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Interest Rate Derivatives

i-PCA: Implied Principal Component Analysis

- 2023 will be a year that likely brings a shift in the monetary policy stance, and early identification of regime shifts will be critical to trading the yield curve next year.
- We developed an "Implied Principal Component Analysis" (i-PCA) framework that shows promise in this regard, has no lags whatsoever, and currently suggests that a regime shift may be imminent.
- Implied principal components are constructed by leveraging forward-looking information: implied volatilities from the swaptions market and implied correlation from the YCSO market, which together determine the covariance structure from which principal components can be inferred via eigenvalue decomposition.
- Within the i-PCA framework, there is a natural analogue to the notion of how much variance is explained by each principal component. The first two implied principal components are sufficient to explain almost the entire implied covariance structure of rates.
- Sharp declines in the percent of variation explained by the first implied principal component could foreshadow an upcoming shift in regime change.
- The beta inferred between two rates using the first implied principal component weightings can be a good predictor of the *ex-post* realized beta between those rates.

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See page 10 for analyst certification and important disclosures.

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i-PCA: Implied Principal Component Analysis

It has been a year for the fixed income market record books. We came into this year with a rebounding post-pandemic economy that had helped set the stage for the Fed to tighten monetary policy, and Fed tightening was the dominant undercurrent beneath our market views. The Fed has tightened 375bp year to date and will likely finish the year having raised the funds rate by at least 425bp. As we approach the year-end, the Fed appears to be on the verge of a downshift in pace. If such a downshift comes to pass and inflation becomes contained next year, we could be entering a new Fed regime.

With that, one of the most important aspects of trading the yield curve in 2023 will be the correct – and early – identification of regime shifts. Being early to spot a shift to a regime where the Fed might be expected to have an easing bias can be quite beneficial. Of course, this is not an easy task by any means. But given its importance, it is well worth developing leading indicators that can potentially signal such regime shifts.

One such approach is to combine forward-looking information from the swaptions markets and forward-looking correlation information from the Yield Curve Swaption Option (YCSO) markets to construct "implied principal components", which are essentially forward-looking analogues of the historical

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principal component analysis (PCA) that many investors are very familiar with. We discuss the development of such an Implied PCA (i-PCA) framework in this paper.

The outline of this paper is as follows. First, **we note that historical betas between two different points on the curve can be wildly different from *ex-post* betas in periods of regime change; this motivates the question of how to develop better forward-looking betas**. We do this by first starting with implied vol ratios (commonly used by many investors) but then improving upon it by using implied correlation information. We then shift gears to a quick recap of historical PCA as it is routinely and widely performed, so as to set the stage for what comes next. We then **develop an implied PCA framework that is analogous to historical PCA but uses only forward-looking implied vol and implied correlation information**; it is thus subject to no lags whatsoever. We also develop the natural analogue of the notion of the percentage of variance explained by each implied principal component – although i-PCA is forward looking and there is no *ex-post* variation that needs to be explained; there is an analogous concept that is based on the magnitudes of the various principal components. Finally, **we finish by noting how i-PCA can be used to extract better betas and how the percent of variation explained by the implied level factor appears to have some ability to provide early warning of regime shifts**.

A framework for characterizing forward-looking yield curve behavior

This year was clearly marked by a dramatic shift in the policy regime, from ZIRP all the way to the most aggressive hiking cycle witnessed in recent memory. As a result, both yield levels and the curve have traded in wide ranges. But equally important, the relative movement of different tenors (e.g., the beta between 2s and 10s, for instance) has also varied wildly. This is problematic for a number of reasons – investors' identification of relative value across the curve relies on estimates of the appropriate beta between different tenors. It is also important for hedging and risk management. Large portfolio managers typical have interest rate risk exposures at various points on the curve but must usually hedge those exposures with the most liquid instruments available. Thus, an investor seeking to hedge risk in one maturity sector with an instrument in another (whether because of liquidity, relative value or other preference) must rely on an estimate of the beta between those two points. In periods characterized by a regime shift, this can be quite a problem. For instance, as the year has unfolded, the rolling 3M beta between changes in 2Y yields versus 10Y yields has varied between a low of 0.3 and a high of 1.2. Thus, an investor looking to construct a beta-weighted relative value trade (or an investor who seeks to hedge 2Y risk exposure with 10s, for instance) risks being wildly off on the hedge ratio. For instance, at the start of the year, an investor looking at backward looking 3M betas would have concluded that 2s would exhibit a 30% beta with respect to 10s, only to discover *ex-post* that the next three months resulted in 2s moving with an 80% beta with respect to 10s. The situation remained the same for much of the year – in May, for instance, a backward-looking beta estimate between 2s and 10s was 0.7, but between May and August 2s exhibited a beta of 1.2 with respect to 10s.

Thus**, it would be useful to have a framework that generates forward-looking betas between different tenor pairs, because in a period of Fed regime change, backward-looking betas can deviate considerably**. But such a framework could be very useful for a different reason as well. Assuming such a framework can be found, perhaps by looking to the options markets, we could use it as a forward-looking indicator of upcoming regime change in yield curve behavior. That is, if our forward-

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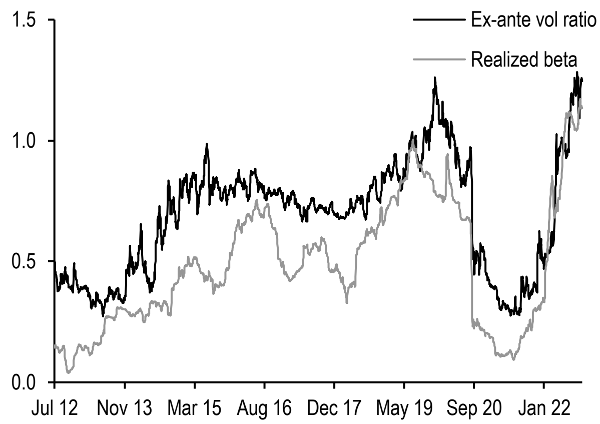
looking betas were to deviate significantly from backward looking betas, that may be equivalent to finding a signal that points to a different behavioral regime going forward.

In short, **active Fed regimes clearly pose difficulties for the statistical estimation of hedge ratios given the dynamic nature of the regime and the potential for future co-movements to differ dramatically from backward looking estimates**. It is therefore tempting to ask if market-implied information can help in this regard. Said differently, **can we extract useful forward-looking information from the options markets**?

Implied betas from options markets

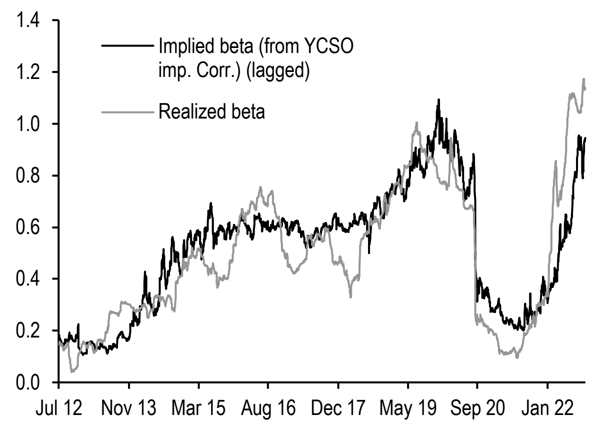
As a first pass, it is tempting to use implied vol ratios as forward-looking estimates of betas. For instance, the ratio of (say) 6Mx2Y implied bp vol to the 6Mx10Y implied bp vol may be used as an estimate of the beta between 2s and 10s over the next six months. While plausible, this turns out not to perform so well – as it turns out, vol ratios are systematically biased higher (for this example) much of the time, and especially so during on-hold periods where risk-premium biases 2Y tail implieds higher and thus biases vol ratios higher (**Exhibit 1**).

Exhibit 1: Implied vol ratios are a natural first attempt at a forward-looking beta, but this falls short and tends to exhibit significant bias
Realized 6M beta between weekly changes in 2Y swap yields and 10Y swap yields, versus the 6M lagged 6Mx2Y-to-6Mx10Y implied volatility ratio, Jul 2012-Oct 2022



Source: J.P. Morgan

Exhibit 2: A forward looking beta estimated using implied correlation from the YCSO market in addition to swaption volatility information performs much better than a simple implied vol ratio
6M realized beta between weekly changes in 2Y and 10Y swap yields, versus the 6M lagged implied beta*, Jul 2012-Oct 2022



* Calculated as the implied correlation between 2Y and 10Y swap yields (inferred from 6M expiry single look YCSO on 2s/10s) times the 6Mx2Y implied volatility and divided by the 6Mx10Y swaption implied volatility
Source: J.P. Morgan

Of course, betas depend on volatility as well as correlation, and the problem with using a simple swaption vol ratio is that it uses no correlation information – said differently, using a vol-ratio as a forward-looking beta estimate effectively means that we are assuming perfect correlation going forward. But we can observe forward-looking implied correlations from the YCSO market – that offers a straightforward way to see if we can improve upon vol ratios and estimate a better "implied beta". Recall that mathematically the beta between some variable Y and X is simply the correlation coefficient between X and Y multiplied by the volatility of Y and divided by the volatility of X (see Technical Appendix 1). Therefore, we can calculate an implied beta as simply the product of the implied vol ratio and the implied

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correlation from the YCSO market (see Technical Appendix 1 for details). As we can see in **Exhibit 2,** such an implied beta improves on a simple implied vol ratio and comes closer to matching the subsequent 6M realized beta between 2s and 10s.

Although this is a considerable improvement, this has its drawbacks as well. The reason is rather technical and nuanced – to illustrate why this is the case and how we can do better, we must first discuss a generalization of the above discussion to calculate what we call implied principal components.

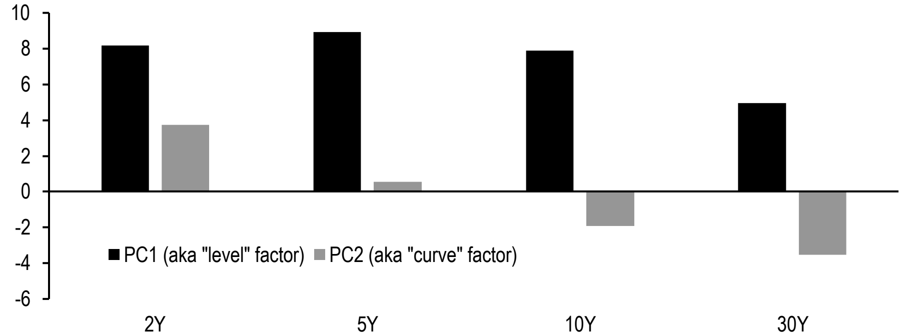
PCA – A brief recap

We begin by recalling the core elements of **historical PCA, which is simply a mathematical tool to express changes in yields at a number of tenors** (which will generally exhibit a high degree of correlation) **as the sum of effects from a small set of uncorrelated "factors"**. For instance, a unit move in the so called first principal component, or level factor, might produce an 8bp move in 2Y rates, a 9bp move in 5Y rates, and 8bp and 5bp moves in 10- and 30-year rates. Thus, on a day when a 1-sigma upward move in the level factor happens to occur (with no other moves), 5Y rates would rise by 9bp and the 5s/30s curve would flatten 4bp, but this flattening is merely the effect of the level factor, which just happens to produce unequal co-movements across different curve points.

Separately, we can imagine a second "curve" factor (or second principal component), which may also move up and down, but in a manner uncorrelated to the level factor. A 1-sigma upward move in this factor might produce, for instance, a 3.5bp increase in 2Y yields, a 2bp decline in 10Y yields, and a 3.5bp decline in 30Y yields. But these moves would be over and above the impact of any yield changes that are the result of the level factor. These principal components are illustrated in **Exhibit 3**, which shows the first and second principal components estimated using 3M history as of the first of November. It is worth noting, and is the case by construction, that the first factor produces the largest impacts on yields, and every successive component produces ever smaller impacts. It is typically the case that the first factor typically explains over 90% of the variance in yields, and the second factor helps to explain most of the remainder.

Exhibit 3: An illustration of the first two principal components and their impact on benchmark yields

Impact of a +1-sigma move in the first two principal factors* (the "level" and "curve" factors), on 2Y, 5Y, 10Y and 30Y swap yields; bp



* Estimated from 3M history, calculated as of 11/1/2022
Source: J.P. Morgan

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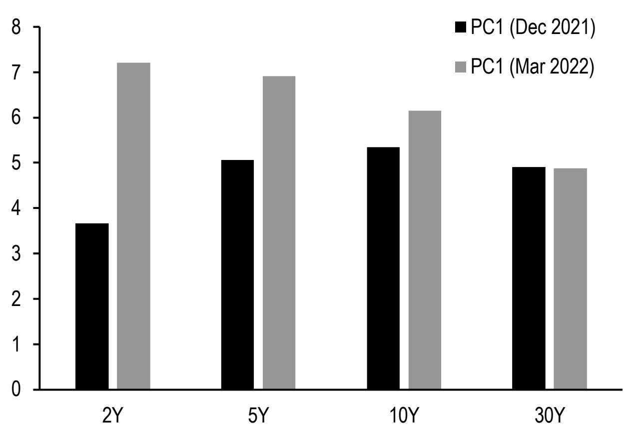
We make two observations before moving to implied PCA. First, since **it is typically the case that the first factor explains most of the variation**, and (as we will see shortly) **the second factor's explanatory power tends to be small most of the time, the information needed to estimate a beta between (say) 2s and 10s is mostly contained in the first component**. In our example above, since a 1-sigma move in the level factor would produce a 9bp rise in 2Y yields and a 5bp move in 30Y yields, we could estimate the beta between 5s and 30s at 1.8 (9bp divided by 5bp), if the noise from other factors can be assumed to decay. Of course, historical PCA suffers from the same drawback of lacking forward-looking information, which can be problematic during periods of regime shift. As seen in **Exhibit 4**, the impact from PC1 that one would have estimated using historical PCA as of December 2021 was considerably different from the impacts estimated as of Mar 2022, because we transitioned into a regime where the Fed was expected to be actively hiking. The second component, in contrast, experienced less reshaping between December 2021 and March, even as the Fed came into play (**Exhibit 5**). Thus, **it appears that regime shifts largely impact the profile of the first principal component and watching for signs of change in the first component can have a signaling benefit**, particularly if we could do this on a forward-looking (rather than historical) basis. We discuss this next.

Exhibit 4: When regime shifts happen, the first principal component can experience significant reshaping …

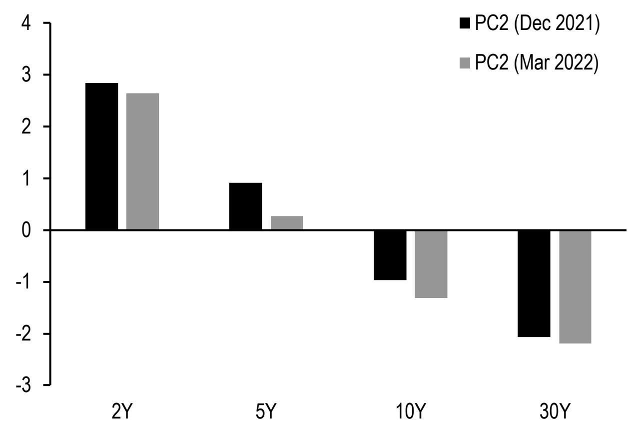
Impact of a 1-sigma upward move in the first principal component, estimated from 3M history as of the end of December 2021 and March 2022; bp



Source: J.P. Morgan

Exhibit 5: … while the second component remains much more stable

Impact of a 1-sigma upward move in the second principal component, estimated from 3M history as of the end of December 2021 and March 2022; bp



Source: J.P. Morgan

Implied principal components

We have already discussed how to calculate implied covariances from options market information. For instance, we can multiply the implied 2s/10s correlation (from, say, 6M expiry YCSOs) by the product of implied volatilities (6Mx2Y and 6Mx10Y) to get the implied covariance between 2s and 10s. We can repeat this exercise for each pair of tenors of interest and thus **create an implied covariance matrix**. **This matrix can then be factorized (see Technical Appendix 1) to yield implied principal components**. This is illustrated in **Exhibit 6**. The factorization is known as an eigenvalue decomposition, which produces so-called eigenvalues and corresponding eigenvectors. **A scaled version of the eigenvectors** (scaled by the square root of the associated eigenvalue) **can be interpreted as implied principal components**. Lastly, **the ratio of each eigenvalue to the sum of all eigenvalues may be interpreted as the percent of variance that is explained by the corresponding principal component**. Thus, this process gives us implied (or

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forward-looking) versions of every notion that we are used to having from historical PCA.

Exhibit 6: Implied correlation from YCSO markets can be combined with implied volatilities from the swaptions market to create an implied covariance matrix, which can be factorized to produce implied principal components

An illustration of the calculation to take implied volatility and correlation information from swaptions and YCSO markets, and produce implied principal components; actual data as of 10/31/2022

Implied correlations, from YCSOs	2Y	5Y	10Y	30Y
2Y	1.00	0.91	0.74	0.57
5Y	0.91	1.00	0.94	0.79
10Y	0.74	0.94	1.00	0.92
30Y	0.57	0.79	0.92	1.00

combined with

Impl. Vol 6M Exp
9.37
9.31
8.72
7.27

gives us

Implied covariance matrix	2Y	5Y	10Y	30Y
2Y	87.8	79.0	60.1	39.0
5Y	79.0	86.6	76.6	53.2
10Y	60.1	76.6	76.0	58.6
30Y	39.0	53.2	58.6	52.9

which when factorized gives

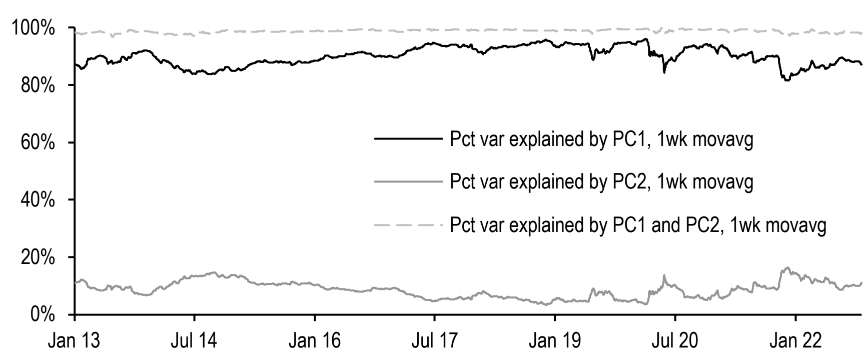
Implied Principal Components	PC1	PC2	PC3	PC4
2Y	8.37	4.09	0.96	0.05
5Y	9.22	0.69	-1.07	-0.12
10Y	8.38	-2.26	-0.89	0.12
30Y	6.19	-3.51	1.48	-0.05

Source: J.P. Morgan

Having developed a framework for calculating implied principal components, we now look to see what they can tell us. First, we note that over long history, **the first two implied principal components are sufficient to explain almost the entire (implied) covariance structure of rates** (**Exhibit 7**). Second, **sharp declines in the percent of variation explained by the first implied principal component tend to foreshadow an upcoming shift in regime** (**Exhibit 8**). For instance, sharp drops were seen in June 2019 (a few weeks before the Fed began cutting rates), in late Feb / early March 2020 (before the Fed went back to ZIRP and QE due to the pandemic's onset), in May 2020 (ahead of the steady steepening in the 5s/10s curve that began a few months later) and in Oct 2021 (ahead of the Fed's pivot to tightening and eventual QT). Third, **the beta we can infer between two different rates based on how they are impacted by the first implied principal component appears to be a very good predictor of the *ex-post* realized beta between those rates (Exhibit 9)**.

Exhibit 7: The first two implied principal components suffice to explain almost the entire covariance structure of rates

Percent of variance explained by the first implied principal component*, the second, and the sum of the two; Jan 2013 – Oct 2022



* For each principal component, we define its loadings on the 2Y, 5Y, 10Y and 30Y sector to be the impact of a 1-sigma move in that component on 2Y, 5Y, 10Y and 30Y rates respectively. For each principal component, we also define a quantity called its norm, which is calculated as the square root of the sum of squares of the loadings. Finally, the percent variation explained by each component is calculated as the square of its norm, divided by the sum of squared norms of all the components.
Source: J.P. Morgan

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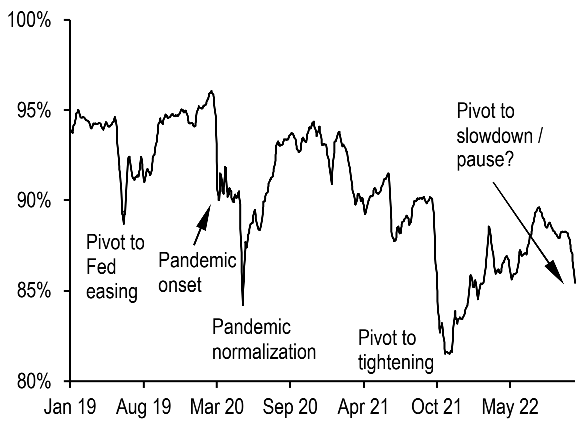
Exhibit 8: The next best thing to a crystal ball? Sharp drops in the percent variation explained by the first implied principal component appear to precede yield curve behavioral regime changes

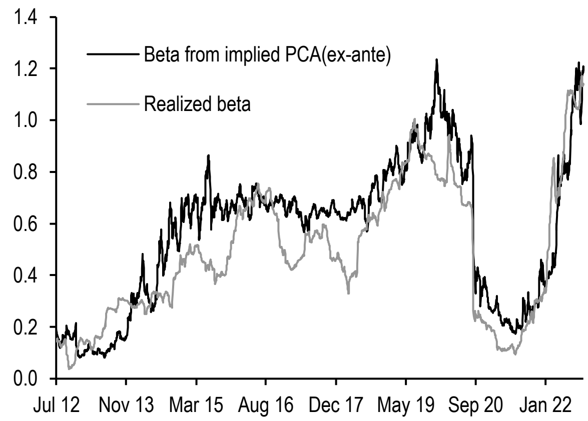
Percent variation explained by the first implied principal component; 01/2019 – Oct 2022



Source: J.P. Morgan

Exhibit 9: Implied principal components can also be useful to estimate forward looking betas between tenor pairs

6M rolling beta between weekly changes in 2Y yields versus 10Y yields, and the 6M lagged implied beta* calculated from the first implied principal component; unitless



* Calculated as the ratio of 2Y weighting to 10Y weighting in the first implied principal component.

Source: J.P. Morgan

Lastly, **what does all this tell us about the future now**? **The sharp drop seen in late October in Exhibit 8 points to an imminent change in yield curve regime, likely anticipating the Fed's downshift in pace as early as next week**. But more broadly, we anticipate that 2023 will be a year of shifting expectations, until and unless inflation data exhibit a clear downward trend. We believe implied principal components will likely provide better hedge ratio estimates between different tenors and also serve as an early warning of any potentially sizeable regime shifts in the year ahead.

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Technical Appendix 1: Implied Beta and Implied Principal Components

1) **Beta**, in the context of fixed income, measures the co-movement of different rates. Using 2s and 10s, for instance, denoted $\boldsymbol{r_2}$ and $\boldsymbol{r_{10}}$, we may write the simple linear regression: $\boldsymbol{\Delta r_2 = \alpha + \beta * \Delta r_{10} + \epsilon}$, where $\boldsymbol{\alpha}$ is the intercept (usually close to zero) and $\boldsymbol{\epsilon \sim N(0, \sigma^2)}$ is the random error term. Mathematically, this beta can be written as $= \frac{Cov(\Delta r_{10}, \Delta r_2)}{Var(\Delta r_{10})}$. Note also that the **correlation coefficient** between changes in 2Y and 10Y yields satisfies $\boldsymbol{\rho} = \frac{Cov(\Delta r_{10}, \Delta r_2)}{\sigma_{\Delta r_{10}} \sigma_{\Delta r_2}}$. This $\boldsymbol{\rho}$ is the correlation coefficient and is always between $\boldsymbol{-1 \leq \rho \leq 1}$ although it is typically non-negative in the context of our application to yields. Simply rearranging, we then get $\boldsymbol{\beta = \rho} * \frac{\sigma_{\Delta r_2}}{\sigma_{\Delta r_{10}}}$. This useful because it allows us to express a beta using correlation coefficient and volatilities, and forward-looking (implied) versions of volatilities and correlation are available from the options market. Implied volatilities are of course available from swaptions, and implied correlations can be inferred from the Yield Curve Spread Options market. For instance, given the premium for an option on the 2s/10s curve, we can back out an implied curve volatility, denoted by $\boldsymbol{\sigma_{r_{10}-r_2}}$. Implied correlation can then be inferred from the 2 swaption implied volatilities and the implied curve volatility. Last, we can plug those into the equation for **implied beta** as calculated above to get: $\boldsymbol{\beta_{imp} = \rho \frac{\sigma_{r_2}}{\sigma_{r_{10}}} = \frac{\sigma^2_{r_{10}} + \sigma^2_{r_2} - \sigma^2_{r_{10}-r_2}}{2\sigma^2_{r_{10}}}}$.

2) To get an **implied covariance matrix**, denoted $\boldsymbol{C_{imp}}$ (and illustrated using 2Y, 5Y, 10Y, and 30Y rates), we simply enter squared vols in the diagonal elements. For the off-diagonal elements, we write the product of the implied correlation and the two implied vols. For instance, the covariance between rates **ri** and **rj** would be $\boldsymbol{Cov(r_i, r_j) = \rho_{(r_i, r_j)} \sigma_{r_i} \sigma_{r_j} = \frac{1}{2}(\sigma^2_{r_i} + \sigma^2_{r_j} - \sigma^2_{r_j - r_i})}$. Thus we get

$$\boldsymbol{C_{imp}} = \begin{bmatrix} \boldsymbol{\sigma_2^2} & \cdots & \boldsymbol{\frac{1}{2}(\sigma^2_{r_2} + \sigma^2_{r_{30}} - \sigma^2_{r_{30}-r_2})} \\ \vdots & \ddots & \vdots \\ \boldsymbol{\frac{1}{2}(\sigma^2_{r_2} + \sigma^2_{r_{30}} - \sigma^2_{r_{30}-r_2})} & \cdots & \boldsymbol{\sigma_{30}^2} \end{bmatrix}.$$

3) This implied matrix can now be factorized to yield implied principal components. This is done by performing an eigenvalue decomposition on the implied covariance matrix to back out unique eigenvalues $\{\boldsymbol{\lambda_i}\}$ and associated eigenvectors $\{\vec{\boldsymbol{v}}\}$. This is typically written as $\boldsymbol{C_{imp} = PDP^T}$ where D is a diagonal matrix with the eigen values and the columns of P are the associated eigen vectors. It is also traditional to sort the eigen values in descending order.

4) After that, we compute the matrix $\boldsymbol{V = P\sqrt{D}}$. The columns of this matrix gives our Implied Principal Components, and are scaled to reflect a sense of magnitude. I.e., the first column represents the impact of a 1-sigma move in the level factor on rates in different tenors, the second column reflects the impact of a 1-sigma move in the second (or curve) factor, and so on.

5) Lastly, the ratio of the first eigen value to the sum of eigen values can be interpreted as the percent of total variance explained by the first factor. The ratio of the second eigen value to the sum of eigen values represents the percent of total variance explained by the second factor, and so on.

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