A Minimal Model for Nonlinear Market Impact

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A fully consistent, minimal model for non-linear market impact

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A Reaction-Diffusion Model of Latent Order Book

Two pivotal ideas

Latent order book

Reaction-Diffusion model

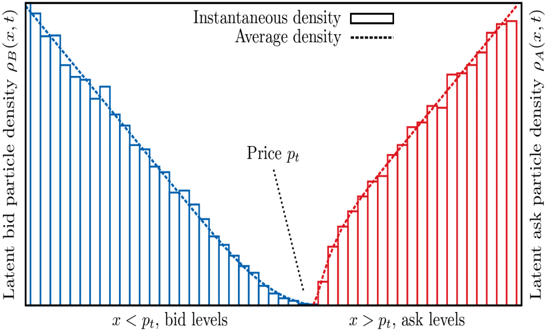
Order Book Dynamics (x : price)

Buy volume density $\rho_B(x,t)$

Sell volume density $\rho_A(x,t)$

Transaction Price p_t

$$\boxed{\rho_A(p_t,t) = \rho_B(p_t,t)}$$



$$\frac{\partial \rho_B(x,t)}{\partial t} = -V_t \frac{\partial \rho_B(x,t)}{\partial x} + D\frac{\partial^2 \rho_B(x,t)}{\partial x^2} - \nu\rho_B(x,t) + \lambda\Theta(p_t - x) - \kappa R_{AB}(x,t)$$

$$\frac{\partial \rho_A(x,t)}{\partial t} = \underbrace{-V_t \frac{\partial \rho_A(x,t)}{\partial x} + D\frac{\partial^2 \rho_A(x,t)}{\partial x^2}}_{\text{Drift-Diffusion: price reassessments}} - \underbrace{\nu\rho_A(x,t)}_{\text{Cancellation}} + \underbrace{\lambda\Theta(x - p_t)}_{\text{Deposition}} - \underbrace{\kappa R_{AB}(x,t)}_{\text{Reaction: trades}}$$

Price Dynamics within a Locally Linear Order Book

Define $\hat{p}_t \triangleq \int_0^t V_s ds$, $y \triangleq x - \hat{p}_t$, the net order density $\phi(x,t) \triangleq \rho_B(x,t) - \rho_A(x,t)$

$$\frac{\partial \phi(y,t)}{\partial t} = D \frac{\partial^2 \phi(y,t)}{\partial y^2} - \nu \phi(y,t) + \lambda \mathrm{sign}(p_t - \hat{p}_t - y)$$

Zoom into the *universal linear regime* $\nu \to 0$, $\lambda \to 0$, $J \triangleq D \left|\partial_y \phi_{\mathrm{s.t.}}\right|_{y=0} = \lambda \sqrt{\frac{D}{\nu}}$ fixed:

$$\phi_{\mathrm{s.t.}} = -\mathcal{L} y,$$

where $\mathcal{L} \triangleq J/D$ is the *latent liquidity* of the market. Add meta-order to the system:

$$\begin{cases} \frac{\partial \phi(y,t)}{\partial t} = D \frac{\partial^2 \phi(y,t)}{\partial y^2} + m_t \delta(y - y_t) \\ \partial_y \phi(y \to \pm\infty, t) = -\mathcal{L} \end{cases} \Rightarrow \phi(y,t) = -\mathcal{L} y + \int_0^t \frac{ds\, m_s}{\sqrt{4\pi(t-s)}} e^{-\frac{(y-y_s)^2}{4D(t-s)}}$$

where m_t is the signed trading intensity at time t. Transaction price $\phi(y_s, s) \equiv 0$

$$\boxed{y_t = \frac{1}{\mathcal{L}} \int_0^t \frac{ds\, m_s}{\sqrt{4\pi(t-s)}} e^{-\frac{(y_t-y_s)^2}{4D(t-s)}}}$$

This is the central equation of the paper: a self-consistent integral equation for $t > 0$.

Impact of Meta-Order and Impact Decay

For a meta-order of size Q executed at constant rate $m_t = \begin{cases} m_0 = Q/T, & t \in [0, T], \\ 0, & t > T. \end{cases}$

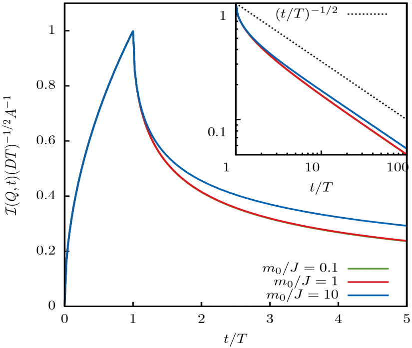
Define market impact $\mathcal{I}(Q,t) \triangleq \langle \epsilon \cdot (p_t - p_0) | Q \rangle = \langle \epsilon \cdot (y_t - y_0) | Q \rangle \underbrace{+ \langle \epsilon \cdot (\hat{p}_t - \hat{p}_0) | Q \rangle}_{=0,\text{ uninformed meta-order}}$.

Solving the self-consistency equation for y_t yields

$$\frac{\mathcal{I}(Q,t)}{\mathcal{I}(Q)} = \begin{cases} \sqrt{\frac{t}{T}}, & t \in [0, T], \\ \sqrt{\frac{t}{T}} - \sqrt{\frac{t-T}{T}}, & t > T, \end{cases}$$

where total market impact gives precisly the celebrated *square-root impact law*:

$$\mathcal{I}(Q) = \mathcal{I}(Q,T) \approx \begin{cases} \sqrt{\frac{m_0}{\pi J}} \times \sqrt{\frac{Q}{\mathcal{L}}}, & m_0 \ll J, \\ \sqrt{2} \times \sqrt{\frac{Q}{\mathcal{L}}}, & m_0 \gg J. \end{cases}$$



Absence of Price Manipulation & Extensions

Average cost of a closed price trajectory: $\mathcal{C} = \int_0^T ds\, m_s y_s$, with $\int_0^T ds\, m_s = 0$.

$$\mathcal{C} = \frac{1}{2} \int_0^T \int_0^T dsds'\, M(s,s') m_s m_{s'}$$

where

$$M(s,s') = \frac{1}{\mathcal{L}\sqrt{4\pi|s-s'|}} e^{-\frac{(y_s - y_{s'})^2}{4D|s-s'|}}$$

is a semi-positive definite kernel. Therefore, $\mathcal{C} \geq 0$ for any execution schedule, i.e. price manipulation is impossible within the model of Locally Linear Order Book (LLOB).

Possible Extensions and Open Problems

- ☐ Relax the approximation made in limit of
  - (1) slow latent order books $\nu T \ll 1$;
  - (2) large liquidity, i.e., meta-order only probes the linear region of order book.
- ☐ Corrections to the LLOB induced by fluctuations.
- ☐ Introduce random fluctuations in the interacting meta-order flows.
- ☐ Cancellation rate ν is expected to increase with the intensity of meta-orders.
- ☐ Deposition rate λ is expected to increase with the distance $|x - p_t|$.
- ☐ Drift term V_t could be non-Gaussian.