Multi-Asset Market Making

Ioanid Roșu, Andriy Shkilko, Elvira Sojli, Wing Wah Tham

Presentation: Ioanid Roșu, HEC Paris

NBER

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Motivation

> *"A market maker's success depends on . . . accurately responding to relevant market data in similar and* **correlated instruments**.*"*
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> — Virtu Financial, S-1 Registration Statement (SEC, 2014)

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  - **Liquidity demand** (e.g., market order): pays the spread
    - E.g., $1 € = \$1.17$; Ask \$1.18, Bid \$1.16 $\implies$ spread $= \$0.02$
  - **Liquidity supply** (e.g., limit order): earns the spread; loses from **inventory**

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- **This paper:** how does a dealer manage inventory **across correlated assets**?

Modeling Liquidity Demand & Supply

- **Liquidity Demand:** Modern Portfolio Theory (MPT) (Markowitz, Sharpe, Tobin)
  - N risky assets ($+$ 1 risk-free), 1 period
  - Inputs: expected returns, standard deviations, correlations
  - Results: efficient frontier, tangency portfolio, optimal portfolio
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- **Liquidity Supply:** How do market makers behave?
  - N risky assets, infinitely many periods
  - Inputs: standard deviations, correlations
  - Results: **?**

Market Makers (Dealers) and Prices

- Market makers supply liquidity by setting the bid and ask quotes at which others trade:
  - How do they set their quotes?
  - How do they manage inventory in multiple assets?
  - How much **cross-hedging** is there?
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  - Hendershott & Menkveld (2014) measure "price pressures" in **one asset**: a \$100,000 inventory shock causes a 0.98% price pressure for small-cap stocks, 0.02% for large-cap
  - If dealers cross-hedge, what does a **single-asset** inventory half-life reveal about risk aversion?
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  - How does cross-stock correlation vary with frequency?
- **This paper:** dynamic model in N correlated assets + tests on TSX message-level data (45 trading days)

Model

- Discrete time $t = 0, 1, 2, \ldots$; N **risky assets**, fundamentals $v_{n,t}$ follow a random walk; Δv has covariance Σ_v
- (Monopolist) dealer posts ask a_t and bid b_t in each asset; aggregate market orders satisfy:

$$Q_t^b = \frac{k}{2}(v_t - a_t) + \ell + \varepsilon_t^b, \quad \text{with} \quad \varepsilon_t^b \overset{IID}{\sim} \mathcal{N}(0, \Sigma_L/2)$$

$$Q_t^s = \frac{k}{2}(b_t - v_t) + \ell + \varepsilon_t^s, \quad \text{with} \quad \varepsilon_t^s \overset{IID}{\sim} \mathcal{N}(0, \Sigma_L/2)$$

$\Longrightarrow$ 3 components: elastic + inelastic + random

- Inventory: $x_{t+1} = x_t + Q_t^s - Q_t^b$
- Dealer maximizes expected profit (time discount $\beta < 1$), penalized by **quadratic inventory cost** (**risk aversion** γ)

Optimal Quotes

- **Proposition 1:** In equilibrium, the dealer sets:

$$a_t = p_t + h, \qquad b_t = p_t - h, \qquad p_t = v_t - \lambda x_t$$

where $h = k^{-1}\ell$, and $\lambda = k^{-1}\Lambda$ is the **pricing matrix**, with Λ the unique symmetric positive definite solution of:

$$\Lambda^2 + \Lambda\left(S + \frac{1-\beta}{\beta} I_N\right) = S, \quad \text{with} \quad S = \gamma k \Sigma_v$$

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- Price pressure: $p_t = v_t - \lambda x_t$
  - Diagonal λ_{ii}: own-stock price pressure
    - One-dimensional intuition (Ho–Stoll 1981): buy imbalance $\Longrightarrow$ $x_t < 0$ $\Longrightarrow$ dealer raises a_t, b_t to discourage buyers & encourage sellers $\Longrightarrow$ p_t rises
  - Off-diagonal λ_{ij}: cross-stock price pressure = **cross-hedging**

Cross-Hedging

- When $\beta \to 1$, the pricing matrix λ converges to:

$$\lambda = \frac{k^{-1}}{2}\left((S^2 + 4S)^{1/2} - S\right), \quad \text{with} \quad S = \gamma k \Sigma_v$$

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  Small $\gamma \implies$ **cross-hedging**:

$$\lambda \;\approx\; \gamma^{\frac{1}{2}} k^{-\frac{1}{2}} \Sigma_v^{\frac{1}{2}}$$

  Large $\gamma \implies$ **no cross-hedging** (Σ_v drops out):

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  - *Intuition:* dealer mean-reverts each inventory to zero so quickly that hedging across assets has no time to be valuable

Two Assets: Pricing Matrix

- **Corollary 2:** Two assets with correlation a, diagonal k:

$$\Sigma_v = \sigma_v^2 \begin{bmatrix} 1 & a \\ a & 1 \end{bmatrix}, \quad k = k_0 I_2.$$

Then the pricing matrix is:

$$\lambda = \frac{1}{k_0(m_1+1)(m_2+1)} \begin{bmatrix} m_1+m_2+2 & m_1-m_2 \\ m_1-m_2 & m_1+m_2+2 \end{bmatrix}$$

$$m_1 = \left(\frac{4}{\gamma k_0 \sigma_v^2 (1-a)} + 1\right)^{1/2}, \quad m_2 = \left(\frac{4}{\gamma k_0 \sigma_v^2 (1+a)} + 1\right)^{1/2}$$

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- Note: off-diagonal λ_{12} is proportional to $m_1 - m_2$:
  - $a = 0 \implies m_1 = m_2 \implies$ no cross-hedging
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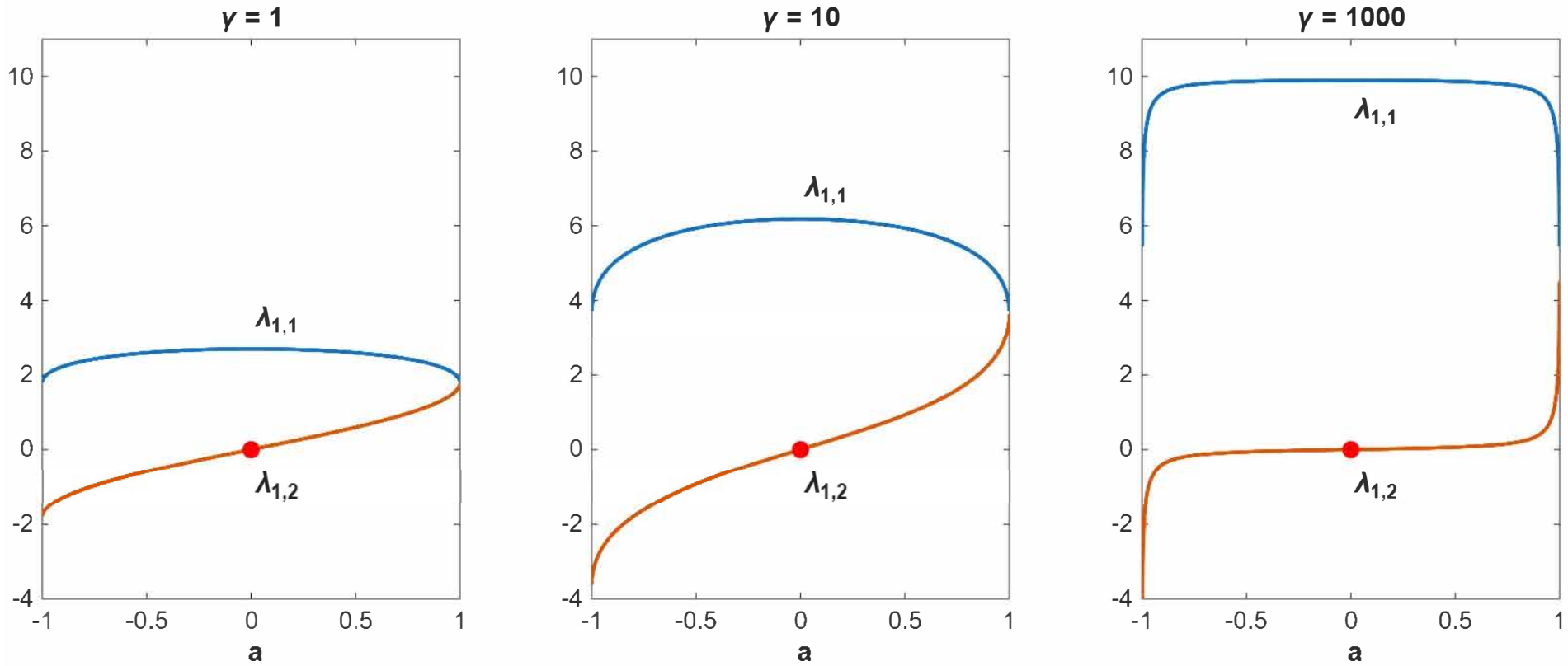
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- For $a \in (0,1)$: λ_{12} is **inverted U-shaped in** γ (vanishes at both extremes)

Pricing Coefficients vs Correlation & Risk Aversion



$\lambda_{1,1}$ (own) and $\lambda_{1,2}$ (cross) vs correlation $a = \mathrm{corr}(\Delta v_1, \Delta v_2)$, for risk aversion $\gamma = 1$ (left), 10 (center), 1000 (right). ($\sigma_v = 1$, $k_0 = 0.1$)

- $\lambda_{1,2}$ **rises with** a: cross-hedging strengthens with correlation
- $|\lambda_{1,2}|$ **rises, then falls with** γ (Cor 2): need risk aversion to cross-hedge, but very high γ eliminates cross-hedging

Two Assets: Numerical Example

- Set $\gamma = 1$, $\sigma_v = 1$, $k_0 = 0.1$, $a = 0.6$ $\implies$ pricing matrix:

$$\lambda = \begin{bmatrix} 2.54 & \mathbf{0.73} \\ \mathbf{0.73} & 2.54 \end{bmatrix}$$

- Suppose $v_t = [10, 10]'$. If $x_t = [-1, +1]'$ $\implies$

$$p_t = \begin{bmatrix} 10 \\ 10 \end{bmatrix} - \begin{bmatrix} 2.54 & 0.73 \\ 0.73 & 2.54 \end{bmatrix} \begin{bmatrix} -1 \\ 1 \end{bmatrix} = \begin{bmatrix} 11.81 \\ 8.19 \end{bmatrix}$$

If instead $x_t = [-1, 0]'$ $\implies$

$$p_t = \begin{bmatrix} 10 \\ 10 \end{bmatrix} - \begin{bmatrix} 2.54 & 0.73 \\ 0.73 & 2.54 \end{bmatrix} \begin{bmatrix} -1 \\ 0 \end{bmatrix} = \begin{bmatrix} 12.54 \\ 10.73 \end{bmatrix}$$

- Long position in (correlated) asset 2 partially hedges short position in asset 1 $\implies$ p_1 rises less (11.81 vs 12.54)
  - Substitution rate: $\lambda_{12}/\lambda_{11} = 0.73/2.54 \approx 29\%$: inventory in asset 2 absorbs about 29% of asset-1's price pressure

Two Assets: Hedging vs Correlations

- If correlation rises from $a = 0.6$ to 0.8, pricing matrix changes:

$$\lambda_{(a=0.6)} = \begin{bmatrix} 2.54 & 0.73 \\ 0.73 & 2.54 \end{bmatrix} \quad \rightarrow \quad \lambda_{(a=0.8)} = \begin{bmatrix} 2.38 & 1.06 \\ 1.06 & 2.38 \end{bmatrix}$$

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- **Own-hedging $\lambda_{1,1}$ falls**: $2.54 \rightarrow 2.38$
  - At $a = 1$, all entries of λ equal $1.79 \implies$ assets are perfect substitutes; less own-hedging needed as a rises

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$$\left(\frac{m_1-1}{m_1+1}\right)^T + \left(\frac{m_2-1}{m_2+1}\right)^T = 1$$

  - Sum inventory $(x_1 + x_2)$ decays at rate $\frac{m_2-1}{m_2+1}$ (fast)
  - Difference inventory $(x_1 - x_2)$ decays at rate $\frac{m_1-1}{m_1+1}$ (slower; cross-hedging works on the difference)
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- Approximation when γ is small:

$$T \approx \frac{m}{\sqrt{1+a}+\sqrt{1-a}}, \qquad m = \frac{1}{\sqrt{\gamma k_0}\,\sigma_v}$$

$\implies$ T depends on correlation a

Risk-Aversion Bias: N Assets

- **Corollary 5:** N assets with same correlation a, diagonal k. When γ is small, the inventory half-life in asset 1 is:

$$T \approx \frac{m}{2\bar{r}}, \quad \text{with} \quad \bar{r} = \frac{\left(1+(N-1)a\right)^{\frac{1}{2}}+(N-1)(1-a)^{\frac{1}{2}}}{N}$$

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- If we estimate γ by observing T (assuming $a = 0$), then $\gamma_{a=0}/\gamma = \bar{r}^2$:
  - $a = 1$: $\bar{r}^2 = \frac{1}{N}$ $\Longrightarrow$ bias $= 1 - \frac{1}{N}$:
    - 50% at $N = 2$, close to 100% for large N
  - Fixed a, large N: $\bar{r}^2 \to 1 - a$ $\Longrightarrow$ bias $\to a$

$\Longrightarrow$ **Single-asset model underestimates γ and bias grows with both N and a**

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- Risk aversion determines which force dominates:
  - High γ: dealer unwinds quickly $\Rightarrow$ **diversification wins**
  - Low γ: dealer holds inventory $\Rightarrow$ **cross-hedging can win**

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$\Longrightarrow$ Asset choice depends on both return correlation and liquidity commonality

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- Then the two components have different correlation:
  - Fundamental news is correlated across assets
  - Inventory pressure is mostly idiosyncratic

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- Therefore, even though $\mathrm{Corr}(\Delta v_{1,t}, \Delta v_{2,t}) = a > 0$,

$$\mathrm{Corr}(\Delta p_{1,t}, \Delta p_{2,t}) \approx 0$$

$\Longrightarrow$ **At short horizons, observed prices can be less correlated than fundamentals**

Price Correlation: One Period

- How does dealer behavior shape **observed** price correlations?
- We consider Σ_L diagonal, to isolate the dealer's effect from the common liquidity demand ($b > 0$)
- **Corollary 6** ($N = 2$, $k = k_0 I$, $\Sigma_L = L_0 I$):

$$L_0 \gg k_0 \sigma_v^2 \gg 1/\gamma \quad \Longrightarrow \quad \rho_p = \text{Corr}(\Delta p_{1,t}, \Delta p_{2,t}) \approx 0$$

  Price returns nearly **uncorrelated** even when fundamentals are correlated ($a > 0$). Why?

  - High γ $\Longrightarrow$ Dealer kills each inventory in almost every period (no cross-hedging) $\Longrightarrow$ λ becomes approximately diagonal $\Longrightarrow$ Quotes move with *own-asset* inventory only
  - $\Sigma_L = L_0 I$ $\Longrightarrow$ Inventories independent across assets

  $\Longrightarrow$ Price moves are uncorrelated

- **Dealer's footprint**: at short horizons, observed correlation $<$ fundamental correlation a (next slide: Epps effect)

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- With high risk aversion and independent liquidity shocks:
  - Short horizon: dealer inventory dominates $\implies \rho_p(H) \approx 0$
  - Long horizon: fundamentals dominate $\implies \rho_p(H) \to a$

Epps Effect: Dealer-Inventory Mechanism

- Dealer quotes satisfy:

$$p_t = v_t - \lambda x_t$$

- Over a horizon of H periods:

$$p_{t+H} - p_t = \underbrace{v_{t+H} - v_t}_{\text{fundamental shocks accumulate}} - \underbrace{\lambda(x_{t+H} - x_t)}_{\text{inventory effect is transitory}}$$

- With high risk aversion and independent liquidity shocks:
  - Short horizon: dealer inventory dominates $\implies \rho_p(H) \approx 0$
  - Long horizon: fundamentals dominate $\implies \rho_p(H) \to a$

$\implies$ Observed return correlation **rises with sampling horizon**

	Pairs of Stocks					
Interval	*AMC-Chrysler*	*AMC-Ford*	*AMC-GM*	*Chrysler-Ford*	*Chrysler-GM*	*Ford-GM*
10 minutes	001	.009	– 009	– 014	007	055
20 minutes	009	018	011	017	026	118
40 minutes	.006	012	.014	041	040	197
One hour	–.043	.057	064	.023	065	.294
Two hours	029	.060	094	.112	129	383
Three hours	031	.158	111	361	518	519
One day	–.067	.170	078	342	442	571
Two days	– 020	223	186	336	449	572
Three days	– 098	203	.100	334	542	645

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- Empirical question:
  - Do individual market makers adjust quotes across correlated stocks in the predicted direction?

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$\Longrightarrow$ Observe **off-diagonal effects** predicted by theory

Classification of Market Makers (549)

- **DMM** (69): designated by the exchange, trades only its assigned stocks

  identified from `AccountType=ST` and the `RTAutofill` auto-participation flag

- **EMM** (252): no designation, sustained two-sided liquidity provision

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- Behavior per day (medians, Table 1):
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- **DMMs turn inventory over; EMMs post and wait**

Inventory at Stock and Portfolio Levels

- Minute-level positions in each stock, summed to the **net** (signed) and **gross** (absolute) portfolio:

	Stock			Portfolio		
(means)	All	DMM	EMM	All	DMM	EMM
End-of-day |position| (000s)	459	158	544	12,729	1,556	6,923
Reversions to zero per day	0.61	1.13	0.38	1.86	3.62	0.97
Minutes between reversions	62.4	71.2	59.7	43.8	41.4	51.1
End-of-day net (000s, median)	1.1	-0.3	0.1	6.4	-2.3	0.7

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- Single-stock positions are carried: the gross mean is CAD 12.7M, while the **net** is flat at the median (CAD 6,400)
- At the close, 46% of held stocks are long and 41% short: a **two-sided portfolio**

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- **Cross-hedging episode**: inventory in i leads ask-heavy quotes in the rest of the portfolio
  - 30-minute rolling correlation: $\text{inv}_i(t)$ with $\text{imb}_{\text{not-}i}(t+5)$
  - At least 5 consecutive minutes with positive correlation

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- **Preview:** cross-hedging appears in all three groups

Cross-Hedging Episodes: Results

	All	DMM	EMM	Both
Episodes	879,942	58,634	449,107	372,201
Market makers	537	68	242	227
Episode length in min. (median)	26	24	26	25
Covariance offset ratio (median)	0.130	0.096	0.131	0.133
Top-3 hedgers' cov. share (median)	0.857	1.000	0.615	0.989
Positive contributors (median)	13	4	24	6

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- Consistent with theory: cross-hedging exists, but pairwise responses are small

Which Stocks Carry the Hedge?

- Most frequent focal–hedger pairs across episodes:

Focal	Hedger	Episodes	Market makers	Mean return corr.
ECA	CNQ	4,878	70	0.446
CNQ	ECA	4,792	68	0.446
PCA	ECA	4,242	53	0.445
PCA	CNQ	4,206	59	0.423
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- They have high return correlations, about **0.44**
- This suggests the hedge is not random: dealers use economically related stocks

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Return $\text{corr}(r_i, r_j)$	Share quoted to sell	Relative to low corr.
Below -0.1	0.583	–
-0.1 to 0	0.623	+4.0 %
0 to 0.1	0.647	+6.4 %
0.1 to 0.3	0.694	+11.1 %
Above 0.3	**0.728**	**+14.5 %**

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- The test is the **slope**: higher return correlation means more selling pressure in the hedger stock

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Return correlation	Negative	Near-zero	Positive	All
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- Return-correlation slope is positive in every inventory-correlation group
- It survives even when inventories in i and j do not move together

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- **Contribution:** Tractable portfolio theory of liquidity supply

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$\Longrightarrow$ Data support theory's off-diagonal pricing matrix