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Abstract

In principle, bank deposits can be withdrawn on demand. In practice, depositors tend to maintain stable balances for long periods, allowing banks to fund long-dated assets. Nevertheless, the cost of deposit funding influences banks' capacity for maturity transformation. Banks and researchers conventionally model the response of deposit interest rates to market interest rates as constant, implying that deposits have nearly constant duration. Contrary to this standard assumption, we show empirically that the "beta" of deposit rates to market rates increases as market rates rise, causing the duration of deposits to fall. The amount of duration risk delivered to bank balance sheets via this channel from March 2022 to September 2023 is comparable in magnitude to the amount of duration risk absorbed by each of the several large-scale asset purchase programs the Federal Reserve has undertaken since 2008. Dynamic betas present a significant challenge to bank portfolio hedgers by introducing large and dynamic risks that are difficult to model and impractical to replicate on the asset side of the balance sheet. As a result, deposit convexity amplifies monetary policy transmission and increases financial fragility, mechanisms that recent banking stresses have highlighted.

JEL Codes: E430, E440, E520, G120, G210

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1 Introduction

Banks fund long-duration assets such as loans in large part by issuing immediately available demand deposits. Although demand deposits nominally have no duration, in practice deposit funding often behaves more like long-term debt: Depositors typically maintain steady balances for long periods of time at relatively stable interest rates. The transformation of nominally immediate-maturity, highly liquid deposits into stable, long-term funding gives banks the capacity to carry long-term, fixed-rate, often illiquid assets and is at the heart of banks' economic function.

Recent stress in the U.S. banking system has drawn attention to gaps in risk identification and measurement related to this funding model. Banking is inherently fragile (Diamond and Dybvig, 1983; Diamond, 2007). Depositors sometimes exercise their right to immediately liquidate. Moreover, depositors may move funds more rapidly when market interest rates rise, thus exposing the bank to complex and dynamic interest rate risks. And those risks can interact, as depositors' response to changing market interest rates can erode the earnings power of a banking franchise and, in the extreme, even trigger a run. An understanding of these effects is a key input into monetary and financial stability policy—an issue made more urgent by the deposit outflows at some banks amid the rapid rise in U.S. interest rates starting in 2022 (e.g., Board of Governors of the Federal Reserve System, 2023).

Typical models of depositor behavior used in both economic research (e.g., Drechsler et al., 2021) and the banking industry treat the equilibrium cost of a bank's deposits as moving in fixed proportion to the short-term, risk-free market interest rate—a constant "beta." Drechsler et al. (2017) provide microfoundations for this model. Drechsler et al. (2023) observe that if higher interest rates lead to deposit outflows, the bank's deposit beta will be higher, but they propose addressing this effect by modeling deposits as having a higher, yet still constant, effective beta.

If deposits actually had a constant beta to market rates, their duration would fall somewhat with rising market rates due to discounting effects, but not enough to eliminate the cost advantage of deposits over long-term debt. In such an environment, banks could match the duration of their liabilities to the duration of assets and could generally expect wider margins between interest income and interest expense and greater profits when interest rates rise. The value of the deposit franchise would then increase with the short-term, risk-free interest rate, a mechanism highlighted by Drechsler et al. (2021) and Luck et al. (2023). The primary interest rate risk that banks would need to hedge would be that of *falling* interest rates, motivating banks to acquire long-term assets to back their deposit liabilities.

Despite the conventional approach to modeling deposit betas, there is ample evidence that the ratio between deposit rates and the short-term, risk-free rate increases as the risk-free rate rises—a dynamic beta.

If a bank does not raise deposit rates more rapidly as the risk-free rate reaches higher levels, the bank can expect to lose deposits. Lost deposit funding is generally replaced with wholesale sources that tend to be closer to market rates, and therefore more expensive. Thus, monetary tightening reduces the duration of deposits by more than the simple effect of discounting. In a sense, commercial banks have sold their depositors options on interest rates, making deposits highly convex. Owing to both practical and accounting considerations, these duration dynamics are difficult to replicate on the asset side of the balance sheet or with derivatives, leaving typical banks with an unhedged exposure that exhibits significant negative convexity.

In this paper, we develop a simple analytical model of deposits' duration and convexity. Through the lens of the model, we show that deposit convexity has three important consequences for monetary policy and financial stability.

First, deposit convexity amplifies the bank lending channel of monetary policy transmission (e.g., Bernanke and Blinder, 1988; Drechsler et al., 2017). That amplification has two sources. All else equal, increasing deposit betas raise the expected interest expense of incremental funding more quickly than static deposit betas. Also, because deposit convexity means that rising interest rates shorten the effective duration of deposits, rising interest rates leave banks holding more net duration on their balance sheets. Thus, rising interest rates more rapidly reduce banks' incentive to lend. Similar to the effects of a central bank reducing holdings of long-duration assets and leaving the private sector to hold more duration (Li and Wei, 2013), this effect erodes banks' capacity to hold other long-duration assets, adding to the headwinds to credit supply. We estimate that the increase in interest rates from December 2021 through July 2023 increased the duration risk on bank balance sheets by the equivalent of $4.5 trillion in 10-year Treasury securities, of which roughly 60% was due to discounting effects and 40% to dynamic betas. The effect of dynamic betas on the duration risk held by banks is larger than the amount of duration in any of the Federal Reserve's pre-Covid-19 asset purchase programs and comparable to the amount of duration in the market functioning purchases in March and April 2020 or the subsequent asset purchases from May 2020 through March 2022.[1]

Second, deposit convexity can amplify the transmission of central bank asset runoff. Since June 2022, the Federal Reserve has not only raised interest rates but also allowed some of its assets to mature. When the central bank reduces its asset holdings, its liabilities also fall. The Federal Reserve's liabilities include both bank reserves and non-reserve liabilities. To the extent that the reduction in liabilities comes from bank reserves—a liability of the central bank and an asset of commercial banks—bank deposits may also fall as commercial banks have fewer assets to fund. Commercial banks then lose deposits at the same time

[1] Deposits are both a liability of banks and an asset of depositors. A change in the aggregate duration of deposits therefore does not change the amount of duration on the consolidated balance sheet of the private sector, including both banks and non-banks. However, the bank lending channel is predicated on a special role for banks in intermediation, such that a change in the distribution of duration risk between banks and non-banks has macroeconomic consequences.

that convexity causes the remaining deposits' duration to fall, further reducing commercial banks' capacity to hold duration. While this channel's effect in the current U.S. tightening cycle has been modest to date, as most of the reduction in Federal Reserve liabilities since 2022 has come from non-reserve liabilities, its effect bears monitoring should reserves fall more notably.

Finally, dynamic betas affect the role of interest rates in the transition from a stable to a run equilibrium in banking. Drechsler et al. (2023) argue that increases in the value of the deposit franchise relative to banking assets can generate fragility, as depositors are increasingly incentivized to withdraw their funding in a coordinated way. We find that modeling interest rate risk with static betas tends to overstate the duration of deposits when rates are low and understate duration when rates are high. Importantly, relying on this overstated duration of deposits increases run risk in the transition away from the effective lower bound (ELB) on interest rates by allowing for the fair value of fixed-income assets to deteriorate more quickly than the fair value of the deposit franchise actually increases. This represents a novel channel through which maintaining interest rates at the lower bound increases financial fragility.

The paper proceeds as follows. Section 2 describes standard approaches that banks use to model deposit betas, which typically ignore the dynamics in favor of assuming a constant beta. Section 3 provides empirical evidence on the dynamics of deposit betas. Section 4 lays out a simple model of dynamic deposit betas. Section 5 uses the model to analyze how dynamic betas affect the bank lending channel of monetary policy, section 6 analyzes the effects of central bank balance sheet expansion and contraction, and section 7 examines how dynamic betas can contribute to bank runs. Section 8 concludes.

2 Bank deposit modeling

Like economic researchers, bankers make assumptions about deposits' sensitivity to market interest rates. While banks have discretion to set the rate of interest on their deposits, in practice they must respond to market forces and must model how those responses will unfold in order to manage risk and maximize profits. Banks' deposit beta modeling can range from standardized assumptions to multivariate regression models and may also include management judgment. Almost all publicly available deposit beta techniques employed in practice are linear. The following describes banks' modeling practices based on the authors' personal experience observing bank practices and working with vendor models of interest rate risk (see, e.g., Greenwald and Gray, 2013).

Default assumptions: Smaller banks often use vendor-supplied interest rate risk models that include vendor-recommended or default assumptions for deposit betas. These models typically apply a constant deposit beta to all scenarios regardless of the magnitude or direction of the change in interest rates. Some vendors derive default betas from empirical models. Others derive them from information published by regulators. For example, in 1995 the federal bank regulatory agencies proposed a standardized measure of banks' interest rate exposures (Office of the Comptroller of the Currency et al., 1995). The proposal included a weighted-average duration maturity ladder for all non-maturity deposits for a 100-basis-point change in rate. Bank regulatory agencies ultimately did not adopt the standardized measure, but some vendor models continue to leverage it to generate default deposit betas. In models of this type, deposit volumes assumed to mature within one year are assigned a 100 percent beta and remaining volumes are assigned a 0 percent beta, resulting in a constant overall beta regardless of the level of market interest rates.

Linear regressions: Vendor models and customized deposit modeling studies predominantly use univariate linear regressions of a time series of deposit rates on market rates to estimate a deposit beta. Models can better account for the effect of market rates on deposit pricing by controlling for other relevant factors, such as deposit volumes. In practice, banks that attempt to control for such other factors typically use multivariate linear regression, thus continuing to assume that the marginal effect of market rates on deposit rates does not change with the level of the market rate. Some models include lags of deposit rates, which allows for a dynamic impulse-response relationship between market rates and deposit rates; however, the model coefficients are still assumed to be independent of the level of market rates.

3 Empirical evidence on deposit betas

This section uses evidence on bank executives' self-reported estimates of deposit betas in different interest rate environments as well as banks' reports of deposit volumes and interest expenses to show how deposit betas vary with risk-free short-term interest rates in practice.

3.1 Bank executives' self-reported deposit betas

The Federal Reserve's Senior Financial Officer Survey (SFOS) periodically questions roughly 80 banks, across a range of sizes and business models, about their funding.[2] The November 2022 and May 2023 surveys included questions on realized deposit betas since the start of the hiking cycle (March 2023) as well as expectations for deposit betas in the next six months.

The survey questions segmented deposits into three types, mirroring those used in liquidity regulations (Bank for International Settlements, 2013): (1) retail deposits held by individuals, (2) wholesale operational deposits held by institutions and which are generated by clearing, custody, and cash management, and (3) non-operational wholesale deposits for balances in excess of those operational deposits. The surveys asked:

[2]See `https://www.federalreserve.gov/data/sfos/sfos.htm`.

- November 2022:
  - "For each of the deposit categories below, please indicate your bank's cumulative deposit beta from March 2022 through the end of October 2022. For reference, the target range for the federal funds rate over this period increased 300 basis points."
  - "Looking ahead six months to April 2023, for each of the deposit categories below, please select your expectations for your bank's cumulative deposit beta since March 2022."
- May 2023:
  - "For each of the deposit categories below, please indicate your bank's cumulative deposit beta from March 2022 through the end of April 2023. For reference, the target range for the federal funds rate over this period increased 475 basis points."
  - "Looking ahead to November 2023, please select your expectations for your bank's cumulative deposit beta since March 2022 for each of the deposit categories below."

For context, the effective federal funds rate (EFFR) averaged 1.49% from the beginning of March 2022 to the end of October 2022 while 6-month spot-starting interest rate swaps tied to EFFR averaged 4.64% over the November 2022 survey month. That suggests the forward-looking cumulative betas for the November 2022 survey apply to a 14-month period with an average EFFR of 2.84%. Similarly, for the May 2023 survey, EFFR averaged 2.74% from March 2022 to April 2023 and 6-month swaps averaged 4.94% over the survey month, suggesting the cumulative betas apply to a 20-month period with an average EFFR of 3.32%.

Because the backward-looking and forward-looking questions apply to different rate levels, we can use the survey results to test whether depository institutions expect dynamic betas.

Figure 1 summarizes the responses for domestic banks. They show a clear expectation of increases in deposit betas through April 2023. This shift in expectations is most pronounced for retail deposits, which are both the largest component of deposit funding at most banks and thought to be among the most stable.

How do the survey responses square with our description of bankers' standard modeling? Typical risk monitoring and management policies may not explicitly recognize a dynamic beta, but banks regularly review model assumptions. If these reviews are sufficiently frequent, they can produce dynamic betas. The SFOS responses suggest that many banks recalibrate their models in this way. As we discuss below, however, implementing dynamic betas via regular review of static assumptions can introduce fragility relative to a dynamic model.

3.2 Banks' realized deposit interest expenses across rate environments

To get a more granular sense of deposit beta behavior, we turn to the Call Reports (Federal Deposit Insurance Corporation, 2023a,b,c). All insured depository institutions in the United States disclose their banking assets, liabilities, income and expenses on these reports on a quarterly basis. We calculate banks' deposit interest rates by examining their interest-bearing domestic and total liabilities, as well as interest expense in total and that associated with depository liabilities.

From these data, we calculate annualized aggregate rates paid for all reporting commercial banks with a domestic parent for two complementary measures: (1) interest expense attributable to domestic deposits as a percentage of total interest-bearing domestic deposit balances (R_D) and (2) total interest expense as a percentage of the book value of total assets (R_F). R_D reflects the behavior of domestic deposits in isolation—in a sense, the pure deposit beta—while R_F reflects the total cost of funds. As we will describe later, both are relevant in measuring interest rate risk in the banking book.

Figure 2 shows how bank deposit interest rates and total funding costs have evolved over three recent monetary policy tightening cycles: 2004–2007, 2015–2019 and the cycle that began in 2022 (for data through June 2023). The relationship of deposit rates and funding costs to the EFFR is visibly nonlinear, with the slope increasing as the EFFR rises. Regression results reported in Table 1 demonstrate that the nonlinearity is statistically significant, rejecting the assumption of a constant beta.

The empirical findings raise the question of why betas are dynamic. Although many observers assume that banks simply "raise rates" across all their deposit products to compete for funding, history suggests that a changing mix of deposit products is a key driver. In particular, as shown in the left panel of Figure 3, depositors have tended to migrate into time deposits from other products as market rates have risen. For example, from March 2022 to September 2023, aggregate time deposit balances among domestically chartered commercial banks increased by nearly \$700 billion while other balances fell by more than \$1.7 trillion[3]. Time deposit rates, shown in the right panel of Figure 3, also move more closely with policy rates than do the rates on other deposits. Call Report data show that time deposits have therefore accounted for a disproportionate fraction of increased commercial bank interest expense during the past few hiking cycles: roughly 52% (1.4 times *ex ante* market share), 34% (1.6x) and 24% (2.6x) in 2004–2006, 2015–2018, and 2022–2023 (through the second quarter of 2023), respectively.

4 A simple model of interest rate risk for a deposit franchise

The mechanism of funding costs rising due to a changing mix of deposits motivates our simple model of the interest rate risk on banks' deposits.

Consider a bank whose liabilities at time t consist of non-maturity demand deposits $\mathcal{D}_t$ and wholesale funding $\mathcal{W}_t$. Suppose that a fraction $\beta(R_t)$ of the deposits come from depositors who care only about interest earnings and will leave immediately if they are not paid the market rate R_t, while a fraction $1 - \beta(R_t)$ come

[3]Data provided by FRED, tickers DPSDCBW027NBOG and LTDDCBW027NBOG.

from depositors who do not respond to market interest rates because they value other services the bank provides. The bank price discriminates between the two groups, paying interest R_t to the rate-sensitive depositors and no interest to the rest. We allow β to be a function of R_t because of the observation that the deposit mix tends to change as market rates rise. We assume $0 < \beta(R_t) < 1$ and $\beta'(R_t) \geq 0$. However, we assume β does not depend directly on time. Both types of depositors also leave the bank for exogenous reasons at rate α per unit time, at which point the bank replaces their deposits with wholesale funding, which also pays R_t. (In practice, a bank might incur marketing costs to obtain new price-insensitive depositors, might pay price-insensitive depositors an interest rate that depends on when they became customers, might have some fixed-rate time deposits, and would have some equity capital; allowing for these details would not change the basic implications of our model.) We further assume a constant balance sheet size and normalize the bank's total liabilities $\mathcal{D}_t + \mathcal{W}_t$ to 1.

In effect, this bank has $\mathcal{W}_t$ of floating-rate wholesale debt, $\beta(R_t)\mathcal{D}_t$ of floating-rate deposits, and $[1 - \beta(R_t)]\mathcal{D}_t$ of zero-coupon, zero-interest debt. The duration of the bank's deposits and its total liabilities depends on the exogenous decay rate α as well as the relationship between β and R_t.

For simplicity, we will work in continuous time and calculate duration by considering perturbations around a steady state where R_t is constant (both on a spot basis and in expectation with no term premium; i.e., a flat yield curve). Each dollar of non-interest-bearing deposits costs the bank less than one dollar because, in expectation, the bank will repay this dollar in the future and can discount that future repayment at rate R. This savings represents the value of the bank's deposit franchise. The wholesale deposits and interest-bearing deposits, on the other hand, cost the bank exactly as much as their par value. The present value of the bank's liabilities when it has deposits $\mathcal{D}_0$, treating $R_t = R$ as constant and adopting the convention that liabilities are negative, is thus

$$\tilde{\mathcal{L}}_R = \left[-1 + \int_0^\infty [1 - \beta(R)]Re^{-(R+\alpha)t}dt\right]\mathcal{D}_0 = -\frac{\alpha + \beta(R)R}{R + \alpha}\mathcal{D}_0 - \mathcal{W}_0. \tag{1}$$

Taking the derivative with respect to R to get duration:

$$\Delta_R = \frac{d\tilde{\mathcal{L}}_R}{dR}\frac{1}{\mathcal{D}_0} = [1 - \beta(R)]\frac{\alpha}{(R + \alpha)^2} - \beta'(R)\frac{R}{(R + \alpha)}. \tag{2}$$

Equation (2) captures key pieces of intuition for both the standard model of constant-beta deposits and our model of dynamic betas.

Consider first the special case where $\beta(R)$ equals a constant $\bar{\beta}$. Then (2) simplifies to

$$\Delta_{R,\bar{\beta}} = (1-\bar{\beta})\frac{\alpha}{(R+\alpha)^2}. \tag{3}$$

The bank's liabilities have positive duration, i.e., the present value of the bank's payments to its creditors falls as interest rates rise. This feature allows the bank to hedge the interest rate risk on long-duration assets. The duration of the bank's liabilities, and thus the size of this hedge, is increasing in the share of liabilities that are deposits $\mathcal{D}_0$ and decreasing in the share of deposits that pay market rates $\bar{\beta}$. For $R < \alpha$, which is the case for typical ranges of market interest rates and typical deposit longevity of 5–7 years, duration is also decreasing in the deposit runoff rate α.

With dynamic betas, equation (2) shows that deposit duration is reduced relative to what it would be with a constant beta. Intuitively, deposits have less duration when rising rates can cause them to reprice faster.[4]

Next, we consider the convexity of the bank's liabilities:

$$\Gamma_R = \frac{d^2\tilde{\mathcal{L}}_R}{dR^2}\frac{1}{\mathcal{D}_0} = -[1-\beta(R)]\frac{2\alpha}{(R+\alpha)^3} - \beta'\frac{2\alpha}{(R+\alpha)^2} - \beta''\frac{R}{R+\alpha}. \tag{4}$$

For constant β, convexity simplifies to:

$$\Gamma_{R,\bar{\beta}} = -\frac{2\alpha(1-\bar{\beta})}{(R+\alpha)^3}, \tag{5}$$

the standard result that a bond has negative convexity (from the issuer's perspective).

When β depends on R, convexity has additional terms related to the first and second derivatives of β, as shown in (4). The second term in the numerator of the fraction in (4) is non-negative given our assumption that $\beta' \geq 0$. However, the sign of the first term in the numerator is ambiguous. In particular, because $\beta(R)$ is bounded above by 1, β'' must become negative for sufficiently large R, and if β'' is sufficiently negative, convexity becomes positive. Where that transition occurs depends on the shape of $\beta(R)$. To the extent that these higher-order terms dominate, the complexity of managing dynamic interest rate risk is only increased.

Finally, Luck et al. (2023) and Drechsler et al. (2021, 2023) point out that deposits' capacity to fund long-duration assets relies on stable or, at least, predictable deposit balances. While aggregate banking deposits have been broadly stable in most interest rate regimes in the United States, empirical studies suggest that runoff (parameterized as α in our model) can rise with interest rates (Duffie and Krishnamurthy, 2016; Kang-Landsberg and Plosser, 2022). Our model can accommodate such a relationship by making α an increasing

[4] Sufficiently large local variation in β with R can even change the sign of Δ_R. Specifically, $\Delta_R < 0$ if $\frac{\beta'(R)}{1-\beta(R)} > \frac{\alpha}{R}\frac{1}{R+\alpha}$. This condition rarely holds in practice: Banks tend to vary deposit rates gradually in light of both the empirical behavior of their deposits and practical constraints on their ability to manage dynamic interest rate risk.

function of R, in which case duration becomes

$$\hat{\Delta}_R = \Delta_R - \underbrace{[1-\beta(R)]\frac{R\alpha'(R)}{[R+\alpha(R)]^2}}_{>0}, \tag{6}$$

where Δ_R shown in (2) is the duration assuming α is constant. Equation (6) shows that if rising rates accelerate deposit runoff, the duration of deposits is reduced. This effect is similar to the dynamic beta effect described above, but in this case value is destroyed by depositors withdrawing their funds rather than demanding higher rates. Additionally, the value of the bank's deposit franchise would be reduced by the cost to acquire replacement depositors.

The remaining sections use the model to examine implications of deposit convexity and dynamic betas for the bank lending channel of monetary policy, the transmission of central bank asset runoff, and the fragility of banks.

5 The bank lending channel

The bank lending channel of monetary policy refers to the idea that changes in monetary policy may influence not only the interest rate on loans but also the quantity of loans that banks are willing to make. In its original formulation (Bernanke and Blinder, 1988), the bank lending channel of monetary policy operated through reserve requirements. However, bank reserve requirements have not significantly constrained banks in the United States for many decades (Bennett and Peristiani, 2002), are generally not expected to bind in the ample reserves operating regime that the Federal Reserve has employed since the Global Financial Crisis (Ihrig et al., 2020), and were set to zero by the Federal Reserve Board in 2020 (Board of Governors of the Federal Reserve System, 2020). More recently, Drechsler et al. (2017) describe another mechanism for the bank lending channel: the behavior of deposits. In that framework, deposits have a constant beta to market rates; the spread between market rates and deposit rates therefore widens when the central bank raises the policy rate, giving depositors an incentive to move balances out of the banking system, which constrains bank lending. We extend Drechsler et al. (2017) by incorporating dynamic betas.

Many bank assets are relatively illiquid, so banks typically do not continuously re-optimize their entire asset books, but rather make marginal decisions about whether to add particular assets. Suppose a bank has the opportunity to make a floating-rate, T-year loan with book value $\mathcal{A}$ that earns a risk-adjusted interest rate $R_t + s$. For example, this could be a commercial loan where the bank is able to earn a risk-adjusted spread s over market rates due to comparative advantage in sourcing or evaluating loans in a particular industry or geography.

If the bank funds the loan with deposits that must be replaced with wholesale funding as they run off at rate α, the present value of the bank's marginal net income from the loan over the loan's life is

$$\begin{aligned}\mathcal{N} &= \int_0^T e^{-R_t t}\left[R_t + s - e^{-\alpha t}\beta(R_t)R_t - (1-e^{-\alpha t})R_t\right]dt \\ &= s\int_0^T e^{-R_t t}dt + \tilde{R}_T(1-\tilde{\beta}_T)\int_0^T e^{-(R_t+\alpha)t}dt + \int_0^T e^{-(R_t+\alpha)t}(R_t-\tilde{R}_T)[1-\beta(R_t)-(1-\tilde{\beta}_T)]dt\end{aligned} \tag{7}$$

where

$$\tilde{R}_T = \frac{\int_0^T e^{-(R_t+\alpha)t}R_t dt}{\int_0^T e^{-(R_t+\alpha)t}dt}, \quad \tilde{\beta}_T = \frac{\int_0^T e^{-(R_t+\alpha)t}\beta(R_t)dt}{\int_0^T e^{-(R_t+\alpha)t}dt}. \tag{8}$$

The first term in (7) is the present value of the bank's spread s on the loan and does not depend on funding costs. The second term is the benefit to the bank of funding the loan with deposits rather than wholesale funds, if market rates remain constant over the life of the loan. The final term is the present value of the covariance between market rates and the bank's funding advantage $1-\beta(R_t)$. This covariance is strictly negative for dynamic betas ($\beta' \geq 0$). Thus, dynamic betas reduce banks' marginal net income from lending and motivate banks to constrain even *floating-rate* lending more than they would if deposit betas were constant.

For fixed-rate lending, dynamic betas have an additional effect. Suppose that, as is typical, the bank has a risk limit on its consolidated net duration exposure. Acquiring a fixed-rate asset increases the bank's net duration exposure, while issuing deposits decreases the bank's net duration exposure. Equation (2) shows that dynamic betas reduce net deposit duration, which means the marginal increase in total duration exposure from acquiring a fixed-rate asset and funding it with deposits is larger. Thus, as rates rise, dynamic betas reduce banks' ability to take on additional net duration risk. Even if the marginal loan would be profitable on a funding cost basis, duration risk considerations could cause banks to curtail the supply of term credit more than they would with static betas.

The magnitude of these effects can be substantial. As of December 2021, domestically chartered commercial banks had approximately \$16.5 trillion of deposit balances (Board of Governors of the Federal Reserve System, 2021). We estimate the duration of these deposits by considering separate betas for retail deposits, which tend to be sticky; wholesale operational deposits, which are associated with institutional payment activity and are less sticky; and wholesale non-operational deposits, which are wholesale customers' funds in excess of operational needs and have interest rates that move most closely with market rates.

On average, respondents to the May 2023 SFOS reported realized retail, operational and non-operational betas of 24%, 41% and 50%, respectively, over the March 2022–April 2023 period, when the federal funds rate averaged 2.75%.[5] Respondents projected cumulative retail, operational and non-operational betas of 35%, 50% and 59% for March 2022–November 2023, a period when interest rates were expected to average 3.4% based on swap rates. Public disclosures by banks designated as Global Systemically Important Banks (GSIBs), representing about half of aggregate deposits, indicate that approximately 55% of deposits are retail deposits, 25% are wholesale operational deposits, and 20% are wholesale non-operational deposits. That distribution of deposit types implies an aggregate deposit beta of 33% for March 2022 to April 2023 and 44% for March 2022 to November 2023, and (comparing the two as well as the interest rates across the periods) an aggregate beta of roughly 60% for the May–November 2023 period when swaps forecast an interest rate of 4.94%. Assuming betas are never modeled below 25%, these aggregate betas and interest rates can be fitted to a quadratic relationship of $\beta(R) \approx 1.79R^2 - 1.90R + 25.4$ (where $\beta(R)$ and R are both expressed in percentage points).

We make three simplifying assumptions to estimate the aggregate duration of deposits. First, we assume deposits have a half-life of 5 years.[6] Second, in practice, banks manage to a medium-term rate outlook. Therefore, we use 5-year Treasury rates instead of EFFR as the R in our calculations. In addition to providing a somewhat conservative estimate of the change in interest rates and resulting duration effect, we believe this is a more accurate reflection of internal modeling choices made by the banks themselves in their asset-liability management decisions.

Third, we calculate duration as if beta is static but updated by bank management at different rate levels (i.e., $\beta(R)$ is stepwise). This corresponds to typical bank practice, as discussed above, and allows us not to estimate $\beta'(R)$. Including the terms in $\beta'(R)$ would increase our estimates.

At a beta of 25% with 5-year Treasury yields at 1.27%, banks' deposits as of December 2021 corresponded to negative duration risk of approximately \$7.5 trillion of 10-year Treasury securities (often referred to as 10-year equivalents, or TYE). By the end of July 2023, higher rates and betas reduced the magnitude of that duration risk to approximately negative \$3.0 trillion TYE. In other words, the change in interest rates effectively delivered the same amount of duration risk to commercial banks as if those institutions had bought nearly \$4.5 trillion of 10-year Treasury securities. Of that, roughly \$1.8 trillion (40% of the total duration delivery) was due to dynamic betas. And, as noted above, that figure represents a lower limit under our framework.

The total quantity of duration delivery to banks via deposit dynamics is comparable to the cumulative duration removed from the private sector by all of the Federal Reserve's large-scale asset purchase programs

[5] The survey response options were categorical. We compute averages by assigning each response to the midpoint of the chosen category.

[6] This assumption is roughly consistent with modeling assumptions reported by national banks in a spring 2023 survey by the Office of the Comptroller of the Currency (OCC) (`https://www.occ.gov/publications-and-resources/publications/interest-rate-risk-statistics-reports/files/pub-interest-rate-risk-statistics-spring-2023.pdf`).

(LSAPs) since the Global Financial Crisis (which total roughly $5.5 trillion TYE; Gulati and Smith, 2022). Focusing specifically on the role of dynamic betas, the $1.4 trillion TYE impact is larger than any of the pre-Covid-19 asset purchase programs and comparable to market functioning purchases in spring 2020 as well as the subsequent LSAPs from approximately May 2020 to March 2022.

These estimates assume a constant deposit runoff rate α. In practice, banks may revise runoff rates upward when interest rates reprice more than expected.[7] The March 2023 banking stresses may also have motivated some banks to assume faster runoff. All else equal, we estimate a 1-year reduction in the half-life of deposits corresponds to an additional $600 billion TYE of duration delivery to banks.

6 The central bank balance sheet channel

As described by Li and Wei (2013), changes in central bank asset holdings are typically modeled as affecting term premia by changing the amount of duration held by the private sector. The negative duration of deposits creates the potential for an additional channel through which central bank asset holdings can affect term premia.

When a central bank acquires assets, it pays for the purchase by creating reserves. Typically, the seller of the assets is some entity other than a commercial bank, such as a securities dealer or an investment fund; the seller's bank is credited with reserves and in turn credits the seller's deposit account. Thus, central bank asset purchases typically create bank deposits (see, e.g., Leonard et al., 2017; Acharya and Rajan, 2022; Acharya et al., 2023).[8] And when a central bank reduces its asset holdings, whether by selling assets or by not rolling over maturing assets and leaving the government to issue replacement debt to the public, bank deposits typically fall. (If banks respond to these dynamics by acquiring or selling assets, there can also be a multiplier effect on the initial change in deposits.)

Because deposits are both a liability of commercial banks and an asset of non-banks, changes in the aggregate quantity of deposits in the banking system do not change the aggregate amount of duration risk on private-sector balance sheets. However, changes in aggregate deposits do change the distribution of duration risk: The creation of bank deposits reduces the aggregate amount of duration held by banks and increases the amount held by non-banks, while the destruction of deposits has the opposite effect.

To the extent that banks and non-banks have different risk appetites or preferences for hedging the duration risks that they face, these distributional changes may influence term premia. For example, while banks may employ sophisticated hedges for duration risk, it seems less likely that a typical household would

[7] For example, large banking institutions reported a shorter median weighted average deposit life in the OCC's spring 2023 survey than in the fall 2022 survey (`https://www.occ.gov/publications-and-resources/publications/interest-rate-risk-statistics-reports/files/pub-interest-rate-risk-statistics-fall-2022.pdf`).

[8] In the unusual case where the seller is a depository institution, no deposits are created.

hedge the duration risk of its checking account in the same way. Thus, while banks typically seek to hedge the duration of deposits by acquiring longer-dated assets, households may be less likely to respond directly to an decrease in their deposit holdings by increasing their holdings of longer-dated assets. If so, banks may be the marginal buyers or sellers of duration risk, and banks' duration hedging could disproportionately influence term premia. The creation of bank deposits as a result of central bank balance sheet expansion would then increase banks' demand for duration and reduce term premia, above and beyond the effect of the change in assets held by the central bank versus the private sector. Conversely, when the central bank allows its asset holdings to mature, any resulting decrease in bank deposits would increase term premia, above and beyond the effect of the change in asset holdings.

Additionally, with dynamic betas, the effect of creating or reducing bank deposits depends on the interest rate environment. Typically, central banks buy assets to stimulate the economy at the same time as they are lowering interest rates or after reducing interest rates to the lower bound (e.g., Hamilton and Wu, 2012), and reduce asset holdings in conjunction with removing accommodation by raising interest rates. With dynamic betas, that correlation amplifies the effect of asset holdings on term premia through the deposits channel in both directions —removing duration from bank balance sheets more quickly when the central bank is adding accommodation, and putting duration back on bank balance sheets more quickly when the central bank is removing accommodation.

However, from June 2022, when the Federal Reserve began reducing its asset holdings, through late-September 2023, reserve balances actually increased by $50 billion from a total of more than $3 trillion, while non-reserve liabilities fell by $960 billion. The central bank balance sheet channel's effect on bank deposits has likely therefore been modest to date.

7 Run risk with dynamic betas

Drechsler et al. (2023) argue that interest rate risk can drive the transition from the stable to unstable equilibrium of Diamond and Dybvig (1983) by shifting value between the asset and liability sides of a bank's balance sheet. When the bank's equity is greater than the value of its deposit franchise, depositors are motivated to retain their balances; when the deposit franchise value is greater than the bank's equity, depositors' incentives shift in favor of withdrawing funds. We find that dynamic betas can amplify this mechanism.

A bank's economic value of equity (EVE) is the net value of its tangible and intangible assets, including the deposit franchise, minus its liabilities. Importantly, EVE ignores the accounting and regulatory treatment of various assets and liabilities, instead capturing the financial values that influence depositors' incentives.

Consider a simple bank that funds assets $\mathcal{A}$ with deposits $\mathcal{D}_0$ and capital $\mathcal{CA}$, where $\mathcal{C} \in (0,1)$ is the bank's required capital ratio. In our simple model, the present value of the bank's deposit liability is given by (1) and is smaller than $\mathcal{D}_0$. Thus, EVE is

$$\text{EVE} = \mathcal{A}\left[1 - \frac{\alpha + \beta(R)R}{R + \alpha}(1 - \mathcal{C})\right] \tag{9}$$

where we have used the relationship $\mathcal{A} = \mathcal{D}_0 + \mathcal{CA}$.

Equation (9) shows that EVE depends on the interest rate R, but in practice, banks do not leave themselves entirely unhedged against this risk. The hedge may come from the duration of the assets $\mathcal{A}$ or from derivatives with no initial cash value. In either case, as a practical matter, the hedge must be established over some finite time horizon and typically with instruments that are (nearly) linear in interest rates. For simplicity, we consider hedges based on one risk-free, zero-coupon asset, but our qualitative results would generalize to a variety of other hedges. We also assume for simplicity that the asset can be liquidated at fair value with no transaction cost and real-time settlement, and thus that the bank does not need to hold cash to manage liquidity risk.[9]

Suppose the zero-coupon asset matures at date T. If its present value is $\mathcal{A}_0$ at $t = 0$ when interest rates are R_0, the asset must pay $\mathcal{A}_0(1 + R_0)^T$ at maturity. The value of this asset as a function of R is then $\mathcal{A}(R) = \mathcal{A}_0[(1 + R_0)/(1 + R)]^T$.

Suppose the bank acquires an asset whose maturity T is such that the asset perfectly hedges EVE as of time 0. That is, the bank chooses $T = T(R)$ such that $d\text{EVE}/dR = 0$. This requires

$$T(R) = T_{\bar{\beta}}(R) - Y(R)\beta'(R) \tag{10}$$

where

$$Y(R) = \frac{(1 + R)(1 - \mathcal{C})R}{R + \alpha - [\alpha + \beta(R)R](1 - \mathcal{C})} \tag{11}$$

and $T_{\bar{\beta}}(R)$ is the duration that would provide a perfect hedge if deposits had a constant beta $\beta(R) = \bar{\beta}$.

There is no underhedging when $R = 0$. Since $R \geq 0$, $\mathcal{C} \in (0,1)$, $\beta \in (0,1)$,$\alpha \in (0,1)$, we have $T(R) < T_{\bar{\beta}}(R)$ whenever $\beta' > 0$ and R is not at the ELB. In consequence, a bank that uses a constant-beta model to construct an exact hedge will be underhedged against dynamic betas.

The gap between $T(R)$ and $T_{\bar{\beta}}(R)$, or the amount of underhedging, is increasing in R so long as

$$\frac{\beta''(R)}{\beta'(R)} > -\frac{Y'(R)}{Y(R)}. \tag{12}$$

[9] Accounting for liquidity requirements would result in a simple adjustment to our calculation of asset duration.

A bit of arithmetic shows that $Y'(R)/Y(R) \geq 0$ for the range of α, β, $\mathcal{C}$, and R above. We then define R_m as the level of interest rates at which this inequality is an equality and $\left[T(R) - T_{\bar{\beta}}(R)\right]$ is maximized—in other words, the level of rates at which the adjustment for incorporating dynamic betas is largest.

Some further assumptions about $\beta(R)$ can help in characterizing the gap. As noted earlier, our assumption that $0 \leq \beta \leq 1$ for $R > 0$ and $\beta'(R) > 0$ argues for a shift in the sign of $\beta''(R)$ from positive when rates are at the ELB to negative at higher rates. Let R_s be the transition point where the sign changes: $\beta''(R_s) = 0$. Based on the sign requirements of equation 12 and assumptions around the range of input parameters above, we can conclude $R_m > R_s > 0$. To give a concrete example, using a sigmoid fit to the SFOS-based $\beta(R)$ above, we find $R_s \approx 4\%$ and $R_m \approx 4.5\%$, compared with EFFR around 5% and 5-year Treasury rates around 3.5% at the time of the survey. This means the gap grows with R at low rates but shrinks with R at higher rates.

This exercise is a formal way of recovering an intuitive point. To the extent that $d\Delta_R/d\beta < 0$ and β is an increasing function of interest rates, then hedges ignoring those dynamics will be oversized (EVE will have net long duration) at low rates and undersized (EVE will have net short duration) at higher rates. That has important consequences for bank portfolio risk management and, when combined with the Drechsler et al. (2023) framework for run risk, implications for financial fragility emanating from the banking system.

To see these implications, we need to generalize our framework to consider uncertainty in R. To do so, we assume, consistent with empirical research (e.g., Rogoff et al., 2022, and references therein) that interest rates are mean reverting over long periods of time with a long-term average of $\bar{R} > 0$. When R is at the ELB, mean reversion implies that the expected value of R is above the ELB. If the bank were to hedge with $T_{\bar{\beta}}$ when R is at the ELB, as shown above it would be net long duration in expectation. That, combined with mean reversion in R, implies that EVE is expected to fall, putting our model bank at greater risk of the run equilibrium of Drechsler et al. (2023).

As many have noted, deposit insurance can mitigate run risk, but Call Report data show that, as of the second quarter of 2023, uninsured deposits and wholesale funding made up more than 50% of total commercial bank liabilities in the U.S.[10] Importantly, as SFOS responses indicate, banks often model uninsured deposits with $\beta < 1$, which means they contribute significantly to the value of the deposit franchise.[11] In addition, individual institutions can have much higher exposures to these more runnable sources of funding, and the events of March 2023 argue for the importance of a more granular view of run risk for assessing systemic vulnerabilities in banking.

[10]This calculation considers reported total liabilities (excluding minority interest), uninsured deposit balances, domestic deposits and foreign deposits.

[11]While the SFOS does not ask explicitly about insured versus uninsured deposits, the vast majority of operational and non-operational wholesale deposits are likely uninsured.

Our analysis shows that, unless properly accounted for in bank deposit models, dynamic betas will increase run risk when interest rates are low. Importantly, to avoid overhedging duration risk, banks would need to consider these dynamics *ex ante*. That is, while periodic revision of static beta models can result in *ex post* dynamic betas, the impact of those dynamics will not affect the size of hedges until the bank makes the revisions. Thus, banks using static models, even ones that are revised on an ongoing basis, will be more likely to overhedge their duration in low-rate environments and therefore may be at increased risk of runs compared with banks that model dynamic betas directly.[12] As discussed in Section 3, industry practice appears more consistent with static rather than dynamic models. Thus, banks' interest rate risk modeling practices are a potential source of financial fragility.

Practitioners may point out the opposite dynamic at higher rates. Were a bank to hedge its structural interest rate risk with a static beta model at interest rates above R_m, it would find itself underhedged should rates return to the ELB. Paired with the same assumptions as above, including mean reversion, this leads to the same directional conclusion that hedging with static betas raises the risk that EVE will fall when rates are high. However, the erosion of EVE in this scenario is driven by declining deposit franchise value, which *reduces* run risk.

The behavior of deposit betas thus has an important asymmetric impact on the stability of a banking franchise. Failing to model and hedge the dynamics of deposit betas increases financial fragility, but only in the transition from low interest rates (e.g., rates at the ELB) to higher rates. The same cannot be said for a scenario where rates fall from previously high levels; in fact, when dynamic betas are not adequately hedged, declining rates enhance the stability of banks as asset values increase relative to the value of the deposit franchise. This asymmetry represents a novel and concrete channel through which interest rates at the ELB can pose vulnerabilities to financial stability.

8 Conclusion

Deposits are the primary funding source of the banking system. That makes deposit interest rates a key driver of credit supply to the economy. The behavior of deposit interest rates is typically summarized by the beta of deposit rates to market overnight rates. Low betas not only support bank net interest margins, they also are the primary reason why banks can make long-term, fixed-rate loans, which make up a sizeable fraction of credit demand.

In this paper, we show that allowing for dynamic rather than static betas more accurately reflects

[12]If the assumptions in static models need to be revised more frequently, these models may also introduce problematic incentives for risk managers to make ill-advised changes in the models. We note the "poorly supported" decision by Silicon Valley Bank's management to revise deposit betas lower to reduce the apparent duration of equity (Board of Governors of the Federal Reserve System, 2023).

depositor behavior and significantly alters the interest rate risk profile of bank balance sheets. First, we summarize the empirical and qualitative evidence for dynamic betas. Second, we use a simple analytic model to consider the consequences of those dynamics for the interest rate risk on bank balance sheets. Third, we show that dynamic betas amplify the transmission of monetary policy through both the bank lending channel and the effect of the central bank's balance sheet on the amount of duration held by the private sector. Finally, we show that dynamic betas can affect the role of interest rates in banking fragility. They do so asymmetrically, introducing additional stability risks in the transition from the ELB to policy rates above the lower bound. These results highlight the importance of a proper understanding of depositor behavior and the resulting dynamics in structural interest rate risk on balance balance sheets in formulating monetary policy and maintaining financial stability.

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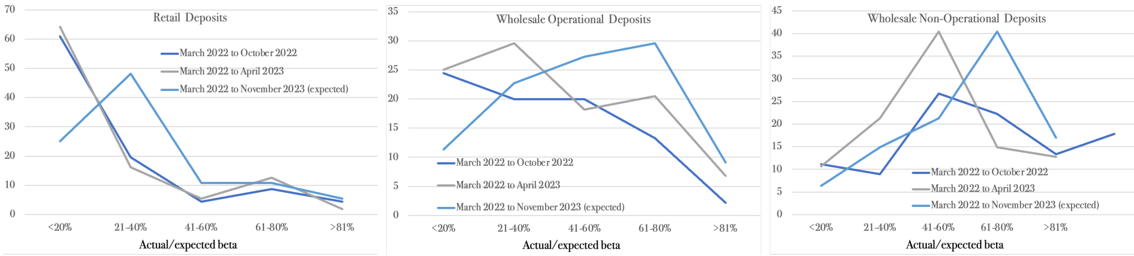
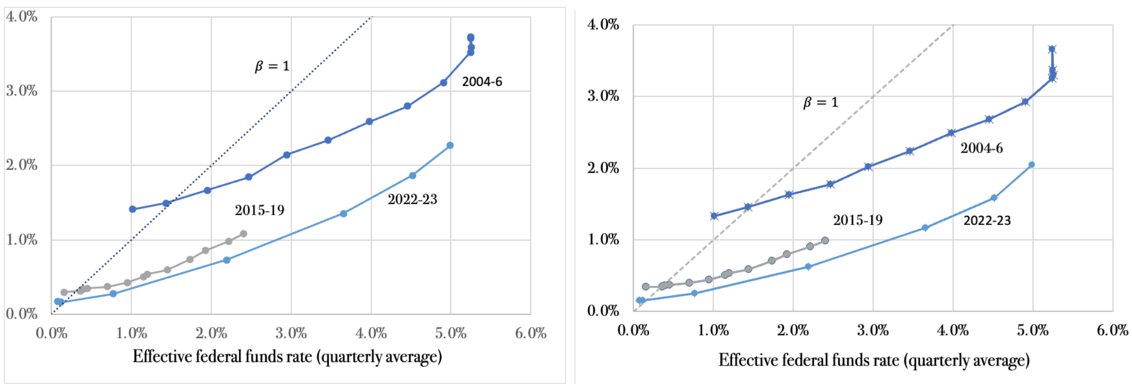


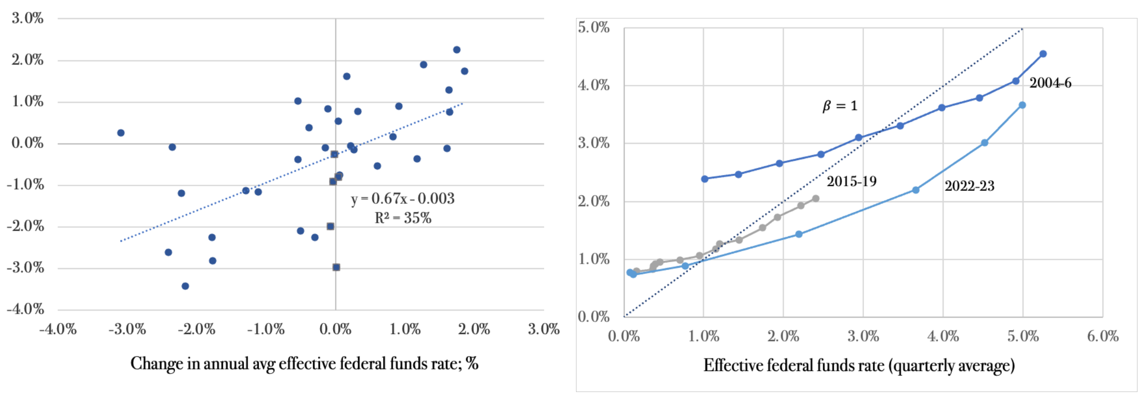
Figure 1: Percentage of domestic bank respondents reporting various levels of actual betas from March 2022 to October 2022 as of the November 2022 survey, actual betas from March 2022 to April 2023 as of the May 2023 survey, and cumulative expected betas through November 2023 as of the May 2023 survey.
Source: November 2022 and May 2023 Senior Financial Officer Survey.



(a) Interest-bearing domestic deposit rates paid

(b) Total cost of funds

Figure 2: Bank funding costs over three recent tightening cycles
Quarterly average data; aggregate commercial bank interest expense on domestic deposits as a percentage of total interest-bearing domestic deposits and aggregate commercial bank interest expense as a percentage of book value of assets, including only commercial banks with a domestic parent.
Source: Call Reports, FRED



(a) Change in large time deposits as a % of total

(b) Annualized interest expense from time deposits

Figure 3: The role of time deposits in overall deposit betas
Left panel: Annual average data, domestically chartered commercial banks (H.8); Right panel: Quarterly average data, commercial banks with a domestic parent (Call Reports).
Source: Call Reports, FRB H.8, FRED

	Monetary Policy Cycle					
	Q2 2004–Q2 2006		Q4 2015–Q2 2019		Q1 2022–Q2 2023	
	R_D	R_F	R_D	R_F	R_D	R_F
EFFR	-0.03	0.03	0.06	0.05	0.11	0.06
	(0.12)	(0.14)	(0.024)	(0.019)	(0.03)	(0.055)
EFFR^2	8.58	6.96	11.73	9.66	6.10	6.13
	(1.78)	(2.08)	(0.95)	(0.73)	(0.61)	(1.10)
Intercept	0.014	0.013	0.003	0.003	0.002	0.02
	(0.002)	(0.002)	(0.0001)	(0.0001)	(0.0002)	(0.00005)

Table 1: Linear regressions of interest-bearing deposit expense R_D and total cost of funds R_F on EFFR and EFFR^2, where EFFR is the quarterly average of the effective federal funds rate. Standard errors in parentheses. Includes all commercial banks in the United States with a domestic parent.
Source: Call Reports, FRED, authors' calculations.