Term Structures of Asset Prices and Returns

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NYU STERN

Look for entropy

Paul Samuelson ("Gibbs in economics," 1989):

> *I have limited tolerance for the perpetual attempts to fabricate for economics concepts of "entropy."*

Look for logarithms

- Think about $\log m_{t,t+1}$ rather than $m_{t,t+1}$
- Sums more user-friendly than products

$$\log(m_{t,t+1} r_{t,t+1}) = \log m_{t,t+1} + \log r_{t,t+1}$$

more user-friendly than

$$m_{t,t+1} r_{t,t+1}$$

$$\log(m_{t,t+1} m_{t+1,t+2}) = \log m_{t,t+1} + \log m_{t+1,t+2}$$

more user-friendly than

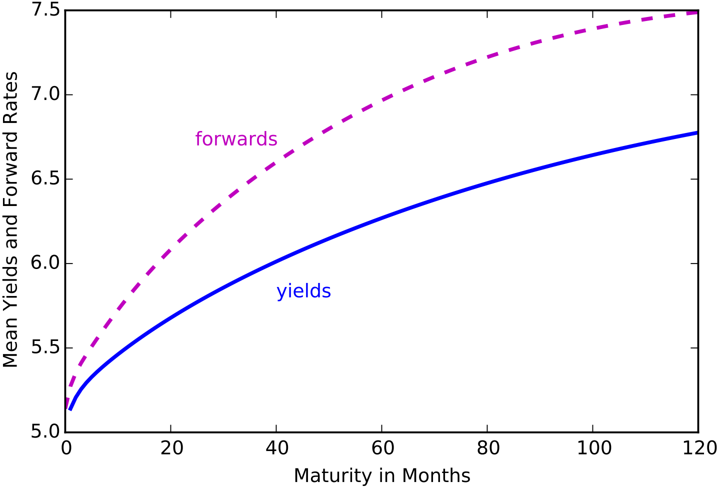
$$m_{t,t+1} m_{t+1,t+2}$$

Excess returns

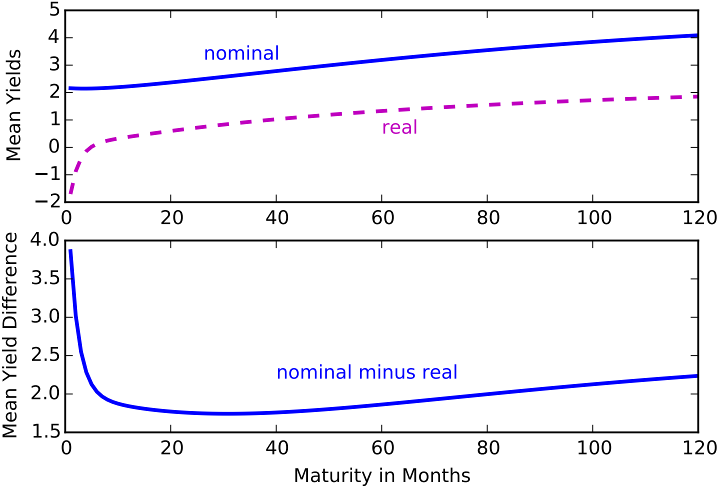
Monthly excess log returns in dollars: $\log r_{t,t+1} - \log r^1_{t,t+1}$

Asset	Mean	Standard Deviation	Skewness	Excess Kurtosis
S&P 500	**0.0040**	0.0556	−0.40	7.90
Fama-French (small, low)	−0.0030	0.1140	0.28	9.40
Fama-French (small, high)	**0.0090**	0.0894	1.00	12.80
Pound Sterling	0.0035	0.0316	−0.50	1.50
5-year bond	**0.0015**	0.0190	0.10	4.87
10-year bond	0.0019			

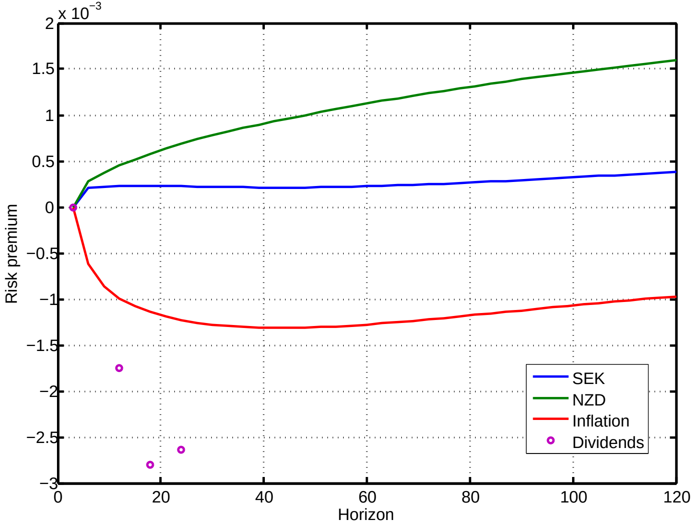
Term structure data: US nominal



Term structure data: US nominal and real



Term structure data: other assets relative to US nominal



Where we're headed

What makes these term structures different?

Plan of attack

- **Entropy:** dispersion in the pricing kernel
- **Risk premiums:** entropy bound
- **Term structure:** pricing kernel dynamics
- **Coentropy:** risk premiums revisited
- **Other term structures:** cash flow dynamics, more coentropy

Entropy

Entropy

- Entropy is a measure of dispersion: for rv $x > 0$

$$L(x) \quad \equiv \quad \log E(x) - E(\log x) \quad \geq \quad 0$$

- Invariant to scale: $L(\alpha x) = L(x)$ for $\alpha > 0$

- Lognormal example: if $\log x \sim \mathcal{N}(\kappa_1, \kappa_2)$, then

$$\begin{aligned} \log E(x) &= \kappa_1 + \kappa_2/2 \\ E(\log x) &= \kappa_1 \\ L(x) &= (\kappa_1 + \kappa_2/2) - \kappa_1 \quad = \quad \kappa_2/2 \end{aligned}$$

Cumulants

- Cumulant generating function (cgf) of rv y

$$k(s;y) \quad = \quad \log \underbrace{E\left(e^{sy}\right)}_{\text{mgf}} \quad = \quad \sum_{j=1}^{\infty} \kappa_j s^j / j!$$

- Cumulants are close relatives of moments

$$\begin{aligned} \text{mean} &= \kappa_1 \\ \text{variance} &= \kappa_2 \\ \text{skewness} &= \kappa_3/\kappa_2^{3/2} \\ \text{excess kurtosis} &= \kappa_4/\kappa_2^2 \end{aligned}$$

- If y is normal: $k(s;y) = \kappa_1 s + \kappa_2 s^2/2$

Entropy and cumulants

- Cumulants of $y = \log x$

$$k(s; \log x) \;=\; \log E(e^{s \log x}) \;=\; \sum_{j=1}^{\infty} \kappa_j(\log x) s^j / j!$$

- Entropy and cumulants (set $s = 1$)

$$\begin{aligned} L(x) &= k(1; \log x) - E(\log x) \;=\; \sum_{j=2}^{\infty} \kappa_j(\log x)/j! \\ &= \underbrace{\kappa_2(\log x)/2!}_{\text{(log)normal term}} + \underbrace{\kappa_3(\log x)/3! + \kappa_4(\log x)/4! + \cdots}_{\text{high-order cumulants}} \end{aligned}$$

Entropy of a stationary stochastic process

- Conditional entropy defined for conditional distribution

$$L_t(x_{t+1}) \quad = \quad \log E_t(x_{t+1}) - E_t(\log x_{t+1})$$

- We define entropy as the mean $E[L_t(x_{t+1})]$

- Connected to entropy for unconditional distribution

$$L(x_{t+1}) \quad = \quad \underbrace{E[L_t(x_{t+1})]}_{\text{entropy}} + L[E_t(x_{t+1})]$$

Risk premiums: the entropy bound

Entropy bound (Alvarez-Jermann)

- Returns satisfy the pricing relation $E_t(m_{t,t+1} r_{t,t+1}) = 1$
- Entropy bound: maximize $E_t(\log r_{t,t+1} - \log r^1_{t,t+1})$
- Maximization leads to the bound

$$\overbrace{E_t(\log r_{t,t+1} - \log r^1_{t,t+1})}^{\text{risk premium?}} \quad \leq \quad L_t(m_{t,t+1})$$

$$E(\log r_{t,t+1} - \log r^1_{t,t+1}) \quad \leq \quad \underbrace{E[L_t(m_{t,t+1})]}_{\text{entropy}}$$

- High return is

$$\log r_{t,t+1} \quad = \quad -\log m_{t,t+1}$$

Hansen-Jagannathan bound

- HJ bound: maximize Sharpe ratio
- Maximization leads to the bound

$$\begin{aligned} \mathrm{SR}_t &\equiv E_t(r_{t,t+1} - r^1_{t,t+1})/\mathrm{Var}_t(r_{t,t+1} - r^1_{t,t+1})^{1/2} \\ &\leq \mathrm{Var}_t(m_{t,t+1})^{1/2}/E_t(m_{t,t+1}) \end{aligned}$$

- High return is

$$r_{t,t+1} = \frac{1 + \mathrm{Var}_t(m_{t,t+1})^{1/2}}{E_t(m_{t,t+1})} - \frac{m_{t,t+1} - E_t(m_{t,t+1})}{\mathrm{Var}_t(m_{t,t+1})^{1/2}}$$

Stan's "never a dull moment" machine

- Entropy of pricing kernel

$$L(m) \;=\; \log E\left(e^{\log m}\right) - E(\log m)$$
$$\;=\; k(1; \log m) - E(\log m) \;=\; \sum_{j=2}^{\infty} \kappa_j(\log m)/j!$$

- Stan's entropy machine (but ask about Lukacs)

$$L(m) \;=\; \underbrace{\kappa_2(\log m)/2!}_{\text{(log)normal term}} + \underbrace{\kappa_3(\log m)/3! + \kappa_4(\log m)/4! + \cdots}_{\text{high-order cumulants}}$$

- Kraus and Litzenberger revisited?

Why is this entropy?

- Humpy Dumpty (in "Through the Looking Glass")

  > *"When I use a word," Humpty Dumpty said, "it means just what I choose it to mean — neither more nor less."*

- Hans-Otto Georgii (quoted by Hansen and Sargent):

  > *When Shannon had invented his quantity and consulted von Neumann on what to call it, von Neumann replied: "Call it entropy. It is already in use under that name and, besides, it will give you a great edge in debates because nobody knows what entropy is anyway."*

Why is this entropy?

- Notation: states z have (true) probabilities $\pi(z)$
- Risk-neutral probabilities π^*

$$\begin{aligned} \pi^*(z) &= \pi(z)m(z)/p^1 \\ m(z) &= p^1\pi^*(z)/\pi(z) \\ p^1 &= E(m) \quad \text{(1-period bond price)} \end{aligned}$$

- Entropy (aka "relative entropy" or "Kullback-Leibler divergence")

$$L(m) = L(\pi^*/\pi) = E\log(\pi/\pi^*)$$

$(\pi^* = \pi \;\; \Rightarrow \; L(m) = 0$, risk premiums $= 0)$

Vasicek model

- Pricing kernel

$$\log m_{t,t+1} = \log \beta + x_t + \lambda w_{t+1}$$

with $\{w_t\}$ iid, mean zero, variance one, and cgf $k(s)$

- Conditional entropy

$$\begin{aligned} L_t(m_{t,t+1}) &= k(\lambda) \\ &= \lambda^2 \kappa_2/2! + \lambda^3 \kappa_3/3! + \lambda^4 \kappa_4/4! + \cdots \end{aligned}$$

- Entropy: the same (maximum risk premium is constant)

State-dependent price of risk

- Pricing kernel

$$\log m_{t,t+1} \quad = \quad \log \beta + x_t + (\lambda_0 + \lambda_1 x_t) w_{t+1}$$

with $\{w_t\} \sim \mathrm{NID}(0,1)$, $k(s) = s^2/2$

- Conditional entropy

$$L_t(m_{t,t+1}) \quad = \quad k(\lambda_0 + \lambda_1 x_t) \quad = \quad (\lambda_0 + \lambda_1 x_t)^2/2$$

- Entropy

$$E[L_t(m_{t,t+1})] \quad = \quad E[(\lambda_0 + \lambda_1 x_t)^2/2]$$

Power utility

- Consumption growth $g_{t,t+1} = c_{t+1}/c_t$ iid

- Pricing kernel

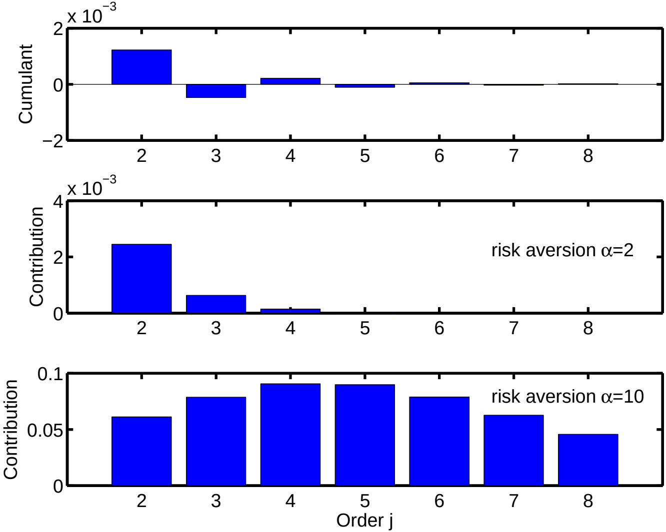
$$\log m_{t,t+1} \quad = \quad \log \beta - \alpha \log g_{t,t+1}$$

(Vasicek with $x_t = 0$, $\lambda = -\alpha$, and $w_{t+1} = \log g_{t,t+1}$)

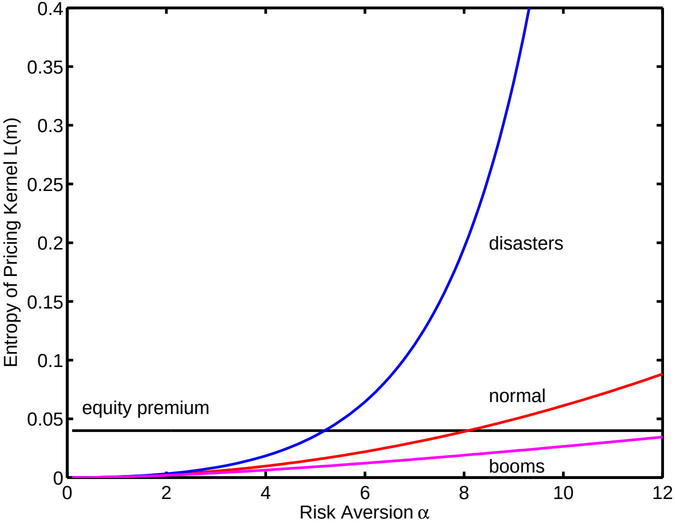
- Yaron's bazooka

$$\begin{aligned} L_t(m_{t,t+1}) &= k(-\alpha) \\ &= (-\alpha)^2 \kappa_2/2! + (-\alpha)^3 \kappa_3/3! + (-\alpha)^4 \kappa_4/4! + \cdots \end{aligned}$$

Power utility: the bazooka



Power utility: the bazooka



Term structure: pricing kernel dynamics

The idea

- In an iid world, entropy is proportional to time interval
- Deviations from proportionality reflect pricing kernel dynamics
- Detectable from mean yields and forward rates

Bond prices, yields, and forward rates

- Bond price: p_t^n is price at t of a claim to one (dollar?) at $t+n$
- Bond yield: $y_t^n = -n^{-1} \log p_t^n$
- Forward rate: $f_t^n = \log(p_t^n / p_t^{n+1}) \;\; \Rightarrow \;\; y_t^n = \sum_{j=1}^n f_t^{j-1}$
- One-period return:

$$\log r_{t,t+1}^{n+1} \; = \; \log(p_{t+1}^n / p_t^{n+1}) \;\; \Rightarrow \;\; E(\log r^{n+1}) \; = \; E(f^n)$$

- Cross sections reflect pricing kernel dynamics

Bond pricing fundamentals

- Markov environment with state variable x
- Bond pricing is recursive

$$p^n(x_t) \quad = \quad E_t\big[m(x_t, x_{t+1})p^{n-1}(x_{t+1})\big]$$

starting with $p^0 = 1$

- Equivalent to

$$p^n(x_t) \quad = \quad E_t\big[m(x_t, x_{t+1})m(x_{t+1}, x_{t+2}) \cdots m(x_{t+n-1}, x_{t+n})\big]$$

- Definitions give us yields $y^n(x_t)$ and forward rates $f^n(x_t)$

Entropy and the term structure

- Entropy over n periods

$$
\begin{aligned}
m_{t,t+n} &= m_{t,t+1} m_{t+1,t+2} \cdots m_{t+n-1,t+n} \\
L_t(m_{t,t+n}) &= \underbrace{\log E_t(m_{t,t+n})}_{\log p_t^n = -n y_t^n} - E_t(\log m_{t,t+n}) \\
\mathcal{L}(n) &\equiv E[L_t(m_{t,t+n})] \;=\; -nE(y^n) - nE(\log m_{t,t+1})
\end{aligned}
$$

- Two measures of horizon dependence

$$
\begin{aligned}
H(n) &\equiv \underbrace{n^{-1}\mathcal{L}(n)}_{\text{avg over n periods}} - \underbrace{\mathcal{L}(1)}_{\text{one period}} \;=\; -E(y_t^n - y_t^1) \\
F(n) &\equiv \mathcal{L}(n+1) - \mathcal{L}(n) - \mathcal{L}(1) \;=\; -E(f_t^n - f_t^0)
\end{aligned}
$$

Entropy and the term structure

- The iid benchmark: $\{m_{t,t+1}\}$ iid $\Rightarrow$

$$\begin{aligned} \mathcal{L}(n) &= n\,\mathcal{L}(1) \\ H(n) &= 0 \\ F(n) &= 0 \end{aligned}$$

- Also: yields and forwards constant, same at all maturities

- Anything different from this reflects dynamics in m

Vasicek model: dynamic structure

- Pricing kernel

$$\begin{aligned}\log m_{t,t+1} &= \log\beta + x_t + \lambda w_{t+1} \\ x_{t+1} &= \varphi x_t + \sigma w_{t+1}\end{aligned}$$

x is (persistent or long-run) risk, λ is price of risk

- Moving average representation

$$\begin{aligned}\log m_{t,t+1} &= \log\beta + x_t + \lambda w_{t+1} \\ &= \log\beta + \lambda w_{t+1} + \underbrace{\sigma w_t + \sigma\varphi w_{t-1} + \cdots}_{x_t}\end{aligned}$$

Vasicek model: entropy

- Pricing kernel dynamics inherited from x
- Term structure of entropy

$$
\begin{aligned}
\mathcal{L}(1) &= k(\lambda) \\
\mathcal{L}(2) &= k(\lambda) + k(\lambda + \sigma) \\
\mathcal{L}(3) &= k(\lambda) + k(\lambda + \sigma) + k(\lambda + \sigma + \sigma\varphi)
\end{aligned}
$$

- What makes this non-iid?

Vasicek model: parameter values

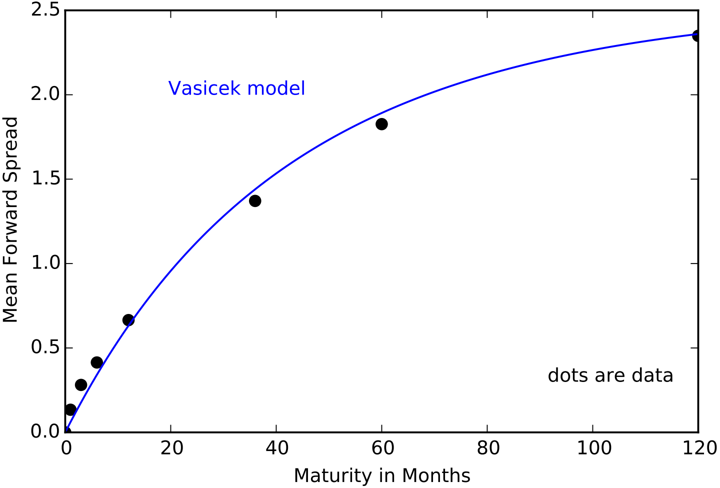
- Short rate

$$y_t^1 \;=\; f_t^0 \;=\; -\log E_t(m_{t,t+1}) \;=\; -[\log\beta + k(\lambda)] - x_t$$

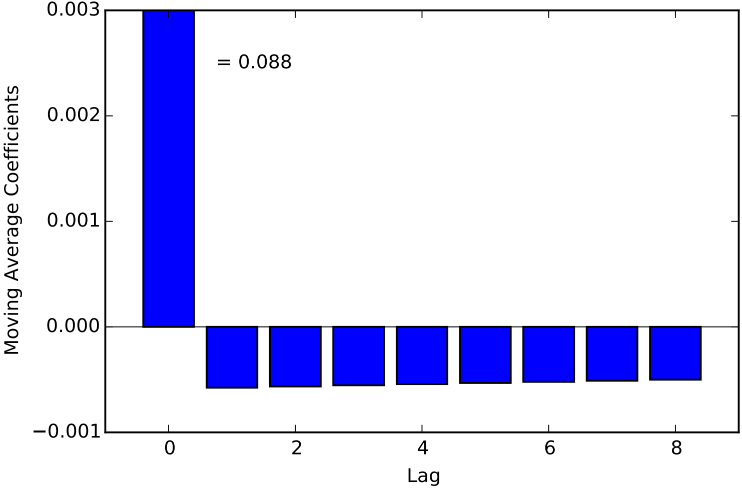
- Choose
  - $(\varphi, \sigma) = (0.98, -0.006)$ match variance and autocorrelation
  - w normal $\Rightarrow$ $k(s) = s^2/2$
  - $\lambda = 0.088$ matches mean forward spread $E(f^n - f^0)$ (ask how this works)

- Features
  - σ and λ must have opposite signs for curve to slope up
  - λ **much** greater than σ in absolute value

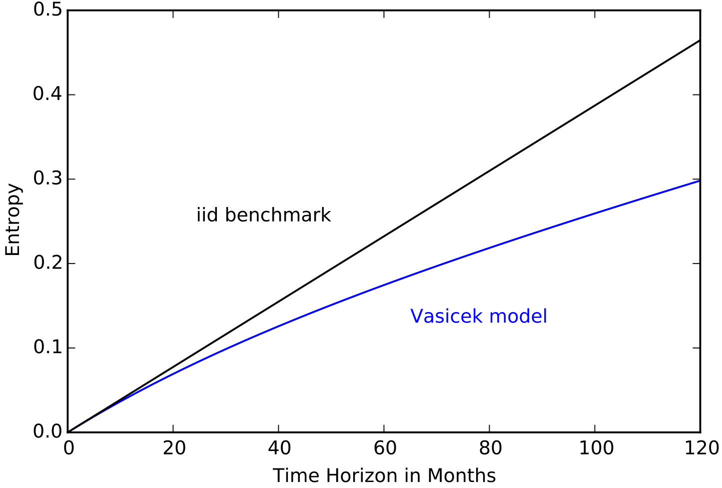
Vasicek model: mean forward spreads



Vasicek model: moving average coefficients



Vasicek model: entropy



Coentropy: risk premiums revisited

The idea

- Expected excess returns differ across assets
- Reflects dependence of pricing kernel and cash flows
- We measure dependence with coentropy
- Extend shortly to long time horizons

Coentropy

- Coentropy is a measure of dependence: for $x_1, x_2 > 0$

$$C(x_1, x_2) \quad \equiv \quad L(x_1 x_2) - L(x_1) - L(x_2)$$

- Features
  - Invariant to scaling
  - Equals zero if x_1 and x_2 are independent

- Related to (joint) cgf $k(s_1, s_2) = \log E(e^{s_1 \log x_1 + s_2 \log s_2})$

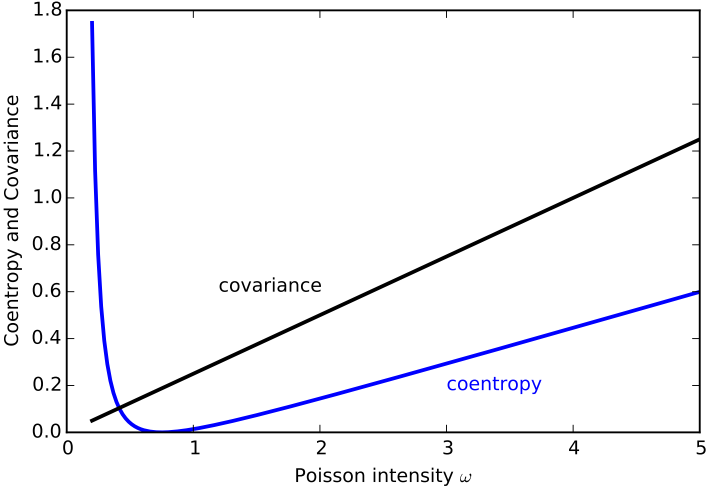
$$C(x_1, x_2) \quad = \quad \underbrace{k(1,1)}_{x_1 x_2} - \underbrace{k(1,0)}_{x_1} - \underbrace{k(0,1)}_{x_2}$$

Coentropy (continued)

- If $\log x = (\log x_1, \log x_2)$ is normal, coentropy = covariance
- Can also be much different
- Example: Poisson mixture ("jump process")
  - Poisson jumps: probability $e^{-\omega}\omega^j/j!$ of $j = 0, 1, 2, \ldots$.
  - Conditional on j, $\log x \sim \mathcal{N}(j\theta, j\Delta)$
- Properties

$$\begin{aligned} \text{Cov}(\log x_1, \log x_2) &= \omega(\theta_1\theta_2 + \delta_{12}) \\ \text{C}(x_1, x_2) &= \text{E2C2E} \end{aligned}$$

Coentropy and covariance



Coentropy and excess returns

- Consider a claim to the cash flow $g_{t,t+1}$
- Return is cash flow over price
- Invariance to scaling implies

$$
\begin{aligned}
L_t(r_{t,t+1}) &= L_t(g_{t,t+1}) \\
C_t(m_{t,t+1}, r_{t,t+1}) &= C_t(m_{t,t+1}, g_{t,t+1})
\end{aligned}
$$

- Expected excess returns ("risk premiums")

$$
\begin{aligned}
E_t(\log r_{t,t+1} - \log r^1_{t,t+1}) &= -L_t(g_{t,t+1}) - C_t(m_{t,t+1}, g_{t,t+1}) \\
E(\log r_{t,t+1} - \log r^1_{t,t+1}) &= -\underbrace{E[L_t(g_{t,t+1})]}_{\text{entropy}} - \underbrace{E[C_t(m_{t,t+1}, g_{t,t+1})]}_{\text{coentropy}}
\end{aligned}
$$

KLV model (streamlined version)

- Add another disturbance to Vasicek

$$\begin{aligned}\log m_{t,t+1} &= \log\beta + x_t + \lambda_1 w_{1t+1} + \lambda_2 w_{2t+1}\\ x_{t+1} &= \varphi x_t + \sigma w_{1t+1}\\ (w_{1t}, w_{2t}) &\sim \text{NID}(0, I)\end{aligned}$$

- Stir in some cash flow growth

$$\log g_{t,t+1} = \log\gamma + \theta x_t + \eta_1 w_{1t+1} + \eta_2 w_{2t+1}$$

- Entropy and coentropy

$$\begin{aligned}E[L_t(m_{t,t+1})] &= (\lambda_1^2 + \lambda_2^2)/2\\ E[L_t(g_{t,t+1})] &= (\eta_1^2 + \eta_2^2)/2\\ E[C_t(m_{t,t+1}, g_{t,t+1})] &= \lambda_1\eta_1 + \lambda_2\eta_2\end{aligned}$$

KLV model: numerical example

- Choose $(\varphi, \sigma, \lambda_1) = (0.98, -0.0006, 0.088)$ as before to fit yields/forwards
- Choose $(\eta_1, \eta_2) = (-0.005, -0.050)$ to match
  - Variance of excess return on equity (0.05)
  - Correlation of excess returns on equity and bonds (0.1)
- Choose $\lambda_2 = 0.097$ to match equity premium
- Results (monthly):
  - Bond premium (10 years): 0.002
  - Equity premium: $0.004 = 0.005$ (coentropy) – 0.001 (entropy)
  - Entropy of *m*: 0.009 (upper bound)

Other term structures: cash flow dynamics

The idea

- Consider claims to currencies, equity indexes, dividends, ...
- How do their term structures compare?
- The time horizon of coentropy
- Explorations with the KLV model

Prices, yields, and forward rates

- Let $\widehat{p}_t^n$ be price at t of claim to cash flow growth $g_{t,t+n}$
- Term structure

$$\begin{aligned}
\widehat{y}_t^n &= -n^{-1} \log \widehat{p}_t^n \\
\widehat{f}_t^n &= \log(\widehat{p}_t^n / \widehat{p}_t^{n+1}) \\
\log \widehat{r}_{t,t+1}^{n+1} &= \log \widehat{p}_{t+1}^n - \log \widehat{p}_t^{n+1} + \log g_{t,t+1} \\
E(\log \widehat{r}^{n+1}) &= E(f^n + \log g)
\end{aligned}$$

- Forward price $q_t^n = \widehat{p}_t^n / p_t^n \quad \Rightarrow$

$$\begin{aligned}
n^{-1} \log q_t^n &= y_t^n - \widehat{y}_t^n \\
\log q_t^{n+1} - \log q_t^n &= f_t^n - \widehat{f}_t^n
\end{aligned}$$

Pricing fundamentals

- Pricing is recursive

$$\begin{aligned}\widehat{p}^n(x_t) &= E_t\big[m(x_t, x_{t+1})g(x_t, x_{t+1})\widehat{p}^{n-1}(x_{t+1})\big] \\ &= E_t\big[\widehat{m}(x_t, x_{t+1})\widehat{p}^{n-1}(x_{t+1})\big]\end{aligned}$$

  with $\widehat{p}^0 = 1$ and $\widehat{m}(x_t, x_{t+1}) = m(x_t, x_{t+1})g(x_t, x_{t+1})$

- Definitions give us yields $\widehat{y}^n(x_t)$ and forward rates $\widehat{f}^n(x_t)$
- Think of this as a change of units: dollars to yen
- Empirical strategy changes: we observe g

Entropy, coentropy, and term structures

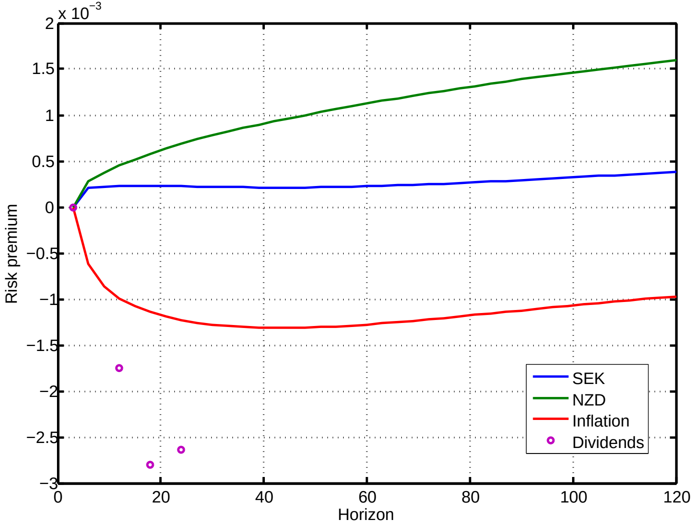
- Entropy and coentropy

$$
\begin{aligned}
L_t(\widehat{m}_{t,t+n}) &= L_t(m_{t,t+n} g_{t,t+n}) \\
&= C_t(m_{t,t+n}, g_{t,t+n}) + L_t(m_{t,t+n}) + L_t(g_{t,t+n})
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{\widehat{m}}(n) &= \mathcal{L}_m(n) + E[C_t(m_{t,t+n}, g_{t,t+n})] + E[L_t(g_{t,t+n})] \\
&= \mathcal{L}_m(n) + \underbrace{\mathcal{C}_{mg}(n)}_{\text{coentropy}} + \underbrace{\mathcal{L}_g(n)}_{\text{entropy}}
\end{aligned}
$$

- Same connection to mean yields and forward rates as before

Term structure data: other assets relative to US nominal



KLV model

- Model

$$
\begin{aligned}
\log m_{t,t+1} &= \log\beta + x_t + \lambda_1 w_{1t+1} + \lambda_2 w_{2t+1} \\
x_{t+1} &= \varphi x_t + \sigma w_{1t+1} \\
\log g_{t,t+1} &= \log\gamma + \theta x_t + \eta_1 w_{1t+1} + \eta_2 w_{2t+1}
\end{aligned}
$$

- Transformed pricing kernel

$$
\begin{aligned}
\log \widehat{m}_{t,t+1} &= (\log\beta + \log\gamma) + \overbrace{(1+\theta)\, x_t}^{\text{long-run risk}} \\
&+ \underbrace{(\lambda_1 + \eta_1)}_{\text{price of lr risk}}\, w_{1t+1} + \underbrace{(\lambda_2 + \eta_2)}_{\text{price of iid risk}}\, w_{2t+1}
\end{aligned}
$$

- Roles of: η_1, λ_2, η_2, θ

KLV model: currencies

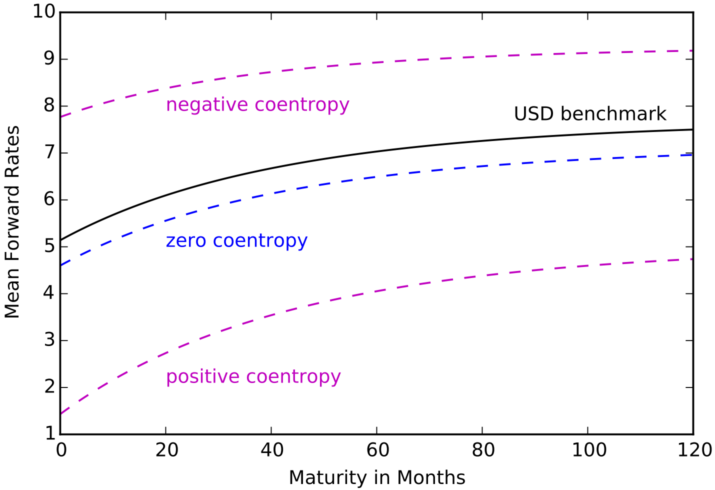
- Model

$$\begin{aligned} \log m_{t,t+1} &= \log\beta + x_t + \lambda_1 w_{1t+1} + \lambda_2 w_{2t+1} \\ x_{t+1} &= \varphi x_t + \sigma w_{1t+1} \\ \log g_{t,t+1} &= \log\gamma + \theta x_t + \eta_1 w_{1t+1} + \eta_2 w_{2t+1} \end{aligned}$$

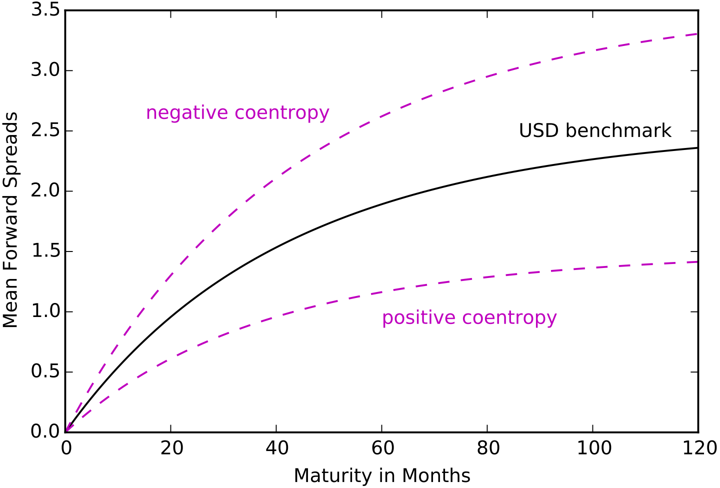
- Currencies: $\theta \approx 0$, $\eta_1^2 + \eta_2^2 \approx 0.03^3$, $\lambda_2 \approx 0$ (for now)

- Then (η_1, η_2) control coentropy
  - $(\eta_1, \eta_2) = (0, 0.3)$: coentropy is zero
  - $(\eta_1, \eta_2) = (0.3, 0)$: coentropy is positive
  - $(\eta_1, \eta_2) = (-0.3, 0)$: coentropy is negative

KLV model: currencies



KLV model: currencies



KLV model: equity

- Model

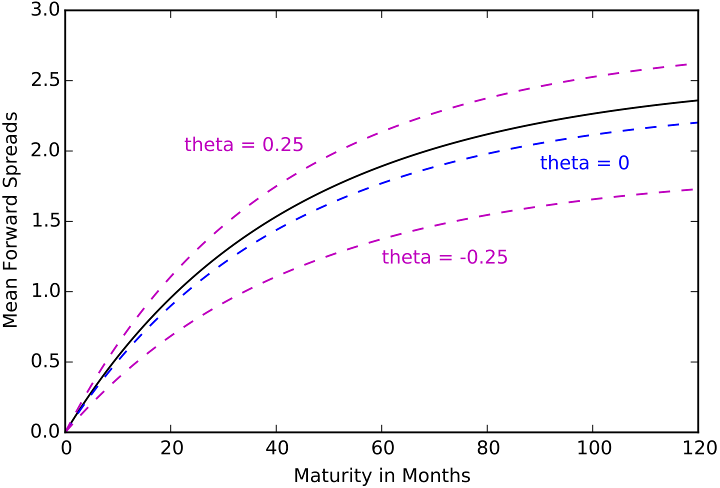
$$\begin{aligned}\log m_{t,t+1} &= \log\beta + x_t + \lambda_1 w_{1t+1} + \lambda_2 w_{2t+1} \\ x_{t+1} &= \varphi x_t + \sigma w_{1t+1} \\ \log g_{t,t+1} &= \log\gamma + \theta x_t + \eta_1 w_{1t+1} + \eta_2 w_{2t+1}\end{aligned}$$

- Reminder: transformed pricing kernel

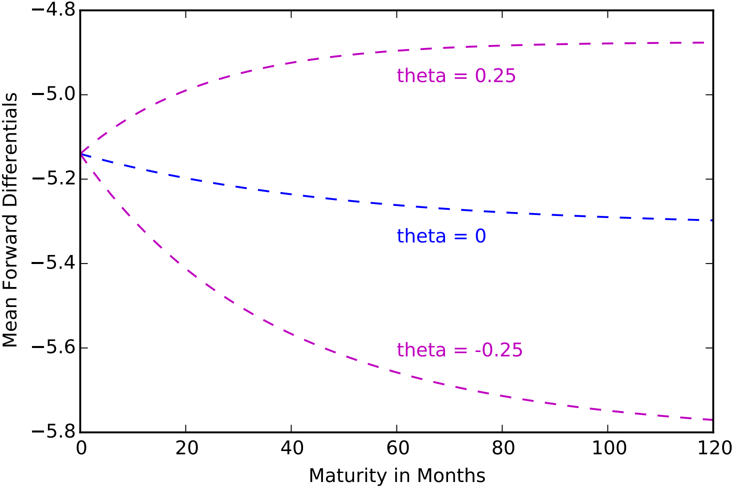
$$\begin{aligned}\log \widehat{m}_{t,t+1} &= (\log\beta + \log\gamma) + \overbrace{(1+\theta)\, x_t}^{\text{long-run risk}} \\ &+ \underbrace{(\lambda_1 + \eta_1)}_{\text{price of lr risk}} w_{1t+1} + \underbrace{(\lambda_2 + \eta_2)}_{\text{price of iid risk}} w_{2t+1}\end{aligned}$$

- Roles of: $\lambda_2 + \eta_2$, η_1 (-0.005), θ (± 0.25)

KLV model: equity



KLV model: equity



Where were we?

Summary and open questions

Summary

- Significant variation in average term structures across assets
- Connected to entropy and coentropy
- Large quantitative effects in simple models (still no bazooka!)

Open questions

- What would you do with these ingredients?
- Would predictability interest you?