Complexity and Shrinkage in Simple Economic Models

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Overview

Motivation:

- Investigate recent factor construction methods ‘out of sample’ – in simulated economies
- Compare performance of Fama-French to Fama-MacBeth-Rosenberg (cf., e.g., Hoberg-Welch) and to recent methods

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Empirical methods: Kelly-Pruitt-Su (2019), Didisheim-Ke-Kelly-Malamud (2023)

Empirical Methods

Empirical Methods: Overview

Kelly-Pruitt-Su (KPS):

- A version of principal components in which the factor loadings are set as linear combinations of firm characteristics
- This shrinks the number of factors.

Didisheim et al. (DKKM):

- Form factors as returns of portfolios in which the weights are random nonlinear combinations of firm characteristics.
- They generate many thousands of such factors. This is complexity. They then estimate the stochastic discount factor using penalized regression on the factors. This is shrinkage.

Kelly-Pruitt-Su, 2019: IPCA = Instrumented PCA

- Latent factors f_t
- Characteristics z_{it}
- Returns $r_{i,t+1} = z_{it}' \Gamma f_{t+1} + \varepsilon_{i,t+1}$
- Choose Γ and f_t to minimize sum over i and t of squared residuals $r_{i,t+1} - z_{it}' \Gamma f_{t+1}$

Kelly-Pruitt-Su Empirics

- 36 firm characteristics
- Rank-standardize characteristics to $[-0.5, +0.5]$ interval
- Test assets: individual stocks
- 5 factors do very well
- Out-of-sample Sharpe ratios:
    - IPCA tangency portfolio: 2.5 annually
    - FF5 tangency portfolio: 1.3 annually

Didisheim-Ke-Kelly-Malamud, 2023: Random Fourier Features

- Factors = returns of portfolios whose weights are rank-standardized characteristic values in $[-0.5, 0.5]$
  - Example: book-to-market factor would be return of portfolio that is long value stocks (above median bm) and short growth stocks (below median bm).

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- Start with M characteristics c_{ik}. Generate M random numbers h_k. Compute two new composite characteristics

$$\cos\left(\sum_{k=1}^{M} h_k c_{ik}\right) \quad \text{and} \quad \sin\left(\sum_{k=1}^{M} h_k c_{ik}\right)$$

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$$\cos\left(\sum_{k=1}^{M} h_k c_{ik}\right) \quad \text{and} \quad \sin\left(\sum_{k=1}^{M} h_k c_{ik}\right)$$

- Repeat many times to get thousands of new composite characteristics.
- Define a factor as described before for each of the new composite characteristics

DKKM Empirical Results

- 130 stock characteristics
- Out-of-sample Sharpe ratios reach 4.0 with high-complexity models (10,000+ factors)
- Fama-French-Carhart 6-factor Sharpe ratio ≈ 1.1

Data-Generating Models

Theoretical Models: Overview

- In all models, risk premia depend on covariances with a stochastic discount factor.
- In all models, the covariances are correlated in the cross-section with firm characteristics.
- Hence, characteristics ‘explain’ risk premia.
- In all models, we can compute size, book-to-market, profitability, asset growth, and momentum (the FFC6 characteristics).
- We can also compute the true traded stochastic discount factor and the true tangency portfolio.

Berk, Green, and Naik (1999)

- Firms invest optimally given an exogenous pricing kernel
- Fixed number of firms, each receives take-it-or-leave-it investment opportunities each period
- Projects generate operating cash flows until they randomly die
- Investment depends on project NPV (which varies with beta and interest rates)
- Model generates: book value, market value, net income, stock returns
- Characteristics: size, book-to-market, ROE, asset growth, momentum

BGN's Simulation Results

- Replicates Fama-French (1992) value and size results in sign and magnitude
- Beta becomes insignificant when size included (as in data)
- Contrarian strategies profitable at short horizons (1-6 months)
- Momentum strategies profitable at longer horizons (1-5 years)

Kogan and Papanikolaou (2014)

- Firms invest optimally given an exogenous pricing kernel
- Two aggregate state variables:
  - Disembodied productivity affecting all capital
  - Productivity of newly installed capital
- Firms acquire projects stochastically at firm-specific rates
- Optimal capital investment choice for each project
- Firm-specific and project-specific productivity processes
- Projects produce cash flows until they randomly expire

KP's Simulation Results

- Firm value = Assets in place (existing projects) + PVGO (future projects)
- Assets in place: affected only by disembodied productivity shock
- PVGO: affected by both embodied and disembodied productivity shocks
- Model replicates value premium in data

Gomes and Schmid (2021)

- General equilibrium model with heterogeneous firms
- Representative household with Epstein-Zin preferences (endogenous SDF)
- Firms make optimal investment and financing decisions
- Single aggregate productivity process (AR(1)) + firm-specific shocks
- Stochastic investment opportunities with random costs
- Lumpy investment (discrete project adoption)
- Debt: consol bonds paying coupons until random expiration
- Tax benefits of debt; costly equity issuance (pecking order)
- Strategic default when equity value ≤ 0

GS's Simulation Results

- Endogenous leverage drives risk premia
- Leverage is countercyclical: rises in recessions when default risk increases
- Credit spreads predict stock returns and business cycles
- Value firms have higher leverage $\Rightarrow$ value premium

Our Simulations

Motivation for Simulations

- In data-generating models, true betas with respect to the SDF depend on entire history of firm-specific and macro shocks
- Characteristics-based factor models use observable firm characteristics to construct traded factors
- Betas with respect to these factors partially explain risk premia
- Our questions: For a given set of characteristics, what is the best way to construct traded factors? Is the answer robust across models?

Simulation Design

- 1,000 firms and 920 months in each panel (discard first 200 as burn-in, leaving 60 years)
- 10 independent panels for each data-generating model (results very consistent across panels for each model)
- In each panel for each model in each month, compute true conditional SDF and true conditional max Sharpe ratio
- Use calibrations from original papers, except we substitute exogenous lognormal SDF in GS, calibrated to match market risk premium

Evaluations of Empirical Methods

Don't use any specific set of test assets. Instead:

- Compare conditional max Sharpe ratios of estimated MVE portfolios of factors

  Barillas-Shanken, 2017: in horse race between factor models, assuming test assets include competing factors, model with highest Sharpe ratio wins

- Estimate conditional SDFs implied by the models and compute Hansen-Jagannathan distance to true conditional SDF

  HJ distance is the maximum pricing error over all test assets with unit uncentered second moment

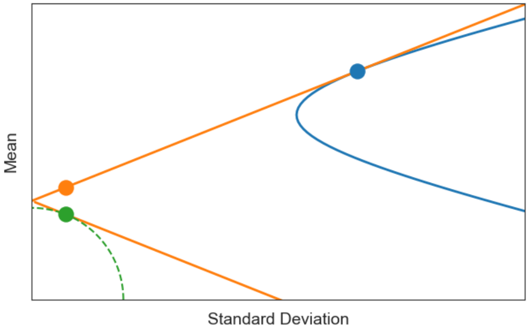
Britten-Jones Regression

- Can find empirical mean-variance frontier by linear regression of constant 1 on asset excess returns
- Write fitted regression as

$$\begin{aligned} 1 &= \sum_{i=1}^{N} \hat{\beta}_i (r_i - r_f) + \hat{\varepsilon} \\ &= \hat{z} + \hat{\varepsilon} \end{aligned}$$

- Max Sharpe ratio is $\bar{z}/\sigma_z$
- Result originally due to Hansen and Richard for population: projection in population rather than regression in sample

Britten-Jones Regression



- Green dot $= (1 + r_f)\hat{\varepsilon}$
- Orange dot $= r_f + (1 + r_f)\hat{z}$, the Sharpe ratio of which equals $\bar{z}/\sigma_z$. Solves max $E[(r-1)^2]$
- Efficient part of frontier is $\{r_f + b\hat{z} \mid b \geq 0\}$

Our Implementation

- Use known true distributions to calculate $\hat{\varepsilon}$. Use as SDF (orthogonal to excess returns).
- In empirical factor models, use Britten-Jones regression on rolling 360 month windows (following DKKM)
- With many factors (maybe more than 360), use ridge penalization in Britten-Jones regression (following DKKM)

Performance Measures for Each Factor Model

- Mean theoretical conditional max Sharpe ratio in each panel
- Realized HJ distance: Square root of mean value of $(\hat{\varepsilon}_{\text{factors}} - \hat{\varepsilon}_{\text{all-returns}})^2$ in each panel
- Both averaged across panels

Ridge Regression

- Minimize: $\frac{1}{T}\sum_{t=1}^{T}(1-\beta' F_t)^2 + \alpha\beta'\beta$
- Penalty parameter α controls shrinkage toward zero
- Essential when number of factors M is large relative to sample size T
- We set $\alpha = \kappa M$ and tune κ to optimize performance
- Tried ridge but performance of Fama-French-Carhart, Fama-MacBeth-Rosenberg, and Kelly-Pruitt-Su declines when regression is penalized

Empirical Factors

- Form factors from size, book-to-market, operating profitability, asset growth, and momentum in all models
- Fama-French-Carhart (FFC): usual 2×3 sorts, use size/book-to-market sort to form SMB
- Fama-MacBeth-Rosenberg (FMR): Fama-MacBeth regressions on characteristics
- Kelly-Pruitt-Su (KPS): latent factors with loadings linearly related to the five characteristics plus an intercept
- Didisheim-Ke-Kelly-Malamud (DKKM): random Fourier features built from the five characteristics plus market return (not penalized in ridge)

Fama-MacBeth-Rosenberg

- Fama-MacBeth (1973), Rosenberg (1976), Fama (1976)
- Regression coefficients $(X'X)^{-1}X'y$ are linear combinations of returns y
- Set $W = X(X'X)^{-1}$ so regression coefficients are $W'y$
- 5 independent variables (characteristics) implies W has 6 columns. $X'W = I$ implies columns of X and W are orthonormal (corresponding columns have unit inner products, others have zero inner products)
- Many solutions W of $X'W = I$, but projection $W = X(X'X)^{-1}$ solves, for each column, min $w'w$ subject to orthonormal constraint
- Being orthogonal to column of 1's implies long-minus-short portfolio. We rescale so long and short sides each sum to 1.

Results

FFC and FMR Perform about the Same

	Berk-Green-Naik		Kogan-Papanikolaou	
	Sh Ratio	HJ Dist	Sh Ratio	HJ Dist
FMR	0.217	0.230	0.194	0.180
FFC	0.209	0.232	0.203	0.168

	Gomes-Schmid	
	Sh Ratio	HJ Dist
FMR	1.640	0.487
FFC	1.457	0.538

DKKM Results

- Performance increases with number of factors (given sufficient penalization)
- Optimal configurations:
  - BGN and KP: $\kappa = 0.1$, 3,600 factors
  - GS: $\kappa = 10^{-4}$, 3,600 factors

DKKM in BGN Model

Berk, Green, and Naik (1999)

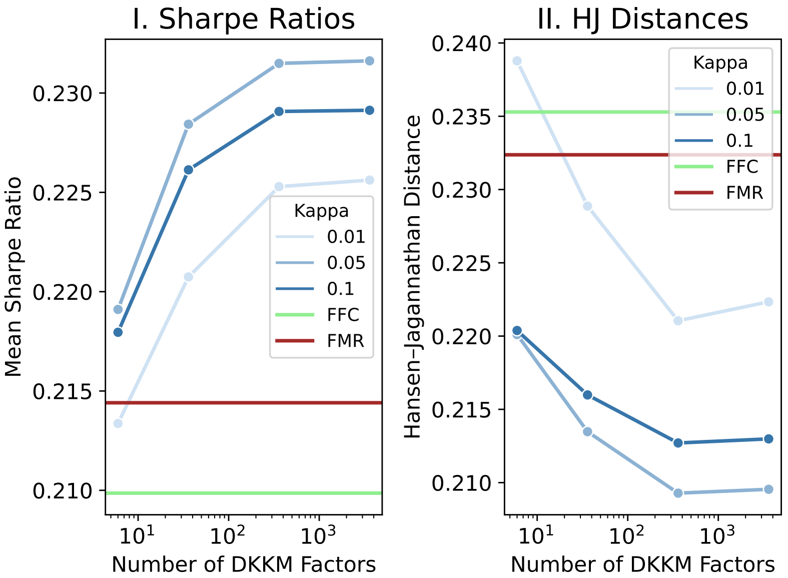
(a) Sharpe Ratio (vs FMR)

κ	6	36	360	3600
0.000	-0.0094	-0.0631	-0.2140	-0.1922
0.001	-0.0082	-0.0168	-0.0179	-0.0152
0.010	-0.0040	0.0054	0.0086	0.0092
0.050	-0.0025	0.0137	0.0154	**0.0157**
0.100	-0.0049	0.0131	0.0147	0.0152
1.000	-0.0398	-0.0265	-0.0257	-0.0245

(b) Hansen-Jagannathan Distance (vs FMR)

κ	6	36	360	3600
0.000	0.0078	0.1930	46.0435	1.0757
0.001	0.0048	0.0357	0.0531	0.0534
0.010	-0.0041	-0.0163	-0.0142	-0.0140
0.050	-0.0026	-0.0228	-0.0246	**-0.0251**
0.100	0.0036	-0.0161	-0.0181	-0.0192

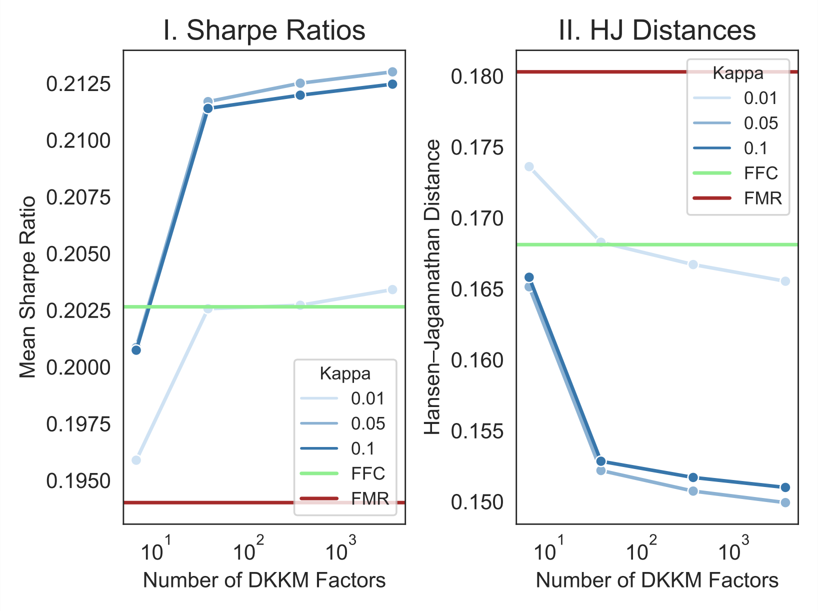
DKKM in BGN Model



DKKM in KP Model

Kogan and Papanikolaou (2014)				
(a) Sharpe Ratio (vs FMR)				
κ	6	36	360	3600
0.000	-0.0083	-0.0673	-0.1928	-0.1766
0.001	-0.0060	-0.0235	-0.0301	-0.0295
0.010	0.0019	0.0085	0.0087	0.0094
0.050	0.0068	0.0177	0.0185	**0.0190**
0.100	0.0067	0.0174	0.0180	0.0184
1.000	-0.0112	0.0012	0.0036	0.0041
(b) Hansen-Jagannathan Distance (vs FMR)				
κ	6	36	360	3600
0.000	0.0121	0.1684	33.0227	0.9500
0.001	0.0075	0.0491	0.0586	0.0580
0.010	-0.0067	-0.0120	-0.0136	-0.0148
0.050	-0.0152	-0.0281	-0.0296	**-0.0304**
0.100	-0.0145	-0.0274	-0.0286	-0.0293

DKKM in KP Model



DKKM in GS Model

Gomes and Schmid (2021)

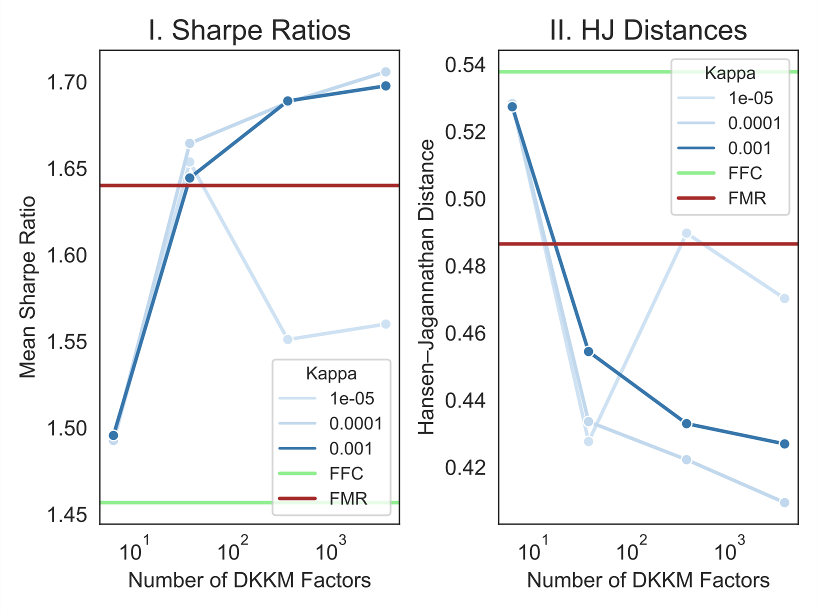
(a) Sharpe Ratio (vs FMR)

κ	6	36	360	3600
0.000	-0.1482	-0.0025	-1.5344	-1.3632
1e-6	-0.1482	0.0018	-0.3309	-0.3049
1e-5	-0.1481	0.0136	-0.0890	-0.0801
1e-4	-0.1474	0.0243	0.0479	**0.0657**
0.001	-0.1445	0.0043	0.0489	0.0576
0.010	-0.1488	-0.0290	-0.0155	-0.0123

(b) Hansen-Jagannathan Distance (vs FMR)

κ	6	36	360	3600
0.000	0.0422	-0.0574	24.8450	0.7238
1e-6	0.0422	-0.0584	0.1318	0.1021
1e-5	0.0421	-0.0589	0.0032	-0.0162
1e-4	0.0418	-0.0529	-0.0643	**-0.0770**
0.001	0.0409	-0.0321	-0.0535	-0.0596

DKKM in GS Model



KPS results

- Optimal with just 2–3 factors
- BGN and GS: 2 factors optimal
- KP: 3 factors optimal

KPS in BGN Model

Berk, Green, and Naik (1999)			
(a) Sharpe Ratio Improvement			
	1 factor	2 factors	3 factors
vs FMR	-0.094	**0.018**	0.014
vs DKKM	-0.110	**0.002**	-0.002
(b) Hansen-Jagannathan Distance Improvement			
	1 factor	2 factors	3 factors
vs FMR	0.059	**-0.038**	-0.028
vs DKKM	0.084	**-0.013**	-0.003

Note: Positive values favor KPS for Sharpe Ratio.
Negative values favor KPS for HJ Distance.

KPS in KP Model

Kogan and Papanikolaou (2014)			
(a) Sharpe Ratio Improvement			
	1 factor	2 factors	3 factors
vs FMR	-0.090	0.013	**0.014**
vs DKKM	-0.109	-0.006	**-0.005**
(b) Hansen-Jagannathan Distance Improvement			
	1 factor	2 factors	3 factors
vs FMR	0.056	-0.023	**-0.024**
vs DKKM	0.086	0.008	**0.006**

Note: Positive values favor KPS for Sharpe Ratio.
Negative values favor KPS for HJ Distance.

KPS in GS Model

Gomes and Schmid (2021)			
(a) Sharpe Ratio Improvement			
	1 factor	2 factors	3 factors
vs FMR	-1.593	**0.042**	0.020
vs DKKM	-1.658	**-0.024**	-0.046
(b) Hansen-Jagannathan Distance Improvement			
	1 factor	2 factors	3 factors
vs FMR	0.408	**-0.009**	0.000
vs DKKM	0.486	**0.069**	0.078

Note: Positive values favor KPS for Sharpe Ratio.
Negative values favor KPS for HJ Distance.

Conclusion

- Usual goal in asset pricing is to find the tradeable SDF
- Usually compute factor portfolio weights from firm characteristics - sorts, regression, etc.
- FFC, FMR, and DKKM follow that process. DKKM is clearly better than FFC and FMR in the models we studied.
- KPS (Instrumented PCA) is a bit different in that it assumes latent factors with betas that are linear in characteristics. It is also clearly superior to FMR and FMC.
- Logical next step, which we're working on, is to do IPCA with a more flexible modeling of betas – linear in an exploded characteristic set as in DKKM.