Game On: Social Networks and Markets

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Extended slide deck - ASSA deck will be abbreviated
Latest version of the paper available here: `www.lhpedersen.com`

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Game on!

- **Social networks have influenced equity trading since**
  - its beginning in the 17th century
  - trading clubs connected to Amsterdam Stock Exchange (De la Vega (1688))
  - coffee houses where London Stock Exchange operated (Standage (2006))
- **Now social media make**
  - social networks larger and more observable to researchers
  - example: GameStop

- **This paper**
  - **Model:** people trade based on what they learn from social network
  - **Application:** GameStop and beyond

Main results

- **Closed-form**
  - **beliefs**:
    - network spillover effects
    - convergence to mix of rational and fanatic views
    - thought leaders and influencers matter
  - **prices**:
    - social network effects
    - bubbles
    - excess volatility
    - price momentum and fundamental momentum (e.g., PEAD)
    - long-run reversal
  - **portfolios**:
    - differ across investors
    - bursts of high volume

- **Helps explain**
  - GameStop
  - the anatomy of historical bubbles (Kindleberger (2000), Shleifer (2000))
  - financial markets more broadly (momentum, reversal, etc.)

Related literature

- **Theory**
  - DeGroot (1974) model and persuasion bias, DeMarzo et al. (2003)
    → **Introduce rational agents+asset markets into DeGroot model**
  - Networks, surveys by Jackson (2010) and Golub and Sadler (2016)
  - Cascades of defaults, survey by Jackson and Pernoud (2020)
  - Information percolation (Duffie et al. (2009)) with social transmission bias (Hirshleifer (2020)) → **Add network effects**
  - Behavioral finance, survey by Barberis and Thaler (2003)
    → **New theory of momentum, reversal, and excess volatility, and network price dynamics (distinguishing feature cf. other theories)**
- **Empirical finance literature: social networks affect**
  - housing market expectations and prices, based on Facebook data (Bailey et al. (2018))
  - local bias and firm values (Kuchler et al. (2020))
  - equity market participation of retail investors (Hong et al. (2004), Brown et al. (2008), Kaustia and Knüpfer (2012))
  - portfolios of money managers (Hong et al. (2005))
    → **Model these phenomena + new predictions: influencers, thought leaders, network as driver of anomalies and volume**

Outline of talk

- **Model**
- Solution and results
- Case study of GameStop

Model: assets and investors

- **Stock trades at discrete times,** $t = 0, 1, 2, \ldots$
  - Supply of shares s
  - Payoff: $v + u_\tau \in \mathbb{R}$ at revelation time $\tau \sim$ geometric(π)
    - u_t observable random walk with $\mathrm{Var}(\Delta u_t) = \sigma_u^2$
    - v unobserved; each time t, $v \begin{cases} \text{is revealed with probability} & \pi \\ \text{remains unknown with prob.} & 1 - \pi \end{cases}$
  - Price:

$$price(t) = p(t)1_{(t<\tau)} + [v + u(t)]1_{(t\geq\tau)}$$

- N **investors**
  - Each investor i receives a signal at time 0: $x_i(0) = v_i$, where
    - $v = \sum_{i=1}^{N} \kappa_i v_i$
    - known weights sum to one, $\sum_{i=1}^{N} \kappa_i = 1$
  - Four types:
    1. Naive (boundedly rational, persuasion bias)
    2. Fanatic
    3. Rational short-term investors
    4. Long-term investors

Model: learning in a social network

- **Naive learning in a social network:**

$$x_i(t) = A_i x(t-1)$$

where weights sum to one, $\sum_j A_{ij} = 1$

- **Example**

$$\begin{pmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \\ x_5(t) \end{pmatrix} = \begin{pmatrix} 70\% & 0 & 0 & 20\% & 10\% \\ 40\% & 40\% & 0 & 10\% & 10\% \\ 40\% & 0 & 40\% & 10\% & 10\% \\ 0 & 0 & 0 & 1 & 0 \\ * & * & * & * & * \end{pmatrix} \begin{pmatrix} x_1(t-1) \\ x_2(t-1) \\ x_3(t-1) \\ x_4(t-1) \\ x_5(t-1) \end{pmatrix}$$

Model: learning in a social network

- **Naive learning in a social network:**

$$x_i(t) = A_i\, x(t-1)$$

where weights sum to one, $\sum_j A_{ij} = 1$

- **Example**

$$\begin{pmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_f \\ x_5(t) \end{pmatrix} = \begin{pmatrix} 70\% & 0 & 0 & 20\% & 10\% \\ 40\% & 40\% & 0 & 10\% & 10\% \\ 40\% & 0 & 40\% & 10\% & 10\% \\ 0 & 0 & 0 & 1 & 0 \\ * & * & * & * & * \end{pmatrix} \begin{pmatrix} x_1(t-1) \\ x_2(t-1) \\ x_3(t-1) \\ x_f \\ x_5(t-1) \end{pmatrix}$$

- **Fanatic:** $A_{ii} = 1$, $A_{ij} = 0$ for $j \neq i$

Model: rational learning in a social network

- **Time 1:**

$$x_i(1) = x_r = E(v|x_1(0), ..., x_N(0)) = (\kappa_1, \ldots, \kappa_N)x(0)$$

Example:

$$\begin{pmatrix} x_1(1) \\ x_2(1) \\ x_3(1) \\ x_f \\ x_5(1) \end{pmatrix} = \begin{pmatrix} 70\% & 0 & 0 & 20\% & 10\% \\ 40\% & 40\% & 0 & 10\% & 10\% \\ 40\% & 0 & 40\% & 10\% & 10\% \\ 0 & 0 & 0 & 1 & 0 \\ 20\% & 20\% & 20\% & 20\% & 20\% \end{pmatrix} \begin{pmatrix} x_1(0) \\ x_2(0) \\ x_3(0) \\ x_4(0) \\ x_5(0) \end{pmatrix}$$

- **Time $t \geq 2$:**

$$x_i(t) = x_r = e_i' x(t-1)$$

Example:

$$\begin{pmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_f \\ x_r \end{pmatrix} = \begin{pmatrix} 70\% & 0 & 0 & 20\% & 10\% \\ 40\% & 40\% & 0 & 10\% & 10\% \\ 40\% & 0 & 40\% & 10\% & 10\% \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_1(t-1) \\ x_2(t-1) \\ x_3(t-1) \\ x_f \\ x_r \end{pmatrix}$$

Model: trading and equilibrium

- **Equilibrium price: supply equals demand**

$$s = \sum_{i=1}^{N} d_i(t)$$

- **Demand from naive, fanatic, or rational long-term investor:**

$$\max_{d_i} d_i E_t \left[x_i(t) + u(\tau) - p(t) \right] - \frac{1}{2w_i} \mathrm{Var}_t \left[d_i(x_i(t) + u(\tau) - p(t)) \right]$$

where $w_i = wealth_i / \gamma_i$ is the absolute risk tolerance.

Solution using that $\mathrm{Var}_t(u_\tau) = \sigma_u^2 E(\tau - t) = \sigma_u^2 / \pi$

$$d_i(t) = \frac{\pi w_i}{\sigma_u^2} (\underbrace{x_i(t) + u(t)}_{\text{fundamental value}} - p(t))$$

- **Demand from rational short-term investor**

$$d_i(t) = \frac{w_i}{\sigma_u^2} (\underbrace{(1-\pi) E_t(p(t+1)) + \pi(x_r + u(t))}_{\text{expected price at time } t+1} - p(t))$$

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Evolution of beliefs (warm-up: special cases)

- **Everyone is naive and connected** (DeGroot, DeMarzo et al.)

$$x(1) = Ax(0) \quad x(2) = Ax(1) = A^2x(0) \quad x(3) = Ax(2) = A^3x(0)$$

$$x(t) = A^t x(0) \to \begin{pmatrix} z_1 & z_2 & \dots & z_N \\ \vdots & \vdots & & \vdots \\ z_1 & z_2 & \dots & z_N \\ z_1 & z_2 & \dots & z_N \end{pmatrix} x(0) = \begin{pmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{pmatrix} z'x(0)$$

where eigenvector $z'A = z'$ is related to Google's page rank

- **Rationality in the echo champer: the stubbornness of truth**

$$x(t) = A^{t-1}x(1) \to 1_N e_N' x(1) = 1_N \, x_r$$

Cf. Golub and Jackson (2010): *all opinions in a large society converge to the truth ⇔ influence of the most influential agent vanishes*

- **One fanatic in the echo chamber**

$$x(t) = A^t x(0) \to 1_N e_N' x(0) = 1_N \, x_N(0)$$

Beliefs with fanatics and rational (key framework)

- Time 2

$$\begin{pmatrix} x_1(2) \\ x_2(2) \\ x_3(2) \\ x_f \\ x_r \end{pmatrix} = A\,x(1) = \begin{pmatrix} 70\% & 0 & 0 & 20\% & 10\% \\ 40\% & 40\% & 0 & 10\% & 10\% \\ 40\% & 0 & 40\% & 10\% & 10\% \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_1(1) \\ x_2(1) \\ x_3(1) \\ x_f \\ x_r \end{pmatrix}$$

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- Time 3

$$\begin{pmatrix} x_1(3) \\ x_2(3) \\ x_3(3) \\ x_f \\ x_r \end{pmatrix} = A^2 x(1) = \begin{pmatrix} 49\% & 0 & 0 & 34\% & 17\% \\ 44\% & 16\% & 0 & 22\% & 18\% \\ 44\% & 0 & 16\% & 22\% & 18\% \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_1(1) \\ x_2(1) \\ x_3(1) \\ x_f \\ x_r \end{pmatrix}$$

Beliefs with fanatics and rational (key framework)

- Time 11

$$\begin{pmatrix} x_1(11) \\ x_2(11) \\ x_3(11) \\ x_f \\ x_r \end{pmatrix} = A^{10}x(1) = \begin{pmatrix} 2.8\% & 0 & 0 & 64.8\% & 32.4\% \\ 3.8\% & .01\% & 0 & 58.6\% & 37.6\% \\ 3.8\% & 0 & .01\% & 58.6\% & 37.6\% \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_1(1) \\ x_2(1) \\ x_3(1) \\ x_f \\ x_r \end{pmatrix}$$

- Time 101

$$\begin{pmatrix} x_1(101) \\ x_2(101) \\ x_3(101) \\ x_f \\ x_r \end{pmatrix} = A^{100}x(1) = \begin{pmatrix} 0\% & 0\% & 0 & 66.7\% & 33.3\% \\ 0\% & 0\% & 0 & 61.1\% & 38.9\% \\ 0\% & 0 & 0\% & 61.1\% & 38.9\% \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_1(1) \\ x_2(1) \\ x_3(1) \\ x_f \\ x_r \end{pmatrix}$$

Beliefs with fanatics and rational (key framework)

- **Hardheaded investors** h: collection of rational and fanatics
- **Transition matrix:**

$$A = \begin{bmatrix} A_{nn} & A_{nh} \\ 0 & I \end{bmatrix}$$

- **Assumption 1 (hardheaded-connected agents)** Any i influenced by a hardheaded j, either
  - directly, i.e., $A_{ij} > 0$, or
  - indirectly, i.e., $A_{ik_1} > 0, A_{k_1k_2} > 0, ..., A_{k_zj} > 0$

Proposition (Network belief spillover and convergence)

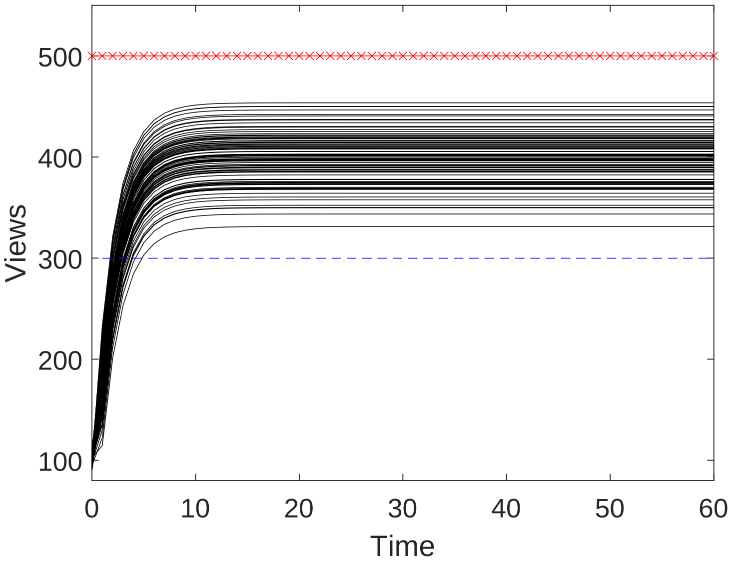
Naive agent views for $t = 2, 3, ...$

$$x_n(t) = A_{nn}^{t-1} x_n(1) + \sum_{k=0}^{t-2} A_{nn}^k A_{nh} x_h$$

In the limits as $t \to \infty$*, convex combination of fanatic and rational views*

$$x_n(t) \to (I - A_{nn})^{-1} A_{nh} x_h$$

Numerical example: beliefs



Influencers and thought leaders

- **Fanatic has 57.8% thought leadership**: $\bar{x}(t) \to 57.8\% x_f + 42.2\% x_r$

Influencers and thought leaders

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- **What determines thought leadership?**
  - How **much people listen**
  - Their **influencer values**

$$57.8\% = \frac{66.7\% + 61.1\% + 61.1\% + 1 + 0}{5}$$

$$57.8\% = \begin{pmatrix} 1.56 & 0.33 & 0.33 \end{pmatrix} \begin{pmatrix} 20\% \\ 10\% \\ 10\% \end{pmatrix} + \frac{1}{5} \qquad A = \begin{pmatrix} 70\% & 0 & 0 & 20\% & 10\% \\ 40\% & 40\% & 0 & 10\% & 10\% \\ 40\% & 0 & 40\% & 10\% & 10\% \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\begin{matrix} 1.56 & 0.33 & 0.33 \end{matrix}$$

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$$1.56 \quad 0.33 \quad 0.33$$

- **Meaning of influencer values**: *1% increase in following leads to*

  $\bar{x}_n \to 59.3\% x_f + 40.7\% x_r$ *an increase of 1.56% in thought leadership*

$$59.3\% = \begin{pmatrix} 1.56 & 0.33 & 0.33 \end{pmatrix} \begin{pmatrix} 21\% \\ 10\% \\ 10\% \end{pmatrix} + \frac{1}{5} \qquad A = \begin{pmatrix} 70\% & 0 & 0 & \mathbf{21\%} & \mathbf{9\%} \\ 40\% & 40\% & 0 & 10\% & 10\% \\ 40\% & 0 & 40\% & 10\% & 10\% \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$1.56 \quad 0.33 \quad 0.33$$

Influencers and thought leaders

Average opinion: $\bar{x}(t) = \sum_{i=1}^{N} \frac{w_i}{w.} x_i(t) = \frac{1}{w.} w' x(t)$

Definition. The vector of all agents' thought leaderships is

$$\theta' = \frac{1}{w.} w' \lim_{t \to \infty} A^t$$

such that , $\sum_{j=1}^{N} \theta_j = 1$, and

$$\bar{x}(t) \rightarrow \theta' x(1) = \sum_{j=1}^{N} \theta_j x_j(1)$$

Definition. The vector μ of naive agents' influencer values is

$$\mu' = \frac{1}{w.} w'_n \underbrace{(I - A_{nn})^{-1}}_{= \sum_{k=0}^{\infty} A_{nn}^k \text{ (echo matrix)}}$$

Influencers and thought leaders, continued

Proposition (Influencers and thought leaders)

A. *The thought leadership of any naive agent is zero,* $\theta_i = 0$*, and the vector of thought leaderships of hardheaded agents,* θ_h*, depends on how much attention they get from naive agents,* A_{nh}*, and their influencer values,* μ*:*

$$\theta_h' = \mu' A_{nh} + \frac{w_h'}{w.}$$

B. *If naive agent* i *increases his following* A_{ij} *of hardheaded agent* j *by* ε *at the expense of a lower following of other hardheaded agents, then*

$$\frac{\partial \theta_j}{\partial \varepsilon} = \mu_i$$

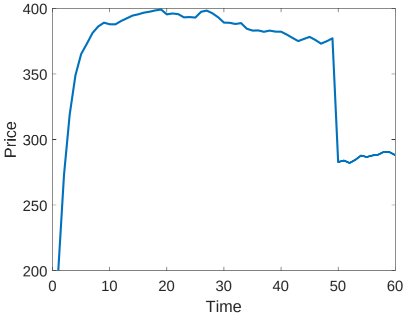
Equilibrium price

- **Equalizing supply and demand,** $s = \sum_{i=1}^{N} d_i(t)$**, yields**

$$p(t) = (1-c)\left[\frac{w_{n\cdot}}{w_{\cdot}}\bar{x}_n(t) + \frac{w_{f\cdot}}{w_{\cdot}}\bar{x}_f + \frac{w_{l\cdot}+w_{s\cdot}}{w_{\cdot}}x_r + u(t) - \frac{s\sigma_u^2}{\pi w_{\cdot}}\right] + cE_t(p(t+1))$$

where $c = \frac{1}{1+\frac{w_{\cdot}}{w_{s\cdot}}\frac{\pi}{1-\pi}} < 1$. **Solution**: iterate forward to infinity

- **Numerical example:**



Social network effect on price

Proposition (Network effects on price)

Equilibrium price

$$p(t) = p_r(t) + p_n(t)$$

- *Rational part:*

$$p_r(t) = x_r + u(t) - \frac{s\sigma_u^2}{\pi w.}$$

- *Network part:*

$$p_n(t) = \frac{w_{n\cdot}(1-c)}{w.} \sum_{k=0}^{\infty} c^k \left(\bar{x}_n(t+k) - x_r\right) + \frac{w_{f\cdot}}{w.}\left(\bar{x}_f - x_r\right)$$

As $t \to \infty$, network part converges to

$$p_n^{\infty} = \sum_{j=N_n+1}^{N_n+N_f} \theta_j (x_j - x_r)$$

Price dependence on thought leaders and influencers

Proposition (Thought leader effect on price)

Fanatic moves the price based on valuation, x_j, and thought leadership θ_j:

$$\frac{\partial p_n^\infty}{\partial x_j} = \theta_j$$

Proposition (Influencer effect on price)

Naive agent i moves price based on influencer value μ_i when increasing following of fanatic agent j by ε at the expense of rational agent:

$$\frac{\partial p_n^\infty}{\partial \varepsilon} = \mu_i \left(x_j - x_r\right)$$

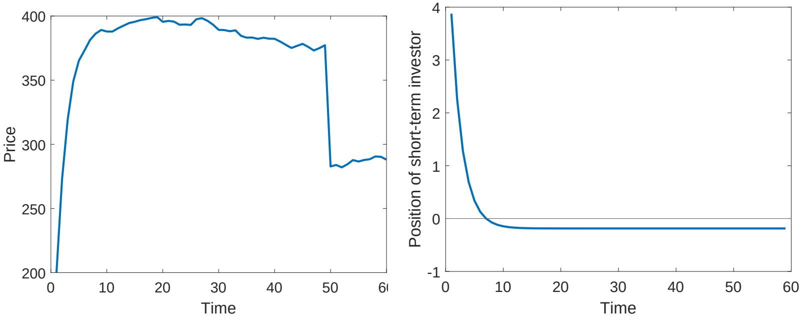
Value and momentum

- **Returns:**

$$E_t(r(t+1)) = (1-\pi)E_t(\Delta p(t+1)) + \pi(x_r + u(t) - p(t))$$
$$= (1-\pi) \underbrace{\Delta p_n(t+1)}_{\text{network momentum}} + \pi \underbrace{b(t)}_{\text{value}}$$

network mom≅price mom, $\Delta p_n(t+1) \cong \Delta p_n(t) = \Delta p(t) - \Delta u(t)$

- **Numerical example**



Short-term trading behavior: momentum and reversal

Proposition (Value and momentum effects)

Under certain conditions, there exists a number $a > 0$ such that the value-momentum strategy, $b(t) + a\Delta p(t)$, has a positive expected return, $E\left[(b(t) + a\Delta p(t))r_{t+1}\right] > 0$, for all t.

Proposition (Value and momentum trading)

Short-term investors

- *initially buy the rising undervalued asset (**value and momentum**)*
- *continue to hold when the asset becomes over-valued (**momentum**)*
- *and finally shorts when the over-valuation is large enough (**value**)*

if the asset is a bubble (vice versa if the asset is undervalued) and if A_{nn} satisfies certain conditions

Spike in volume and excess price variation

Proposition (Spike in volume and excess volatility)

With naive and fanatic agents,

- *the trading volume is greater, but dies down over time*
- *the valuation ratio (price minus fundamental $u(t)$) varies more*

Outline of talk

- Model
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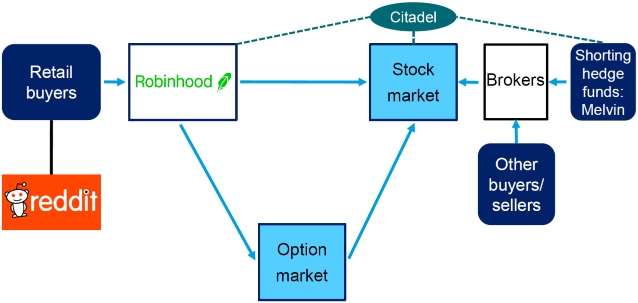
- **Case study of GameStop**

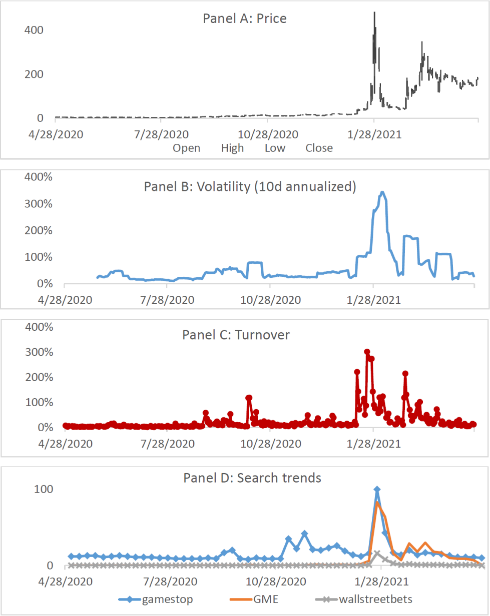
Overview of the GameStop event



Further details, YouTube talk at Markus' Academy, Princeton University:

https://bcf.princeton.edu/events/lasse-pedersen-on-gamestop-and-predatory-trading/

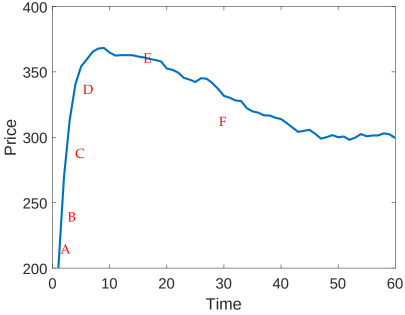
GameStop: price, volatility, volume, public interest



Links between model and GameStop

1. Investment idea spreads via social networks (Proposition 1)
2. Fanatic ideas gain prominence over time (Propositions 2)
   - E.g. Keith Gill, aka DeepF**ingValue, Roaring Kitty
   - Diamond hands meme: $A_{ff} = 1$
3. Social network effects on price (Proposition 4)
4. Fanatic view creates a bubble (Proposition 5)
   - Extreme view: Rocket meme and YOLO trade
5. Price increases when influencer follows fanatics (Proposition 6)
   - Tweet by Elon Musk: "Gamestonk!!" with link to WallStreetBets
   - Influencer: $A_{i,\text{Elon Musk}} > 0$ for many i
   - Following fanatic: $A_{\text{Elon Musk,WallStreetBets}} > 0$
6. Sophisticated momentum and value investors (Proposition 7-8)
7. Spike in trading volume and volatility that die down faster than the bubble (Proposition 9)

Conclusion: social network effects everywhere



	Model elements	Bubble anatomy†	GameStop	Asset pricing
A	Investors receive news, fanatics focus on one element	Initial displacement	Retail investors focus on plan to pivot online	Announcement effects, e.g.post-earnings drift
B	Short-term investors bet on network spillovers	Speculation	Some institutional investors are long	Momentum and fundamental momentum
C	Opinions spread through the network	Mania and emulation	More and more people hear about GameStop	Local bias and network spillover effects
D	Influencers follow a fanatic	Authoritative blessing	Elon Musk tweets a link to WallStreetBets	Excess volatility
E	Rational traders bet on reversal	Insiders sell out	Institutional investors sell	Value investing
F	Fundamentals are revealed or fanatics gradually learn	Crash: revelation or revulsion	Drops in January, March earnings announcement	Long-run reversal and value effect

†Stylized evolution of historical bubbles of Kindleberger (2000) and Shleifer (2000)

References cited in slides

Brief list – numerous additional references cited in the actual paper

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