Completed 04 Aug 2017 05:46 PM EDT
Disseminated 04 Aug 2017 05:46 PM EDT

J.P.Morgan

North America Fixed Income Strategy
04 August 2017

Every possible series of events is happening, all at once

Extracting market-implied policy rate outcomes from OIS and vol markets

- OIS provide a direct expression of the market's view on the Fed's future policy rate changes, and are frequently used to compute the number of hikes priced into markets out to future dates.
- We present an extension of this framework, able to compute the likelihood of a wide range of scenarios for the Fed funds rate out to three SEP-inclusive meetings.
- Markets are very skeptical of a September hike, placing the probability below 10% since the June meeting ...
- ... but in December the outlook is more dispersed, with roughly equal likelihood of a hike or pause in December. And moving out to March, markets place a 40% chance that IOER will stand at its current level, 25% that it will be 25 bp higher, and 25% that it will be 50 bp higher.
- The market-implied probability of a cut at the next meeting is below 2%, but going out past September, the chance of corrective action in any scenario by the Fed grows, to roughly 2-5% by September and roughly 20% by March.

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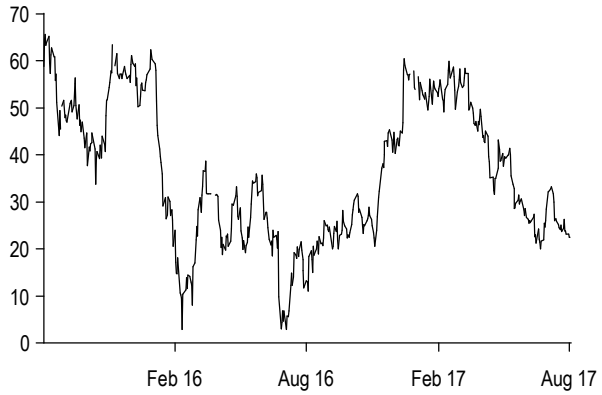
The era of ZIRP is now behind us, and after three consecutive quarters with rate hikes, the march to higher policy rates has begun in earnest. But going forward, we cannot help but view the outlook as clouded. The July FOMC statement has ramped up language signaling for balance sheet normalization to commence at the September meeting (see *Next Stop: balance sheet normalization*, M. Feroli, 7/26/17), which the market has mostly taken to mean the next hike will be postponed until at least December. Even then a hike is anything but a foregone conclusion, especially after the recent spate of tepid inflation prints. Into 2018, the uncertainties only grow, with Yellen's term as chair coming to a close in February and with significant uncertainty associated with who her successor will be (see *Who will run the Fed?* M. Feroli, 7/27/17). And beyond then? After nearly a decade of declining unemployment and bull markets, one can't help but wonder if winter is coming...

All this leaves us wondering: what exactly are markets thinking for the future of policy rates? To find an answer, we can appeal to OIS. Forward OIS rates represent the geometric average of expected daily Fed Funds settings over the swap's lifetime. And since the FFE/IOER basis has remained fairly stable over the past few years (including month-, quarter- and year-end turns; see **Appendix 1**), OIS provide a direct expression of the market's view on the Fed's future policy rate changes.

Exhibit 1: The slope of the front-end OIS forwards is consistent with a Fed on hold for much of the next year, though this may obscure more detailed information
1Yx3M/3M OIS curve; bp



Source: J.P. Morgan

The simplest information you can extract from OIS forwards is the likelihood of a rate change in the weeks leading up to an FOMC meeting: a swap spanning the period between the upcoming meeting and the meeting thereafter trades at a level consistent with the probability-weighted average of Fed Funds under all possible policy rate actions.

In the current cycle, for all practical purposes we can restrict the range of potential outcomes to no change or 25 bp moves in rates on meetings associated with a press conference and Summary of Economic Projections[1]. If the forward trades close to the current fed funds, the market is highly skeptical of a rate change; if it trades near FFE + 25bp, the market considers a hike to be a foregone conclusion. **This logic is frequently extended to meetings further into the future, and it is rather straightforward to come to the conclusion that the market now expects roughly one hike over the next year (Exhibit 1)**.

Though intuitive, we believe this framework does not incorporate all the available information, and therefore does not resolve important degeneracies. For example, were the market expecting equal probabilities of a 25 bp hike and cut, it would manifest as a flat forward curve. **This can be resolved by considering all possible paths for the Fed funds rate over a given horizon, and incorporating additional constraints from other markets**.

In this piece, we consider a framework for tracking the likelihood of a wide range of scenarios for FFE as priced into various market observables. These can then be compared to investor views in order to identify trading opportunities. We can also better distinguish between macroeconomically-disparate outcomes, such as a policy mistake and a Fed on hold.

The next meeting

To tease out the likelihood of a rate cut at the upcoming September meeting, we assume OIS levels are consistent with a probability-weighted average of three possible policy outcomes: a 25bp hike, a "pause" (IOER unchanged), and a 25 bp cut in rates. The fundamental theorem of algebra informs us this requires three equations to solve. The forward OIS level and the fact that all probabilities must sum to unity provide two. For the third, we turn to the vol market. **From current OTC cap pricing we can obtain the implied distribution of forward rates, and then require that our three**

[1] Though the FOMC insists that all meetings are "live," in practice we believe they are very unlikely to take significant policy action—both traditional and non-traditional—in the absence of a pre-scheduled press conference.

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outcomes prove consistent with the spread in this distribution (see the Appendices for a full explanation of the math behind these results)[2].

Perform this exercise, and you reach the shocking conclusion that the OIS market is highly skeptical of a September rate cut: the probability has stood below 2% since the June meeting (the odds of a pause are currently at roughly 90%). **But this null result belies the importance of considering such "policy corrections" when projecting a longer path horizon**.

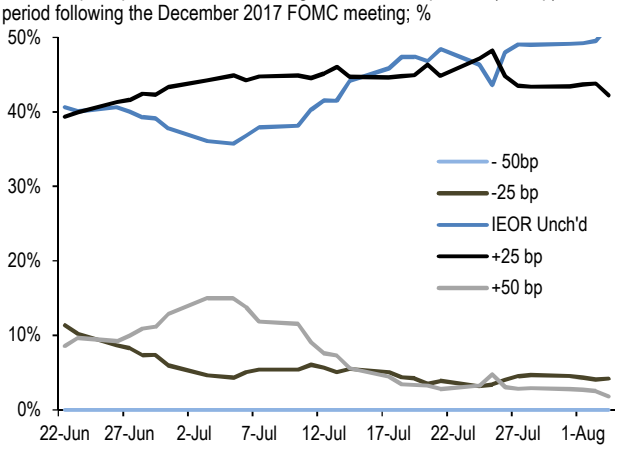
Beyond the Next Meeting

The second-simplest bit of information you can extract from OIS forwards is how many hikes are "priced in" heading into October, December, 2018 and beyond. Again this involves taking the basis between increasingly forward-starting OIS and the current level of FFE and dividing by roughly 25 bp[3] to obtain the number of rate hikes market participants expect out to a given time horizon. For instance, as of publication, OIS forwards imply 0.9 hikes out to July 2018, compared to our house view of a December hike followed by 3 hikes in 2018. **While this number is indeed the "expected" outcome, it represents only a rough view of the broad range of scenarios being traded, and in general could be quite different from the outcome(s) the market deems most likely to occur**. We thus explored a more powerful approach that attempts to solve for the "full" suite of probabilities surrounding rate action at upcoming FOMC meetings.

To start, we attempted to solve for all market-implied probabilities out to two FOMC SEP meetings: September and December. A more general approach would consider every meeting as a live one, including the non-SEP October date, but we ignore this possibility in our preliminary pass at an answer. Specifically, we solve for the conditional hike, pause and cut likelihoods at the December meeting, given the likelihoods found for September (roughly 1/10 odds of a hike, with essentially no chance of a cut).

There are 9 unknowns as of the December meeting (the odds of a hike given a pause in September, the probability of a cut given a hike in September, etc. …), although the outside chance of a September cut allows us to eliminate three unknowns right off the bat. For the remaining six, there are two normalization conditions (each set of conditional likelihoods must sum to one) and four readily observed market values: rate volatility spanning the Sep/Mar inter-meeting period, and OIS levels and rate volatility and skew spanning the Dec/Mar inter-meeting period. This six-equations/six-unkowns setup is readily solvable on a daily basis with a bit of matrix inversion, and allows us to compute the market-implied likelihood of moves in IOER past the December meeting (**Exhibit 2).** From this we find the market lending equal weight to IOER flat-lining between now and year-end and one hike transpiring before 2018. Beyond this bimodality, we note the weight given to more extreme outcomes: the likelihood of both a double-hike and a cut before year-end has hovered around 5-10% since the June meeting.

Exhibit 2: Since the June meeting, OIS and vol markets have consistently priced in a roughly equal likelihood that IOER will remain unchanged or rise 25 bp by the December FOMC meeting
Market-implied probabilities* of a change in IOER from present (125 bp) to the period following the December 2017 FOMC meeting; %



* Extracted from forward OIS and swaptions. See appendix for details of the methodology
Source: J.P. Morgan

A fair criticism of this approach is that it relies on zeroing-out the September cut. **Although its observed likelihood is small, this branch of the 'scenario tree' could have outsize influence in matching higher-order observed moments, such as skew**. We thus re-ran our framework relaxing this assumption while introducing others to fully constrain the solution (e.g., zeroing out the chance of a hike immediately following a cut, or

[2] Although volatility in Libor-indexed swaps is not precisely the same as volatility in FF-indexed OIS, the ratio of the two has hovered about parity for the past few years.
[3] The denominator is not precisely 25 bp but rather the difference between the projected OIS level should a hike (or two) occur, versus no policy action. The discrepancy arises from the month-, quarter- and year-end turns observed in FF. These turns can have a substantial effect on the OIS rate, particularly as some of them are timed with weekends and holidays, where the suppressed rate persists over the entire close period. We take these turns into account for the work presented here, as they can alter probabilities by a couple percent.

minimizing the probability of a double-cut). These alternative assumptions yielded results consistent to a few percentage points, which leads us to believe that while this framework is hardly an accurate way to extract razor-thin arbitrage opportunities, it nonetheless provides a meaningful way to explore the implications of current OIS pricing.

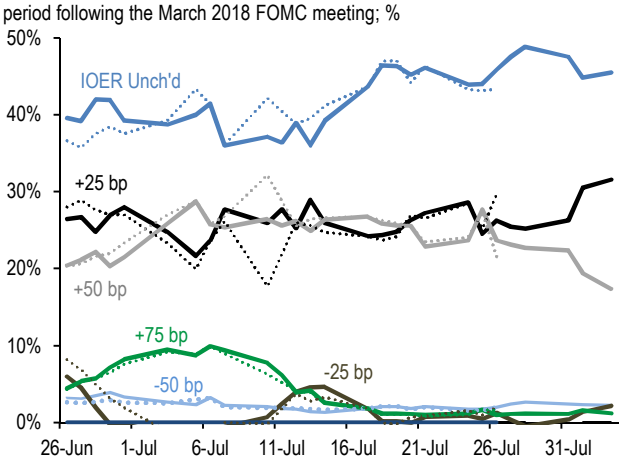
Success thus far inclined us to seek out a solution to the *third* SEP-inclusive FOMC meeting, in March 2018. Here things get a bit dodgy: allowing all three outcomes (cut, pause or hike) out to three meetings generates 27 unknown conditional probabilities (e.g., the odds of a hike given two pauses thus far, or the odds of a cut, given a hike and then a pause, etc …) and only 14 incontrovertible constraints (9 normalizations, 1 observed OIS forward, 3 volatilities and 1 skew, leaving us under-constrained within a daunting 13-dimensional hyperplane: see appendix for details). **In general, we cannot assume "path independence" considering the drivers of the Fed's dual mandate often exhibit significant autocorrelation on timescales much longer than the intermeeting period—particularly given the Fed's explicit focus on data-dependency in the current regime**.

To proceed, we introduce the following assumptions, enumerated here from least- to most-controversial. **First**, we eliminate all paths that begin with a September cut, which has proven immaterial to the solution up to now[4]. **Second**, we deem it harmless to zero-out the probability of any path involving a hike following a cut: a deterioration of the labor market or inflation landscape dire enough to trigger a cut would virtually eliminate any serious consideration of hikes at the following meetings. **Finally**, we assume no path-dependence for the cases where we're up 25 bp heading into the March meeting (i.e. for a single-hike by then, either in September or December), which is consistent with Chair Yellen's past remarks that every meeting is a "live meeting" dependent foremost on the data at hand. This still leaves us under-constrained in 3 dimensions. To proceed to a final answer, we generate a mesh of all possible solutions within this subspace, eliminating "unphysical" answers (those with negative probabilities along reasonable outcome paths). **This generates a set of tightly clustered solutions, uncertain to roughly 5% in the higher-probability branches. We then select the "answer" closest[5] to the median of these outcomes**.

Exhibit 3 shows the result of this exercise: since the June meeting, the market has lent the strongest weight to IOER sitting at its current level of 125 bp following the March SEP meeting. The next most-plausible outcomes involve IOER landing either 25 or 50bp above current levels – with the two scenarios roughly equally likely. While the market appeared to have flirted with the idea of a triple-hike in the weeks surrounding Independence Day, the probability of such a robust tightening path has since dropped (along with other outside paths, like one or multiple drops in the policy corridor). These levels are all consistent with the current flatness of the OIS term structure, coupled with increasingly suppressed volatility in rates markets.

Exhibit 3: Following the March 2018 meeting, markets place the heaviest weight on IOER sitting at its current level, while assigning roughly equal likelihood to 150 or 175 bp

Market-implied probabilities* of change in IOER from present (125 bp) to the period following the March 2018 FOMC meeting; %



* Extracted from forward OIS and OTC caps. The dotted curves show results using an alternative set of assumptions. See appendix for details of the methodology

Source: J.P. Morgan

"As soon as you discard scientific rigor, you're no longer a mathematician, you're a numerologist." – such is the advice given to the protagonist of the 1998 film "Pi", a movie that, like this note, was preoccupied with prediction and financial markets. **To assuage fears of**

[4] At the third meeting step, we actually employed four different sets of assumptions. While the no-September-cut approach reliably produced physically meaningful answers (avoided negative probabilities) on most days, some of the others did not fare as well. However, when they did produce meaningful solutions, the four methods were in good agreement with one-another, to within a few percent for most branches of the scenario tree. As market levels shift about, we think a pragmatic approach that searches out for the most self-consistent solutions is best. We show a couple of these alternative approaches in Exhibits 3 and 5
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[5] "Closest" meaning the solution with the smallest Euclidean distance (L2 norm) from the median likelihoods

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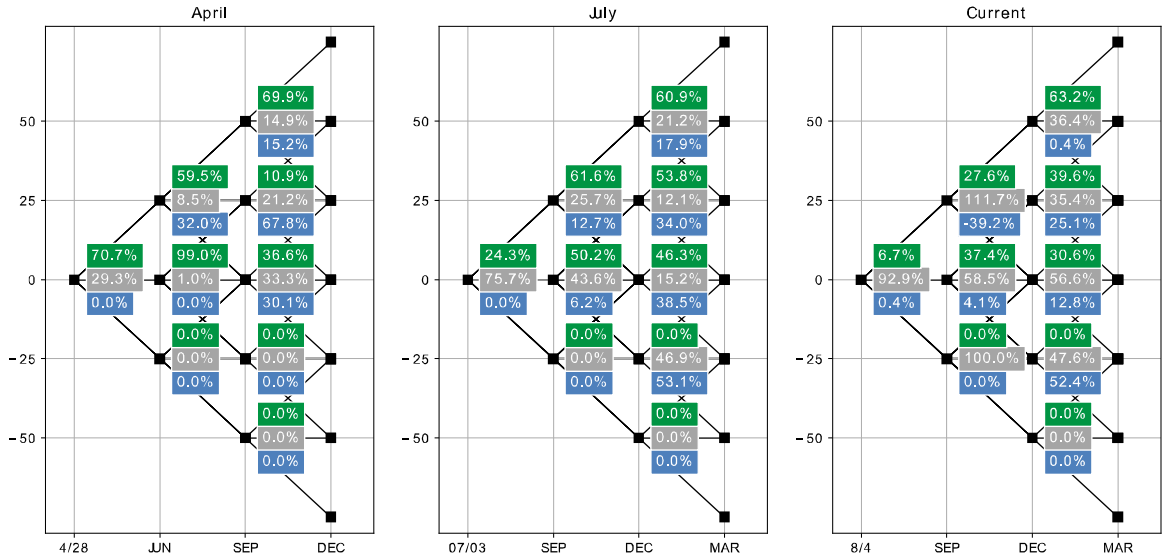
such tea-leaf machinations, we stop to note that a few other sets of assumptions were employed in reaching the probabilities found out to the third SEP meeting, with one of them (which produced physically consistent solutions on a majority of days) also shown in Exhibit 3. We take comfort in its roughly equivalent outcomes, and also from the fact that both solutions vary smoothly from day-to-day since the June meeting.

Exhibit 4 summarizes all results out to three meetings, first prior to the June hike, in early April, and twice in the present pre-September period (in early July and August). The April market-implied probabilities reflected a well-broadcast imminent hike: over a month out from the meeting, the market was already pricing in a 70% likelihood of a bump. Beyond that meeting, the April numbers pointed to an aggressive, quarter-by-quarter path as the modal outcome, though summing across all paths, the most likely outcome was ending up at just 25bp above April's IOER levels. At that point in time the market was pricing in 1.2 hikes by year-end. The seemingly contradictory nature of these statements (the most likely outcome is up 25 bp, but the most likely path is three hikes) is reconciled by appreciating how much weight the market is giving to future cuts (i.e. policy mistakes) within our framework: as of April 28, provided we hiked in June, the likelihood of a cut was 32% in September. Whether or not participants were indeed trading on this view, it is an inevitable implication of the OIS and vol markets in late April.

Moving on to the current inter-meeting regime, **Exhibit 4** again shows substantial weight given to easing action at future meetings: given a September pause (priced in at roughly 92% as of now) followed by a December hike (consistent with our Econ team's view, and priced in as equally likely as a pause), a cut in March is priced in at roughly 25%, a figure that has come down a bit since earlier this month. From all these conditional probabilities, we can compute the market-implied chance of *any* corrective action by the Fed (shown in **Exhibit 5**, as computed with three distinct sets of assumptions). Out to December, this is priced in at roughly 2-5%, down from roughly 20% following the June meeting. And out to March, market levels are consistent with a roughly 25% likelihood of easing action, down from 40% following the June meeting. This landscape is broadly consistent with the flat profile of term OIS seen in recent weeks. While the expected outcome has been very stable over this period, the distribution of outcomes has materially shifted, from a bimodal landscape to a more diffuse distribution, emphasizing central paths (**Exhibit 6**).

Exhibit 4: While OIS forwards point to 0.6 hikes by March 2018, a broad range of outcomes are currently priced in, including substantial risk of a cut in the policy rate over the next few quarters

Market-implied conditional probabilities* for possible Fed rate actions at the three meetings following each observed date; Y-axis is IOER (bp); blue, gray and green values are cut, pause and hike probabilities**†, respectively (%)



* Extracted from forward OIS and OTC caps. The dotted curves show results using an alternative set of assumptions. See appendix for details of the methodology

** For instance, in the central (July Start) panel, the green 61.6% to the right of the square at 25/SEP represents the probability of a 25 bp hike heading into December, given that IOER was 25 bp above its current value (i.e., 150 bp) after the September meeting. Each triplet of conditional probabilities must sum to 1.0 and the *unconditional* probability of realizing any one path between the current date and post-March consists of multiplying together the three relevant boxes (e.g., the likelihood of a triple hike through March as of 7/03 would be 24.3 x 61.6 x 60.9 = 9.1%).

Source: J.P. Morgan

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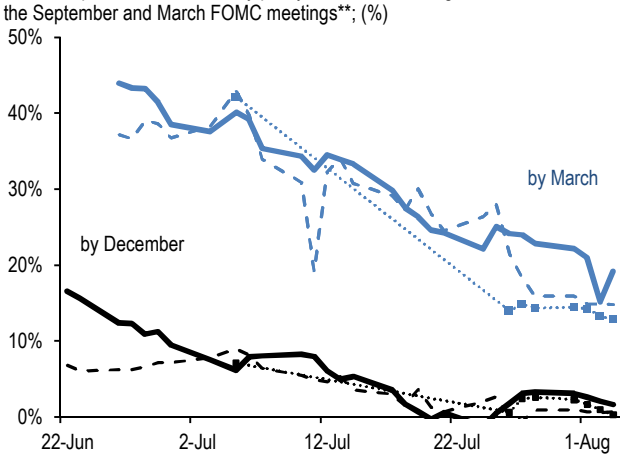
Exhibit 5: The implied likelihood of any policy rate cut (i.e. a policy 'mistake' triggering easing) out to the March FOMC are quite elevated: currently roughly 20%, down from 40% post-June
Market-implied likelihood* of any policy rate cuts occurring between now and the September and March FOMC meetings**; (%)

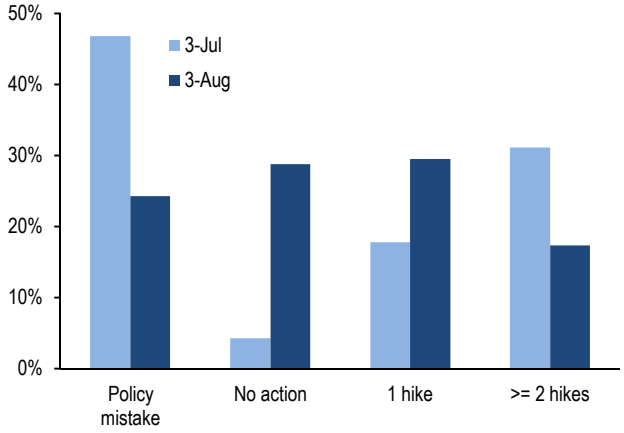


* Extracted from forward OIS and swaptions. The dashed and dotted curves show results using alternative assumptions. See appendix for details of the methodology

**This is computed as the sum of the unconditional probability of any rate path that involves at least one cut between the date of interest just after the September or March meetings.

Source: J.P. Morgan

Exhibit 6: Our framework suggests near-term market implied likelihoods for the Fed have shifted from bimodal to a more diffuse distribution over the past few weeks
Market-implied probability of various Fed policy rate scenarios* through the March FOMC meeting; %



* 'Policy mistake' defined as any scenario with one or more cuts up to and including the March FOMC meeting. 'No action' is three pauses. 1 and >=2 hikes can include a pause as well. We only consider SEP meetings.

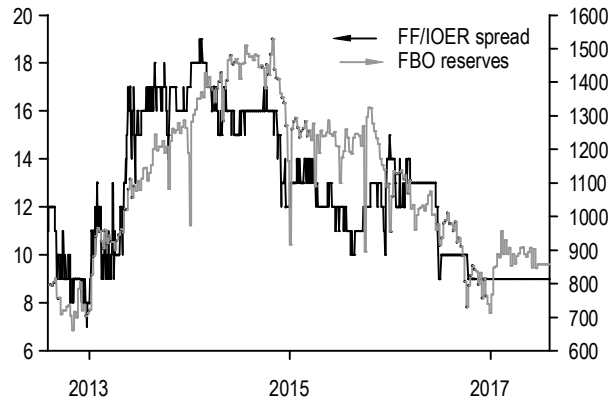
Source: J.P. Morgan

These results serve as a reminder that while "The Market" can often feel like a monolithic voice, it is in fact composed of individuals trading on many contradictory views. Appealing only to expected, averaged quantities, like the number of hikes priced by some future date, can conceal the diversity of these perspectives, whereas a framework that incorporates volatility and attempts to tease out the likelihood of off-consensus outcomes can paint a slightly broader picture of what is currently priced in to rates products. At the moment, this includes surprisingly high odds of corrective action within the next three quarters.

Appendix 1: Projecting FFE including month-, quarter-, and year-end turns

Because OIS swaps reference FFE rather than IOER, the projections on which our scenario analysis rely must incorporate some of the technical dynamics that can drive pricing in the Fed funds market. The first and most important is the location of FFE in the IOER/RRP policy rate corridor. This is driven by a balance between the GSEs and FHLBs, who do not earn interest on reserves and are willing to lend Fed funds at a rate below IOER, and banks seeking to borrow and earn an arbitrage profit. Foreign banking organizations in particular are most active in this trade because their capital costs are generally lower—at least intra-month—making them that much more active in the trade. As a consequence, FF/IOER spreads have generally tracked the overall stock of FBO reserves which we use as a proxy for their overall activity in the Fed funds market (**Exhibit A1**).

Exhibit A1: As activity in the FF/IOER arbitrage trade has declined, FFE has migrated higher in the corridor
Rolling FF/IOER spread (excluding month-end, LHS; bp) and FBO reserves (RHS; $bn)



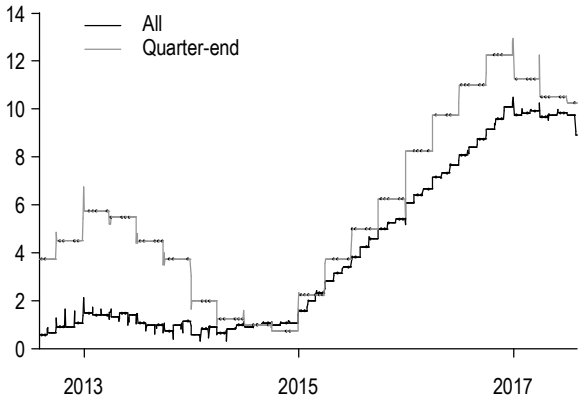
Source: J.P. Morgan, NYFRB, Bloomberg

For the next few months, we expect these spreads to remain stable around 9 bp, which we incorporate into our projections as an assumption. But it is worth noting that the likely beginning of balance sheet normalization in September (see *Next stop: balance sheet normalization*, M. Feroli, 7/26/17) suggests overall reserve balances should decline further in the coming years. Empirically

every $100bn further decline in FBO reserves should push FFE 1-2 bp higher in the corridor (see Interest Rate Derivatives, *US Fixed Income Markets Weekly*, 4/7/17). Therefore, while we do not expect significant changes to reserve balances over the projection windows considered here, over time we will occasionally revisit that assumption.

Exhibit A2: Balance sheet costs among the FBOs active in the Fed funds market lead to sharp drops in FFE around month- and quarter-end

Rolling 1-year average of month- and quarter-end turns in FFE; bp



Source: J.P. Morgan

Second, as alluded to above the behavior of FFE changes around month-end. This is because Basel Leverage Ratio calculations for FBOs use month-end snapshots averaged over the quarter. This significantly increases the breakeven level at which these institutions are willing to participate in the FFE/IOER arbitrage. As a result, month-end turns increased steadily as these regulations were phased in over the past few years, with a modestly larger effect around quarter-ends (**Exhibit A2**). For this piece, we assume 8, 9, and 11 bp turns around month-, quarter-, and year-end, based primarily on recently observed levels. That said, the impact is not large: under current assumptions they are worth approximately 0.5 bp for most FOMC meetings.

Appendix 2: The math behind our approach

For the likelihood of a 25 bp hike in the policy rate at the next (September 2017) FOMC meeting, we would typically quote the following:

$$p_+ = \frac{\text{OIS}_{\text{fwd}}(U7 \rightarrow Z7) - \text{OIS}_0}{\text{OIS}_+ - \text{OIS}_0}$$

where OIS_{fwd}(U7-Z7) represents the traded level of forward OIS with a swap start date on the September 2017 FOMC meeting date and maturity on the December meeting date. OIS_0 and OIS_+ represent the projected spot OIS rates over that period, provided the Fed either holds IOER unchanged or indeed hikes by 25 bp. These projected levels involve compounding daily FF levels, assuming an FFE/IOER basis of 9 bp along with an additional 8, 9 and 11 bp dip at month-, quarter- and year-ends due to window-dressing activity by foreign banks (consistent with dynamics in recent years, see previous Appendix). The above formula comes from matching the probability-weighted average of projected OIS levels under the two policy scenarios with the current forward OIS rate (an expectations hypothesis), along with stipulating that the sum of the two probabilities equal unity (a normalization constraint). This particular formula assumes the Fed will only pursue rate action on an FOMC meeting date which includes a Summary of Economic Projections (SEP), that the hike would be by precisely 25 bp, and that there is essentially no chance of a policy rate cut. We view the first two as quite reasonable: while the Fed has pursued "surprise" cuts of varying magnitudes during past easing cycles, the potential impact of an off-meeting or oddly sized rate move in the current tightening cycle would

likely have an unnecessarily adverse impact on financial conditions and would be inconsistent with the FOMC's desire for transparency and measured action. The third assumption, that a cut is out of the question at the upcoming meeting, is worth relaxing, however.

If we consider the chance of a cut at the next meeting (e.g., September), we now have three unknown probabilities. The normalization constraint and the expectations hypothesis again provide two constraints, but we require one more to "close the system." Beyond matching the forward level, we can also match the forward uncertainty in outcomes: specifically, the second moment—closely related to standard deviation—of outcomes must match the second moment of the implied distribution of future spot OIS. For this we turn to the vol market, using the observed premium of OTM cap-floor swaptions (3-month tails) to reconstruct the market-implied distribution of future spot Libor. We assume this spread in Libor is indicative of the spread in FF-indexed OIS; in fact, over the past few years, realized vols in the two markets have been comparable, with the ratio oscillating closely about unity from month to month. We can then compute the standard deviation of this distribution[6], which we denote $\boldsymbol{S}_{\text{LIBOR}}$, forgoing the usual sigma notation to avoid confusion with volatility. At this point we are in a position to equate the second moment[7] of the implied probabilities to the market level, and solve the follow matrix:

$$\begin{bmatrix} 1 & 1 & 1 \\ \text{OIS}_- & \text{OIS}_0 & \text{OIS}_+ \\ \text{OIS}_-^2 & \text{OIS}_0^2 & \text{OIS}_+^2 \end{bmatrix} \begin{bmatrix} p_- \\ p_0 \\ p_+ \end{bmatrix} = \begin{bmatrix} 1 \\ \text{OIS}_{\text{fwd}}(U7 \to Z7) \\ S_{\text{Libor}}^2 + \text{OIS}_{\text{fwd}}(U7 \to Z7)^2 \end{bmatrix}$$

the rows of the above system can be interpreted as the zeroth, first and second moments of the implied OIS distribution for the Sep/Dec intermeeting period. The LHS matrix is computed from projected future FF settings under the various policy scenarios, essentially fixed and known in advance, while the RHS vector is taken from market observables which vary day-to-day. This linear system emits a closed-form solution for the three probabilities, but in practice we solve numerically.

It's straightforward to extend this approach from one meeting forward to two meetings (at press time, the December 2017 meeting). We choose to formulate the problem in terms of the conditional probabilities (e.g., p(+,-) is the probability of a cut in December given that there was a hike in September). In this setting, there are now 9 outcomes, and the expectations hypothesis can be formulated as

$$\text{OIS}_{\text{fwd}} = \sum_{i,j \in \{-,0,+\}} p_i p_{ij} \text{OIS}_{ij} \;\; ; \;\; p_{ij} = p(j \mid i)$$

where the summation runs over outcomes i at the September meeting and j at the December meeting. OISij are the projected OIS rates given these outcomes, and OIS_{fwd} is the traded level for swaps spanning the intermeeting period. The same formulation with the projected rates squared and cubed gives equations for the second- and third moments (related to vol and skew), and the vol constraint can be sourced for swaps running from the second meeting date until March as well as swaps running from the *first* meeting date (September)

[6] Moments of the implied distribution were found via numerical integrals applying Simpson's rule at 200 equally spaced sample points covering out-strikes well below .001 delta, and then used to compute mean, standard deviation and skew of the distribution.
[7] Note that while we assume the standard deviation of the Libor and OIS implied distributions are equal, this does *not* imply the second moments are equal, since the ATMF levels are disparate across the two markets.

through March[8]. Thus we have *four* market observables. In practice observed market skew is quite low and the third moment is hard to extract properly, since it's very sensitive to the extremes of the distribution. Therefore we zero-out skew in the fitted probabilities, without too much loss of accuracy. Beyond observables, each triplet of conditional probabilities obeys a normalization constraint (e.g. the odds of a hike, pause or cut in Dec given a pause in Sep must sum to one). This adds up to 7 total equations for 9 unknowns. To close the system, we need to impose two more constraints. In general this calls for a pragmatic approach. In recent weeks, the market has priced a September cut at near-zero. We can thus use that to close the system. A similar approach is to zero-out the chance of a double-cut over the next two meetings, along with the chance that the Fed would hike in December having just cut in September. This "no-double-cut" approach would yield the following system of equations:

$$\begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ p(i)\times \mathrm{OIS}(Z7\to H8\mid i,j) & & & & & & & & \\ p(i)\times \mathrm{OIS}(Z7\to H8\mid i,j)^2 & & & & & & & & \\ p(i)\times \mathrm{OIS}(Z7\to H8\mid i,j)^3 & & & & & & & & \\ p(i)\times \mathrm{OIS}(U7\to H8\mid i,j)^2 & & & & & & & & \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} p(-,-) \\ p(-,0) \\ p(-,+) \\ p(0,-) \\ p(0,0) \\ p(0,+) \\ p(+,-) \\ p(+,0) \\ p(+,+) \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \\ \mathrm{OIS}_{\mathrm{fwd}}(Z7\to H8) \\ S_{\mathrm{L}}(ZH)^2+\mathrm{OIS}_{\mathrm{fwd}}(Z7\to H8)^2 \\ \gamma_{\mathrm{L}}S_{\mathrm{L}}(ZH)^3+3\mathrm{OIS}_{\mathrm{fwd}}(Z7\to H8)S_{\mathrm{L}}(ZH)^2+\mathrm{OIS}_{\mathrm{fwd}}(Z7\to H8)^3 \\ S_{\mathrm{L}}(UH)^2+\mathrm{OIS}_{\mathrm{fwd}}(U7\to H8)^2 \\ 0 \\ 0 \end{bmatrix}$$

where the first three rows represent normalization constraints on the conditional probabilities. The next three represent observed moments, related to OIS forwards, OTC cap vol via $\boldsymbol{S}_{\mathrm{L}}$, and skew via γ_{L}, for the Dec/Mar period (hence Z7 > H8). The various combinations of *i* and *j* meeting outcomes fill out the 9 columns in the LHS matrix. The seventh row represents the second moment (vol) for Sep/Mar OIS. And the final two encode our no-double-cut and no-hike-following-cut constraints. This system again admits an algebraic solution in theory, but in practice we solve numerically to obtain the daily probabilities. This solution and the no-Sep-cut approach yield nearly identical results. A third approach, which zeros-out a cut immediately following a hike (a so-called "policy mistake") while allowing for the double-cut does a worse job, admitting many non-positive probabilities on most days.

At the third step, there are 27 unknown conditional probabilities, formulated in a similar fashion to the second step. There are up to 9 normalization constraints and 5 well-behaved market observables (the Mar/June 2018 forward, vol and skew, and two longer-dated vols from Sep and Dec 2017 to June 2018). These 14 constraints leave a gap of 13 unknowns. In practice, by the second step, several extreme outcomes have been eliminated (a double cut, hikes after cuts) and this typically zero's out 6-9 of the unknowns, which leaves us in search of 7 additional constraints. 2-3 come from eliminating further examples of hikes after cuts. We also typically assume no strong path-dependence if the Fed has hiked once prior to the third meeting (either at the first or second). This typically leaves us under-constrained in just three dimensions. From there, we explore this 3-dimensional parameter space, varying three high-likelihood outcomes between 0 and 1 in increments of one-hundredth (typically P(0,0), P(+,0) and P(+,+)), for a totally of 10^6 "solutions". Thus we evaluate a system of 27 equations at each mesh point in the 3D parameter space, obtaining

[8] The Sep/Mar OIS forward contains no new information we haven't already incorporated from the Sep/Dec and Dec/Mar forwards, since the first can be bootstrapped from the others. However, the Sep/Mar vol level *does* contain distinct information from the Sep/Dec and Dec/Mar levels, since it depends on implied correlation.

10^6 length-27 solution vectors of conditional probabilities[9]. The vast majority of these outcomes have highly unphysical probabilities (some less than zero, others far larger than one). When we eliminate all but the best solutions, we're typically left with ~100 answers, and the computed conditional probabilities among this set do not vary dramatically, typically in disagreement by ~5% for heavily weighted branches. To proceed to an answer, we take the median of each probability in the solution set and then select the individual solution closest to this set of medians by Euclidean distance (L2-norm). Selecting a specific answer is necessary since the median values are not guaranteed to sum to unity.

While this approach involves a bit of mathematical tomfoolery, we can bolster its validity by employing disparate sets of assumptions. We took five different approaches: zeroing out the double cut, zeroing out a first-meeting cut, zeroing out "whipsaw" paths, zeroing out cuts from the baseline prior to the third meeting, and a "binary" approach where no cuts were allowed at all. Some of these assumptions seemed to directly contradict the market, and failed to yield physical results on most days (in particular zero-whipsaw performed poorly most days and the binary approach failed miserably). Others were quite robust and in good agreement with each other (the no-double-cut and no-Sep-cut approaches). Some performed best in one regime only to fail in another (not allowing IOER to drop below the current level until the third meeting worked well heading into the June meeting, but is less successful in today's market). Where the approaches did yield "physical" solutions, those solutions tended to agree with one another reasonably well (see Exhibits 3 and 5). Further, the solutions varied in a smooth and continuous fashion from day to day, particularly along paths deemed likely to be realized. From all this, we feel confident the framework delivers a meaningful gauge of market-implied path probabilities.

[9] In an *over-constrained* systems, where there are typically well-established scalar metrics for an optimal answer (e.g., maximal likelihood) you can employ a gradient-decent or Markov chain Monte Carlo approach to solving, and avoid an exhaustive search of parameter space. But for an *under-constrained* system like ours there doesn't seem to be an obvious metric for success beyond eliminating bad solutions. While you can impose some scalar metric, like minimizing the largest probability (min L1-norm), there's no intuitive motivation for such an objective, except in declaring it the market's "lowest conviction" solution. Fortunately, computing outcomes within a uniform mesh is not a terrible idea for a linear set of equations for probabilities, since the solution set is a finite, bounded hyperplane, and not some poorly behaved, unbounded, non-linear surface.

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