

Semi-strong Factors in Asset Returns^{*□}

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Abstract

We refine the approximate factor model of asset returns by distinguishing between natural rate factors, whose sum of squared factor betas grow at the same rate as the number of assets, and semi-strong factors, whose sum of squared factor betas grow to infinity, but at a slower rate. We characterize the cross-sectional mean and mean-square of semi-strong factor betas, and differentiate them from natural rate factors.

We apply the methodology to daily equity returns to characterize some pre-specified factors as natural rate or semi-strong.

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1 Introduction

The approximate factor model of asset returns is a workhorse of research on asset pricing and portfolio construction. It uses the many-asset framework of Ross's (1976) Arbitrage Pricing Theory, in which we consider a sequence of economies with a growing number of assets and rely on limiting conditions as the number of assets grows large. In the classic formulation of Chamberlain and Rothschild (1983), an approximate factor model is defined by the asymptotic behavior of the eigenvalues of the asset return covariance matrix when the number of assets, n , grows large. If the largest k eigenvalues of the covariance matrix grow unboundedly with n and the remaining eigenvalues are bounded above for all n , then returns obey an approximate factor model with k factors. Chamberlain and Rothschild also show that the eigenvectors of the return covariance matrix associated with the k largest eigenvalues can serve as factor exposures (factor betas) up to an arbitrary nonsingular rotation of the factors.

Chamberlain and Rothschild work with the true covariance matrix and do not directly address estimation issues. In empirical implementations of their framework, it is standard to impose slightly more structure. In particular, standard empirical implementations assume that the k dominant eigenvalues grow at the "natural" rate of n . See, for example, Connor and Korajczyk (1986), Stock and Watson (2002), and Bai (2003) who all impose this natural rate assumption. This paper considers the case in which the Chamberlain and Rothschild assumptions hold, but some eigenvalues grow at a slower rate, $n^{\frac{1}{2}}$, $0 < \frac{1}{2} < \psi$. We show that the associated factors can be interpreted as systematic, but less important, sources of

return variation. Following the terminology of Chudik, Pesaran, and Tosetti (2011), we call these *semi-strong* factors. Semi-strong factors are stronger than *weak factors* which have bounded eigenvalues, but weaker than *natural rate* factors whose eigenvalues grow at the rate n .¹

We work with the case in which factors are observed directly, so the eigenvalue condition is more simply stated as a condition on the sum of squared betas for a given factor. A natural rate factor has sum of squared betas going to infinity at rate n whereas a semi-strong factor has sum of squared betas going to infinity at rate $n^{1-2\psi}$, with $0 < \psi < \frac{1}{2}$. We estimate the factor betas with simple time series ordinary least squares of individual returns data regressed on the set of factors. We show that by using the large cross-section of time-series regression-estimated factor betas one can measure cross-sectional features such as the average factor beta and the mean-squared factor beta. We derive the asymptotic distributions of the cross-sectional mean and mean-square of the time-series estimated factor betas, and propose test statistics for distinguishing them from zero and for distinguishing natural rate from semi-strong factors.

Uematsu and Yamagata (2019) provide a procedure for estimating latent semi-strong factor models. They impose a sparsity condition, requiring that only a small proportion of the semi-strong factor betas are substantially different from zero. We treat the much simpler case in which the factors are directly observed, so that only the betas must be estimated.

¹Note that the term "grow" is used here in terms of the asymptotic approximation for large n ; in actual data, n is fixed. A difference in "rate of growth" means in practice that the approximation for natural rate factors has different statistical properties than the approximation for semi-strong factors.

We do not impose a sparsity condition on the semi-strong factor betas; we allow the betas to be diffusely spread across a large proportion of the assets.

Ross's Arbitrage Pricing Theory has two basic steps: step one is identification of the pervasive factors in random returns; step two is estimating the risk premium (if any) in asset expected returns associated with each factor. In this paper we only address the former; we do not consider the vexing problem of identifying risk premia associated with the factors. See Lo and MacKinlay (1990), Kan and Zhang (1999), Harvey, Liu and Zhu (2015) for discussion and overview on the vast array of potential factor risk premia which have been examined.

An important issue with semi-strong factors is that standard approaches to estimating latent factors, such as factor analysis or asymptotic principal components, have difficulty recovering semi-strong factors. This implies that standard latent factor approaches may fail to identify semi-strong factors (we demonstrate this empirically below). Therefore, risk models for portfolios with particular tilts toward those semi-strong factors may underestimate the risk of the portfolios.

It is certainly possible that "smart beta" or factor investing might lead to portfolios tilted toward a semi-strong factor without a PCA-based risk analysis detecting the exposure. In unreported results, we find that the returns on a Quality minus Junk (QMJ) smart beta portfolio (Asness, Frazzini, and Pedersen (2019)) has significant exposure to the gold factor we use in our analysis.

As a concrete example of an application of our framework, consider the sensitivity of individual US equities to fluctuations in the South Korean Won exchange rate against an

international currency basket. The many US companies who import Korean goods may benefit from a relative decline in the Korean Won exchange rate, whereas many others, such as domestic manufacturers exporting to Korea or competing against Korean imports, may benefit somewhat from a relative increase. Economists may be interested in measuring the cross-sectional features of assets' exposures to this small common factor, even it is only a negligible source of risk in most well-diversified portfolios. For example, we can examine whether the aggregate features of the cross-section of individual betas of US firms to Korean Won movements has changed over time. We may wish to measure the magnitude of the (relatively small) influence of Korean exchange rate changes on US equities, and examine whether the changing nature of the trade relationship between the US and Korea is reflected in the changing magnitude of this influence over subperiods. Portfolio analysts may be interested in measuring or hedging Korean Won risk if for some reason they are holding a portfolio which included a non-negligible position in this risk.

Section 2 presents the statistical framework for our analysis. We use a random coefficients specification to model both natural rate and semi-strong factors within a unified approximate factor model framework. Section 3 presents theoretical results on the estimation of factor betas and drawing inferences about their cross-sectional distribution (average and mean-square). We give conditions such that the factor betas' cross-sectional moments can be consistently estimated from a large- n cross-section of individual fixed- T time-series regression coefficient estimates. We also devise a statistical test for distinguishing natural rate factors from semi-strong factors.

We apply the methodology to individual US equity returns using the Fama-French market, size and value indices and changes in foreign exchange rates and commodity prices as factors. We use daily data over six five-year subperiods, 1989-2018. The Fama-French indices are natural rate factors. Oil and gold price changes are statistically significant factors, but the evidence is mixed as to whether they are better classified as natural rate or semi-strong. Foreign exchange factors are significant only in the more recent subperiods and are only semi-strong factors. Lumber is not significant as a natural rate or semi-strong factor; it is at best a weak factor with average squared beta indistinguishable from zero. Section 5 concludes.

2 An approximate factor model with semi-strong factors

We begin by assuming a factor model of returns, and then differentiate between natural-rate and semi-strong factors within the model. We consider a sequence of return models with increasing cross-sectional dimension. For each n , let $r_{t\sqcup}$ denote the n -vector of asset returns. We assume that for each n the vector of returns obeys the following model:

$$r_{t\sqcup} = a + Bf_{t\sqcup} + \varepsilon_{t\sqcup} \quad t = 1, T, \psi \tag{1}$$

where a is an n -vector of constants, B is a $n \times k$ -matrix of factor betas, $f_{t\sqcup}$ is a k -vector of random factors, and $\varepsilon_{t\sqcup}$ is an n -vector of idiosyncratic returns. We assume that $f_{t\sqcup}$ and $\varepsilon_{t\sqcup}$ are

mutually independent and each is distributed i.i.d. through time. All elements of f_t and ε_t are assumed to have zero means without loss of generality, due to the inclusion of the vector of constants, a . Let $\Sigma_r = E[(r - a)(r - a)']$, $\Sigma_f = E[ff']$, and $\Sigma_\varepsilon = E[\varepsilon\varepsilon']$ denote covariance matrices; we assume that all three are nonsingular. All the elements in (1) implicitly include an n superscript, since we are working with asymptotic properties not fixed- n properties, but we leave this implicit throughout. Of course, when we apply the econometric model to actual data, the number of assets n will be a constant; the increasing- n framework is just an asymptotic model to derive meaningful approximations for large n .

We impose the standard Chamberlain-Rothschild assumptions that the largest k eigenvalues of the return covariance matrix increase unboundedly with n and the remaining eigenvalues are bounded. Let $\|\cdot\|$ denote the matrix norm over square matrices $\|A\| = \sup_x \frac{|x'Ax|}{\sqrt{(x'x)}}$; recall that in the case of a symmetric positive semidefinite matrix this equals the largest eigenvalue. Since Σ_ε captures the idiosyncratic risks, we impose:

$$\|\Sigma_\varepsilon\| \leq c_1 \text{ for all } n. \quad (2)$$

We also impose the Chamberlain-Rothschild unboundedness assumption on the first k eigenvalues, not restricting their rate of increase. Note that $\Sigma_r = \beta B \Sigma_f B' + \Sigma_\varepsilon$. Since Σ_ε has bounded eigenvalues by assumption above, and the eigenvalues of Σ_f are fixed, k unbounded eigenvalues for Σ_r is identical to assuming that all k eigenvalues of the inner product matrix of the betas, $(B'B)$, increase without bound:

$$\lim_{n \rightarrow \infty} (\min \text{eigval}[B'B]) = \infty. \quad (3)$$

Note that (3) implies that all the eigenvalues of $B'B$ are strictly positive except possibly for $n < \bar{n}$ for some finite \bar{n} . All eigenvalues strictly positive means that $B'B$ is nonsingular. Therefore, except possibly on a finite subset of $n < \bar{n}$, (3) can be written equivalently as:

$$\lim_{n \rightarrow \infty} \|(B'B)^{-1}\| = 0, \quad (4)$$

since the eigenvalues of a symmetric positive definite matrix are the reciprocals of the eigenvalues of its inverse.

We keep the two assumptions (2) and (3) throughout. We note however that these two assumptions alone are not sufficient for empirical work. Empirical implementations typically strengthen (3) slightly, in particular by requiring that all k dominant eigenvalues increase at the "natural" rate n . That is, most empirical analysts replace (3) with:

$$\lim_{n \rightarrow \infty} \frac{1}{n} \min \text{eigval}[B'B] > 0, \quad (5)$$

or equivalently (ignoring some technically uninteresting cases²):

$$\lim_{n \rightarrow \infty} \frac{1}{n} (B'B) = M, \quad \text{a nonsingular matrix.} \quad (6)$$

which differs from (4) in the speed at which the eigenvalues must grow with n ; (6) requires that the eigenvalues of $B'B$ go to infinity at rate n whereas (4) only requires that they go to infinity, at any rate.

We call (6) the "natural" rate of increase since many plausible specifications of the series of factor beta matrices will result in (6). Condition (6) will also hold with probability one

²We must exclude the case in which the beta matrix grows explosively with n , and also exclude cases in which the $k \times k$ -matrix series $\frac{1}{n} B'B$ only converges on a subsequence or on multiple subsequences. These cases are automatically excluded with probability one in our random coefficients framework described later.

if the coefficients in B are chosen randomly (over $i \neq 1, n$) from an i.i.d. process with nonsingular covariance matrix, by the strong law of large numbers (shown later).

By using a less straightforward rule for choosing the sequence of beta matrices, the natural rate can be replaced with a slower, semi-strong, rate of increase; this is easily done by scaling fixed factor betas so that the individual betas shrink with n . So, as a simple example with $k \neq 1$, consider the sequence of n -vectors $B^n = \frac{1}{n^{1/3}} \times \iota_n$, where ι_n is an n -vector of ones. This fulfils the Chamberlain-Rothschild condition (4), since $B^n B^n = (n \cdot n^{-2/3}) = n^{1/3} \rightarrow \infty$, but not the natural rate condition (6), since $\frac{1}{n} B^n B^n = (n^{-1} \cdot n \cdot n^{-2/3}) = n^{-2/3} \rightarrow 0$. Stated simplistically and intuitively, semi-strong factors have sum of squared factor betas going to infinity but average squared factor beta going to zero with n . A more precise definition appears later.

Our empirical implementation does not require the natural rate assumption; it allows some of the dominant k eigenvalues to have a slower, semi-strong rate of increase. To give structure to the problem, we specify the factor exposure matrix B with a random coefficients model as described in the next subsection.

2.1 Generating factor betas with a random coefficients model

In our factor model, the beta matrix and factors divide into two subsets with k^{nr} and k^{ss} elements, depending upon the average cross-sectional magnitude of the factor betas:

$$B f = B^{nr} f^{nr} + B^{ss} f^{ss} \quad (7)$$

where the superscript nr denotes "natural rate" and ss denotes "semi-strong." The beta matrix B is assumed to be generated from the first n random draws of an i.i.d. sequence of realizations of a k -vector random variable b with finite mean vector and nonsingular covariance matrix:

$$E[b] = \mu_b; \quad E[(b - \mu_b)(b - \mu_b)'] = \Sigma_b;$$

note that the block-diagonal submatrices Σ_b^{nr} and Σ_b^{ss} are also nonsingular given that Σ_b is nonsingular. We also assume that all k components of the random vector b have finite fourth moments. We use the sequence of random draws of b to create the factor beta matrix, scaling appropriately to differentiate between natural-rate and semi-strong factors.

Let B^* denote the $n \times k$ -matrix of the first n draws of the vector stochastic process b . We call B^* the beta generating matrix. Partition the beta generating matrix into the first k^{nr} and remaining k^{ss} columns; $B^* = [B^{nr*} | B^{ss*}]$. The first k^{nr} factors are natural rate factors; their betas are simply the random draws of the first k^{nr} elements of b :

$$B^{nr} = B^{nr*};$$

The remaining k^{ss} factors are semi-strong. We fix a rate exponent $\psi > 0$ and assume that the factors betas are of the order $n^{-\psi}$; they are generated by scaled versions of the generating matrix:

$$B^{ss} = (n^{-\psi}) B^{ss*}. \quad (8)$$

We impose the condition $\psi < \frac{1}{2}$. As we will discuss later, this condition is required in order for the sum of squared factor betas to increase with n . If we were to allow $\psi > \frac{1}{2}$ we

would generate "semi-weak" factors, using the terminology of Chudik et al. (2011). It is possible (although cumbersome) to allow B_{it} to vary across the semi-strong factors; we do not pursue that here.

Since the vector stochastic process b_{it} is i.i.d. and has finite fourth moments, it follows from the strong law of large numbers (see White (1984, Proposition 2.11)) that the first two cross-sectional moments of B_{it} converge almost surely, so that:

$$\lim_{n \rightarrow \infty} \frac{1}{n} B^{nr'} B^{nr} = \mu_{b, nr} \text{ a.s.}, \quad (9)$$

and:

$$\lim_{n \rightarrow \infty} \left(\frac{1}{n^{1-2}} \right) B^{ss'} B^{ss} = \lim_{n \rightarrow \infty} \left(\frac{n^2}{n^2} \right) \left(\frac{1}{n} \right) B^{ss*'} B^{ss*} = \mu_{b, ss} \text{ a.s.}, \quad (10)$$

and the cross-product matrix:

$$\lim_{n \rightarrow \infty} \left(\frac{1}{n^{1-}} \right) B^{ss*'} B^{nr} = \lim_{n \rightarrow \infty} \left(\frac{n\psi}{n\psi} \right) \left(\frac{1}{n} \right) B^{ss*'} B^{nr*} = \mu_{b, ss, nr} \text{ a.s.} \quad (11)$$

The strong law of large numbers also applies to the first moment vectors (appropriately scaled):

$$\lim_{n \rightarrow \infty} \left(\frac{1}{n} \right) B^{nr'} \mathbf{1}^n = \mu_{b, nr} \text{ a.s.}, \quad (12)$$

and:

$$\lim_{n \rightarrow \infty} \left(\frac{1}{n} \right) B^{ss'} \mathbf{1}^n = \lim_{n \rightarrow \infty} \left(\frac{n\psi}{n} \right) \left(\frac{1}{n} \right) B^{ss*'} \mathbf{1}^n = \mu_{b, ss} \text{ a.s.} \quad (13)$$

From here on in the paper, we condition on a particular sequence of random realizations of B_{it} and so treat B_{it} for estimation purposes as a nonrandom matrix. We assume that the

particular matrix sequence obeys the almost-sure limit conditions (9),(10), (11), (12) and (13).

2.2 Failure of Standard Factor Estimation Methods in Recovering Semi-Strong Factors

Factor analysis and principal components-based methods are well-suited to recover natural rate factors, but have difficulties estimating semi-strong and weak factors (see Chudik, Pesaran, Tosetti (2011), Onatski (2012), and Pesaran (2015)). We demonstrate this issue by simulating a two-factor economy in which the first factor is a natural rate factor and the second factor is a semi-strong factor. We then use the asymptotic principal components estimator of Connor and Korajczyk (1986) to estimate the factors on the simulated data where we know the true factors. We then regress the estimated factors on the true factors. For natural rate factors, the estimated factors will converge to the true factors, up to the standard rotational indeterminacy of latent factor estimates. Thus the R^2 values will approach 1.0 as the cross-sectional sample increases. This does not happen for semi-strong factors.

We simulate daily factor realizations for 21,000 assets over a five-year period where each factor has an annual standard deviation of 20%. B^* is an $n \times 2$ matrix of factor loadings that are drawn from an i.i.d. Normal distribution with mean 1 and standard deviation of 0.3. For the first factor, B^{nr} is equal to the first column of B^* . For the second factor, the i^{th} element of B^{ss} is equal to the second i^{th} element of column B^* divided by $n^{0.45}$. For increasing n , the average squared beta for the semi-strong second factor shrinks at the rate $n^{0.1}$ while the

sum of squared beta grows at rate $n^{0.9}$. Therefore, the factor is semi-strong, but not natural rate. The non-factor, idiosyncratic, returns are drawn from a normal distribution with zero mean and annual standard deviation of 35%.

Let $\widehat{f}_{j,t}$ denote the asymptotic principal components estimator of factor $j \in \{1, 2\}$ for period t and f_t denote the true simulated 2×1 factor vector for time t . We estimate the regression

$$\widehat{f}_{j,t} = a_j + b_j f_t + u_{j,t} \quad (14)$$

and report the results in Table 1. We show results for three cross-sectional sample sizes: 3,000 and 6,000 assets (which bracket our sample size in the empirical work below) as well as 21,000 assets. We perform 10,000 iteration of the simulation. The first column of Table 1 shows the number of assets used in estimating $\widehat{f}_{j,t}$. The second column lists the dependent variable, either $\widehat{f}_{1,t}$ or $\widehat{f}_{2,t}$. The third and fourth columns list the percentage of the 10,000 simulations for which the t -statistics on $b_{j,1}$ and $b_{j,2}$ are greater than 1.96. The last column is the average, across the simulations, R^2 . The table shows that $\widehat{f}_{1,t}$ is estimated very precisely. One hundred percent of its coefficients, $b_{j,1}$ and $b_{j,2}$, are statistically significant, for all cross-sectional sample sizes. The coefficient of the second true factor is significant due to the rotational indeterminacy of principal components-based estimators of factor scores. The average R^2 values are nearly 1.0, meaning that $\widehat{f}_{1,t}$ is nearly perfectly correlated with a linear combination of the two factors. The table also shows that $\widehat{f}_{2,t}$ is estimated very imprecisely. While a very large number of its coefficients on the second true factor, $b_{j,2}$,

are statistically significant, with the percentage growing in the cross-sectional sample size, the average R^2 values are all below 1%. Thus, $\widehat{f}_{2,t}$ has extremely low correlation with the semi-strong factor. Increasing the cross-sectional sample size does not much improve the precision of $\widehat{f}_{2,t}$. These results argue for a different approach when attempting to identify semi-strong factors.

3 Estimation of betas and their cross-sectional average and mean-square

We assume that the factors are observed exactly, so that the statistical problem involves estimating the factor betas, and features of their cross-sectional distribution (in particular, their average and mean-square). Since $f_{i,t}$ and $\varepsilon_{i,t}$ are assumed mutually independent with $\varepsilon_{i,t}$ conditionally mean zero, (1) gives a seemingly unrelated regression model (Zellner (1962)) without cross-equation restrictions:

$$r_{it} = a_i + B_i f_{t} + \varepsilon_{it}; \quad i = 1, n; t = 1, T. \quad (15)$$

We condition upon f_t and so treat it for the purposes of parameter estimation as a nonrandom time series of fixed length T . Since there are no cross-equation restrictions, the regression system (15) is identical to n separate time-series ordinary least squares problems. Let F denote the $T \times (k + 1)$ -matrix of the explanatory variables in (15), where the first column is a T -vector of ones, and column $j + 1$ is the time-series of factor realizations for

factor j ; the regression estimates for any particular i are:

$$\{\widehat{a}_i, \widehat{B}_i\} = (F'F)^{-1}F'R_{i,\psi}$$

where $R_{i,\psi}$ is the T -vector of asset returns. By standard regression theory for any j we can describe \widehat{B}_{ij} as the true value plus a linear combination of the residuals, in particular:

$$\widehat{B}_{ij} = B_{ij} + \sum_{t=1}^T m_{jt} \varepsilon_{it} \quad (16)$$

where $m_{jt} = [(F'F)^{-1}F']_{j+1,t}$. The ordinary least squares estimates are unbiased, with estimation variance:

$$E[(\widehat{B}_{ij} - B_{ij})^2] = [(F'F)^{-1}]_{j+1,j+1} \sigma_{\varepsilon_i}^2 \quad (17)$$

We consider the estimation-error corrected squared regression coefficient:

$$(\widehat{B}_{ij})^2 - [(F'F)^{-1}]_{j+1,j+1} \widehat{\sigma}_{\varepsilon_i}^2 \quad (18)$$

where $\widehat{\sigma}_{\varepsilon_i}^2 = \frac{1}{T-k-1} \sum_{t=1}^T \widehat{\varepsilon}_{it}^2$, which is an unbiased estimate of $\sigma_{\varepsilon_i}^2$. The estimate $\widehat{\sigma}_{\varepsilon_i}^2$ can be written as a quadratic function of ε_{it} , $t = 1, T$, in particular:

$$\widehat{\sigma}_{\varepsilon_i}^2 = \sum_{t=1}^T \sum_{\tau=1}^T p_{t\tau} \varepsilon_{it} \varepsilon_{i\tau}$$

where $p_{t\tau} = \left(\frac{1}{T-k-1}\right) [I - F(F'F)^{-1}F']_{t,\tau}$.

The estimation-error-adjusted squared beta (18) is a key input to our mean-squared beta estimate in the next subsection. Since its two components, \widehat{B}_{ij} and $\widehat{\sigma}_{\varepsilon_i}^2$, are (respectively) linear and quadratic functions of the innovations ε_{it} , $t = 1, T$, its estimation variance is a linear combination of the first four moments and squared second moment of ε_{it} . The weights in this linear combination are products and cross-products of m_{jt} and $p_{t\tau}$, $t, \tau = 1, T$.

Define \bar{m}_{2j} , \bar{m}_{3j} , \bar{m}_{4j} as the second, third and fourth power sums of m_{jt} , $t \neq 1, T$, and

\bar{m}_{22j} as the sum of cross-products:

$$\begin{aligned}\bar{m}_{2j} &= \sum_{t=1}^T m_{jt}^2 \\ \bar{m}_{3j} &= \sum_{t=1}^T m_{jt}^3 \\ \bar{m}_{4j} &= \sum_{t=1}^T m_{jt}^4 \\ \bar{m}_{22j} &= \sum_{t=1}^T \sum_{\tau \neq t}^T m_{j\tau}^2 m_{jt}^2.\end{aligned}$$

Similarly, define the following product sums and cross-product sums of $p_{t\tau}$, $t = 1, T$; $\tau \neq 1, T$:

$$\begin{aligned}\bar{p}_2 &= \sum_{t=1}^T p_{tt}^2 \\ p \times p &= \sum_{t=1}^T \sum_{\tau \neq t}^T (2p_{t\tau}^2 + p_{tt}p_{\tau\tau}) \\ \bar{p}\bar{m} &= \sum_{t=1}^T p_{tt}m_{jt} \\ \bar{p}\bar{m}_2 &= \sum_{t=1}^T p_{tt}m_{jt}^2 \\ p \times m &= \sum_{t=1}^T \sum_{\tau \neq t}^T (2p_{t\tau}m_{jt} + p_{tt}m_{jt}^2)\end{aligned}$$

By straightforward algebra (see Appendix 1 for detailed steps) the estimation variance of $\widehat{B}_{ij}^2 - [(F'F)^{-1}]_{j+1, j+1} \widehat{\sigma}_{\varepsilon_i}^2$ is:

$$Var[(\widehat{B}_{ij}^2 - \bar{m}_{2j}\widehat{\sigma}_{\varepsilon_i}^2)] = c_{1ij}\sigma_{\varepsilon_i}^2 + c_{2ij}E[\varepsilon_i^3] + c_{3j}E[\varepsilon_i^4] + c_{4j}(\sigma_{\varepsilon_i}^2)^2, \psi \quad (19)$$

where:

$$c_{1ij} = 4\bar{m}_{2j}B_{ij}^2$$

$$c_{2ij} = 4B_{ij}\bar{m}_{3j} - 4\bar{m}_{2j}B_{ij}(\bar{p}m_j)$$

$$c_{3j} = \bar{m}_{4j} + (\bar{m}_{2j})^2\bar{p}_2 - 2\bar{m}_{2j}(\bar{p}m_{2j})$$

$$c_{4j} = 3\bar{m}_{22j} + (\bar{m}_{2j})^2(p \times p) - 2\bar{m}_{2j}(p \times m)$$

Readers will be pleased to know (or at least relieved) that we do not estimate this complicated variance expression directly, but instead invoke bootstrap methods (see below) to obtain estimated standard errors.

3.1 Statistical identification of the cross-sectional average and mean-square of semi-strong factor betas

In the case of a semi-strong factor, estimates of the individual betas have limited information since $B_{ij} = n^{-1}B_{ij}^*$ implies that the magnitude of most betas is too small to detect reliably. However, as we now show, it is possible to detect the aggregate influence of semi-strong factors by averaging the cross-section of individual time-series regression estimates and their squares. Define $\mu_{j\psi}$ and $\chi_{j\psi}$, $j\psi = 1, k$, as the cross-sectional averages and average sums of squares of the factor betas:

$$\mu_{j\psi} = \frac{1}{n} \sum_{i=1}^n B_{ij\psi}$$

$$\chi_{j\psi} = \frac{1}{n} \sum_{i=1}^n B_{ij\psi}^2, \quad j\psi = 1, k, \psi$$

We use the cross-section of estimated betas to construct simple estimation-error-adjusted estimates:

$$\hat{\mu}_{j\Box} = \frac{1}{n\Box} \sum_{i=1}^{n\Box} \hat{B}_{ij\Box} \quad (20)$$

$$\hat{\chi}_{j\Box} = \frac{1}{n\Box} \sum_{i=1}^{n\Box} [B_{ij\Box}^2 - \bar{m}_{2j} \hat{\sigma}_{\varepsilon_i\Box}^2] \cdot \psi \quad (21)$$

We assume that $\varepsilon_{i\Box}$ $i\Box \neq 1, n\Box$ is independent across i, \Box with bounded fourth moments for all i, \Box . It is possible in theory to extend our results to the case in which the idiosyncratic returns are weakly cross-sectionally correlated, but that would substantially complicate the derivation of the estimation variance and we do not pursue that extension here. Let $m\Box$ denote any fixed, finite T -vector (constant across $i = 1, n$) and let $\tilde{\varepsilon}_{i\Box}$ denote a T -vector of independent realization of $\varepsilon_{i\Box}$. For a given $j\Box \in \{1, 2, \dots, k\}$ define the random series $\tilde{y}_{i\Box} = m'\tilde{\varepsilon}_{i\Box}$ and $\theta_{i\Box} = 2B_{ij\Box}m'\tilde{\varepsilon}_{i\Box} + (m'\tilde{\varepsilon}_{i\Box})^2$. We assume that for any fixed $m\Box$ the Lindeberg condition (see White (1984, pp 111)) holds for both $\tilde{y}_{i\Box}$ and $\theta_{i\Box}$. Since the estimation error in $\hat{B}_{ij\Box}$ has the form $m'\tilde{\varepsilon}_{i\Box}$ this guarantees that the central limit theorem applies to cross-sectional averages of beta estimates and squared beta estimates. Since the regression estimates are independent across i , the variance of the cross-sectional average is $\frac{1}{n\Box}$ times the average of the variances. Using (17) and (19):

$$\begin{aligned} nVar[\hat{\mu}_j] &= \frac{1}{n\Box} \sum_{i=1}^{n\Box} \bar{m}_{2j} \sigma_{\varepsilon_i\Box}^2 \\ nVar[\hat{\chi}_j] &= \frac{1}{n\Box} \sum_{i=1}^{n\Box} c_{1ij} \sigma_{\varepsilon_i\Box}^2 + c_{2ij} E[\varepsilon_{i\Box}^3] + c_{3j} E[\varepsilon_{i\Box}^4] + c_{4j} (\sigma_{\varepsilon_i\Box}^2)^2 \cdot \psi \end{aligned} \quad (22)$$

We assume that the cross-sectional averages converge for large $n\Box$ and let $\phi\Box$ and $\psi\Box$ denote

these convergent limits:

$$\phi\psi = \lim_{n \rightarrow \infty} \frac{1}{n} \sum_{i=1}^n \sigma_{\varepsilon_i}^2 \quad (23)$$

$$j = \lim_{n \rightarrow \infty} \frac{1}{n} \sum_{i=1}^n c_{1ij} \sigma_{\varepsilon_i}^2 + c_{2ij} E[\varepsilon_i^3] + c_{3j} E[\varepsilon_i^4] + c_{4j} (\sigma_{\varepsilon_i}^2)^2 \cdot \psi \quad (24)$$

It is straightforward to derive the convergence conditions (23) and (24) from more fundamental assumptions, for example by placing bounds on the first four moments of ε_i for all i , and restricting the co-relations between B_{ij} and these moments for all i . This additional complexity would add little value to the analysis so we simply directly assume that these limits exist.

Since the test statistics are asymptotically normal we have:

$$d \lim_{n \rightarrow \infty} n^{\frac{1}{2}} (\hat{\mu}_j - \mu_j) \sim N(0, \bar{m}_{2j} \phi) \quad (25)$$

and:

$$d \lim_{n \rightarrow \infty} n^{\frac{1}{2}} (\hat{\chi}_j - \chi_j) \sim N(0, \psi_j), \quad j \neq 1, k, \psi \quad (26)$$

Note that for semi-strong factors $j > k^{nr}$ we have $\lim_{n \rightarrow \infty} \mu_j = \lim_{n \rightarrow \infty} n^{-1} \mu_j^* = 0$ and $\lim_{n \rightarrow \infty} \chi_j = \lim_{n \rightarrow \infty} n^{-2} \chi_j^* = 0$. As long as $\psi_j < \frac{1}{2}$ then the test statistic (25) has rejection power against $H_0: \mu_j^* = 0$ approaching one for $n\psi \rightarrow \infty$ whenever $\mu_j^* \neq 0$. Test statistic (26) requires the stronger condition $\psi_j < \frac{1}{4}$ for unit asymptotic power against $H_0: \chi_j^* = 0$.

The population value of mean-squared beta is always positive if the true mean beta is nonzero, whereas it is possible to have a positive mean-squared beta when the true mean beta is exactly zero. This might give the false impression that the mean-squared beta test

"dominates" the mean beta test, but the relationship between the statistical tests for nonzero mean-squared beta and nonzero mean beta is actually ambiguous. The estimation error in the test of mean-square beta can be much higher than in the test of mean beta, so either test can reject when the other does not. In the case of semi-strong factors, in terms of asymptotic power, the test for a nonzero mean beta only requires $\sqrt{n} > \sqrt{\frac{1}{2}}$ whereas the test for positive mean-squared beta requires $\sqrt{n} > \sqrt{\frac{1}{4}}$. In this sense, the mean beta test is asymptotically stronger than the mean-squared beta test.

3.2 Bootstrap estimation of the mean-square beta estimation variance

We have derived an explicit formula for the variances of the mean-squared beta estimates, $\hat{\beta}_j/n\hat{\sigma}_j^2 = 1, k, \psi_m$ (22), but the formula involves the cross-sectional average of a complicated linear combination of higher moments of asset-specific returns. A naive approach would be to proxy each term in (22) with time-series estimates from each asset in the sample, and then take cross-sectional averages. Instead we use a bootstrap methodology, which obviates the need to estimate the individual components of (22); we discuss our motivation and justification for this bootstrapped estimator in more detail in Appendix 2. The procedure is as follows. Let F_t denote the $k \times T$ matrix of factor realizations. First, we randomly resample with replacement the T -vector of dates $t = 1, T$ producing a random mapping $t^*(t); t = 1, T$. We then replace the matrix of returns R_t and factors F_t with the resampled

alternatives R^* and F^* based on this random selection of dates:

$$R_{it}^* = R_{it^*}(t); i = 1, n; t = 1, T$$

$$F_{jt}^* = F_{jt^*}(t); j = 1, k; t = 1, T$$

Using R^* and F^* in place of R and F we re-estimate \hat{B} and $\hat{\chi}_j$ and repeat this random bootstrap a large number of times, $h = 1, m$. For each j , the variances \hat{n}_j are found from the collection of m bootstrapped estimates of $\hat{\chi}_j$:

$$\hat{n}_j = \frac{1}{m} \sum_{h=1}^m (\hat{\chi}_j^h)^2 - \left(\frac{1}{m} \sum_{h=1}^m \hat{\chi}_j^h \right)^2$$

3.3 Distinguishing semi-strong from natural-rate factors

We now consider the problem of empirically distinguishing semi-strong factors from natural rate factors. Either type of factor has sum of squared betas going to infinity with n , but a natural rate factor has mean-squared beta converging to a strictly positive value whereas a semi-strong factor has mean-squared beta going to zero. For large n , the semi-strong factors are statistically significant (in terms of their mean squared betas being testably greater than zero as the estimation variance shrinks) but also inconsequential (in terms of their contribution to average explanatory power going to zero). In the subsections above we have developed an estimation method which allows us to identify both natural-rate and semi-strong factors. Now in this subsection we attempt to find methods to distinguish between the two types. First we propose the use of marginal R^2 of each factor in our model as a descriptive statistic; semi-strong factors will have "small" values for marginal R-square. Then

we present a formal test statistic using a penalized version of our adjusted mean-squared beta estimate.

3.3.1 Marginal explanatory power of each factor

The seemingly unrelated regression system (15) can be viewed as a single stacked regression model with n intercepts (also called asset fixed effects) and nk factor betas, with heteroskedasticity across the n assets. Define the adjusted R^2 for this stacked regression model as one minus unexplained variance over total variance:

$$\bar{R}^2_\psi = 1 - \left(\frac{(T\psi - 1)}{(T\psi - k - 1)} \right) \left(\frac{1}{nT\psi} \sum_{t=1}^T \sum_{i=1}^{n\psi} \hat{\varepsilon}_{it}^2 \right) / \left(\frac{1}{nT\psi} \sum_{t=1}^T \sum_{i=1}^{n\psi} (r_{it} - \bar{r}_i)^2 \right),$$

where \bar{r}_i is the time-series sample mean return of asset i . Next, we re-estimate the linear regression model with all factors except factor j and re-calculate the stacked regression \bar{R}^2_ψ using the newly estimated residuals $\hat{\varepsilon}_{it}^{*2}$:

$$\bar{R}^2_{(j)} = 1 - \left(\frac{(T\psi - 1)}{(T\psi - k)} \right) \left(\frac{1}{nT\psi} \sum_{t=1}^T \sum_{i=1}^{n\psi} \hat{\varepsilon}_{it}^{*2} \right) / \left(\frac{1}{nT\psi} \sum_{t=1}^T \sum_{i=1}^{n\psi} (r_{it} - \bar{r}_i)^2 \right).$$

The difference between \bar{R}^2_ψ and $\bar{R}^2_{(j)}$ gives our marginal R^2 statistic.

$$\Delta \bar{R}^2_\psi = \bar{R}^2_\psi - \bar{R}^2_{(j)}. \quad (27)$$

The intuition behind (27) is that when factor j is only semi-strong, the marginal R^2 should be small for large n , since $\lim_{n \rightarrow \infty} \frac{1}{n} \sum_{i=1}^{n\psi} (B_{ij})^2 = 0$. To understand the intuition, define $\sigma_{fj}^2 = \frac{1}{T} \sum_{t=1}^T f_{jt}^2$ and $\sigma_r^2 = \frac{1}{nT} \sum_{t=1}^T \sum_{i=1}^n (r_{it} - \bar{r}_i)^2$. Consider the population equivalents of the two R^2 's, that is, $R^2 = 1 - (\frac{1}{n} \sum_{i=1}^n \sigma_{\varepsilon i}^2) / \sigma_r^2$ and $R^2_{(j)} = 1 - (\frac{1}{n} \sum_{i=1}^n \sigma_{\varepsilon i}^2 + B_{ij}^2 \sigma_{fj}^2) / \sigma_r^2$. Taking the difference

between these two population R-squareds gives: \square

$$\Delta R_{j\square}^2 = \square \frac{\sigma_{fj}^2}{\sigma_r^2} \left(\frac{1}{n} \sum_{i=1}^{n\square} B_{ij}^2 \right), \psi \quad (28)$$

hence the population marginal R^2 is a scaled version of mean-squared beta. The estimated marginal R^2 (27) is not a formal test statistic since we do not give its sample distribution, but it is a useful descriptive statistic based on (28).

3.3.2 A penalized test statistic for mean-squared beta

We now construct a test statistic for empirically distinguishing natural-rate factors from semi-strong factors. Either type of factor has sum of squared betas going to infinity with n , but a natural rate factor has mean-squared beta converging to a strictly positive value whereas a semi-strong factor has mean-squared beta shrinking to zero at rate n^{-2} . Consider a nonrandom sequence $a_{n\square} = \square a^j n^{-2\delta\square}$ with $a > \psi, \psi \square < \delta < \psi$. We allow the multiplicative constant a^j to vary across factors j , setting $a^j = \left(\frac{\sigma_{f,j}^2}{\sigma_r^2} \right) / k$. This choice of a^j is motivated by the marginal R^2 shown above, see (28).

The sequence $a_{n\square}$ distinguishes natural rate from semi-strong factors, in the sense that:

$$\lim_{n \rightarrow \infty} (\chi_{j\square} - a_n) = \square \chi_{j\square}^* > 0 \text{ for all } j \leq k^{nr}, \psi \text{ whereas}$$

$$\limsup_{n \rightarrow \infty} (\chi_{j\square} - a_n) \leq \square 0 \text{ for all } j > k^{nr}. \psi$$

Once we have chosen the parameters of the sequence a_n , we compute the statistic:

$$z_{j\square} = n^{\frac{1}{2}} \left(\frac{\hat{\chi}_{j\square} - a_{n\square}}{\frac{1}{2} j} \right) \square \quad (29)$$

and note that for a natural rate factor $j \leq k^{nr}$ the statistic (29) has unit asymptotic power to reject $E[z_j] = 0$, whereas it has zero asymptotic power to reject $E[z_j] = 0$ for a semi-strong factor $j > k^{nr}$. The test statistic establishes a penalized benchmark value for the sum of squared betas as a function of n ; if the estimated sum of squared betas is significantly above this benchmark, the factor is identified as a natural-rate factor.

4 Application to U.S. equity returns using Fama-French, currency, and commodity factors

In this section we apply the methodology to analyze the currency and commodity exposures of US equity returns.

4.1 Data and Winsorization

We consider percentage changes in commodity prices and foreign exchange rates (against a currency basket) as possible semi-strong factors. We use daily data on US equity returns over six periods, 1989-1993, 1994-1998, 1999-2003, 2004-2008, 2009-2013, and 2014-2018. In each subperiod we restrict the sample to equities with full return records over the 5-year subperiod. To moderate the influence of extreme return observations (which are often due to small, isolated trades of illiquid securities) we Winsorize the returns data at 99%; setting all observations in the top 0.5% and bottom 0.5% within each subperiod equal to the relevant boundary value. Table 2 shows the cross-sectional average of the first four time-

series moments of returns in each of the subperiods, both before and after Winsorization. We also show the maximum and minimum returns in each subperiod; for the after-Winsorization case, these equal the Winsorization boundary values.

For currency factors, we use the U.S. Dollar, British Pound, Japanese Yen, and Korean Won, each measured against the global currency basket maintained by the International Monetary Fund (the Special Drawing Rights Index of the IMF). For commodities, we use the prices of oil, gold, aluminum, and forest products. The currency and commodity factors are obtained from Bloomberg. The daily factors are the percentage daily price changes. The codes in Bloomberg are: U.S. Dollar (XDRUSD), British Pound (XDRUSD divided by GBPUSD), Japanese Yen (USDJPY times XDRUSD), and Korean Won (USDKRW times XDRUSD), Brent crude futures traded on ICE (CO1), gold (XAU), aluminum (LMAHDY), random length lumber futures on the CME (LB1). In addition to the currency and commodity factors, we include the Fama and French (1993) market, size and value factors from the Kenneth French data library.³ Table 3 shows the first four time-series moments of the eleven factors for each of the six subperiods.

4.2 Estimation of mean and mean-square factor betas

Since the seemingly unrelated regression model has the same independent variables for all assets and no cross-equation restrictions, for the purpose of finding the cross-sectional averages of the coefficients (20), the set of n regressions "collapses" into a single time-series

³Available at: http://mba.tuck.dartmouth.edu/pages/faculty/ken.french/data_library.html.

regression with an equally-weighted average of returns as the dependent variable. The results are shown in Table 4. The average asset betas for all three Fama-French factors are statistically significant in all subperiods (with t-statistics in excess of 45). The average asset betas relative to the currencies are significant in the post-2004 period, with the exception of the Japanese Yen. Additionally, the average betas relative to the Korean Won are significant in the second and third subperiods. The average betas for the Japanese Yen are only significant in the first subperiod, 1989-1993. The average betas for oil and aluminum are significant in all subperiods (aluminum) except one (oil). The average betas for lumber are generally insignificant. Table 4 clearly shows that the Fama-French factors have a much stronger average relation to individual equity returns than the other factors.

To estimate mean-squared betas, we perform individual factor regressions for each of the securities in each subsample, and then compute the cross-sectional adjusted-mean-squared estimated betas shown in Table 5. To estimate the variances of the estimated mean-squared betas we repeat this full estimation process fifty thousand times with bootstrapped returns and compute the fifty-thousand-sample bootstrap variances for each mean-squared beta. In the latter three subperiods all of the factors except lumber have estimated mean-squared beta significantly greater than zero. Oil and gold are also significant in the other three, earlier, subperiods. The currency factors are mostly insignificant in these earlier three subperiods; aluminum also has mixed results in these earlier subperiods.

4.3 Distinguishing natural-rate from semi-strong factors

Table 6 shows the marginal R^2 found by dropping one factor $j \neq 1, k$ from the stacked regression model. Other than the three Fama-French factors, oil and gold show some non-negligible explanatory power by this measure. The stacked regression R^2 shows evidence of a secular increase from the earlier subperiods to the later ones.

Next we implement our test statistic (29) for distinguishing natural-rate from semi-strong factors. We set $\delta = \frac{1}{5}$ so that $n^{-2\delta}$ gives a reasonably small, but not excessively small, benchmark for mean-squared beta; for $k = 11$ and $n = 4250$, which is roughly the cross-sectional size in our subperiods, $n^{-2\delta}/k = 4250^{-(.4)}/11 = 0.0032$. Interpreted using (28), a factor must have a marginal R^2 above 0.3% to qualify as a natural-rate factor.

Table 7 shows the results of the statistical test for whether each factor has mean-square beta greater than $(\frac{\sigma_i^2}{\sigma_{f,j}^2})n^{-.4}/11$. The results in Table 7 provide strong support for the Fama-French factors being natural rate factors. The penalized mean-squared betas of the market factor MKTRF and size factor SMB are significantly positive in all subperiods; the value factor HML is significantly positive in four of the six subperiods. Oil and gold are significantly positive in two and three subperiods, respectively, thus showing mixed results as to whether they are best classified as natural-rate or semi-strong factors. We cannot reject the hypothesis that the remaining factors other than lumber are only semi-strong rather than natural rate factors (recall from Table 5 that lumber does not even qualify as a semi-strong factor).

The results in Tables 4, 5, and 7 suggest that the Fama-French factors are natural rate factors and that lumber is not a statistically identifiable semi-strong factor. Oil and gold

are both significant factors, but give some conflicting results as to whether they should be considered natural rate or semi-strong factors. The remaining factors seem to be semi-strong but not natural-rate.

Lastly, to give an alternative perspective on the data, we use the Akaike Information Criterion (AIC) to choose factors with positive explanatory power by this criterion. To do this we must impose an assumption of normality on the asset-specific residuals in the stacked regression model (15), while still allowing heteroskedasticity across assets. We continue to assume independence of the asset specific returns across assets and across time. Under this normality assumption the ordinary least squares estimates are maximum likelihood, as is obvious. Including the unknown asset-specific return variances, the stacked regression model has $n(k + 2)$ parameters and $nT\psi$ observations, so the AIC criterion is:

$$AIC = 2n(k + 2) - 2 \log(\widehat{L}) \quad (30)$$

where \widehat{L} is the log likelihood, which in this stacked linear regression model is

$$\widehat{L} = -\frac{nT\psi}{2} \log(2\pi) - \frac{T\psi}{2} \sum_{i=1}^n \log(\widehat{\sigma}_{\varepsilon i}^2) - \frac{n}{2}$$

Akaike's approach is different from our earlier approach, in that it treats different specifications (in our case, models with more or fewer factors) as competing approximate models of the data, rather than as nested models that are the true data generating process. Although it does not fit exactly into our modeling framework we believe it gives a useful alternative perspective on the data. (See also Bai and Ng (2002) who use an AIC-type metric to choose natural-rate factors in a statistical factor model.) Table 8 shows the results from stepwise

regression based on (30). The three Fama-French factors are always included in the final model. Gold is included in the final model in all six subperiods, and oil in five of the six. The results are mixed for aluminum and the four foreign exchange factors; they are dropped in the earlier subperiods, but kept in the later ones. Lumber is the only factor to be dropped in all six subperiods.

4.4 An empirical comparison of statistically-estimated and pre-specified factors

As discussed in subsection 2.2 above, conventional statistical methodologies such as asymptotic principal components are not reliable for identifying semi-strong factors. Nonetheless, as an exploratory exercise, we examine the empirical relationship between statistically-estimated factors and our pre-specified factors. For each subsample we compute the first twenty eigenvectors of the cross-product matrix of excess returns. In Table 9 panel A we show the adjusted R^2 s from time-series regression of these twenty eigenvectors on each of the eleven pre-specified factors (we drop lumber from the list of pre-specified factors, based on its poor performance above). In Table 9 panels B and C we do the reverse, regressing the eleven pre-specified factors on each of the twenty eigenvectors. There are two interesting impressionistic findings from this exploratory exercise. One, both for the larger eigenvectors and for the more important pre-specified factors (Fama-French factors, oil, gold) there is a strong secular increase in average R^2 s in more recent subperiods relative to earlier ones. Two, neither the smaller eigenvectors nor the less-important pre-specified factors are well-explained

by these regressions. This reinforces the message found in the simulation exercise in subsection 2.2 above: conventional statistical methods do not seem able to identify semi-strong factors in the panel data set of returns.

5 Conclusions

This paper develops and implements a new econometric methodology for estimating the cross-sectional influence of "small" factors (that is, factors with only modest explanatory power) in a large cross-section of asset returns. We build upon the approximate factor modeling framework of Chamberlain and Rothschild (1983) in which pervasive factors are identified by the unbounded growth of their sum of squared factor betas as the number of assets n grows large. Following Chudik et al. (2011), we differentiate between natural-rate factors, whose sum of squared betas grow at rate n ; semi-strong factors, whose sum of squared betas grow to infinity, but at a slower rate; and weak factors, whose sum of squared betas is bounded. We provide a unified framework by embedding a factor model with both natural-rate and semi-strong factors into a random coefficients framework. We develop an estimation methodology based on the large- n statistical distributions of the cross-sectional mean and mean-square of time-series regression-estimated factor betas. In asymptotically large cross-sections, in order to be statistically identified the mean or mean-squared beta must have a magnitude declining at a slower rate than the standard deviation of estimation, which declines at rate square-root- n .

We apply the methodology to the daily returns of U.S. equity returns using Fama and

French's market, size, and value factors, four currency factors (US dollar, British pound, Japanese Yen, and Korean Won) and four commodity factors (oil, gold, aluminum and lumber). The three Fama-French factors are clearly natural-rate factors. Oil and gold are both significant factors but give some conflicting results as to whether they are natural-rate or semi-strong factors. Aluminum and the four currency factors are semi-strong factors in the more recent subperiods, but not natural-rate factors. Lumber is at best a weak factor, that is, neither a natural-rate nor a semi-strong factor.

Appendix 1: The Sample Variance of the Squared Regression Coefficient

This appendix derives the sample variance of the adjusted squared ordinary least squares regression coefficient within the context of our model. Recall the expression (16) for the time-series estimated regression coefficient:

$$\widehat{B}_{ij} = B_{ij} + \sum_{t=1}^T m_{jt} \varepsilon_{it} \quad (\text{A1})$$

and the adjusted square of this estimate $(\widehat{B}_{ij})^2 - [(F'F)^{-1}]_{j+1,j+1} \widehat{\sigma}_{\varepsilon_i}^2$. Note that $[(F'F)^{-1}]_{j+1,j+1} = \bar{m}_{2j}$ (to see this, write $(F'F)^{-1} = (F'F)^{-1} F' F (F'F)^{-1}$ and note that \bar{m}_{2j} is the j th diagonal entry). It is easy to show that $E[\widehat{B}_{ij}^2 - \bar{m}_{2j} \widehat{\sigma}_{\varepsilon_i}^2] = B_{ij}^2$. Now we derive the variance of this estimator, that is:

$$\text{Var}[(\widehat{B}_{ij})^2 - \bar{m}_{2j} \widehat{\sigma}_{\varepsilon_i}^2] = \text{Var}[(\widehat{B}_{ij})^2] + (\bar{m}_{2j})^2 \text{Var}[\widehat{\sigma}_{\varepsilon_i}^2] - 2\bar{m}_{2j} \text{Cov}[(\widehat{B}_{ij})^2, \widehat{\sigma}_{\varepsilon_i}^2]. \quad (\text{A2})$$

We compute each of the three components on the right-hand side of (A2) separately, beginning with the first. Note that:

$$\text{Var}[(\widehat{B}_{ij})^2] = E[(\widehat{B}_{ij})^2 - \bar{m}_{2j} \widehat{\sigma}_{\varepsilon_i}^2 - B_{ij}^2]^2. \quad (\text{A3})$$

Expressing $(\widehat{B}_{ij})^2$ using (A1) :

$$(\widehat{B}_{ij})^2 = B_{ij}^2 + 2B_{ij} \sum_{t=1}^T m_{jt} \varepsilon_{it} + \sum_{t=1}^T \sum_{\tau=1}^T m_{jt} m_{j\tau} \varepsilon_{it} \varepsilon_{i\tau}. \quad (\text{A4})$$

Inserting (A4) into the right-hand side of (A3) gives:

$$E[(\widehat{B}_{ij})^2 - \bar{m}_{2j} \widehat{\sigma}_{\varepsilon_i}^2 - B_{ij}^2]^2 = E[(2B_{ij} \sum_{t=1}^T m_{jt} \varepsilon_{it} + \sum_{t=1}^T \sum_{\tau=1}^T m_{jt} m_{j\tau} \varepsilon_{it} \varepsilon_{i\tau} - \bar{m}_{2j} \widehat{\sigma}_{\varepsilon_i}^2)^2]. \quad (\text{A5})$$

Expanding out the square on the right-hand side of (A5) gives three square terms and three cross terms:

$$E[(2B_{ij}\sum_{t=1}^T m_{jt}\varepsilon_{it} + \sum_{t=1}^T \sum_{\tau=1}^T m_{jt}m_{j\tau}\varepsilon_{it}\varepsilon_{i\tau} - \bar{m}_{2j}\sigma_{\varepsilon_i}^2)^2]$$

$$= 4B_{ij}^2 \sum_{t=1}^T \sum_{\tau=1}^T m_{jt}m_{j\tau}\varepsilon_{it}\varepsilon_{i\tau} + \sum_{t=1}^T \sum_{\tau=1}^T \sum_{s=1}^T \sum_{u=1}^T m_{jt}m_{j\tau}m_{js}m_{ju}\varepsilon_{it}\varepsilon_{i\tau}\varepsilon_{is}\varepsilon_{iu} + (\bar{m}_{2j}\sigma_{\varepsilon_i}^2)^2 + 4B_{ij}\bar{m}_{2j}\sigma_{\varepsilon_i}^2 \sum_{t=1}^T m_{jt}\varepsilon_{it} + 2\bar{m}_{2j}\sigma_{\varepsilon_i}^2 \sum_{t=1}^T \sum_{\tau=1}^T m_{jt}m_{j\tau}\varepsilon_{it}\varepsilon_{i\tau}.$$
(A6)

$$\sum_{t=1}^T \sum_{\tau=1}^T \sum_{s=1}^T \sum_{u=1}^T m_{jt}m_{j\tau}m_{js}m_{ju}\varepsilon_{it}\varepsilon_{i\tau}\varepsilon_{is}\varepsilon_{iu} + \sum_{t=1}^T \sum_{\tau=1}^T \sum_{s=1}^T m_{jt}m_{j\tau}m_{js}\varepsilon_{it}\varepsilon_{i\tau}\varepsilon_{is} + 4B_{ij}\bar{m}_{2j}\sigma_{\varepsilon_i}^2 \sum_{t=1}^T m_{jt}\varepsilon_{it} + 2\bar{m}_{2j}\sigma_{\varepsilon_i}^2 \sum_{t=1}^T \sum_{\tau=1}^T m_{jt}m_{j\tau}\varepsilon_{it}\varepsilon_{i\tau}.$$
(A7)

$$(\bar{m}_{2j}\sigma_{\varepsilon_i}^2)^2 + 4B_{ij}\bar{m}_{2j}\sigma_{\varepsilon_i}^2 \sum_{t=1}^T m_{jt}\varepsilon_{it} + 2\bar{m}_{2j}\sigma_{\varepsilon_i}^2 \sum_{t=1}^T \sum_{\tau=1}^T m_{jt}m_{j\tau}\varepsilon_{it}\varepsilon_{i\tau}.$$
(A8)

$$4B_{ij}\bar{m}_{2j}\sigma_{\varepsilon_i}^2 \sum_{t=1}^T m_{jt}\varepsilon_{it} + 2\bar{m}_{2j}\sigma_{\varepsilon_i}^2 \sum_{t=1}^T \sum_{\tau=1}^T m_{jt}m_{j\tau}\varepsilon_{it}\varepsilon_{i\tau}.$$
(A9)

$$4B_{ij}\bar{m}_{2j}\sigma_{\varepsilon_i}^2 \sum_{t=1}^T m_{jt}\varepsilon_{it} + 2\bar{m}_{2j}\sigma_{\varepsilon_i}^2 \sum_{t=1}^T \sum_{\tau=1}^T m_{jt}m_{j\tau}\varepsilon_{it}\varepsilon_{i\tau}.$$
(A10)

$$2\bar{m}_{2j}\sigma_{\varepsilon_i}^2 \sum_{t=1}^T \sum_{\tau=1}^T m_{jt}m_{j\tau}\varepsilon_{it}\varepsilon_{i\tau}.$$
(A11)

We will consider each of the six additive components above in order. For (A6), all the cross-terms $E[\varepsilon_{it}\varepsilon_{i\tau}]$, $t \neq \tau$ have expectation of zero and all the pure terms $E[\varepsilon_{it}^2]$ have expectation $\sigma_{\varepsilon_i}^2$ giving

$$E[4B_{ij}^2 \sum_{t=1}^T \sum_{\tau=1}^T m_{jt}m_{j\tau}\varepsilon_{it}\varepsilon_{i\tau}] = 4B_{ij}^2 \bar{m}_{2j} \sigma_{\varepsilon_i}^2 \psi$$

For (A7), there is one pure term where all four time indices are equal and three cross-product terms where two pairs of time indices are equal:

$$E[\sum_{t=1}^T \sum_{\tau=1}^T \sum_{s=1}^T \sum_{u=1}^T m_{jt}m_{j\tau}m_{js}m_{ju}\varepsilon_{it}\varepsilon_{i\tau}\varepsilon_{is}\varepsilon_{iu}] = \bar{m}_{4j} E[\varepsilon_{it}^4] + 3\bar{m}_{22j} (\sigma_{\varepsilon_i}^2)^2 \psi$$

(A8) is in a simple form already. For (A9), the only nonzero expectation is the pure sum

when all three time indices are equal:

$$E[4B_{ij} \sum_{t=1}^T \sum_{\tau=1}^T \sum_{s=1}^T m_{jt} m_{j\tau} m_{js} \varepsilon_{it} \varepsilon_{i\tau} \varepsilon_{is}] = 4B_{ij} \bar{m}_{3j} E[\varepsilon_i^3]. \psi$$

Term (A10) has expectation zero. For (A11):

$$E[2\bar{m}_{2j} \sigma_{\varepsilon_{\bar{j}}}^2 \sum_{t=1}^T \sum_{\tau=1}^T m_{jt} m_{j\tau} \varepsilon_{it} \varepsilon_{i\tau}] = 2(\bar{m}_{2j} \sigma_{\varepsilon_{\bar{j}}}^2)^2 \cdot \psi$$

Adding together the components:

$$\begin{aligned} \text{Var}[(\widehat{B}_{ij})^2] &= 4B_{ij}^2 \bar{m}_{2j} \sigma_{\varepsilon_{\bar{j}}}^2 + \bar{m}_{4j} E[\varepsilon_i^4] + 3\bar{m}_{22j} (\sigma_{\varepsilon_{\bar{j}}}^2)^2 + (\bar{m}_{2j} \sigma_{\varepsilon_{\bar{j}}}^2)^2 + \square \\ &\quad 4B_{ij} \bar{m}_{3j} E[\varepsilon_i^3] - 2(\bar{m}_{2j} \sigma_{\varepsilon_{\bar{j}}}^2)^2 \\ &= 4\bar{m}_{2j} B_{ij}^2 \sigma_{\varepsilon_{\bar{j}}}^2 + 4B_{ij} \bar{m}_{3j} E[\varepsilon_i^3] + \bar{m}_{4j} E[\varepsilon_i^4] + (3\bar{m}_{22j} - (\bar{m}_{2j})^2) (\sigma_{\varepsilon_{\bar{j}}}^2)^2 \end{aligned} \quad (\text{A12})$$

Next we derive the second term of (A2). Recall that $\widehat{\sigma}_{\varepsilon_{\bar{j}}}^2 = \square \sum_{t=1}^T \sum_{\tau=1}^T p_{t\tau} \varepsilon_{it} \varepsilon_{i\tau} \cdot \psi$. Taking the expectation of the square minus the squared expectation:

$$\text{Var}[\widehat{\sigma}_{\varepsilon_{\bar{j}}}^2] = E[\square \sum_{t=1}^T \sum_{\tau=1}^T \sum_{s=1}^T \sum_{u=1}^T p_{t\tau} p_{su} \varepsilon_{it} \varepsilon_{i\tau} \varepsilon_{is} \varepsilon_{iu}] - (\sigma_{\varepsilon_{\bar{j}}}^2)^2 \cdot \psi$$

and using that ε_{it} is independent across time with zero mean:

$$\begin{aligned} &= \square E[\varepsilon_i^4] \sum_{t=1}^T p_{tt}^2 + (\sigma_{\varepsilon_{\bar{j}}}^2)^2 (\sum_{t=1}^T \sum_{\tau \neq t}^T 2p_{t\tau}^2 + p_{tt} p_{\tau\tau}) - (\sigma_{\varepsilon_{\bar{j}}}^2)^2 \\ &= \square \bar{p}_2 E[\varepsilon_i^4] + ((p \times p) - 1) (\sigma_{\varepsilon_{\bar{j}}}^2)^2 \end{aligned} \quad (\text{A13})$$

The last term in (A2) involves the covariance between $(\widehat{B}_{ij})^2$ and $\widehat{\sigma}_{\varepsilon_{\bar{j}}}^2$. Taking the product of their de-measured values:

$$\text{Cov}[(\widehat{B}_{ij})^2, \widehat{\sigma}_{\varepsilon_{\bar{j}}}^2] = E[(\square \sum_{t=1}^T \sum_{\tau=1}^T p_{t\tau} \varepsilon_{it} \varepsilon_{i\tau} - \sigma_{\varepsilon_{\bar{j}}}^2) (2B_{ij} \sum_{t=1}^T m_{jt} \varepsilon_{it} + \square \sum_{t=1}^T \sum_{\tau=1}^T m_{jt} m_{j\tau} \varepsilon_{it} \varepsilon_{i\tau})] \cdot \psi \quad (\text{A14})$$

Expanding out the four terms in (A14):

$$\begin{aligned}
&= 2B_{ij}E\left[\sum_{t=1}^T\sum_{\tau=1}^T\sum_{s=1}^T p_{t\tau}m_{js}\varepsilon_{it}\varepsilon_{t\tau}\varepsilon_{ts}\right] + \square \\
&E\left[\sum_{t=1}^T\sum_{\tau=1}^T\sum_{s=1}^T\sum_{u=1}^T p_{t\tau}m_{js}m_{ju}\varepsilon_{it}\varepsilon_{t\tau}\varepsilon_{ts}\varepsilon_{tu}\right] \square \\
&- \sigma_{\varepsilon_i}^2 2B_{ij}E\left[\sum_{t=1}^T m_{jt}\varepsilon_{it}\right] - \sigma_{\varepsilon_i}^2 E\left[\sum_{t=1}^T\sum_{\tau=1}^T m_{jt}m_{j\tau}\varepsilon_{it}\varepsilon_{t\tau}\right]. \psi
\end{aligned}$$

and then using the ε_{it} is independent through time with zero mean:

$$\begin{aligned}
&= 2B_{ij}E[\varepsilon_i^3]\sum_{t=1}^T p_{tt}m_{jt} + E[\varepsilon_i^4]\sum_{t=1}^T p_{tt}m_{jt}^2 \\
&+ (\sigma_{\varepsilon_i}^2)^2 \sum_{t=1}^T \sum_{\tau \neq t} (2p_{t\tau}m_{jt}m_{j\tau} + p_{tt}m_{j\tau}^2) - (\sigma_{\varepsilon_i}^2)^2 \sum_{t=1}^T m_{jt}^2 \\
&= 2B_{ij}\bar{p}\bar{m}_j E[\varepsilon_i^3] + \bar{p}\bar{m}_{2j} E[\varepsilon_i^4] + ((p \times m) - \bar{m}_{2j})(\sigma_{\varepsilon_i}^2)^2. \psi \tag{A15}
\end{aligned}$$

Now we collect the terms from (A12), (A13), and (A15) and combine them into (A1), multiplying (A13) terms by $(\bar{m}_{2j})^2$ and (A15) terms by $-2\bar{m}_{2j}$, giving:

$$\begin{aligned}
Var[(\widehat{B}_{ij})^2 - \bar{m}_{j2}\widehat{\sigma}_{\varepsilon_i}^2] &= \square \\
&4\bar{m}_{2j}B_{ij}^2\sigma_{\varepsilon_i}^2 + 4B_{ij}\bar{m}_{3j}E[\varepsilon_i^3] + \bar{m}_{4j}E[\varepsilon_i^4] + (3\bar{m}_{2j} - (\bar{m}_{2j})^2)(\sigma_{\varepsilon_i}^2)^2 \\
&+ (\bar{m}_{2j})^2(\bar{p}_2E[\varepsilon_i^4] + ((p \times p) - 1)(\sigma_{\varepsilon_i}^2)^2) \square \\
&- 2\bar{m}_{2j}(2B_{ij}\bar{p}\bar{m}_j E[\varepsilon_i^3] + \bar{p}\bar{m}_{2j} E[\varepsilon_i^4] + ((p \times m) - \bar{m}_{2j})(\sigma_{\varepsilon_i}^2)^2).
\end{aligned}$$

Sorting by the moments and simplifying, this becomes:

$$\text{Var}[(\widehat{B}_{ij})^2 - \overline{m}_{2j}\widehat{\sigma}_{\varepsilon_i}^2] = c_{1ij}\sigma_{\varepsilon_i}^2 + c_{2ij}E[\varepsilon_i^3] + c_{3j}E[\varepsilon_i^4] + c_{4j}(\sigma_{\varepsilon_i}^2)^2$$

$$c_{1ij} = 4\overline{m}_{2j}B_{ij}^2$$

$$c_{2ij} = 4B_{ij}\overline{m}_{3j} - 4\overline{m}_{2j}B_{ij}(\overline{p}\overline{m}_j)$$

$$c_{3j} = \overline{m}_{4j} + (\overline{m}_{2j})^2\overline{p}_2 - 2\overline{m}_{2j}(\overline{p}\overline{m}_{2j})$$

$$c_{4j} = 3\overline{m}_{2j} + (\overline{m}_{2j})^2(p \times p) - 2\overline{m}_{2j}(p \times m)$$

Appendix 2: Discussion of the Bootstrap Estimation of the Chi Statistic's Estimation Variance

This appendix discusses the application of random-case bootstrapping to our model. We use the technique to estimate the variance of our chi-statistic (24).

We have derived an exact formula for the variance of the chi-statistic under the assumptions of the model, but it is a function of the third and fourth moments of asset-specific returns, which are difficult to estimate consistently from time-series regression residuals. The bootstrapping approach to estimating $var[\hat{\chi}_j]$ is natural in this context. Bootstrapping uses the full available sample to estimate this variance directly from the sample data. To implement this estimator we act as if the time series i.i.d. multivariate probability distribution generating returns and factors consists of an $n + k$ -vector process, s_{τ} which has T discrete possible realizations

$$s_{\tau} = [vec[R_{\tau}], vec[F_{\tau}]]$$

The discrete set of potential state realizations for s_{τ} are assumed equal to our observed sample values, and each of these T random states is assumed to have equal probability $\frac{1}{T}$. This is fully consistent with all of our factor model assumptions on returns.

Within the context of this discretized probability distribution we can derive the exact variance of the chi-statistic. We note that the chi-statistic is a function of a sample of T random realizations of the state process:

$$\hat{\chi}_j = f(s_1, \dots, s_T)$$

where s_1, \dots, s_T are independently and identically distributed realizations, and the formula for $f(\cdot)$ is the estimation formula for $\hat{\chi}_j$. Using the discretized probability distribution, the exact variance of $\hat{\chi}_j$ is:

$$\text{var}[\hat{\chi}_j] = \frac{1}{T^T} \sum_{S^T} f(s_1, \dots, s_T)^2 - \left(\frac{1}{T^T} \sum_{S^T} f(s_1, \dots, s_T) \right)^2 \quad (31)$$

where the averages run across the set of all T -tuples s_1, \dots, s_T . Computing (31) is straightforward but impractical since with $T=1200$ (roughly our sample size) there are 1200^{1200} terms in the averages. However the averages are easily and closely approximated by simply averaging over a large number of random draws of (s_1, \dots, s_T) ; we use 50,000 draws in each subperiod.

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Table 1: Regression of estimated factors on the true factors in simulated panel data.

n – number of assets	Dependent variable	Independent variables, % significant t-statistics		Average Adjusted R^2
		$f_{1,t}$ - natural rate factor	$f_{2,t}$ - semi strong factor	
3,000	$\hat{f}_{1,t}$	100.0%	100.0%	99.91
	$\hat{f}_{2,t}$	0.0%	5.5%	0.08
6,000	$\hat{f}_{1,t}$	100.0%	100.0%	99.95
	$\hat{f}_{2,t}$	0.0%	5.8%	0.08
21,000	$\hat{f}_{1,t}$	100.0%	100.0%	99.99
	$\hat{f}_{2,t}$	0.0%	5.4%	0.09

Notes on Table 1: The table shows results from regressions of each of the two estimated factors on the true factors using simulated panel data sets with one natural rate and one semi-strong factor. $\hat{f}_{1,t}$ and $\hat{f}_{2,t}$ are the estimated factors; $f_{1,t}$ and $f_{2,t}$ are the true natural rate and semi-strong factors, respectively. The table reports the percentage of slope coefficients, over 10,000 simulations, which are significant at the 5% level, and well as the average Adjusted R^2 of the regressions.

Table 2: Cross-sectional averages of time-series moments of daily returns before and after Winsorization

		Mean	Variance	Skewness	Kurtosis	Minimum	Maximum	n; T
1989-1993	Before Winsorization	0.00106	0.00200	2.536	66.411	87.51%	483.32%	4254; 1265
	After Winsorization	0.00106	0.00156	0.672	11.471	18.75%	23.08%	
1994-1998	Before Winsorization	0.00076	0.00163	2.1913	61.048	86.02%	585.70%	4817; 1263
	After Winsorization	0.00081	0.00133	0.63243	10.194	16.67%	20.83%	
1999-2003	Before Winsorization	0.00097	0.00186	2.6552	80.335	95.66%	1595.50%	4656; 1256
	After Winsorization	0.00095	0.00143	0.77538	10.919	17.46%	22.92%	
2004-2008	Before Winsorization	0.00005	0.00102	2.6821	100.94	89.64%	600.00%	4313; 1259
	After Winsorization	0.00003	0.00072	0.53839	10.625	12.90%	14.54%	
2009-2013	Before Winsorization	0.00106	0.00090	3.6146	134.5	82.96%	360.49%	4795; 1258
	After Winsorization	0.00092	0.00064	0.6271	11.236	11.67%	14.29%	
2014-2018	Before Winsorization	0.00020	0.00069	4.2352	210.85	92.28%	677.49%	4904; 1258
	After Winsorization	0.00011	0.00043	0.33897	10.683	9.93%	11.11%	

Notes on Table 2: The table shows the first four moments of returns and the minimum and maximum return within each of the six five-year subperiods, before and after Winsorization at the 0.5% and 99.5% fractiles. The last column shows the number of cross-sectional (n) and time-series (T) observations. CRSP daily returns in excess of the risk-free rate for all securities with full five-year return histories.

Table 3: First four moments of time-series factors

		MKTRF	SMB	HML	USDSDR	GBPSDR	JPYSDR	KRWSDR	Oil	Gold	Alum	Lumber
1989-1993	Mean	0.00035	0.00004	0.00009	0.00003	0.00019	0.00004	0.00017	0.00018	0.00001	0.00055	0.00093
	Variance	0.00005	0.00002	0.00001	0.00002	0.00006	0.00004	0.00002	0.00056	0.00007	0.00022	0.00033
	Skewness	0.518	0.496	0.463	0.088	0.008	0.091	0.022	2.376	0.942	0.189	0.904
	Kurtosis	7.610	6.257	6.514	6.078	4.688	6.011	7.524	45.501	11.979	7.925	17.818
1994-1998	Mean	0.00063	0.00032	0.00010	0.00003	0.00010	0.00005	0.00034	0.00002	0.00022	0.00011	0.00007
	Variance	0.00007	0.00003	0.00002	0.00001	0.00003	0.00006	0.00022	0.00039	0.00004	0.00015	0.00057
	Skewness	0.759	0.041	0.060	0.577	0.293	0.605	1.203	0.040	0.115	0.308	0.429
	Kurtosis	11.485	4.458	6.006	7.589	5.549	7.398	55.386	7.618	7.224	7.000	10.484
1999-2003	Mean	0.00002	0.00040	0.00031	0.00004	0.00002	0.00000	0.00003	0.00103	0.00033	0.00026	0.00030
	Variance	0.00018	0.00006	0.00006	0.00001	0.00003	0.00004	0.00003	0.00055	0.00009	0.00010	0.00047
	Skewness	0.140	0.734	0.060	0.284	0.044	0.002	0.390	0.310	1.349	0.299	0.654
	Kurtosis	4.303	7.092	5.399	4.520	3.374	4.598	4.364	4.999	14.951	4.472	7.386
2004-2008	Mean	0.00010	0.00001	0.00015	0.00003	0.00018	0.00008	0.00010	0.00072	0.00067	0.00009	0.00025
	Variance	0.00018	0.00004	0.00004	0.00001	0.00003	0.00005	0.00007	0.00054	0.00018	0.00025	0.00048
	Skewness	0.077	0.161	1.176	0.143	0.511	0.072	0.463	0.084	0.058	0.387	1.322
	Kurtosis	17.675	9.384	20.043	6.141	7.883	10.465	62.219	6.143	8.841	4.885	14.892
2009-2013	Mean	0.00076	0.00017	0.00002	0.00001	0.00014	0.00016	0.00014	0.00098	0.00026	0.00032	0.00089
	Variance	0.00016	0.00003	0.00005	0.00001	0.00003	0.00005	0.00005	0.00035	0.00014	0.00024	0.00060
	Skewness	0.179	0.166	0.236	0.186	0.074	0.084	0.460	0.007	0.641	0.027	1.448
	Kurtosis	6.881	4.806	10.807	7.157	4.275	4.916	10.118	6.265	7.201	4.473	11.694
2014-2018	Mean	0.00032	0.00009	0.00011	0.00008	0.00013	0.00004	0.00004	0.00020	0.00008	0.00014	0.00012
	Variance	0.00007	0.00003	0.00003	0.00001	0.00003	0.00003	0.00002	0.00047	0.00007	0.00014	0.00034
	Skewness	0.44598	0.19017	0.54189	0.40807	1.4283	0.71277	0.03695	0.32194	0.31169	0.33381	0.17648
	Kurtosis	6.4183	3.842	4.7662	7.5632	20.953	10.716	3.5675	5.6263	5.5637	6.0374	7.8895

Notes on Table 3: The table shows the first four moments of the eleven factors within each of the six five-year subperiods. MKTRF, SMB, and HML are the Fama-French market, size and value factors; USDSDR, GBPSDR, JPYSDR and KRWSDR are the percentage change in the US dollar, British Pound Sterling,

Japanese Yen, and Korean Won in units of IMF Special Drawing Rights; Oil, Gold, Aluminum and Lumber are the percentage changes in the prices of these commodities. See text for details of data sources.

Table 4: Cross-sectional average factor betas and their t-statistics

	MKTRF	SMB	HML	USDSDR	GBPSDR	JPYSDR	KRWSDR	Oil	Gold	Alum	Lumber	Rbar2
1989-1993	0.803	0.671	0.225	-0.009	0.003	-0.016	0.004	0.006	0.007	0.005	0.003	94.42%
	126.835	75.835	20.410	-0.506	0.619	-2.725	0.290	4.127	1.749	2.098	1.654	
1994-1998	0.843	0.659	0.291	0.006	0.000	0.002	-0.006	0.004	0.009	0.007	0.003	95.35%
	126.631	77.063	22.969	0.423	0.046	0.463	-2.503	1.890	1.415	2.300	1.820	
1999-2003	0.726	0.446	0.337	0.034	0.011	0.015	-0.063	0.007	0.013	0.025	0.010	93.16%
	105.838	45.254	27.443	1.287	0.764	1.397	-4.371	2.608	1.811	3.788	3.166	
2004-2008	0.790	0.449	0.158	0.071	0.030	0.003	-0.083	0.021	0.006	0.022	0.005	97.31%
	157.293	48.342	17.563	3.697	2.858	0.274	-12.389	7.950	1.186	5.898	1.857	
2009-2013	0.805	0.410	0.159	0.105	0.041	-0.002	-0.045	0.019	0.021	0.012	0.004	98.30%
	141.050	45.772	19.549	6.103	4.555	-0.226	-6.462	6.180	5.036	3.314	1.911	
2014-2018	0.733	0.417	0.129	0.066	0.043	-0.003	-0.062	0.030	0.054	0.011	0.003	96.51%
	132.515	54.598	15.692	3.772	6.152	-0.318	-7.681	14.665	9.614	3.160	1.434	

Notes on Table 4: The table shows the regression coefficients (first row in each subperiod) and their t-statistics (second row in each subperiod) from the regression of the equally-weighted asset return on the eleven factors and an intercept. Numbers in bold are significantly different from zero with at the 5% confidence level.

Table 5: Adjusted mean-squared beta estimates and their z-statistics

	MKTRF	SMB	HML	USDSDR	GBPSDR	JPYSDR	KRWSDR	Oil	Gold	Alum	Lumber
1989-1993	0.844	0.647	0.164	0.035	0.005	0.004	0.025	0.001	0.019	-0.001	0.000
	59.683	28.359	7.060	0.367	1.550	0.884	0.266	1.921	4.976	-0.612	0.274
1994-1998	0.873	0.627	0.259	0.003	0.000	0.004	0.001	0.001	0.040	0.001	0.000
	48.788	26.927	12.156	0.166	0.070	1.279	0.433	1.947	7.404	0.615	0.109
1999-2003	0.753	0.422	0.310	0.011	0.005	0.004	0.023	0.003	0.023	0.003	0.000
	50.787	18.841	16.105	0.490	0.888	0.933	2.149	5.062	5.753	1.681	0.126
2004-2008	0.791	0.469	0.183	0.064	0.022	0.017	0.038	0.009	0.021	0.004	0.000
	56.175	23.876	13.057	2.569	2.807	2.753	2.599	8.575	7.270	2.844	1.015
2009-2013	0.887	0.431	0.189	0.101	0.022	0.008	0.020	0.007	0.036	0.002	0.000
	51.236	32.853	15.165	4.696	4.209	2.787	3.271	6.648	12.816	3.001	1.109
2014-2018	0.803	0.441	0.235	0.050	0.016	0.015	0.017	0.016	0.113	0.002	0.000
	55.153	39.644	26.888	3.550	4.451	4.075	4.151	13.434	16.428	2.979	-0.020

Notes on Table 5: The table shows the adjusted mean-squared beta estimates (first row in each subperiod) and their z-statistics (second row in each subperiod) for the test that the mean-squared beta of the factor is greater than zero. Numbers in bold are significantly greater than zero with 95% confidence.

Table 6: Panel regression marginal R²'s for each factor

	MKTRF	SMB	HML	USDSDR	GBPSDR	JPYSDR	KRWSDR	Oil	Gold	Alum	Lumber	Stacked R-squared
1989-1993	1.511%	0.594%	0.097%	0.008%	0.016%	0.009%	0.008%	0.035%	0.080%	0.007%	0.004%	2.640%
1994-1998	1.996%	0.868%	0.164%	0.002%	0.001%	0.015%	0.009%	0.022%	0.098%	0.006%	0.001%	4.109%
1999-2003	4.569%	1.237%	0.589%	0.004%	0.007%	0.011%	0.031%	0.090%	0.128%	0.018%	0.001%	9.552%
2004-2008	10.670%	1.850%	0.769%	0.059%	0.065%	0.065%	0.288%	0.441%	0.295%	0.085%	0.016%	22.726%
2009-2013	7.175%	1.414%	0.753%	0.091%	0.071%	0.036%	0.109%	0.199%	0.535%	0.053%	0.021%	28.821%
2014-2018	8.144%	2.342%	1.075%	0.051%	0.100%	0.058%	0.080%	1.226%	1.103%	0.048%	0.000%	21.674%

Notes on Table 6: The table shows the marginal R-squared found by deleting each factor individually from the stacked regression model. The last column is the R-squared of the stacked regression model; see the text for the precise formulas.

Table 7: Test for natural rate versus semi-strong factors (z-statistics)

	MKTRF	SMB	HML	USDSR	GBPSR	JPYSR	KRWSDR	Oil	Gold	Alum	Lumber
1989-1993	53.000	17.025	-8.847	2.981	25.246	25.791	2.364	14.527	13.513	27.095	23.122
1994-1998	45.576	20.222	0.681	22.739	24.545	20.926	14.473	24.635	13.166	31.582	25.382
1999-2003	49.085	15.188	12.007	-23.735	27.380	21.214	14.140	11.865	6.900	25.959	28.110
2004-2008	55.069	19.973	8.296	-8.282	7.378	6.449	0.211	3.566	2.055	-5.956	18.687
2009-2013	50.343	27.261	11.290	-7.220	9.734	14.946	5.463	0.120	6.684	-9.493	14.095
2014-2018	53.780	34.773	20.671	-13.643	7.976	7.995	11.051	10.862	13.279	-14.366	32.988

Notes on Table 7: The table shows the z-statistics for the test that the mean-square beta of the factor is significantly above the natural-rate benchmark value. See the text for the definition of the natural rate benchmark value. Numbers in bold are significantly greater than zero.

Table 8: Stepwise Regression Using the Akaike Information Criterion

	MKTRF	SMB	HML	USDSR	GBPSR	JPYSR	KRWSDR	Oil	Gold	Alum	Lumber
1989-1993	*	*	*	5	6	4	3	*	*	2	1
1994-1998	*	*	*	5	4	6	2	7	*	3	1
1999-2003	*	*	*	2	3	5	6	*	*	4	1
2004-2008	*	*	*	*	*	*	*	*	*	*	1
2009-2013	*	*	*	*	*	*	*	*	*	*	1
2014-2018	*	*	*	*	*	*	*	*	*	*	1

Notes on Table 8: The table shows the results of stepwise regression using the AIC benchmark to select factors with positive explanatory power. Asterisks denote factors which pass the AIC test for inclusion at all steps. The integers denote the step order at which other factors were dropped (1 denotes the factor dropped after the first step, and so on).

Table 9: Time series regression fit of each statistically estimated factor using the eleven pre-specified factors and vice-versa

Panel A: Regression fit of each pre-specified factor using twenty statistically estimated factors

	MKTRF	SMB	HML	USDSR	GBPSR	JPYSR	KWRSDR	Oil	Gold	Silver	Alum
1989-1993	87.56%	34.63%	32.21%	1.27%	0.03%	0.89%	0.51%	9.86%	24.31%	0.70%	0.09%
1994-1998	90.12%	52.91%	59.10%	4.10%	0.92%	3.75%	0.28%	7.50%	33.65%	0.96%	0.42%
1999-2003	94.23%	74.91%	71.09%	1.81%	4.66%	3.03%	4.31%	19.54%	46.72%	6.13%	1.05%
2004-2008	98.14%	81.96%	71.55%	10.61%	15.79%	26.44%	25.75%	46.79%	63.09%	20.19%	1.41%
2009-2013	98.63%	85.00%	83.18%	15.58%	18.48%	18.10%	12.54%	50.48%	70.40%	29.32%	4.78%
2014-2018	98.28%	89.01%	87.06%	4.09%	16.26%	34.10%	9.35%	62.05%	68.41%	10.89%	1.75%

Panels B: Regression fit of each statistically estimated factor using the eleven pre-specified factors (statistical factors one to ten)

	APC1	APC2	APC3	APC4	APC5	APC6	APC7	APC8	APC9	APC10
1989-1993	96.78%	37.98%	0.73%	6.60%	0.11%	13.72%	0.26%	0.02%	0.76%	1.69%
1994-1998	95.83%	33.87%	39.19%	30.96%	0.90%	0.85%	1.01%	0.06%	3.71%	1.26%
1999-2003	93.30%	53.22%	18.72%	11.34%	19.19%	40.74%	8.18%	37.60%	1.49%	0.81%
2004-2008	98.63%	57.54%	15.01%	58.62%	36.49%	27.54%	5.28%	6.54%	13.34%	8.46%
2009-2013	98.82%	46.47%	63.46%	43.92%	35.02%	9.10%	21.85%	16.14%	9.48%	6.88%
2014-2018	96.43%	65.52%	65.99%	44.43%	62.59%	9.07%	6.29%	12.24%	21.80%	4.28%

Panels C: Regression fit of each statistically estimated factor using the eleven pre-specified factors (statistical factors eleven to twenty)

	APC11	APC12	APC13	APC14	APC15	APC16	APC17	APC18	APC19	APC20
1989-1993	0.59%	0.09%	0.69%	1.11%	0.82%	0.28%	0.10%	0.24%	0.69%	1.53%
1994-1998	3.99%	1.80%	0.39%	1.20%	0.06%	1.47%	0.92%	0.13%	1.56%	0.12%
1999-2003	0.25%	2.82%	0.21%	0.15%	1.46%	0.07%	0.09%	0.62%	0.09%	0.52%
2004-2008	10.10%	12.40%	7.89%	2.33%	3.44%	3.13%	7.50%	4.13%	3.03%	1.91%
2009-2013	2.62%	1.14%	6.84%	4.12%	4.25%	0.98%	2.24%	3.72%	0.42%	5.26%
2014-2018	1.49%	2.54%	3.35%	1.60%	3.07%	1.53%	7.95%	3.47%	4.38%	2.31%

Notes on Table 9: The table shows the Adjusted R^2 from the time-series regression of each factor on the full set of alternative factors and an intercept. In Panel A the dependent variable in the regression is one of the eleven pre-specified factors and the explanatory variables are the twenty statistically estimated factors; in panels B and C the dependent variable is one of the statistically-estimated factors and the explanatory variables are the eleven pre-specified factors.