Term Structures of Asset Prices and Returns

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(With thanks to Ian Martin and Stan Zin)

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*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: \( \log r_{t,t+1} - \log r_{t,t+1}^1 \)

<table>
<thead>
<tr>
<th>Asset</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Skewness</th>
<th>Excess Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>S&amp;P 500</td>
<td>0.0040</td>
<td>0.0556</td>
<td>−0.40</td>
<td>7.90</td>
</tr>
<tr>
<td>Fama-French (small, low)</td>
<td>−0.0030</td>
<td>0.1140</td>
<td>0.28</td>
<td>9.40</td>
</tr>
<tr>
<td>Fama-French (small, high)</td>
<td>0.0090</td>
<td>0.0894</td>
<td>1.00</td>
<td>12.80</td>
</tr>
<tr>
<td>Pound Sterling</td>
<td>0.0035</td>
<td>0.0316</td>
<td>−0.50</td>
<td>1.50</td>
</tr>
<tr>
<td>5-year bond</td>
<td>0.0015</td>
<td>0.0190</td>
<td>0.10</td>
<td>4.87</td>
</tr>
<tr>
<td>10-year bond</td>
<td>0.0019</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Term structure data: US nominal

![Graph showing term structure data with maturity in months on the x-axis and mean yields and forward rates on the y-axis. The graph includes two curves labeled 'yields' and 'forwards'.]
Term structure data: US nominal and real

- **Mean Yields**
  - **Nominal**
  - **Real**

- **Mean Yield Difference**
  - Nominal minus real
Term structure data: other assets relative to US nominal

![Graph showing term structure data with lines for SEK, NZD, Inflation, and Dividends.](image-url)

- **Risk premium**
- **Horizon**
- **SEK**
- **NZD**
- **Inflation**
- **Dividends**
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 $x > 0$
  \[ L(x) \equiv \log E(x) - E(\log x) \geq 0 \]

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

- Lognormal example: if $\log x \sim \mathcal{N}(\kappa_1, \kappa_2)$, then
  \[
  \log E(x) = \kappa_1 + \kappa_2/2 \\
  E(\log x) = \kappa_1 \\
  L(x) = (\kappa_1 + \kappa_2/2) - \kappa_1 = \kappa_2/2
  \]
Cumulants

- Cumulant generating function (cgf) of rv $y$

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

- Cumulants are close relatives of moments

  mean $= \kappa_1$
  variance $= \kappa_2$
  skewness $= \frac{\kappa_3}{\kappa_2^{3/2}}$
  excess kurtosis $= \frac{\kappa_4}{\kappa_2^2}$

- If $y$ is normal: $k(s; y) = \kappa_1 s + \frac{\kappa_2 s^2}{2}$
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 $s = 1$)

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

$$= \frac{\kappa_2(\log x)}{2!} + \frac{\kappa_3(\log x)}{3!} + \frac{\kappa_4(\log x)}{4!} + \cdots$$

(log)normal term high-order cumulants
Entropy of a stationary stochastic process

- Conditional entropy defined for conditional distribution

\[ L_t(x_{t+1}) = \log E_t(x_{t+1}) - E_t(\log x_{t+1}) \]

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

- Connected to entropy for unconditional distribution

\[ L(x_{t+1}) = E[L_t(x_{t+1})] + L[E_t(x_{t+1})] \]
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

$$E_t(\log r_{t,t+1} - \log r^{1}_{t,t+1}) \leq L_t(m_{t,t+1})$$

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

- High return is

$$\log r_{t,t+1} = -\log m_{t,t+1}$$
Hansen-Jagannathan bound

- **HJ bound**: maximize Sharpe ratio

- Maximization leads to the bound

\[
\text{SR}_t \equiv E_t(r_{t,t+1} - r_{t,t+1}^1)/\text{Var}_t(r_{t,t+1} - r_{t,t+1}^1)^{1/2} \leq \text{Var}_t(m_{t,t+1})^{1/2}/E_t(m_{t,t+1})
\]

- High return is

\[
r_{t,t+1} = \frac{1 + \text{Var}_t(m_{t,t+1})^{1/2}}{E_t(m_{t,t+1})} - \frac{m_{t,t+1} - E_t(m_{t,t+1})}{\text{Var}_t(m_{t,t+1})^{1/2}}
\]
Stan’s “never a dull moment” machine

- Entropy of pricing kernel

\[
L(m) = \log E(e^{\log m}) - E(\log m) = k(1; \log m) - E(\log m) = \sum_{j=2}^{\infty} \frac{\kappa_j(\log m)}{j!}
\]

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

\[
L(m) = \frac{\kappa_2(\log m)}{2!} + \frac{\kappa_3(\log m)}{3!} + \frac{\kappa_4(\log m)}{4!} + \cdots
\]

  (log)normal term + 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 $\pi^*$

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

- 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
  \[ L_t(m_{t,t+1}) = k(\lambda) = \lambda^2 \kappa_2 / 2! + \lambda^3 \kappa_3 / 3! + \lambda^4 \kappa_4 / 4! + \cdots \]

- Entropy: the same (maximum risk premium is constant)
State-dependent price of risk

- Pricing kernel

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

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

- Conditional entropy

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

- Entropy

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

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

- Pricing kernel

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

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

- Yaron’s bazooka

$$L_t(m_{t,t+1}) = k(-\alpha)$$

$$= (-\alpha)^2 \kappa_2 / 2! + (-\alpha)^3 \kappa_3 / 3! + (-\alpha)^4 \kappa_4 / 4! + \cdots$$
Power utility: the bazooka

- Cumulant
- Contribution
- Risk aversion $\alpha = 2$
- Risk aversion $\alpha = 10$
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: $f_t^n = \log\left(p_t^n / p_{t+1}^{n+1}\right) \Rightarrow y_t^n = \sum_{j=1}^n f_t^{j-1}$

- One-period return:

  \[
  \log r_{t,t+1}^{n+1} = \log\left(p_{t+1}^n / p_{t+1}^{n+1}\right) \Rightarrow E(\log r^{n+1}) = E(f^n)
  \]

- Cross sections reflect pricing kernel dynamics
Bond pricing fundamentals

- Markov environment with state variable $x$

- Bond pricing is recursive

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

starting with $p^0 = 1$

- Equivalent to

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

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

- **Entropy over \( n \) periods**

\[
m_{t,t+n} = m_{t,t+1} m_{t+1,t+2} \cdots m_{t+n-1,t+n}
\]

\[
L_t(m_{t,t+n}) = \log E_t(m_{t,t+n}) - E_t(\log m_{t,t+n})
\]

\[
L_t(m_{t,t+n}) = \log E_t(m_{t,t+n}) - E_t(\log m_{t,t+n})
\]

\[
\log p_t^n = -n y_t^n
\]

\[
\mathcal{L}(n) \equiv E[L_t(m_{t,t+n})] = -nE(y^n_t) - nE(\log m_{t,t+1})
\]

- **Two measures of horizon dependence**

\[
H(n) \equiv n^{-1} \mathcal{L}(n) - \mathcal{L}(1) = -E(y_t^n - y_t^1)
\]

\[
F(n) \equiv \mathcal{L}(n + 1) - \mathcal{L}(n) - \mathcal{L}(1) = -E(f_t^n - f_t^0)
\]
Entrophy and the term structure

▶ The iid benchmark: \( \{m_{t,t+1}\} \text{ iid} \Rightarrow \)

\[
\mathcal{L}(n) = n \mathcal{L}(1) \\
H(n) = 0 \\
F(n) = 0
\]

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

▶ Anything different from this reflects dynamics in \( m \)
Vasicek model: dynamic structure

- Pricing kernel

\[
\log m_{t,t+1} = \log \beta + x_t + \lambda w_{t+1} \\
x_{t+1} = \varphi x_t + \sigma w_{t+1}
\]

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

- Moving average representation

\[
\log m_{t,t+1} = \log \beta + x_t + \lambda w_{t+1} \\
= \log \beta + \lambda w_{t+1} + \sigma w_t + \sigma \varphi w_{t-1} + \cdots \\
\hspace{1cm} x_t
\]
Vasicek model: entropy

- Pricing kernel dynamics inherited from $x$

- Term structure of entropy

  $\mathcal{L}(1) = k(\lambda)$

  $\mathcal{L}(2) = k(\lambda) + k(\lambda + \sigma)$

  $\mathcal{L}(3) = k(\lambda) + k(\lambda + \sigma) + k(\lambda + \sigma + \sigma \varphi)$

- What makes this non-iid?
Vasicek model: parameter values

- **Short rate**

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

- **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**

  - \(\sigma\) and \(\lambda\) must have opposite signs for curve to slope up
  - \(\lambda\) **much** greater than \(\sigma\) in absolute value
Vasicek model: mean forward spreads

![Graph showing mean forward spreads and the Vasicek model curve with data points. The x-axis represents maturity in months, and the y-axis represents mean forward spread. The graph includes a blue curve labeled 'Vasicek model' and black dots labeled 'dots are data.'
Vasicek model: moving average coefficients

Moving Average Coefficients

\[ = 0.088 \]
Vasicek model: entropy

![Graph showing the entropy of the Vasicek model compared to the iid benchmark over time horizon in months. The graph plots entropy on the y-axis against time horizon in months on the x-axis. The Vasicek model line is shown in black, and the iid benchmark line is shown in blue. As time horizon increases, both lines show an increase in 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 $x_1, x_2 > 0$

\[ C(x_1, x_2) \equiv L(x_1 x_2) - L(x_1) - L(x_2) \]

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

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

\[ C(x_1, x_2) = k(1, 1) - k(1, 0) - k(0, 1) \]
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 \( j \), \( \log x \sim N(j\theta, j\Delta) \)

- Properties

\[
\text{Cov}(\log x_1, \log x_2) = \omega(\theta_1 \theta_2 + \delta_{12})
\]
\[
C(x_1, x_2) = E_2C_2E
\]
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

\[
L_t(r_{t,t+1}) = L_t(g_{t,t+1}) \\
C_t(m_{t,t+1}, r_{t,t+1}) = C_t(m_{t,t+1}, g_{t,t+1})
\]

- Expected excess returns ("risk premiums")

\[
E_t(\log r_{t,t+1} - \log r_{t,t+1}^{1}) = -L_t(g_{t,t+1}) - C_t(m_{t,t+1}, g_{t,t+1})
\]

\[
E(\log r_{t,t+1} - \log r_{t,t+1}^{1}) = -E[L_t(g_{t,t+1})] - E[C_t(m_{t,t+1}, g_{t,t+1})]
\]

\[\text{entropy} - \text{coentropy}\]
KLV model (streamlined version)

▶ Add another disturbance to Vasicek

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

▶ Stir in some cash flow growth

\[
\begin{align*}
\log g_{t,t+1} &= \log \gamma + \theta x_t + \eta_1 w_{1t+1} + \eta_2 w_{2t+1}
\end{align*}
\]

▶ Entropy and coentropy

\[
\begin{align*}
E[L_t(m_{t,t+1})] &= (\lambda_1^2 + \lambda_2^2)/2 \\
E[L_t(g_{t,t+1})] &= (\eta_1^2 + \eta_2^2)/2 \\
E[C_t(m_{t,t+1}, g_{t,t+1})] &= \lambda_1 \eta_1 + \lambda_2 \eta_2
\end{align*}
\]
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 $\hat{p}_t^n$ be price at $t$ of claim to cash flow growth $g_{t,t+n}$

- Term structure

  $$\hat{y}_t^n = -n^{-1} \log \hat{p}_t^n$$

  $$\hat{f}_t^n = \log(\hat{p}_t^n / \hat{p}_{t+1}^n)$$

  $$\log \hat{r}_{t,t+1}^{n+1} = \log \hat{p}_{t+1}^n - \log \hat{p}_{t+1}^{n+1} + \log g_{t,t+1}$$

  $$E(\log \hat{r}_{t,t+1}^{n+1}) = E(f^n + \log g)$$

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

  $$n^{-1} \log q_t^n = y_t^n - \hat{y}_t^n$$

  $$\log q_{t+1}^{n+1} - \log q_t^n = f_t^n - \hat{f}_t^n$$
Pricing fundamentals

- Pricing is recursive

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

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

- Definitions give us yields \( \hat{y}^n(x_t) \) and forward rates \( \hat{f}^n(x_t) \)

- 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

\[
L_t(\hat{m}_{t,t+n}) = L_t(m_{t,t+n}g_{t,t+n})
= C_t(m_{t,t+n}, g_{t,t+n}) + L_t(m_{t,t+n}) + L_t(g_{t,t+n})
\]

\[
\mathcal{L}_{\hat{m}}(n) = \mathcal{L}_m(n) + E[C_t(m_{t,t+n}, g_{t,t+n})] + E[L_t(g_{t,t+n})]
= \mathcal{L}_m(n) + \mathcal{C}_{mg}(n) + \mathcal{L}_g(n)
\]

- Same connection to mean yields and forward rates as before
Term structure data: other assets relative to US nominal
KLV model

- Model

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

- Transformed pricing kernel

\[
\log \hat{m}_{t,t+1} = (\log \beta + \log \gamma) + (1 + \theta) x_t + (\lambda_1 + \eta_1) w_{1t+1} + (\lambda_2 + \eta_2) w_{2t+1}
\]

Roles of: \(\eta_1, \lambda_2, \eta_2, \theta\)
KLV model: currencies

- Model

\[
\log m_{t,t+1} = \log \beta + x_t + \lambda_1 w_{1t+1} + \lambda_2 w_{2t+1} \\
x_{t+1} = \varphi x_t + \sigma w_{1t+1} \\
\log g_{t,t+1} = \log \gamma + \theta x_t + \eta_1 w_{1t+1} + \eta_2 w_{2t+1}
\]

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

- Then \((\eta_1, \eta_2)\) 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

Mean Forward Spreads

Maturity in Months

USD benchmark

negative coentropy

positive coentropy
KLV model: equity

- Model

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

- Reminder: transformed pricing kernel

\[
\log \hat{m}_{t,t+1} = (\log \beta + \log \gamma) + (1 + \theta) x_t + (\lambda_1 + \eta_1) w_{1t+1} + (\lambda_2 + \eta_2) w_{2t+1}
\]

- Roles of: \( \lambda_2 + \eta_2, \eta_1 \ (-0.005), \theta \ (\pm 0.25) \)
KLV model: equity

Maturity in Months

Mean Forward Spreads

theta = 0.25
theta = 0
theta = -0.25
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?