta}{2\gamma (N - 2n)} \left[ f_n^{(N-1)}(s) - f_{N-n}^{(N-1)}(s) \right]$$

suggests strictly increasing equilibrium strategy exists when

$$\max_{s \in \Theta} \left[ f_n^{(N-1)}(s) - f_{N-n}^{(N-1)}(s) \right] < (N - 2n) \frac{2\gamma}{\delta}$$

(2.2)

Nevertheless, it does not mean that there will be a non-monotonic equilibrium strategy when the condition (2.2) does not hold. In case every other bank $j \neq i$ has non-monotonic strategy, bank $i$’s optimal strategy is still non-decreasing, as we have proved in the previous section. When the implied penalty coefficient $\gamma$ as well as distribution of order statistics do not satisfy the condition (2.2) the monotonicity constraint is binding and $\frac{\partial \beta^*(s)}{\partial s} = 0$ for some $s$.

Optimal LIBOR submissions when monotonicity constraint is binding

When the condition of strictly increasing equilibrium strategy (2.2) does not hold, banks solve a constrained optimization problem. Specifically, the best response $\beta^*(s)$ satisfies that, for any other $\beta': \Theta \Rightarrow \Theta$

$$\int_0^s \mathbb{E} \left[ \Pi(s_i, b_i, B_{-i}^*) \mid \mathcal{I}_i \right] f(s_i) ds_i \geq \int_0^s \mathbb{E} \left[ \Pi(s_i, b_i', B_{-i}^*) \mid \mathcal{I}_i \right] f(s_i) ds_i$$

s.t. $\frac{\partial \beta(s_i)}{\partial s_i} \geq 0$
Figure 2.1: **Strictly increasing equilibrium strategy** The properties of equilibrium strategy when LIBOR panel is formed by \( N = 16 \) banks with i.i.d. normally distributed true borrowing cost. The first subplot is equilibrium strategy \( \beta^* (s) \) as a function of borrowing cost \( s \). The second and the third subplot show the CDF and PDF of borrowing cost as well as submissions in equilibrium. Under tacit collusion, the submissions of banks cluster around the lower half of the distribution.
in which for bank $i$, its $b_i^* \in \beta(s_i)$, and $b'_i \in \beta'(s_i)$. Submission from bank $j$ is $B_j^* \in \beta_j(S_j)$, $B_j^* \notin \mathcal{I}_i$. $B^*_{i} = \{B_j^*\}_{j \neq i}$. I assume $\beta^*(s)$ is a function instead of a correspondence.

Let $\theta \subset [0, \bar{s}]$ be the set in which the constraint $\partial \beta(s_i)/\partial s_i \geq 0$ binds. I also assume $\theta$ is a convex set. Therefore, there is only one $\bar{b}$ such that $\exists s', s'' \in \theta, s' \neq s''$, s.t. $\beta^*(s') = \beta^*(s'') = \bar{b}$.

**Lemma 14.** When constraint $\partial \beta(s)/\partial s \geq 0$ binds for $s$ in a convex set $\theta \subset [0, \bar{s}]$, the expectation $\mathbb{E}[L(b_i, B_{-i}) | \mathcal{I}_i]$ is twice differentiable at $b_i \neq \bar{b}$, where $\bar{b} = \beta(s)$ for $s \in \theta$. At $b_i = \bar{b}$, $\mathbb{E}[L(b_i, B_{-i}) | \mathcal{I}_i]$ is continuous but not differentiable. In fact, we have $\forall b_i \in [0, s_i]$

$$\frac{\partial}{\partial b_i} \mathbb{E}[L(b_i, B_{-i}) | \mathcal{I}_i] = \frac{1}{N - 2n} \left[ G_n^{(N-1)}(b_i) - G_n^{(N-1)}(b_i) \right]$$

so $\frac{\partial}{\partial b_i} \mathbb{E}[L(b_i, B_{-i}) | \mathcal{I}_i]$ is right continuous with left limits (RCLL) at $b_i = \bar{b}$.

The proof is in the appendix.

**Theorem 15.** Under i.i.d. borrowing cost and

$$\max_{s \in \Theta} \left[ f_n^{(N-1)}(s) - f_n^{(N-1)}(s) \right] \geq - (N - 2n) \frac{2\gamma}{\delta}$$

so the monotonicity constraint is binding when $s \in \theta$, the equilibrium strategy $\beta^* : \Theta \rightarrow \Theta$ for bank with realized borrowing cost $s \notin \theta$ is the same as the unconstrained case

$$\beta^*(s) = s - \frac{\delta}{2\gamma (N - 2n)} \frac{\Gamma(N)}{\Gamma(n)} \left( \frac{F(s)}{(1 - y)^{N-2n}} - y^{N-2n} \right)$$

and for $s \in \theta = [\theta, \bar{\theta}] \subset [0, \bar{s}]$, $\beta^*(s) = \bar{b}$ which is a 'bunching' level that maximizes

$$\int_0^\bar{s} \mathbb{E}[\Pi(s_i, b_i, B_{-i}^*) | \mathcal{I}_i] f(s_i) ds_i$$

where $b_i \in \beta^*(s_i)$.

The proof is in the appendix. The proof also describe how to obtain the optimal bunching level $\bar{b}$.

We can find the 'bunching' level $\bar{b}$ and the region $\theta$ using the following procedure:

As we have seen in the Theorem 15 for $s \notin \theta$, we have the constrained problem $\max_{\beta(s_i) \in \Theta} \Pi(s_i, \beta(s_i), B_{-i}^*)$ s.t. $\partial \beta(s_i)/\partial s_i \geq 0$ equivalent to the unconstrained problem $\max_{\beta(s_i) \in \Theta} \Pi(s_i, \beta(s_i), B_{-i}^*)$. We write the solution of the unconstrained problem as $\tilde{\beta}(s)$. 

Figure 2.2: Determining the bunching level The bunching level is between $b_{\text{max}}$ and $b_{\text{min}}$. 

With the help of the theorem, together with the continuity, we first notice $\bar{b}$ should be between two stationary points of $\tilde{\beta}(s)$, aka $\bar{b} \in [\bar{b}_{\text{min}}, \bar{b}_{\text{max}}]$, as shown in figure 2.2. With this range, $\bar{b}$ is optimally chosen to maximize

$$\int_{\Theta} \Pi(s_i, \beta^*(s_i), B^*_{-i}) f(s_i) ds_i$$

where $\theta$ and $\tilde{\theta}$ are the intersection of $\bar{b}$ with $\tilde{\beta}(s)$. $\beta^*(s)$ can be found using numerical search procedure.

Figure 2.3 shows the properties of equilibrium strategy when LIBOR panel is formed by $N = 16$ banks with i.i.d. normally distributed true borrowing cost. The mean borrowing cost $\mu = 5\%$ and standard deviation $\sigma = 1.5\%$. The penalty ratio $\gamma/\delta = 0.02$. Similar to
Figure 2.3: **Equilibrium strategy with binding monotonicity constraint** The properties of equilibrium strategy when LIBOR panel is formed by $N = 16$ banks with i.i.d. normally distributed true borrowing cost. The first subplot is equilibrium strategy $\beta^*(s)$ as a function of borrowing cost $s$. The second and the third subplot show the CDF and PDF of borrowing cost as well as submissions in equilibrium. It shows the bunching level is around the lowest quartile of the distribution.
CHAPTER 2. LIBOR’S POKER: DISCOVER INTERBANK BORROWING COSTS AMID BANKS’ STRATEGIC BEHAVIOR

Figure 2.1, the first subplot is equilibrium strategy $\beta^*(s)$ as a function of borrowing cost $s$. The second and the third subplot show the CDF and PDF of borrowing cost as well as submissions in equilibrium. It shows the bunching level is around the lowest quartile of the distribution. When the monotonicity constraint binds, the dispersion of banks’ LIBOR submissions is even smaller.

2.3 Signaling

Besides tacit collusion, banks also concerns about the signaling effect of their LIBOR submissions. By releasing a high interbank borrowing cost to public, a bank signals a weak balance sheet. Such signals may invite costly bank runs as in Diamond and Dybvig (1983). Banks’ trading and funding counter-parties may also close up positions abruptly, which usually leads to costly fire sale of assets as Shleifer and Vishny (2011) suggests.

Consider for each bank $i$, it can be in any one of hidden states $\theta \in \{f, g\}$. In a good state, $\theta = g$ and the bank is solid, while in a ‘failing’ state, $\theta = f$ and the bank has solvency problem. The true state of each bank is unknown. Banks’ borrowing cost follows different distributions in two states. Naive consumers, unaware of banks’ strategic behavior of LIBOR submission, update the likelihood of states for each of the LIBOR panel banks, base on its LIBOR quotes. Consumers then become panic and run on the bank according to the probability of bank in the failing state. Once the bank run happen, the bank loses value $\rho > 0$.

Suppose in each state the borrowing costs of bank is i.i.d. normally distributed with equal volatility: in good state $S \sim N(\mu_g, \sigma^2)$, while in the failing state $S \sim N(\mu_f, \sigma^2)$, and $\mu_f > \mu_g$. I denote the pdf $f(b) = \Pr (S_i = b_i|\theta = f)$, and $g(b_i) = \Pr (S_i = b_i|\theta = g)$. With prior belief that banks are in the failing state with probability $p = \Pr (\theta = f)$, consumers update the probability to be $\pi(b_i)$, after observe bank’s LIBOR quote $b_i$. Hence $\pi(b_i) = \Pr (\theta = f|S_i = b_i)$.

For banks in the LIBOR panel, it is reasonable to assume $p$ is close to 0, therefore $1 - p >> p$. Since banks’ USD LIBOR quote are usually low, I also assume for the LIBOR quotes we have observed, $\Pr (S_i = b_i|\theta = g) >> \Pr (S_i = b_i|\theta = f)$. Therefore first order approximation suggests

$$
\pi(b_i) = \frac{\Pr (S_i = b_i|\theta = f)}{\Pr (S_i = b_i|\theta = g)} \frac{p}{1 - p} = \frac{p}{1 - p} \frac{f(b)}{g(b)}
$$

$$
= \frac{p}{1 - p} \exp \left\{ \frac{\mu_g^2 - \mu_f^2}{\sigma^2} \right\} \exp \left\{ \frac{2 (\mu_f - \mu_g)}{\sigma^2} b_i \right\}
$$
The ex ante bank run cost is
\[ \rho \pi(b_i) = \rho \phi \exp\{\eta b_i\} \]
where
\[ \phi = \frac{p}{1-p} \exp\left\{-\frac{\mu_f^2 - \mu_g^2}{\sigma^2}\right\} > 0 \]
\[ \eta = \frac{2(\mu_f - \mu_g)}{\sigma^2} > 0 \]

I can then augment the payoff function for bank \( i \), with the effect of signaling, as
\[ \Pi_i(s_i, b_i, \{B_j\}_{j \neq i}) = \delta \left[ \bar{S} - L(b_i, \{B_j\}_{j \neq i}) \right] - \gamma (s_i - b_i)^2 - \rho \phi \exp\{\eta b_i\} \]
with aforementioned \( \phi \) and \( \eta \). Furthermore, bank \( i \) does not know other banks’ borrowing costs \( S_{-i} \), but shares the same belief as consumers about the probability of states. So for bank \( i \), a bank \( j \neq i \)’s borrowing cost \( S_j \sim i.i.d. N(\bar{\mu}, \bar{\sigma}^2) \), where \( \bar{\mu} = p\mu_f + (1-p)\mu_g \), and \( \bar{\sigma}^2 = (p^2 + (1-p)^2)\sigma^2 \). I denote \( \bar{F}(\cdot) \) and \( \bar{f}(\cdot) \) as the CDF and PDF of \( S_j \) respectively.

The expected payoff function still satisfies the supermodularity
\[ \Pi(s_i', b_i', B^*_{-i}) - \Pi(s_i', b_i, B^*_{-i}) < \Pi(s_i, b_i', B^*_{-i}) - \Pi(s_i, b_i, B^*_{-i}) \]
so Proposition 10 and 11 suggest the existence and monotonicity of equilibrium.

**Theorem 16.** Under i.i.d. borrowing cost, and the signaling effect, if the pdf of distribution of \( n \)th and \( N - n \)th order statistics satisfies the condition
\[ \max_{s \in \Theta} \left[ \bar{f}_{n(N-1)}(s) - \bar{f}_{N-n}^{(N-2)}(s) \right] < 2\gamma (N - 2n) \]
, the strictly increasing equilibrium strategy \( \beta^* : \Theta \rightarrow \Theta \) for bank with realized borrowing cost \( s \) is
\[ \beta^*(s) = s - \Delta - \frac{1}{\eta} W\left( \frac{\rho \phi \eta^2}{2\gamma} \exp\{\eta (s - \Delta)\} \right) \]
where \( W \) is Lambert-W function \( \text{\textbullet} \) and
\[ \Delta = \frac{\delta}{2\gamma (N - 2n)} \frac{\Gamma(N)}{\Gamma(n) \Gamma(N-n)} \int_0^{F(s)} \frac{(1 - y)^{N-2n} - y^{N-2n}}{[y (1 - y)]^{1-n}} dy \]
as in the previous section.

\( \text{\textbullet} \)The Lambert-W function, also called the omega function is the inverse function of \( f(W) = We^W \). It is implemented in Mathematica as ProductLog[x], and in Matlab as lambertw(x). The Lambert-W function \( W(x) \) is strictly increasing in \( x \) when \( x > 0 \). Hence higher \( p \) will lead to more LIBOR bias.
CHAPTER 2. LIBOR'S POKER: DISCOVER INTERBANK BORROWING COSTS AMID BANKS’ STRATEGIC BEHAVIOR

The proof is in the appendix.

Figure 2.4 shows the properties of equilibrium strategy when LIBOR panel is formed by $N = 16$ banks with i.i.d. normally distributed true borrowing cost. The mean borrowing cost is normally distributed with mean $\mu = 3\%$ in good state, and $\mu = 13\%$ in bad state. The standard deviation $\sigma = 1.819\%$. The prior belief assigns $p = 0.2$ probability that banks are in the bad state. Therefore, the ex ante distribution is normal with $\mu = 5\%$ and $\sigma = 1.5\%$, similar to Figure 2.1. The penalty ratio is also the same $\gamma/\delta = 0.05$, with the implied bank run cost $\rho/\delta = 100$. The first subplot is equilibrium strategy $\beta^*(s)$ as a function of borrowing cost $s$. The second and the third subplot show the CDF and PDF of borrowing cost as well as submissions in equilibrium. It shows the submissions of banks cluster around the lower half of the distribution.

Compared to Figure 2.1 in which the signaling effect is not present and banks with the highest borrowing cost do not submit lower LIBOR quotes. Figure 2.4 shows how does the signaling effect changes the behavior of banks with high borrowing cost, since they have the highest incentive to cover up their high borrowing cost. Comparing the $\beta^*(s)$ under two cases shows that signaling effect introduces an extra term $-\frac{1}{\eta} W\left(\frac{\rho \phi \eta^2}{2 \gamma} \exp\{\eta (s - \Delta)\}\right) < 0$.

When the monotonic constraint is binding, I have a similar result as before

**Theorem 17.** Under i.i.d. borrowing cost and

$$\max_{s \in \Theta} \left[ \tilde{f}^{(N-1)}_n (s) - \tilde{f}^{(N-1)}_{N-n} (s) \right] \geq - (N - 2n) \frac{2 \gamma}{\delta}$$

so the monotonicity constraint is binding when $s \in \theta$, the equilibrium strategy $\beta^*: \Theta \to \Theta$ for bank with realized borrowing cost $s \notin \theta$ is the same as the unconstrained case

$$\beta^*(s) = s - \Delta - \frac{1}{\eta} W\left(\frac{\rho \phi \eta^2}{2 \gamma} \exp\{\eta (s - \Delta)\}\right)$$

where

$$\Delta = \frac{\delta}{2 \gamma (N - 2n)} \frac{\Gamma(N)}{\Gamma(n) \Gamma(N - n)} \int_{0}^{\tilde{F}(s)} \frac{(1 - y)^{N-2n} - y^{N-2n}}{[y (1 - y)]^{1-n}} dy$$

and for $s \in \theta = [\theta, \bar{\theta}] \subset [0, \bar{s}]$, $\beta^*(s) = \bar{b}$ which is a 'bunching' level that maximizes $f^s E \left[ \Pi \left( s_i, b_i, B^*_{s_i} \right) \right] f(s_i) ds_i$, where $b_i \in \beta^*(s_i)$.

The proof is in appendix.

Figure 2.5 shows the properties of equilibrium strategy when LIBOR panel is formed by $N = 16$ banks with i.i.d. normally distributed true borrowing cost. The mean borrowing
Figure 2.4: **Strictly increasing equilibrium strategy with signaling** The properties of equilibrium strategy when LIBOR panel with signaling. The panel contains $N = 16$ banks with i.i.d. normally distributed true borrowing cost. The first subplot is equilibrium strategy $\beta^*(s)$ as a function of borrowing cost $s$. The second and the third subplot show the CDF and PDF of borrowing cost as well as submissions in equilibrium.

**Equilibrium Strategy When $N = 16$, $n = 4$, Implied Penalty Coeff. $\gamma/\delta = 0.05$**

Implied bank run cost $\rho/\delta = 100$, and $S \sim N(5.000, 1.500)$, while in failing state $S \sim N(13.000, 1.819)$.

**CDF of Borrowing Costs $s$ vs Optimal Submission $\beta^*(s)$**

Cost: MAD = 1.0117; Submission: MAD = 0.5700

**Histogram of Borrowing Costs $s$ vs Optimal Submissions with bin size as 20 bps**
cost $\mu = 5\%$ and standard deviation $\sigma = 1.5\%$. The penalty ratio $\gamma/\delta = 0.02$. Similar to Figure [2.1] the first subplot is equilibrium strategy $\beta^*(s)$ as a function of borrowing cost $s$. The second and the third subplot show the CDF and PDF of borrowing cost as well as submissions in equilibrium. Signaling has similar effect to banks’ LIBOR submission in this case.

In summary, signaling effect causes bank to depress its LIBOR submission even further, especially for banks with higher borrowing costs. The impact of signaling is also affected by the prior belief among banks’ customers and trading partners. When consumers are less confident in a bank’s solidness, the prior probability of bank failure $p$ becomes higher, which suggests the bank should depress its LIBOR submission even more.

2.4 Mechanism design

The fact that the LIBOR rate is not what it supposed to be - a truncated arithmetic average of banks’ true borrowing cost - motivates a LIBOR fixing mechanism in which banks truthfully report so the LIBOR rate is ‘correct’. I first define direct mechanism:

**Definition.** A LIBOR fixing mechanism is direct if each bank reports its true borrowing cost in equilibrium.

I note the direct mechanism as $(L^*, M^*)$, in which $L^* : \Theta \to \mathbb{R}^+$ defines how the LIBOR is calculated, and $M^*_i : \Theta^N \to \mathbb{R}$ is the payment rule which sets the amount every bank $i$ pays BBA to participate into the LIBOR panel. Assume the social welfare gets maximized when the LIBOR fixing mechanism, as a price discovery mechanism, gives out the trimmed average of panel banks’ borrowing costs.

**Definition.** A direct LIBOR fixing mechanism $(L^*, M^*)$ is efficient if it generates the LIBOR rate equals to

$$r_f + \frac{1}{N-2n} \sum_{j=n+1}^{N-n} s_j^{(N)}$$

in equilibrium.

The existence of payment rule motivates the direct and efficient LIBOR fixing mechanism $(L^*, M^*)$ to be budget balanced as well. Since borrowing cost $s$ is random, it is hard to have BBA as a central planner to remain budget balanced under any realization of banks’ borrowing costs. It is then natural to check whether there exists mechanism that BBA is able to remain budget balanced in expectation over the realization of borrowing cost $s$. 
Figure 2.5: **Equilibrium strategy with binding monotonicity constraint with signaling** The properties of equilibrium strategy when LIBOR panel with signaling. The panel contains \( N = 16 \) banks with i.i.d. normally distributed true borrowing cost. The first subplot is equilibrium strategy \( \beta^*(s) \) as a function of borrowing cost \( s \). The second and the third subplot show the CDF and PDF of borrowing cost as well as submissions in equilibrium.
Definition. A direct LIBOR fixing mechanism is *ex ante* budget balanced if the sum of banks’ expected payment to BBA is zero.

$$
\sum_{i=1}^{N} \mathbb{E} [M_i^* (s)] = 0
$$

Now I propose a direct, efficient and *ex ante* budget balanced LIBOR fixing mechanism, along the line of AGV mechanism by d’Aspremont and Gérard-Varet (1979).

**Proposition 18.** There is a direct, efficient, and *ex ante* budget balanced LIBOR fixing mechanism \((L^*, M^*)\) in which banks report \(z = \{z_1, \ldots, z_N\}\), where \(z_i = s_i\) for all \(i\). The LIBOR is calculated as

$$
L^* (z) = r_f + \frac{1}{N - 2n} \sum_{j=n+1}^{N-n} z_j^{(N)}
$$

and every bank \(i\) pays BBA

$$
M_i^* (z) = -\frac{\delta}{N - 2n} \sum_{j=n+1}^{N-n} \left[ z_j^{(N)} - \beta^* \left( z_j^{(N)} \right) \right] + \frac{\delta}{N - 2n} \frac{N}{N - 1} \sum_{j=n+1, z_j^{(N)} \neq z_i}^{N-n} \left[ z_j^{(N)} - \beta^* \left( z_j^{(N)} \right) \right] + \gamma (z_i - \beta^* (z_i))^2 - \frac{1}{N - 1} \sum_{k \neq i} \gamma (z_k - \beta^* (z_k))^2
$$

**Proof.** I first prove the mechanism is incentive compatible. Assume bank \(i\) reports \(z_i\) when all the other banks report their true borrowing cost \(s_{-i}\). Bank \(i\)'s payoff function is

$$
\delta \left[ \bar{S} - L^* (z_i, s_{-i}) \right] - M_i^* (z_i, s_{-i})
$$

therefore the optimal reporting value \(z_i^*\) is

$$
z_i^* = \arg \max_{z_i} \delta \left[ \bar{S} - L^* (z_i, s_{-i}) \right] - M_i^* (z_i, s_{-i})
$$

Remove all the terms that do not contain \(z_i\), we have

$$
z_i^* = \arg \max_{z_i} \delta \left[ \bar{S} - \frac{1}{N - 2n} \sum_{j=n+1}^{N-n} \beta^* \left( s_j^{(N)} \right) \right] - \gamma (s_i - \beta^* (z_i))^2
$$
CHAPTER 2. LIBOR’S POKER: DISCOVER INTERBANK BORROWING COSTS AMID BANKS’ STRATEGIC BEHAVIOR

The construction of $\beta^*$ suggests $z_i^* = s_i$
hence $(L^*, M^*)$ is direct and efficient.

In addition,
\[
\sum_{i=1}^{N} \mathbb{E}[M_i^* (z)] = \sum_{i=1}^{N} \mathbb{E}[M_i^* (s)] \\
= -\frac{\delta}{N-2n} \sum_{i=1}^{N} \sum_{j=n+1}^{N-n} \mathbb{E} \left[ s_j^{(N)} - \beta^* \left( s_j^{(N)} \right) \right] \\
+ \frac{\delta}{N-2n} \sum_{i=1}^{N} \sum_{j=n+1, s_j^{(N)} \neq s_i}^{N-n} \mathbb{E} \left[ s_j^{(N)} - \beta^* \left( s_j^{(N)} \right) \right] \\
+ \sum_{i=1}^{N} \left\{ \gamma \mathbb{E} \left[ (s_i - \beta^* (s_i))^2 \right] - \frac{1}{N-1} \sum_{k \neq i} \gamma \mathbb{E} \left[ (s_k - \beta^* (s_k))^2 \right] \right\} \\
= 0
\]
suggests $(L^*, M^*)$ is ex ante budget balanced.

\[\square\]

2.5 Economic implications

The previous analysis shows the symmetric equilibrium submission strategy is not revealing. Banks may not always submit their true borrowing cost, and the LIBOR rates are error-prone. This section focuses on the economic implications of the model according to the comparative statics of banks’ equilibrium submissions. To simplify the notation, I omit the subscript $i$ in the payoff function.

Economic conditions - More Dispersed Borrowing Costs

Consider first the LIBOR fixing process under various economic conditions. As a crucial benchmark of overall health of the financial system, LIBOR rates get more attention during the financial crisis than during normal times. Unfortunately, since the dispersion of banks’ borrowing cost are higher during the financial crisis, the current LIBOR fixing process causes higher LIBOR bias during the turmoil, exactly when a solid benchmark is needed the most.
Proposition 19. When the distribution of borrowing cost $S$ goes more dispersed, each bank’s equilibrium submission diverges from its true borrowing cost.

Proof. When the distribution of borrowing cost $S$ gets more dispersed, $F_{n(N-1)}(s) - F_{N-n}(s)$ goes up, hence lowers $\beta^*(s)$.

Economic conditions - Less Confidence in Banks

In normal times, consumers assign a very low $p$ to their belief about banks are in the failing state. As a result, $\phi$ is approaching zero therefore the signaling term in the equilibrium is negligible. However, during the financial crisis, the $p$ becomes much higher. Hence the bank will have a bigger incentive to downplay the LIBOR rate, even its own borrowing cost is unchanged at all.

Proposition 20. When the consumers are less confident in banks, the equilibrium LIBOR submission goes down.

Proof. Under signaling effect the equilibrium submission is

$$\beta^*(s) = s - \Delta - \frac{1}{\eta} W \left( \frac{\rho \eta^2}{2 \gamma} \exp \left\{ \eta (s - \Delta) \right\} \right)$$

in which $\frac{1}{\eta} W \left( \frac{\rho \eta^2}{2 \gamma} \exp \left\{ \eta (s - \Delta) \right\} \right)$ is the additional term due to signaling. When consumers are less confident in banks, they assign a higher prior probability of failure $p$. Since $\phi = \frac{p}{1-p} \exp \left\{ -\frac{\mu^2 - \mu^2}{\sigma^2} \right\}$, and lambert-W function $W(x)$ is strictly increasing in $x$, $\beta^*(s)$ will bias below further from the true borrowing cost $s$, even $s$ itself is unchanged by the prior belief.

Financial regulation

Next I evaluate the implication of penalty to banks’ submission strategy. Intuitively, when banks are allowed to report untruthfully without any consequence, banks will push the LIBOR to the lowest level. Therefore, banks LIBOR submissions contain no information about their interbank borrowing cost. This will not happen when penalty exists, which could either be explicit audit to check whether a bank reports its borrowing cost truthfully or a threat of audit. The intuition is confirmed in the following proposition.
Proposition 21. If there is no penalty, then strategically behaved banks will report the lowest possible borrowing cost. If there is penalty for misreporting, then strategically behaved banks will not report the lowest possible borrowing cost as long as their borrowing cost is higher than the riskless rate. This is true even with arbitrarily small positive $\gamma$.

Proof. Suppose banks adopt symmetric strategy. When there is no penalty, $\gamma = 0$,

$$\frac{\partial}{\partial \beta(s)} \mathbb{E} [\Pi (s, \beta(s)) | I_i] = -\frac{\delta}{N-2n} \left[ F^{(N-1)}_n(s) - F^{(N-1)}_{N-n}(s) \right] < 0$$

so for any $\beta(s) > 0$, there is always another $\tilde{\beta}(s) = \beta(s) - \varepsilon < \beta(s)$ that Pareto dominates $\beta(s)$. In other word, banks will report lowest possible borrowing costs, aka $b = \beta(s) = 0$, and the LIBOR rate will converge to the riskless rate.

In case $\gamma > 0$, assume $\beta(s) = 0$ for some $s > 0$, then

$$\frac{\partial}{\partial \beta(s)} \mathbb{E} [\Pi (s, \beta(s)) | I_i] \bigg|_{\beta(s)=0} = \gamma s > 0$$

so submitting $\tilde{\beta}(s) = \varepsilon > 0$ Pareto dominates submitting $\beta(s) = 0$. Hence banks’ submission will be higher than riskless rate.

Panel bank formation

Finally, the number of banks in the panel also changes the LIBOR submission strategy. When the panel includes more banks, the LIBOR rate will converge to the true borrowing cost. Therefore, adding more banks into the LIBOR panel will help to reduce the LIBOR bias.

Proposition 22. When the number of banks in the pool goes to infinity, each bank’s equilibrium submission converges to its true borrowing cost from below.

Proof. Given $\beta^*(s) = s - \frac{\delta}{2\gamma(N-2n)} \left[ F^{(N-1)}_n(s) - F^{(N-1)}_{N-n}(s) \right]$, and by construction $F^{(N-1)}_n(s) - F^{(N-1)}_{N-n}(s) \in [0, 1]$, so when $N \uparrow \infty$, we have $\beta^*(s) \uparrow s$. 


2.6 Empirical study

Institutions and data

This study focuses on 1 Year USD LIBOR fixing process from 2008 to 2010. The USD LIBOR panel contains sixteen banks in these three years. Thomson Reuters provides 1 year LIBOR fixing data. The CDS par spread with 1 year tenor is drawn from CMA Datavision as well as Thomson Reuters. To calculate the LIBOR quote-OIS spread, aka the spread between panel banks’ LIBOR quotes and OIS rates, I also download 1 year OIS rates from Bloomberg.

There are 784 daily records in CDS spreads and LIBOR quote-OIS spreads. Since not every bank has liquid CDS trading, the dataset contains eleven out of sixteen panel banks.

Figure 2.6 contains the LIBOR quote-OIS spread for each panel bank in the dataset, as well as banks’ CDS par spread.

Summary statistics and stylized facts

Table 2.3 shows the summary statistics of the dataset. Besides number of data points, variance ratio, and median absolute deviation (MAD) ratio, all other statistics are the cross-sectional statistics averaged over the time period. The financial market has undergone a severe crisis in 2008 to 2010, and banks’ CDS spread as well as their LIBOR submissions have varied significantly. Therefore, I divide the 3-year period into six sub-periods: in each sub-period CDS spreads and LIBOR submissions are more stable.

The cross-sectional dispersions among CDS spreads and LIBOR quote-OIS spreads are different by order of magnitude: the variance ratio of LIBOR quote-OIS spread over CDS spread is less than 0.1. Table 2.4 shows the result of Levene’s test as well as non-parametric Ansari-Bradley test of equivalent dispersion. The null hypothesis of LIBOR-OIS spread and CDS spread, as well as the log of spreads, have the same dispersion is rejected in every sub-period with $p$-value < 0.001.

---

8The LIBOR panel from July 27th, 2005 to Feb. 1st, 2011 contains Bank of Tokyo Mitsubishi - UFJ, Bank of America, Barclays, Citibank, Credit Suisse, Deutsche Bank AG, HBOS/Societe Generale, HSBC, J. P. Morgan Chase, Lloyds TSB Bank plc, Norinchukin, Rabobank, Royal Bank of Canada, Royal Bank of Scotland, UBS AG, and WestLB. Effective from Feb 9, 2009, Societe Generale replaced HBOS, which was acquired by Lloyds. After Feb. 1st, 2011, the USD LIBOR panel has undergone a couple of changes. Currently it contains eighteen banks, and the LIBOR is calculated by averaging the 10 quotes in the middle.

9OIS (Overnight Index Swap) measures bank’s expected unsecured overnight borrowing rates for the period of fixed-for-floating interest rate swap, in which the floating rate is the average fed fund rate during the period. OIS rates is used as the benchmark for riskless rate.

10There are no senior CDS spread for Credit Suisse, Norinchukin, and Royal Bank of Canada. The CDS spreads for Bank of Mitsubishi UFJ and HSBC are also dropped from the dataset due to data quality concern.
Table 2.3: Summary statistics of panel banks’ 1Yr CDS spreads and 1Yr USD LIBOR quote-OIS spreads 2008-2010

<table>
<thead>
<tr>
<th></th>
<th>H1 ’08</th>
<th>H2 ’08</th>
<th>H1 ’09</th>
<th>H2 ’09</th>
<th>H1 ’10</th>
<th>H2 ’10</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Data Points</td>
<td>130</td>
<td>132</td>
<td>129</td>
<td>132</td>
<td>129</td>
<td>132</td>
</tr>
<tr>
<td>Average 1Yr USD LIBOR (%)</td>
<td>3.016</td>
<td>3.148</td>
<td>1.896</td>
<td>1.250</td>
<td>0.984</td>
<td>0.863</td>
</tr>
<tr>
<td>Parametric</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean CDS Spread (%)</td>
<td>0.6131</td>
<td>1.0185</td>
<td>2.1114</td>
<td>0.9013</td>
<td>0.7917</td>
<td>0.8010</td>
</tr>
<tr>
<td>Mean LIBOR quote-OIS Spread (%)</td>
<td>0.7063</td>
<td>1.6026</td>
<td>1.5403</td>
<td>0.8426</td>
<td>0.6023</td>
<td>0.6438</td>
</tr>
<tr>
<td>Var. of CDS Spread</td>
<td>0.0476</td>
<td>0.2319</td>
<td>2.1616</td>
<td>0.3270</td>
<td>0.0953</td>
<td>0.1157</td>
</tr>
<tr>
<td>Variance Ratio</td>
<td>0.0476</td>
<td>0.2319</td>
<td>2.1616</td>
<td>0.3270</td>
<td>0.0953</td>
<td>0.1157</td>
</tr>
<tr>
<td>Non-parametric</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median CDS Spread (%)</td>
<td>0.5920</td>
<td>0.8868</td>
<td>1.6497</td>
<td>0.7816</td>
<td>0.6909</td>
<td>0.7532</td>
</tr>
<tr>
<td>Median LIBOR quote-OIS Spread (%)</td>
<td>0.7006</td>
<td>1.5914</td>
<td>1.5002</td>
<td>0.8301</td>
<td>0.6028</td>
<td>0.6335</td>
</tr>
<tr>
<td>MAD of CDS Spread (%)</td>
<td>0.1353</td>
<td>0.1703</td>
<td>0.3059</td>
<td>0.2260</td>
<td>0.1892</td>
<td>0.2217</td>
</tr>
<tr>
<td>MAD Ratio</td>
<td>0.0796</td>
<td>0.2224</td>
<td>0.0986</td>
<td>0.1820</td>
<td>0.1556</td>
<td>0.1829</td>
</tr>
</tbody>
</table>

Table 2.4: Test for equal dispersions between 1Yr CDS spreads and 1Yr USD LIBOR quote-OIS spreads 2008-2010

<table>
<thead>
<tr>
<th></th>
<th>H1 ’08</th>
<th>H2 ’08</th>
<th>H1 ’09</th>
<th>H2 ’09</th>
<th>H1 ’10</th>
<th>H2 ’10</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDS and LIBOR-OIS Spread</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Levene’s test p-value</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Ansari-Bradley test p-value</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Log CDS and log LIBOR-OIS Spread</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Levene’s test p-value</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Ansari-Bradley test p-value</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>
It is very difficult to explain this phenomena, if indeed banks report their borrowing costs truthfully. Suppose a lender is facing two different banks say A and B, each with different CDS spreads $s_A > s_B$. Assume liquidity premium component of CDS spread is the same for two banks A and B, and bid-ask spread is negligible, non-arbitrage condition suggests the lender should offer two different rates $r_A > r_B$ to bank A and B, and the difference $r_A - r_B$ should be very close to $s_A - s_B$. In other words, if banks report truthfully, the dispersion of CDS spreads should be comparable to the dispersion of LIBOR quote-OIS spreads. Therefore, although the level of CDS spread cannot be used directly to check the validity of LIBOR, the comparison of the cross-sectional dispersion of CDS spreads and LIBOR quote-OIS spreads is helpful.

As the model suggests, strategic behavior among panel banks will cause their submissions to cluster together. Therefore by matching the difference in the measure of scale among
bank’s LIBOR quotes, I will be able to calibrate the implied penalty ratio $\gamma/\delta$. Furthermore, I can also estimate by how much the LIBOR has been understated in each sub-period.

I rely on median and median absolute deviation (MAD), non-parametric measures of location and scale, for data analysis and model calibration for two reasons. First, the model relies heavily on order statistics, which is very sensitive to the correctness of distribution functions: matching moments in the empirical data using a presumed distribution is not enough. Second, empirical tests indicate the distribution of CDS spread is neither normal nor log-normal. Table 2.5 shows the result of Kolmogorov-Smirnov (K-S) test for normality: the normality null hypothesis is rejected in every sub-period with $p$-value < 0.001.

Table 2.5: K-S test for 1Yr CDS spread

<table>
<thead>
<tr>
<th></th>
<th>H1 ’08</th>
<th>H2 ’08</th>
<th>H1 ’09</th>
<th>H2 ’09</th>
<th>H1 ’10</th>
<th>H2 ’10</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDS Spread Normality Test</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-S test p-value</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Log CDS Spread Normality Test</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-S test p-value</td>
<td>0.0029</td>
<td>0.0045</td>
<td>0.0000</td>
<td>0.0011</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Calibration and empirical results

To calibrate the implied penalty coefficient, I first construct a non-parametric distribution of CDS spreads, using kernel smoothing method. Assuming the liquidity premium is the same for all the panel banks, non-arbitrage condition suggests that the distribution of CDS spreads should be a close proxy of the distribution of borrowing costs. Therefore we can use the median absolute deviation of CDS spread to proxy the dispersion of borrowing cost $MAD_s$. Given a penalty coefficient $\gamma$, the equilibrium strategy yields a distribution of LIBOR submissions, as well as a median absolute deviation $MAD_b$. I define the ratio of MAD as $MAD_b/MAD_s$. A search procedure over the support of penalty coefficient will find a $\gamma$ that matches the model generated ratio of MAD to data. Once I have calibrated the implied penalty coefficient $\gamma$, I can also back out banks’ strategies and calculate how much the LIBOR was suppressed in each of the sub-period.

Table 2.6 shows the calibration results, as well as the LIBOR bias. Together with Figure 2.7, they show the historical average 1Yr USD LIBOR as well as adjusted LIBOR in each sub-period. The results suggest that LIBOR was heavily understated during the recent financial crisis. The level of LIBOR bias in the first half of 2008 coincides with practitioner’s
CHAPETER 2. LIBOR’S POKER: DISCOVER INTERBANK BORROWING COSTS AMID BANKS’ STRATEGIC BEHAVIOR

Table 2.6: 1Yr USD LIBOR bias and adjustment during 2008-2010

<table>
<thead>
<tr>
<th></th>
<th>H1 ’08</th>
<th>H2 ’08</th>
<th>H1 ’09</th>
<th>H2 ’09</th>
<th>H1 ’10</th>
<th>H2 ’10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implied Penalty Coefficient</td>
<td>0.16</td>
<td>0.097</td>
<td>0.037</td>
<td>0.090</td>
<td>0.085</td>
<td>0.093</td>
</tr>
<tr>
<td>LIBOR bias (bps)</td>
<td>-30.6</td>
<td>-50.0</td>
<td>-134.0</td>
<td>-54.6</td>
<td>-56.6</td>
<td>-52.9</td>
</tr>
<tr>
<td>Historical 1Yr USD LIBOR (%)</td>
<td>3.016</td>
<td>3.148</td>
<td>1.896</td>
<td>1.250</td>
<td>0.984</td>
<td>0.863</td>
</tr>
<tr>
<td>Adjusted 1Yr USD LIBOR (%)</td>
<td>3.322</td>
<td>3.648</td>
<td>3.236</td>
<td>1.796</td>
<td>1.550</td>
<td>1.392</td>
</tr>
</tbody>
</table>

Figure 2.7: 1Yr USD LIBOR adjustment during 2008-2010

As the turmoil in financial market unfolds, LIBOR biases further from its true level. The level of LIBOR bias peaked in the first half of 2009, when financial crisis was in its deepest stage. LIBOR biases reduced to a much smaller level when the banking sector stabilized after later 2009.

I have not considered the signaling effect in the empirical calibration here. Since the signaling effect will cause high borrowing cost banks report lower LIBOR, it will lead to smaller LIBOR dispersion. Therefore the estimated LIBOR bias will be a smaller number in absolute term. This is the next step of the paper.

CHAPTER 2. LIBOR’S POKER: DISCOVER INTERBANK BORROWING COSTS AMID BANKS’ STRATEGIC BEHAVIOR

2.7 Conclusion

LIBOR is so widely referenced that people seem to believe it is as reliable as Big Ben. However, its abnormal movements in the last couple of years suggest further investigation. Banks’ LIBOR submissions seem too low, and dispersion among the submissions seems too small. In this article, I develop an auction-theoretic model that explains both stylized facts. Recent investigation in LIBOR fraud suggests that instead of reporting their borrowing cost truthfully, banks report their borrowing costs strategically for various reasons. Current LIBOR fixing mechanism induces truthful revelation if borrowing costs among banks are identical. However, tacit collusion among panel banks occurs when their borrowing costs are not the same. Assuming banks benefit from lower rate due to derivative trading or net interest income, the equilibrium strategy of banks under the current mechanism leads to an understated LIBOR rate. Releasing banks’ LIBOR submission to public also causes a signaling effect, which causes even more LIBOR bias. In addition, the LIBOR submissions will cluster together and show a much smaller dispersion than other indicators of borrowing cost, such as CDS spreads, do.

Furthermore, the model suggests the LIBOR bias, defined as the deviation of LIBOR from its true level, is not a constant. When banks’ bottom line becomes more sensitive to the level of LIBOR rate, the LIBOR bias becomes bigger. Regulator also plays a role: when regulator impose higher penalty to fraudulent activity, banks’ strategic behavior become less significant, and LIBOR will be closer to its true level. Finally, the state of financial market also impacts the LIBOR bias from two channels. Firstly, during financial crisis, bank’s credit spreads are more volatile and the cross-sectional dispersion of CDS spreads becomes higher: the strategic behavior of panel banks will cause the LIBOR bias to be bigger. In addition, when consumers and trading partners become less confident about the credit worthiness of panel bank, the bank will depress its LIBOR submission even more to avoid the bank run. In other words, LIBOR, arguably the most important benchmark in financial market, becomes least reliable when the market needs the measure of funding stress most extensively.

This study also gives suggestion on the mechanism design of the LIBOR fixing process. Increasing the number of banks in the panel will push the LIBOR rate closer to the true level. In addition, there is an optimal size of truncation on bank quotes. Most importantly, there exists a direct and ex ante budget balanced mechanism under which each bank reports its true borrowing cost.

The application for the analysis of equilibrium strategy goes beyond LIBOR fixing process. For a lot of financial contracts without liquid market, prices are usually determined by a trimmed average of players’ quotes. For instance, the daily closing price of many derivatives traded in the over-the-counter market, such as ABX, is formed in a similar manner. Baltic Dry Index is another example. This paper extends the theory literature by studying these price fixing practice.
Initial empirical calibration and estimation suggests LIBOR bias is significant. Similar to the general opinion among some bankers, the 1 Year USD LIBOR biases were -31 basis points and -50 basis points in the first and second half of 2008, respectively. In the first half of 2009 when the economy is deep into the recession, LIBOR bias spiked. When banking sector got stabilized in later 2009 and 2010, the LIBOR bias also got lower.
Bibliography


Appendix A

Off-Balance Sheet Financing and Bank Capital Regulation: Lessons from Asset-Backed Commercial Paper

Proof of Proposition 1

Proof. The bank equity holder has an option to shirk at the optimal time. The optimal shirking level \( y_\theta \) is determined by the smooth pasting of shirking value function \( E_s(y) \) and the value function of monitoring stage \( \bar{E}(y) \). Notice the \( \bar{E}(y) \) is different from the \( E(y) \) since the boundary conditions are different due to the smooth pasting. The \( y_\theta \) is determined together with two coefficients \( C_1 \) and \( C_2 \) such that

\[
V_m(y_\theta) - P + C_1 \frac{1}{1-\tau} \left( \frac{y_\theta}{y_b} \right)^{H_m} + C_2 \frac{1}{1-\tau} \left( \frac{y_\theta}{y_b} \right)^{H_m'}
\]

\[
= V_s(y_\theta) - P + (P - V_s(y_{bs})) \left( \frac{y_\theta}{y_{bs}} \right)^{H_s}
\]

and

\[
V_m(y_\theta) + C_1 \frac{1}{1-\tau} H_m \left( \frac{y_\theta}{y_b} \right)^{H_m} + C_2 \frac{1}{1-\tau} H'_m \left( \frac{y_\theta}{y_b} \right)^{H_m'}
\]

\[
= V_s(y_\theta) \left( 1 - \left( \frac{y_\theta}{y_{bs}} \right)^{H_s} \right) + H_s (P - V_s(y_{bs})) \left( \frac{y_\theta}{y_{bs}} \right)^{H_s}
\]

the singular boundary condition suggests that when the \( y \) is high, the bank equity holder’s value does not grow to infinity faster than \( y \). So \( \lim_{y \to \infty} E(y)/y < \infty \), or

\[
\lim_{y \to \infty} \frac{1-\tau}{r-\mu_m} + \frac{C_1}{y} \left( \frac{y}{y_b} \right)^{H_m} + \frac{C_2}{y} \left( \frac{y}{y_b} \right)^{H_m'} < \infty
\]
APPENDIX A. OFF-BALANCE SHEET FINANCING AND BANK CAPITAL REGULATION: LESSONS FROM ASSET-BACKED COMMERCIAL PAPER

which suggests \( C_2 = 0 \). Therefore I can solve for \( y_θ \) and \( C_1 \)

The credit guarantee ensures that the ABCP investor will always be able to collect the coupon payment, and have no credit risk even if the conduit defaulted. Therefore, the ABCP value function \( A^K (y) \) is

\[
ra^K (y) = kP_a + m (P_a - A^K (y)) \mathbf{1}_{\{A^K (y) < P_a\}} + \mu_m y \frac{\partial A^K (y)}{\partial y} + \frac{1}{2} \sigma_m^2 y^2 \frac{\partial^2 A^K (y)}{\partial y^2}
\]

with boundary value

\[
A^K (y_a) = P_a
\]

and since the maturity of ABCP is finite with probability 1, together with limited liability, I also have the boundary condition for \( A (y) \) at singular point \( y \to \infty \) as

\[
\lim_{y \to \infty} |A^K (y)| < +\infty.
\]

Since the ABCP with a credit guarantee is a riskless investment, the par coupon, by non-arbitrage, has to be \( r \). Therefore, ODE becomes

\[
(r - m \mathbf{1}_{\{A^K (y) < P_a\}}) (A^K (y) - P_a) = \mu_m y \frac{\partial A^K (y)}{\partial y} + \frac{1}{2} \sigma_m^2 y^2 \frac{\partial^2 A^K (y)}{\partial y^2}.
\]

It is easy to see this ODE has a unique solution \( A^K (y) = P_a \). So the ABCP under a credit guarantee is riskless, same as the deposits.

The value function of rollover in the credit guarantee satisfies

\[
ra^K (y) = kP_a + m (P_a - A^K (y)) \mathbf{1}_{\{A^K (y) < P_a\}} + \mu_m y \frac{\partial A^K (y)}{\partial y} + \frac{1}{2} \sigma_m^2 y^2 \frac{\partial^2 A^K (y)}{\partial y^2}
\]

which leads to cashflow to bank in each period

\[
m [A^K (y) - P_a] = 0
\]

so the rollover value \( K_r (y) = 0 \) for all \( y \). In other words, since \( A^K (y) = P_a \), the rollover is riskless, and the rollover frequency \( m \) does not change the value of the rollover part of credit guarantee either, so \( m \) is irrelevant.

The value function of credit protection part of credit guarantee \( K_w (y) \) satisfies

\[
rK_w (y) = \mu_m y \frac{\partial K_w (y)}{\partial y} + \frac{1}{2} \sigma_m^2 y^2 \frac{\partial^2 K_w (y)}{\partial y^2}
\]

with a boundary condition such that at the stopping time \( \nu = \inf \{ t : y_t < y_a \} \), the bank consolidates the ABCP conduit and compensates the ABCP creditors \( P_a \).

\[
K_w (y_a) = -P_a + SV_m (y_a)
\]
When $y \to \infty$, the probability of having $y$ hits $y_a$ and the ABCP conduit consolidation converges to zero: so
\[
\lim_{y \to \infty} K_w(y) = 0.
\]

The solution is
\[
K_w(y) = (-P_a + SV_m(y_a)) \phi_m(y; y_a)
\]
hence the credit guarantee value function is
\[
K(y) = K_r(y) + K_w(y) = (-P_a + SV_m(y_a)) \phi_m(y; y_a).
\]

The rest of the derivation of ODEs and solutions follows standard practice as in Leland 1994. The fact that all the value functions do not depend on the maturity $m$ suggest that
\[
\square
\]

**Proof of Proposition 2**

Proof. Let’s start with the scenario that the project has lost monitoring, and the cashflow is $y > y_b$. Note the total value in the economy as $\Sigma_s(y)$ in this case, then
\[
\Sigma_s(y) = D(y) + A(y) + E(y) + S(y) + [\Sigma_s(y_b) - (1 - \alpha) V_s(y_b)] \phi_s(y; y_b)
\]
\[
= V_s(y) - \alpha V_s(y_b) \phi_s(y; y_b) + [\Sigma(y) - (1 - \alpha) V_s(y_b)] \phi_s(y; y_b),
\]
according to the value functions $D(y)$, $A(y)$, and $S(y)$ from Proposition 1.

Since the cashflow level in the economy is normalized to 1, it is easy to see that $\Sigma_s(y_b) = \frac{y_b}{y} \Sigma_s(y)$, and $V_s(y_b) = \frac{y_b}{y} V_s(y)$. Hence for any $y$,
\[
[\Sigma_s(y) - V_s(y)] \left[1 - \frac{y_b}{y} \phi_s(y; y_b)\right] = 0.
\]

Since $\frac{y_b}{y} \phi_s(y; y_b)$ does not equal to 1 for any $y$, $\Sigma_s(y) = V_s(y)$.

Now I check the case in which the project is in the monitored state since inception, and the current cashflow $y > y_\theta > y_b$. With the value functions $D(y)$, $A(y)$, $S(y)$, as well as $\Sigma_s(y)$,
\[
\Sigma(y) = D(y) + A(y) + E(y) + S(y) + [\Sigma_s(y_b) - (1 - \alpha) V_s(y_b)] \phi_m(y; y_\theta) \phi_s(y; y_b)
\]
\[
= D(y) + A(y) + E(y) + S(y) + \alpha V_s(y_b) \phi_m(y; y_\theta) \phi_s(y; y_b),
\]
since
\[
D(y) + A(y) + E(y) + S(y)
\]
\[
= (1 - \phi_m(y; y_\theta)) V_m(y) + \phi_m(y; y_\theta) V_s(y) - \alpha V_s(y_b) \phi_m(y; y_\theta) \phi_s(y_\theta; y_b)
\]
hence
\[ \Sigma(y) = V_m(y) + \phi_m(y; y_\theta) [V_m(y) - V_s(y)] \] for \( y_\theta > y_b \).

For the case in which the project is in the monitored state since inception, and the current cashflow \( y > y_b > y_\theta \), the bank will not shirk before \( y \) hits the default barrier. Shirking will not happen in this case, therefore, similar to \( \Sigma_s(y) \) above,
\[ \Sigma(y) = V_m(y) \] for \( y_\theta \leq y_b \).

\[ \square \]

**Proof of Proposition 3**

**Proof.** First, since the ABCP value function does not depend on the level of \( y_a \), it is the bank’s best interest to set \( y_a \) as low as possible. Therefore, in the equilibrium, the bank always choose \( y_a^* = y_b^* \).

I note \( \bar{E}(y; y_b^*) \) as the equity value function in which the equity holder’s shirking threshold \( y_\theta = y_b^* \). I have \( \bar{E}(y_b^*; y_b^*) = E_s(y_b^*; y_b^*) = 0 \) for any \( y_b^* \).

Now I check the domain \([y_b^*, y_b^* + \epsilon)\). I need to find the smallest \( y_b^* \) such that \( \bar{E}(y; y_b^*) \geq E_s(y; y_b^*) \) for all \( y \in [y_b^*, y_b^* + \epsilon) \). By smooth pasting, such \( y_b^* \) satisfies
\[
\lim_{y \to y_b^*} \frac{\partial \bar{E}(y; y_b^*)}{\partial y} - \frac{\partial E_s(y; y_b^*)}{\partial y} = 0
\]
which suggests
\[ y_b^* = \frac{P(H_m - H_s)}{(1 - H_s) / (r - \mu_s) - (1 - H_m) / (r - \mu_m)} \]
where \( P = P_a + P_d \).

Lemma 23 shows the equity value function under monitoring \( E_m(y; y_b^*) \geq E_s(y; y_b^*) \) for all \( y > y_b^* \). Therefore, when \( y > y_b^* \), there is no shirking region.

To see why \( y_b^* \) is the smallest barrier, notice for any new default barrier \( y_b < y_b^* \), I still have \( E_m(y; y_b) = E_s(y; y_b) \), however for any \( y > y_b \),
\[ \lim_{y \to y_b} \frac{\partial E_m(y; y_b)}{\partial y} < \lim_{y \to y_b} \frac{\partial E_s(y; y_b)}{\partial y}, \]
so there exists some \( y \in [y_b^*, y_b^* + \epsilon) \) such that \( E_m(y; y_b) < E_s(y; y_b) \), so the bank will shirk.
APPENDIX A. OFF-BALANCE SHEET FINANCING AND BANK CAPITAL REGULATION: LESSONS FROM ASSET-BACKED COMMERCIAL PAPER

Consider the capital ratio defined as $\kappa = (V_i(y) - P) / V_i(y)$, which is an increasing function of $y$. So $\kappa$ is lowest when the cashflow hits the default barrier $y_b^*$. The linearity between $y_b^*$ and $P$ suggests that the social planner can watch the capital ratio instead of the cashflow per se, and the minimum capital ratio to ensure bank monitoring is therefore,

$$\kappa^* = \frac{(-1 + H_s)(\mu_m - \mu_s)}{(H_m - H_s)(r - \mu_s)}.$$  

Given the bank’s total origination value $v(y; y_b)$, and use the REE default barrier $y_b^*$, first order condition with respect to $P$ gives us the optimal level of debt as

$$P^* = \frac{1 - \kappa^*}{r - \mu_m} \left( \frac{(1 - \kappa^*) \tau}{(1 - H_m)(\alpha - \kappa^* \tau)} \right)^{-\frac{1}{\tau m}}.$$  

Finally, since $y_b^*$ is higher than the endogenous default barrier $y^*$, the default barrier $y_b^*$ is binding in the equilibrium.\[1\]

**Lemma 23.** $\bar{E}(y; y_b^*) \geq E_s(y; y_b^*)$ for all $y > y_b^*$.

**Proof.** First, $\bar{E}(y; y_b^*) = E_m(y; y_b^*)$ for all $y > y_b^*$. Then check $\frac{y E_m(y; y_b^*) - y E_s(y; y_b^*)}{1 - \tau}$. I have

$$\begin{align*}
\frac{y E_m'(y; y_b^*) - y E_s'(y; y_b^*)}{1 - \tau} &= V_m(y) + PH_m \left( \frac{y}{y_b^*} \right)^{H_m} - V_s(y) \\
&\quad - PH_s \left( \frac{y}{y_b^*} \right)^{H_s} + V_s(y_b^*) H_s \left( \frac{y}{y_b^*} \right)^{H_s} \\
&\quad - [P - V_m(y_b^*)] H_m \left( \frac{y}{y_b^*} \right)^{H_m} - [P - V_s(y_b^*)] H_s \left( \frac{y}{y_b^*} \right)^{H_s}.
\end{align*}$$

\[1\] To see this, notice that

$$\begin{align*}
\frac{1}{y_b^*} \left( \frac{1 - H_m}{1 - H_s} \right) / (r - \mu_m) &= \frac{PH_m}{1 - H_m} / (1 - H_s) / (r - \mu_m) \\
&= \frac{1 - H_m}{1 - H_s} / (r - \mu_m) < \frac{1 - H_m}{1 - H_m} = \frac{1 - H_s}{1 - H_m} = \frac{-H_m}{H_m - H_s} = -1 < 1.
\end{align*}$$
Since the REE default barrier \( y_b^* \) suggests that
\[
P - V_m (y_b^*) \geq 0
\]
I have
\[
y E'_m (y; y_b^*) - y E'_s (y; y_b^*) \quad \frac{1 - \tau}{1 - \tau} \geq V_m (y) - V_s (y) + \left\{ [P - V_m (y_b^*)] H_m - [P - V_s (y_b^*)] H_s \right\} \left( \frac{y}{y_b^*} \right)^{H_s}
\]
because for all \( y > y_b^* \),
\[
0 < \left( \frac{y}{y_b^*} \right)^{H_m} < \left( \frac{y}{y_b^*} \right)^{H_s} < 1.
\]
Now since
\[
[P - V_m (y_b^*)] H_m - [P - V_s (y_b^*)] H_s
= PH_m - V_m (y_b^*) + V_m (y_b^*) (1 - H_m) - PH_s + V_s (y_b^*) - V_s (y_b^*) (1 - H_s)
= - (V_m (y_b^*) - V_s (y_b^*)) + PH_m - PH_s + [1 - H_m] V (y_b^*) - (1 - H_s) V_s (y_b^*)
= - (V_m (y_b^*) - V_s (y_b^*)) + PH_m - PH_s - PH_m + PH_s
= - (V_m (y_b^*) - V_s (y_b^*))
\]
therefore
\[
y E'_m (y; y_b^*) - y E'_s (y; y_b^*) \quad \frac{1 - \tau}{1 - \tau} \geq V_m (y) - V_s (y) - (V_m (y_b^*) - V_s (y_b^*)) \left( \frac{y}{y_b^*} \right)^{H_s}
\]
In other words, \( E'_m (y; y_b^*) > E'_s (y; y_b^*) \) for all \( y > y_b^* \). Therefore, the exogenous \( y_b^* \) makes sure \( E_m (y; y_b^*) > E_s (y; y_b^*) \) for all \( y > y_b^* \).

Proof of Proposition 6

Proof. Under monitoring, the ABCP creditor’s value function \( A (y) \) satisfies the ODE
\[
r A (y) = k P_a + m (P_a - A (y)) 1_{(A(y) < P_a)} + \mu m y \frac{\partial A (y)}{\partial y} + \frac{1}{2} \sigma^2 m y^2 \frac{\partial^2 A (y)}{\partial y^2}
\]
because the non-arbitrage condition suggests that the required return of ABCP equals the sum of the following terms. The first term is the ABCP coupon payment \( k P_a \). The second term is the value of maturity payoff as the difference between face value \( P_a \) and ABCP value \( A (y) \) multiplies the maturity intensity \( m \), controlled by the rollover condition \( A (y) < P_a \), since the sponsoring bank only steps in when the maturing ABCP investors are unwilling
to rollover. The third and fourth terms, similarly, capture the change of $A(y)$ with the fluctuation of underlying assets.

At the stopping time $\nu = \inf \{ t : y_t \leq y_a \}$, the continuity of geometric Brownian motion ensures $y_\nu = y_a$, and the bank’s reconsolidation covenant and the credit guarantee from the residual tranche determines the boundary condition as

$$A(y_a) = SV_m(y_a).$$

Since the maturity of ABCP is finite with probability 1, together with limited liability, I also have the boundary condition for $A(y)$ at singular point $y \to \infty$ as

$$\lim_{y \to \infty} |A(y)| < +\infty.$$

Following standard solution technique, I can get the value function of ABCP.

The residual tranche investor gets the residual of the pre-tax dividend $Sy_t$ after the ABCP coupon payment $kpSV_s(y_0)$. Similar non-arbitrage arguments lead to the following ODE for residual tranche value $R(y)$:

$$rR(y) = yS - kPa + \mu_s y \frac{\partial R(y)}{\partial y} + \frac{1}{2} \sigma^2_s y^2 \frac{\partial^2 R(y)}{\partial y^2}.$$

Since the residual tranche investor did not get any guarantee from the bank, she loses all the value when the conduit got consolidated at $y = y_a$. The boundary condition is therefore

$$R(y_a) = 0$$

In addition, with the underlying assets value approaches infinity, I have the boundary condition for $R(y)$ at the singular point as

$$\lim_{y \to \infty} \left| \frac{R(y)}{y} \right| < +\infty$$

Intuitively, when $y$ approaches infinity, the probability of having underlying asset $y$ hits $y_a$ within a finite period converges to zero. The residual tranche investor expects to receive $-yS + kPa$ until the liquidity shock happens. Given that $kPa$ is finite, the perpetuity paying $kPa$ also has finite present value, I know $K$ drops out in $R(y)/y$ when $y$ approaches infinity. Therefore, the value $R(y)$ is proportional to $y$ when $y \to \infty$. $\Box$
Proof of Proposition 7

Proof. The liquidity guarantee $L(y)$ contains two parts: the first part is the rollover support, and the second is the conduit consolidation covenant. The rollover support value function $L_r(y)$ satisfies ODE

$$rL_r(y) = m[A(y) - P_a]1_{\{A(y) < P_a\}} + \mu_m y \frac{\partial L_r(y)}{\partial y} + \frac{1}{2} \sigma^2 m y^2 \frac{\partial^2 L_r(y)}{\partial y^2}$$

with a boundary condition motivated by the fact that the liquidity guarantee at stopping time $\nu = \inf \{t : y_t < y_a\}$ leads to the bank consolidating the conduit and compensates the ABCP creditors $y_a$. Since the rollover operation involves the payoff of maturing commercial paper and origination of new commercial paper, the difference between the two cashflows is not taxed. The rollover stops when the conduit ceases to exist, so $L_r(y_a) = 0$.

Furthermore, since upon $y \to \infty$, $A(y) = \frac{k + m}{m + r} P_a$ is finite, the bank only makes finite amount of profit when ABCP creditors rollover, and the probability of having $y$ hit $y_a$ and the conduit consolidation converges to zero, so the value of liquidity guarantee is finite. Therefore, I have the second boundary condition

$$\lim_{y \to \infty} \frac{L_r(y)}{y} = 0.$$

Solving this ODE is not trivial due to $A(y)$. However, with proper substitution of variables and a Laplace transform, I can still obtain the solution.

Since $L_w(y) = 0$ for all $y$, I have $L(y) = L_r(y)$.

On the other hand, in order to show the convergence of the liquidity guarantee value function to the credit guarantee value function, I only need to check the difference between the value functions for the liquidity guarantee and the credit guarantee. Let $\delta(y) = L(y) - K(y)$ be the difference. Then

$$r\delta(y) = m[A(y) - P_a]1_{\{A(y) < P_a\}} + \mu_m y \frac{\partial \delta(y)}{\partial y} + \frac{1}{2} \sigma^2 m y^2 \frac{\partial^2 \delta(y)}{\partial y^2}$$

with boundary condition

$$\lim_{y \to \infty} \frac{\delta(y)}{y} = 0$$

and

$$\delta(y_a) = L(y_a) - K(y_a) = P_a - SV_m(y_a).$$

When the bank issues shorter maturity ABCP, $m$ goes up, and the riskiness of ABCP goes down, since it is less and less likely to have $y$ hit $y_a$ before the ABCP matures. To see
this, notice $\phi_a$, the state price of having $\$1$ payoff upon the state that $y$ hits $y_a$ before ABCP matures, becomes zero when $m$ goes up

$$
\lim_{m \to \infty} G_s = \infty \\
\lim_{m \to \infty} G'_s = 0
$$

therefore

$$
\lim_{m \to \infty} \phi_s (y; y_a) = \lim_{m \to \infty} \left( \frac{y}{y_a} \right)^{G_s} = 0 \\
\lim_{m \to \infty} \phi'_s (y; y_a) = \lim_{m \to \infty} \left( \frac{y}{y_a} \right)^{G'_s} = \infty.
$$

However since $A_L (y)$ is bounded, I have $C_L = 0$. So $\lim_{m \to \infty} A_L (y) = P_a$ with $A_H (y_0) = A_L (y_0)$, I have

$$
\lim_{m \to \infty} A_L (y_0) = \lim_{m \to \infty} A_H (y_0)
$$

and the value of ABCP is a constant

$$
\lim_{m \to \infty} A (y) = P_a
$$

for any $y > y_a$, except at $y = y_a$, I have $A (y_a) = SV_m (y_a)$.

What about $m [A (y) - pSV_s (y_0)]$ then? Let

$$
B (y) = m [A (y) - P_a]
$$

so

$$
A (y) = \frac{1}{m} B (y) + pSV_s (y_0)
$$

then

$$
(r + m 1_{\{B (y) < 0\}}) B (y) = (k - r) m P_a + \mu_m y \frac{\partial B (y)}{\partial y} + \frac{1}{2} \sigma^2_m y^2 \frac{\partial^2 B (y)}{\partial y^2}
$$

when $m \to \infty$, I can ignore the term $\mu_m y \frac{\partial B (y)}{\partial y} + \frac{1}{2} \sigma^2_m y^2 \frac{\partial^2 B (y)}{\partial y^2}$, and the ODE becomes

$$
(r + m 1_{\{B (y) < 0\}}) B (y) = (k - r) m P_a
$$

and therefore

$$
B (y) = \frac{(k - r) m}{r + m} pSV_s (y_0)
$$

for any $y > y_a$.

However since when $m \to \infty$, $k \to r$, therefore $\lim_{m \to \infty} B (y) \to 0$ for any $y > y_a$, but $\lim_{m \to \infty} B (y_a) = m [SV_m (y_a) - P_a] \to -\infty.$
APPENDIX A. OFF-BALANCE SHEET FINANCING AND BANK CAPITAL
REGULATION: LESSONS FROM ASSET-BACKED COMMERCIAL PAPER

The ODE for \( \hat{\delta} (y) = \lim_{m \to \infty} \delta (y) \) becomes
\[
r \hat{\delta} (y) = B (y) + \mu_s y \frac{\partial \hat{\delta} (y)}{\partial y} + \frac{1}{2} \sigma_s^2 y^2 \frac{\partial^2 \hat{\delta} (y)}{\partial y^2}
\]
where \( B (y) \) is a step function, and the ODE has boundary condition
\[
\lim_{y \to \infty} \hat{\delta} (y) = 0
\]
\[
\hat{\delta} (y_a) = P_a - SV_m (y_a).
\]

The solution is
\[
\hat{\delta} (y) = 0
\]
for any \( y > y_a \). In other words, the value function of the liquidity guarantee and the credit
guarantee is the same when the ABCP conduit is funded using commercial paper with short
maturity.

\[ \square \]

Proof of Proposition 8

Proof. Notice that the liquidity guarantee value function has a negative value when \( y \) approaches \( y_a \). This may or may not create a saddle in the bank’s equity value function. When
the parameters \( m \) or \( S \) are still big enough to create a saddle on the bank’s equity value function, using the smooth pasting rule, I know that the optimal level of \( y_a^+ \), which determines
the conduit capital structure at \( t = 0 \), causes the value function of bank equity to ‘paste’
with the value zero when the bank suffers the most from providing the liquidity guarantee.
Otherwise the bank can always lower \( y_a^+ \) a bit further to increase the leverage and therefore
the total origination value. In this case, \( y_a^+ > y_b^+ \).

When the fraction of ABCP \( S \) or the inverse of maturity \( m \) becomes very small, the
equity value function has
\[
\frac{\partial}{\partial y} \tilde{E} (y; y_b^+) = (1 - S) E_m (y; y_b^+) + L (y; y_b^+) > 0
\]
when \( y \to y_b^+ \), I will have the bank set \( y_a^+ = y_b^+ \) to maximize the leverage and total origination value.

For the first case, when the maturity becomes shorter after the origination, the value of
liquidity guarantee will drop and the smooth pasting condition will not hold. In other words,
the equity value function will become negative. For the second case, I check the derivative
of liquidity guarantee when the maturity $m \to \infty$, and $y$ approaching the default barrier $y_b$. With a little abuse of notation I note this derivative as $\lim_{y \to y_b} \frac{\partial}{\partial y} L_m(y)$. So

$$
\lim_{y \to y_b} \frac{\partial}{\partial y} L_m(y) = \lim_{y \to y_b} \left[ -1 + \frac{(G_m - \bar{G}_m) y_b^{\bar{G}_m}}{(H_m - \bar{G}_m) y_b^{G_m} + (G_m - H_m) y_b^{\bar{G}_m}} \right]
\frac{(G_m - H_m) (SV_m(y_b) - P_a)}{y_b}.
$$

Notice that

$$
\lim_{y \to y_b} G_m = -\infty,
\lim_{y \to y_b} \bar{G}_m = +\infty,
\lim_{y \to y_b} \bar{G}_m y_b^{G_m} = 0
$$

hence

$$
\lim_{y \to y_b} \frac{(G_m - G_m) y_b^{\bar{G}_m}}{(H_m - \bar{G}_m) y_b^{G_m} + (G_m - H_m) y_b^{\bar{G}_m}} = 0,
$$

with $SV_m(y_b) - P_a < 0$, 

$$
\lim_{y \to y_b} \frac{\partial}{\partial y} L_m(y) = \lim_{y \to y_b} \frac{(G_m - H_m) (SV_m(y_b) - P_a)}{y_b} = -\infty.
$$

This means that if $y_a^+ = y_b^+$, then there exists some $\delta$ such that the equity value of the bank becomes negative when $y \in (y_b^+, y_b^+ + \delta)$. \qed
Appendix B

LIBOR’s Poker: Discover Interbank Borrowing Costs Amid Banks’ Strategic Behavior

Proofs

Proof of Proposition 10

Proof. The single crossing property holds thanks to the supermodularity condition. In addition, \( E[\Pi(s_i, b_i', B_{-i}^*)] \) exists since for any realization of \( B_{-i} \), \( \Pi(s_i, b_i', B_{-i}^*) \) exists and is bounded: therefore the A1 assumption in Athey (2001) also holds. Therefore, by Theorem 1 of Athey (2001), for any finite type space \( \Theta' \subset \Theta \), there is a pure strategy Nash equilibrium in nondecreasing strategies.

Now let me extend the proof to the continuum type space \( \Theta \). Since (i) for all bank \( i \), \( \Theta = [0, S] \), and (ii) for all bank \( i \), \( E[L(b_i, B_{-i})] \) is continuous in \( b_i \), so does \( \Pi(s_i, b_i, B_{-i}) \). Together with the existence of pure strategy Nash equilibrium in nondecreasing strategies in any finite type space \( \Theta' \), the Theorem 2 of Athey (2001) suggests the existence of pure strategy Nash equilibrium in nondecreasing strategies in continuum type space \( \Theta \).

Proof of Proposition 11

Proof. Using monotone selection theorem in Milgrom and Shannon (1994), an alternative for Topkis’ theorem when supermodularity, aka, the strictly increasing difference (SID) holds. The function satisfies SID since given \( s_i < s_i' \), and \( b_i < b_i' \), we have \( \Pi(s_i, b_i', B_{-i}^*) - \Pi(s_i, b_i, B_{-i}^*) > \Pi(s_i', b_i', B_{-i}^*) - \Pi(s_i, b_i, B_{-i}^*) \). Then for \( b_i^* \in \beta(s') = \arg \max_{b_i} \Pi(s_i', b_i, B_{-i}^*) \), and \( b_i^* \in \beta(s) \), monotone selection theorem says \( b_i^* \leq b_i'^* \).
Proof of Lemma 12

Proof. First, \( \{ B_{n+1}^{(N-1)}, \ldots, B_{N-1-n}^{(N-1)} \} \) are always in the calculation of LIBOR, regardless the choice of \( b_i \). With the CDF of \( n \)th order statistics of \( N-1 \) quotes as \( G_{j}^{(N-1)}(x) \equiv \Pr \{ B_{j}^{(N-1)} \leq x \} \). When the CDF \( G(x) \) is absolute continuous, \( G_{j}^{(N-1)}(x) \) is also absolute continuous, therefore PDF \( g_{j}^{(N-1)}(x) \) exists and we can write

\[
\mathbb{E} [L(b_i, B_{-i}) | I_i] = r_f \frac{1}{N-2n} \sum_{j=n+1}^{N-1} \mathbb{E} [B_{j}^{(N-1)}] + \frac{1}{N-2n} \int_{b_i}^{b_i}\! x g_{n}^{(N-1)}(x) dx + \frac{1}{N-2n} \int_{b_i}^{b_i}\! x g_{N-n}^{(N-1)}(x) dx + \frac{1}{N-2n} b_i \left[ 1 - \int_{b_i}^{b_i}\! g_{n}^{(N-1)}(x) dx - \int_{0}^{b_i}\! g_{N-n}^{(N-1)}(x) dx \right]
\]

(B.1)

It is easy to show \( \mathbb{E} [L(b_i, B_{-i}) | I_i] \) is once and twice differentiable in \( b_i \), since \( g_{j}^{(N-1)}(x) \) is continuous. In addition,

\[
\frac{\partial}{\partial b_i} \mathbb{E} [L(b_i, B_{-i}) | I_i] = \frac{1}{N-2n} \left[ 1 - \int_{b_i}^{b_i}\! g_{n}^{(N-1)}(x) dx - \int_{0}^{b_i}\! g_{N-n}^{(N-1)}(x) dx \right] = \frac{1}{N-2n} \left[ G_{n}^{(N-1)}(b_i) - G_{N-n}^{(N-1)}(b_i) \right]
\]

Proof of Theorem 13

Proof. Given \( \beta(S) \) is strictly increasing, banks’ submissions maintain the same order as its own realization of borrowing cost \( B_i^{(N)} = \beta \left( S_i^{(N)} \right) \ \forall i \in \{1, \ldots, N\} \). Hence instead of working with the CDF of \( n \)th order statistics of \( N-1 \) submissions as \( G_{j}^{(N-1)}(x) \equiv \Pr \{ B_{j}^{(N-1)} \leq x \} \), I can focus on the realization of borrowing cost \( S \) among banks. Write the CDF of \( j \)th order statistic of \( N-1 \) realization of \( S \) as \( F_{j}^{(N-1)}(x) \equiv \Pr \{ S_{j}^{(N-1)} \leq x \} \). Strictly increasing \( \beta(s) \) suggests \( G_{j}^{(N-1)}(\beta(s)) = F_{j}^{(N-1)}(s) \), as well as the PDFs \( g_{j}^{(N-1)}(\beta(s)) = f_{j}^{(N-1)}(s) \).
Therefore, for bank $i$ with borrowing cost as $r_f + s$, and submitting $b$, replace the $g_j^{(N-1)} (\cdot)$ with $f_j^{(N-1)} (\cdot)$ in equation B.1 yields

$$
\mathbb{E} [L(b, B_{-i}) | I_i] = r_f + \frac{1}{N-2n} \sum_{j=n+1}^{N-1-n} \mathbb{E} [B_j^{(N-1)}] + \frac{1}{N-2n} \int_{\beta^{-1}(b)}^{s} \beta(t) f_n^{(N-1)}(t) \, dt + \frac{1}{N-2n} \int_{0}^{\beta^{-1}(b)} \beta(t) f_{N-n}^{(N-1)}(t) \, dt + \frac{1}{N-2n} b_i \left[ 1 - \int_{\beta^{-1}(b)}^{s} f_n^{(N-1)}(t) \, dt - \int_{0}^{\beta^{-1}(b)} f_{N-n}^{(N-1)}(t) \, dt \right]
$$

Since $\mathbb{E} [L(b, B_{-i})]$ is twice differentiable in $b$,

$$
\frac{\partial}{\partial b} \mathbb{E} [L(b, B_{-i}) | I_i] = \frac{1}{N-2n} \left[ F_n^{(N-1)}(\beta^{-1}(b)) - F_{N-n}^{(N-1)}(\beta^{-1}(b)) \right]
$$

Let's get back to the bank's expected payoff $\mathbb{E} [\Pi (s, b, B_{-i})]$. FOC of suggests

$$
\beta^* (s) = s - \frac{\delta}{2\gamma (N-2n)} \left[ F_n^{(N-1)}(s) - F_{N-n}^{(N-1)}(s) \right]
$$

By the property of order statistics, $F_n^{(N-1)}(s) - F_{N-n}^{(N-1)}(s) \geq 0$, therefore

$$
\beta (s) = s - \frac{\delta}{2\gamma (N-2n)} \left[ F_n^{(N-1)}(s) - F_{N-n}^{(N-1)}(s) \right] \leq s
$$

the best response is to weakly lower than the actual borrowing cost, and $\beta (0) = 0$ regardless of the distribution of borrowing cost $S$.

Plug in the order statistics:

$$
\beta^* (s) = s - \frac{\delta \Gamma(N)}{2\gamma (N-2n) \Gamma(n) \Gamma(N-n)} \int_{0}^{F(s)} \frac{(1-y)^{N-2n} - y^{N-2n}}{[y(1-y)]^{1-n}} \, dy
$$

notice here I have not assumed the distribution of $S$.

Let’s now look at the case in which monotonicity constraint is binding.
Proof of Lemma 14

Proof. In this case, CDF $G(x)$ is RCLL, and is continuous everywhere except at $\bar{b}$. In this case, CDF $G_j^{(N-1)}(x)$ is also RCLL, and is continuous everywhere except at $\bar{b}$. Define

$$
\hat{g}_j^{(N-1)}(x) = \begin{cases} 
\frac{\partial}{\partial x} G_j^{(N-1)}(x) & x \neq \bar{b} \\
0 & x = \bar{b}
\end{cases}
$$

Suppose that $\Pr \{ B_j^{(N-1)} = \bar{b} \} = p_j = 1 - \int_{x \neq \bar{b}} \hat{g}_j^{(N-1)}(x) \, dx$. Using Dirac function $\delta$, the PDF is

$$
g_j^{(N-1)}(x) = p_j \delta(x - \bar{b}) + \hat{g}_j^{(N-1)}(x)
$$

In this case, we can write $\mathbb{E} [L(b_i, B_{-i})]$ similarly as [B.1] and we know it is twice differentiable when $b_i \neq \bar{b}$.

While for $b_i = \bar{b} + \varepsilon$, and $\varepsilon \downarrow 0$, we have

$$
\lim_{\varepsilon \downarrow 0} \frac{\mathbb{E} [L(\bar{b} + \varepsilon, B_{-i}) | \mathcal{I}_i] - \mathbb{E} [L(\bar{b}, B_{-i}) | \mathcal{I}_i]}{\varepsilon} = \frac{1}{N - 2n} \left[ 1 - \int_0^\bar{b} \hat{g}_n^{(N-1)}(x) \, dx - \left( \int_0^\bar{b} \hat{g}_N^{(N-1)}(x) \, dx + p_{N-n} \right) \right]
$$

$$
= \frac{1}{N - 2n} \left[ \left( \int_0^\bar{b} \hat{g}_n^{(N-1)}(x) \, dx + p_n \right) - \left( \int_0^\bar{b} \hat{g}_N^{(N-1)}(x) \, dx + p_{N-n} \right) \right]
$$

$$
= \frac{1}{N - 2n} \left[ G_n^{(N-1)}(\bar{b}) - G_N^{(N-1)}(\bar{b}) \right]
$$

at the same time

$$
\lim_{\varepsilon \downarrow 0} \mathbb{E} [L(\bar{b} + \varepsilon, B_{-i}) | \mathcal{I}_i] = \mathbb{E} [L(\bar{b}, B_{-i}) | \mathcal{I}_i]
$$

and

$$
\lim_{\varepsilon \downarrow 0} \frac{\mathbb{E} [L(\bar{b}, B_{-i}) | \mathcal{I}_i] - \mathbb{E} [L(\bar{b} + \varepsilon, B_{-i}) | \mathcal{I}_i]}{\varepsilon} = \frac{1}{N - 2n} \left[ 1 - \left( \int_\bar{b}^{\bar{b} + \varepsilon} \hat{g}_n^{(N-1)}(x) \, dx + p_n \right) - \int_\bar{b}^{\bar{b} + \varepsilon} \hat{g}_N^{(N-1)}(x) \, dx \right]
$$

$$
= \frac{1}{N - 2n} \left[ G_n^{(N-1)}(\bar{b} + \varepsilon) - G_N^{(N-1)}(\bar{b} + \varepsilon) - (p_n - p_{N-n}) \right]
$$

$$
= \frac{1}{N - 2n} \left[ G_n^{(N-1)}(\bar{b}+) - G_N^{(N-1)}(\bar{b}+) \right]
$$
hence we have showed that at $\bar{b}$, $\mathbb{E} [L (b_i, B_{-i}) | I_i]$ is continuous and $\frac{\partial}{\partial b_i} \mathbb{E} [L (b_i, B_{-i}) | I_i]$ is RCLL.

Before working on the equilibrium strategy under monotonicity constraint, let’s look at the relationship between the $j$th order statistic CDF of borrowing cost $F_j^{(N-1)} (\cdot)$, and that of banks’ submissions $G_j^{(N-1)} (\cdot)$.

Corollary 24. For any borrowing cost $s$ such that the monotonicity constraint is not binding, there is a one-to-one mapping between the CDF of borrowing cost $F (\cdot)$ to the CDF of submissions $G (\cdot)$. Similarly, there is a one-to-one mapping between the $j$th order statistic CDF of borrowing cost $F_j^{(N-1)} (\cdot)$ to that of submissions $G_j^{(N-1)} (\cdot)$.

Notice in the proof of previous theorem, we need the strict monotonicity of $\beta (s)$ to get a one-to-one mapping from the CDF of borrowing cost $F (\cdot)$ to the CDF of submissions $G (\cdot)$. The introcution of region $\theta$ in which the monotone constraint is binding make the one-to-one mapping not holding everywhere. However, we still have, as shown in Figure 2.2 $G (\beta (s)) = \Pr \{ \beta (s) \leq \beta (s) \} = \Pr \{ x \leq s \} = F (s)$, for the area $\Theta \setminus [s_1, s_2]$. I can proceed to the proof of Theorem 15.

Proof of Theorem 15

Proof. The constrained problem is to find $\beta (\cdot)$, using its derivative $\mu (\cdot)$ as a constrained control, such that

$$\max_{\beta} \int_0^s \left\{ \delta \left[ \bar{S} - \mathbb{E} [L (\beta (s_i), B_{-i}) | I_i] \right] - \gamma (s_i - \beta (s_i))^2 \right\} f (s_i) ds_i \text{ s.t. } \partial \beta (s_i) / \partial s_i$$

$$\mu (s_i) \geq 0$$

By [Gelfand and Fomin 1963], with the continuity proved in Lemma 14, the Hamiltonian is

$$\mathcal{H} (s_i, \beta (s_i), \lambda (s_i), \mu (s_i)) = \left\{ \delta \left[ \bar{S} - \mathbb{E} [L (\beta (s_i), B_{-i}) | I_i] \right] - \gamma (s_i - \beta (s_i))^2 \right\} f (s_i) + \lambda (s_i)$$

and Pontryagin’s principle suggests an optimum $\beta^* (s)$ and $\mu^* (s)$ satisfies

$$\mathcal{H} (s_i, \beta^* (s_i), \lambda (s_i), \mu^* (s_i)) \geq \mathcal{H} (s_i, \beta (s_i), \lambda (s_i), \mu (s_i))$$
and in the region that derivative exists,
\[
\frac{\partial \lambda(s_i)}{\partial s_i} = - \frac{\partial \mathcal{H}(s_i, \beta(s_i), \lambda(s_i), \mu(s_i))}{\partial \beta(s_i)}
\]

From complementary slackness, when constraint is not binding, we have \( \lambda(s_i) = 0 \), so \( \frac{\partial \lambda(s_i)}{\partial s_i} = 0 \). Therefore, for \( s \not\in \Theta \), the FOC is same as before:
\[
\beta^*(s) = s - \frac{\delta}{2 \gamma (N - 2n)} \left[ G_{n}^{(N-1)}(\beta^*(s)) - G_{N-n}^{(N-1)}(\beta^*(s)) \right]
\]

From the Corollary 24, for \( s \in \Theta \setminus \theta \), there is a one-to-one mapping from \( F(s) \) to \( G(\beta(s)) \), therefore,
\[
\beta^*(s) = s - \frac{\delta}{2 \gamma (N - 2n)} \left[ F_{n}^{(N-1)}(s) - F_{N-n}^{(N-1)}(s) \right] \quad \forall s \in \Theta \setminus \theta
\]
which is same as the unconstrained optimization problem.

We now prove \( \beta^*(s) \) is continuous. It is straightforward to see \( \beta^*(s) \) is continuous when \( s \in (\bar{\theta}, \bar{\theta}) \), as well as \( s \in [0, \bar{\theta}) \cup (\bar{\theta}, \bar{s}] \). The continuity of Hamiltonian \( \mathcal{H}(s_i, \beta^*(s_i), \lambda(s_i), \mu^*(s_i)) \) as well as the costate variable \( \lambda(s_i) \) when \( s = \{\bar{\theta}, \bar{\theta}\} \) suggests \( \beta^*(s_i) \) is also continuous at point \( \bar{\theta} \) and \( \bar{\theta} \).

We now focus on how to determine \( \bar{b} \), as shown in Figure 2.2. The continuity of \( \beta(\cdot) \) together with the constraint suggests that \( \beta^*(\bar{\theta}) = \beta^*(\bar{\theta}) = \bar{b} \), the bunching level. In order to determine the bunching level \( \bar{b} \), we write
\[
J(\bar{b}) = \int_{0}^{\bar{\theta}} \left\{ \delta \left[ \bar{S} - \mathbb{E}[L(\beta^*(s_i), B_{-i}) | \mathcal{I}_i] \right] - \gamma (s_i - \beta^*(s_i))^2 \right\} f(s_i) ds_i \\
+ \int_{\bar{\theta}}^{\bar{s}} \left\{ \delta \left[ \bar{S} - \mathbb{E}[L(\bar{b}, B_{-i}) | \mathcal{I}_i] \right] - \gamma (s_i - \bar{b})^2 \right\} f(s_i) ds_i \\
+ \int_{\bar{s}}^{\bar{s}} \left\{ \delta \left[ \bar{S} - \mathbb{E}[L(\beta^*(s_i), B_{-i}) | \mathcal{I}_i] \right] - \gamma (s_i - \beta^*(s_i))^2 \right\} f(s_i) ds_i
\]
in which \( \{\underline{\theta}, \bar{\theta}\} \) are the minimum and maximum value of \( \beta^{*-1}(\bar{b}) \). If \( \bar{b} \) is indeed the optimal bunching level, varying the level should not change \( J(\bar{b}) \) in the first order. Therefore FOC suggests
\[
\frac{\partial}{\partial \bar{b}} J(\bar{b}) = 0
\]
which can be used to solve for \( \bar{b} \). \( \Box \)
Proof of Theorem 16

Proof. Recall

\[ \frac{\partial}{\partial b} \mathbb{E} [L(b, B_{-1}) | I_i] = \frac{1}{N - 2n} \left[ F^{(N-1)}_n (\beta^{-1}(b)) - F^{(N-1)}_{N-n} (\beta^{-1}(b)) \right] \]

and \( \beta(S) \) leads to \( G^{(N-1)}_j (\beta(s)) = F^{(N-1)}_j (s) \), as well as the PDFs \( g^{(N-1)}_j (\beta(s)) = f^{(N-1)}_j (s) \).

Therefore the FOC of the expected payoff \( \mathbb{E} [\Pi (s, b, B_{-1})] \) suggests

\[ \beta^*(s) = s - \Delta - \frac{1}{\eta} W \left( \frac{\rho \phi \eta^2}{2 \gamma} \exp \{ \eta (s - \Delta) \} \right) \]

where

\[ \Delta = \frac{\delta}{2 \gamma (N - 2n)} \left[ F^{(N-1)}_n (s) - F^{(N-1)}_{N-n} (s) \right] \]

\[ = \frac{\delta}{2 \gamma (N - 2n) \Gamma (N) \Gamma (N - n)} \int_0^{F(s)} (1 - y)^{N-2n} - y^{N-2n} [y (1 - y)]^{1-n} dy \]

Consider

\[ \frac{\partial}{\partial s} \beta^*(s) = 1 - \frac{\partial}{\partial s} \Delta - \frac{1}{\eta} W' \left( \frac{\rho \phi \eta^2}{2 \gamma} \exp \{ \eta (s - \Delta) \} \right) \frac{\rho \phi \eta^2}{2 \gamma} \exp \{ \eta (s - \Delta) \} \eta \left( 1 - \frac{\partial}{\partial s} \Delta \right) \]

\[ = 1 - \frac{\partial}{\partial s} \Delta - \frac{W \left( \frac{\rho \phi \eta^2}{2 \gamma} \exp \{ \eta (s - \Delta) \} \right)}{1 + W \left( \frac{\rho \phi \eta^2}{2 \gamma} \exp \{ \eta (s - \Delta) \} \right)} \left( 1 - \frac{\partial}{\partial s} \Delta \right) \]

\[ = \frac{1}{1 + W \left( \frac{\rho \phi \eta^2}{2 \gamma} \exp \{ \eta (s - \Delta) \} \right)} \left( 1 - \frac{\partial}{\partial s} \Delta \right) \]

Since \( \frac{\rho \phi \eta^2}{2 \gamma} \exp \{ \eta (s - \Delta) \} > 0 \), by the property of Lambert-W function \( W (\cdot) > 0 \). Hence \( \frac{\partial}{\partial s} \beta^*(s) > 0 \) iff \( 1 - \frac{\partial}{\partial s} \Delta > 0 \). Therefore, the same monotonicity condition

\[ \max_{s \in \Theta} \left[ \tilde{f}^{(N-1)}_n (s) - \tilde{f}^{(N-1)}_{N-n} (s) \right] \geq - (N - 2n) \frac{2 \gamma}{\delta} \]

will ensure the equilibrium strategy with signaling is also strictly increasing. \( \square \)
APPENDIX B. LIBOR’S POKER: DISCOVER INTERBANK BORROWING COSTS AMID BANKS’ STRATEGIC BEHAVIOR

Proof of Theorem 17

Proof. Similar to the previous proof, the constrained problem is to find $\beta(\cdot)$, using its derivative $\mu(\cdot)$ as a constrained control, such that

$$\max_{\beta} \int_0^s \left\{ \delta \left[ \bar{S} - \mathbb{E} [L(\beta(s_i), B_{-i}) | I_i] \right] - \gamma (s_i - \beta(s_i))^2 - \rho \exp \{\eta b_i\} \right\} f(s_i) \, ds_i$$

s.t.

$$\frac{\partial \beta(s_i)}{\partial s_i} = \mu(s_i) \geq 0$$

By Gelfand and Fomin [1963], with the continuity proved in Lemma 14, the Hamiltonian is

$$H(s_i, \beta(s_i), \lambda(s_i), \mu(s_i)) = \left\{ \delta \left[ \bar{S} - \mathbb{E} [L(\beta(s_i), B_{-i}) | I_i] \right] - \gamma (s_i - \beta(s_i))^2 - \rho \exp \{\eta b_i\} \right\} f(s_i) + \lambda(s_i)$$

and Pontryagin’s principle suggests an optimum $\beta^*(s)$ and $\mu^*(s_i)$ satisfies

$$H(s_i, \beta^*(s_i), \lambda(s_i), \mu^*(s_i)) \geq H(s_i, \beta(s_i), \lambda(s_i), \mu(s_i))$$

and in the region that derivative exists,

$$\frac{\partial \lambda(s_i)}{\partial s_i} = -\frac{\partial H(s_i, \beta(s_i), \lambda(s_i), \mu(s_i))}{\partial \beta(s_i)}$$

From complementary slackness, when constraint is not binding, we have $\lambda(s_i) = 0$, so $\partial \lambda(s_i) / \partial s_i = 0$. Therefore, for $s \notin \Theta$, the FOC is same as before:

$$\beta^*(s) = s - \Delta - \frac{1}{\eta} W \left( \frac{\rho \phi \eta^2}{2 \gamma} \exp \{\eta (s - \Delta)\} \right)$$

where

$$\Delta = \frac{\delta}{2 \gamma (N - 2n)} \left[ G^{(N-1)}_{\beta^*(s)} - G^{(N-1)}_{\beta^*(s)} \right]$$

From the Corollary 24, for $s \in \Theta \setminus \theta$, there is a one-to-one mapping from $F(s)$ to $G(\beta(s))$, therefore,

$$\beta^*(s) = s - \Delta - \frac{1}{\eta} W \left( \frac{\rho \phi \eta^2}{2 \gamma} \exp \{\eta (s - \Delta)\} \right)$$
where
\[
\Delta = \frac{1}{2\gamma(N-2n)} \left[ F_n^{(N-1)}(s) - F_{N-n}^{(N-1)}(s) \right]
\]
which is same as the unconstrained optimization problem.

Similarly, \( \beta^*(s) \) is continuous. It is straightforward to see \( \beta^*(s) \) is continuous when \( s \in (\bar{\theta}, \bar{\theta}) \), as well as \( s \in [0, \bar{\theta}) \cup (\bar{\theta}, \bar{s}] \). The continuity of Hamiltonian \( H(s_i, \beta^*(s_i), \lambda(s_i), \mu^*(s_i)) \) as well as the costate variable \( \lambda(s_i) \) when \( s = \{\bar{\theta}, \bar{\theta}\} \) suggests \( \beta^*(s_i) \) is also continuous at point \( \bar{\theta} \) and \( \bar{\theta} \).

To determine \( \bar{b} \), as shown in Figure 2.2, Notice the continuity of \( \beta(\cdot) \) together with the constraint suggests that \( \beta^*(\bar{\theta}) = \beta^*(\bar{\theta}) = \bar{b} \), the bunching level. So

\[
J(\bar{b}) = \int_{\bar{\theta}}^{\bar{b}} \left\{ \delta \left[ \bar{S} - \mathbb{E} [L(\beta^*(s_i), B_{-i}) | I_i] \right] - \gamma (s_i - \beta^*(s_i))^2 - \rho \exp \{ \eta b_i \} \right\} f(s_i) \, ds_i
\]
\[
+ \int_{\bar{\theta}}^{\theta} \left\{ \delta \left[ \bar{S} - \mathbb{E} [L(\bar{b}, B_{-i}) | I_i] \right] - \gamma (s_i - \bar{b})^2 - \rho \exp \{ \eta \bar{b} \} \right\} f(s_i) \, ds_i
\]
\[
+ \int_{\bar{s}}^{\bar{\theta}} \left\{ \delta \left[ \bar{S} - \mathbb{E} [L(\beta^*(s_i), B_{-i}) | I_i] \right] - \gamma (s_i - \beta^*(s_i))^2 - \rho \exp \{ \eta b_i \} \right\} f(s_i) \, ds_i
\]
in which \( \{\bar{\theta}, \bar{\theta}\} \) are the minimum and maximum value of \( \beta^{*-1}(\bar{b}) \). If \( \bar{b} \) is indeed the optimal bunching level, varying the level should not change \( J(\bar{b}) \) in the first order. Therefore FOC suggests

\[
\frac{\partial}{\partial \bar{b}} J(\bar{b}) = 0
\]
which can be used to solve for \( \bar{b} \). \( \square \)