Complex Adaptive System of Systems (CASoS) Engineering Initiative

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SAND2014-19628 C

On Applications of Game-Theoretic Probability and Defensive Forecasting to Agent-based Market Models

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GTP 2014. November 13-15, 2014

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Abstract

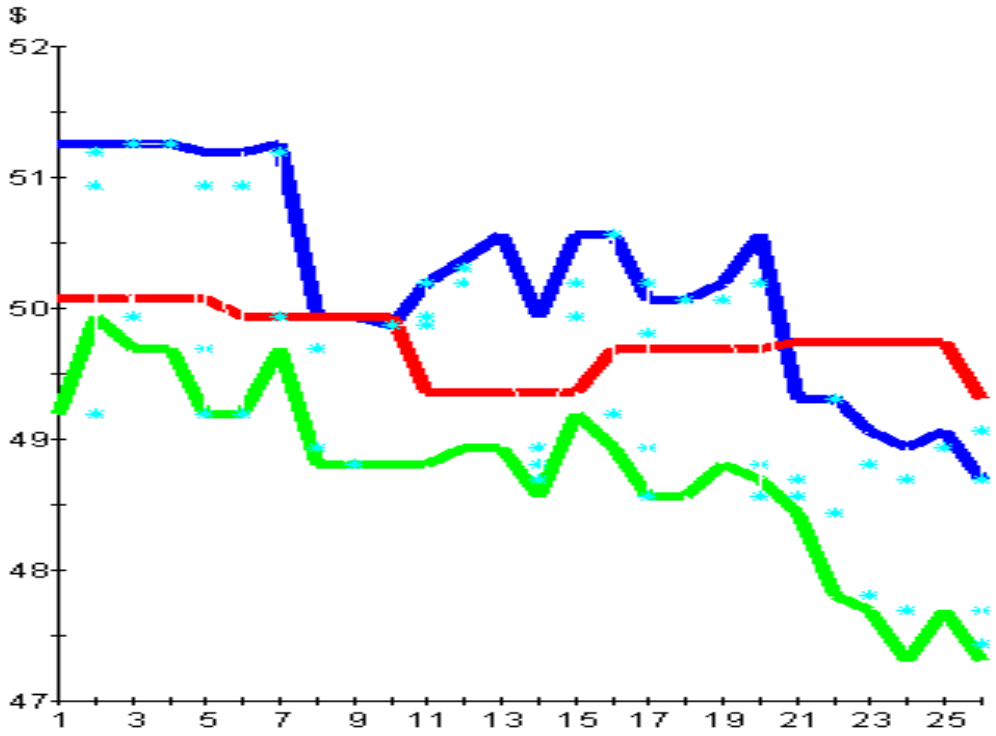
We present an attempt on connecting agent-based modeling with Game-Theoretic Probability (GTP) and defensive forecasting and outline a framework connecting elements of game-theoretic probability with agent-based models. We illustrate this framework on an example of our model of the Nasdaq stock market and of a natural gas market model and show how game-theoretic probability can be used to test the simulated market price dynamics, the individual agent trading strategies, rule changes, and the overall agent-based model.

What Is Agent-Based Modeling?

- In ABMs, complex, real-world systems are represented in software as collections of *autonomous decision-making entities, situated in an appropriate environment and interaction structure*.
  - Agent executes behaviors appropriate to it and its context
  - Agents produce, consume, trade securities, ship freight,…
  - Agents are heterogeneous
  - Agents interact and affect each other
- The dynamics of systems *emerge* from large numbers of interactions among many kinds of agents. System behavior thus arises from the bottom up.

Market Maker - Investor Interaction

- Market makers: adjust their quotes
- Investors: submit market orders



Advantages of Agent-Based Models

- Agent-Based Model's (ABM's) bottom-up approach leverages the organization's knowledge of the details
  - Allows modeling of individual behaviors, rules, incentives
  - Allows modeling of complex interactions and interaction structures
  - Allows incorporating of human expertise and AI techniques in building the market's agents
- Intuitive, concrete, easy to understand
- Produces actionable results and counter-intuitive insights at many levels

Advantages of ABMs(cont'd)

- ABMs and traditional statistical methods produce the same results when the assumptions required by traditional methods are valid (e.g. independence, etc.)
- Models can be validated using historical data but can be applied to *unique situations* that lack history
  - Allows combining both a hindsight and foresight perspective
- Agents can be programmed to *evolve* and *learn*. This permits the emergence of new, unanticipated behaviors and strategies
- A variety of what-if scenarios can be investigated

Key Features of ABMs

- *Represent casual structure of the world*
- Can be calibrated against individual behaviors and global system behaviors
- Span micro- to macro- gap
- Allow representation of existing emergent properties of the system and of previously unobserved behaviors

Disadvantages of ABMs

- Difficult to calibrate and to validate
- Much of the data is missing (even if trades are observable, the information they were based on is generally not)
- Complete information on individual strategies is rarely available
- Treating the available data as generated by a probabilistic mechanism is problematic
  - Lack of data
  - Fundamental goal of ABMs is to model causal decisions of agents, based on unique conditions and contexts

GTP + ABMs

GTP - conceptual, quantitative foundation for ABMs

- Forecaster: market, as combination of agent strategies
- Skeptic: one specific agent strategy

AMBs – a simulation tool for GTP?

GTP + ABMs (cont.)

- *Strategy development*
  - Abnormal returns to an individual strategy?
- *Rule changes*:
  - Abnormal returns under new rules?
  - With abnormal returns, the *new* system may not be stable
  - What are plausible new strategies? (learning)
- Defensive forecasting:
  - Can market (Forecaster) ensure no abnormal strategy returns?

Shaver and Vovk (2001), Takemura and Suzuki (2005), Wu and Shafer (2007), Shafer (2007), Vovk (2011)

Nasdaq Example

- Nasdaq had to consider decimalization and its impacts in 1998.
- How reducing the tick size may affect the market behavior? Why should it have any effect?
  - How a change to decimals can be modeled?
  - What is the mechanism through which changed tick size would affect the market?
  - Given specific mechanisms, what other effects may occur?

- Nasdaq decimalization study: an empirical example.
  - Study done during 1998-2000.
  - Decimalization occurred in April 2001.
  - *Darley and Outkin (2007)*

Goals

- Investigate effects of policy and environment changes:
  - Evaluate the effects of changing the tick size (decimalization) and of parasitism
- Represent the influence of market rules and structure on market dynamics and strategies
- Demonstrate that simulated market participants and aggregate market parameters are “sufficiently similar” to those in the real world to validate model empirically

Nasdaq Model

- Agents: investors and market makers
  - Rule of thumb, data-driven, expert knowledge, learning, experimentation
- Market infrastructure and rules:
  - Tick size,
  - Priority rules
- Calibration: audit trail data
  - Ensure simulated distribution of trade sizes, volumes, prices is similar to that observed in the real world
  - Represent individual market maker strategies

Nasdaq Model Basics

- Single stock
- **Investors**
  - Receive noisy information on fundamental value / price target
  - Decide whether to trade by
    - Comparing this target with available price
    - Incorporating market trends …
- **Market makers**
  - Receive buy and sell orders
  - Must learn how to set their quotes profitably

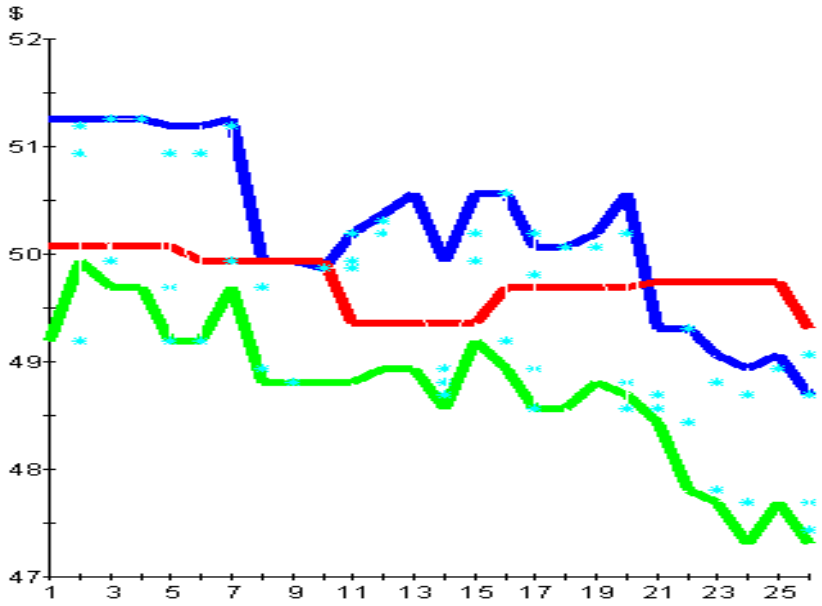
Nasdaq Model and GTP

- Individual strategy testing
  - Basic strategy (reactive)
  - Parasitic strategies (active, undercuts)
  - Learning strategies (learns undercutting, …)
- Market testing
  - Does market allow abnormal returns?
  - Is market stable against specific strategies?

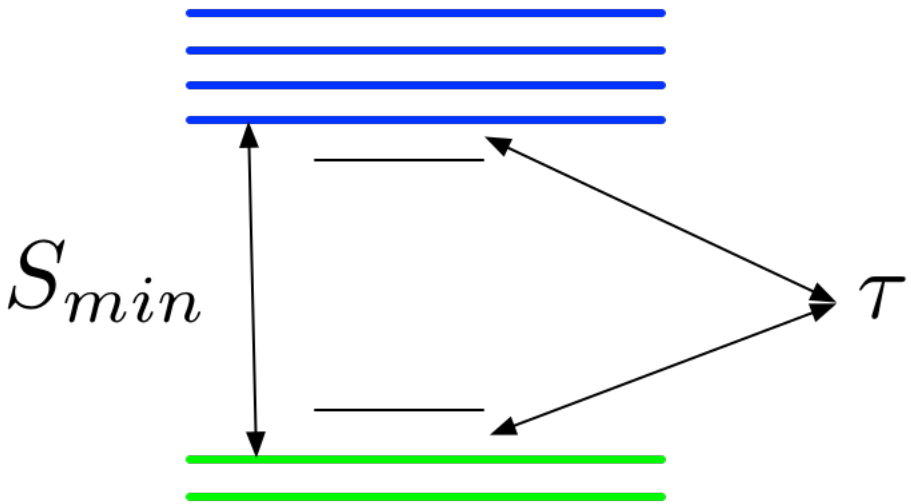
Individual Strategy: Parasitic

Parasitic strategy:

- Attempts to undercut the current bid/offer by a small increment (tick size)
- Is not a major source of liquidity for the market



Undercutting (parasitic) Strategy



Contrived GTP Protocol: Parasitic vs. Basic Dealers

Protocol for Parasitic Strategy

$K_0 = 1$:

For $n = 1, 2, \ldots$:

$S_{min} >> \tau$

$n - 1$:

Skeptic: decide if undercut by 2τ and buy or sell one share

Market: move quotes by at most τ

n:

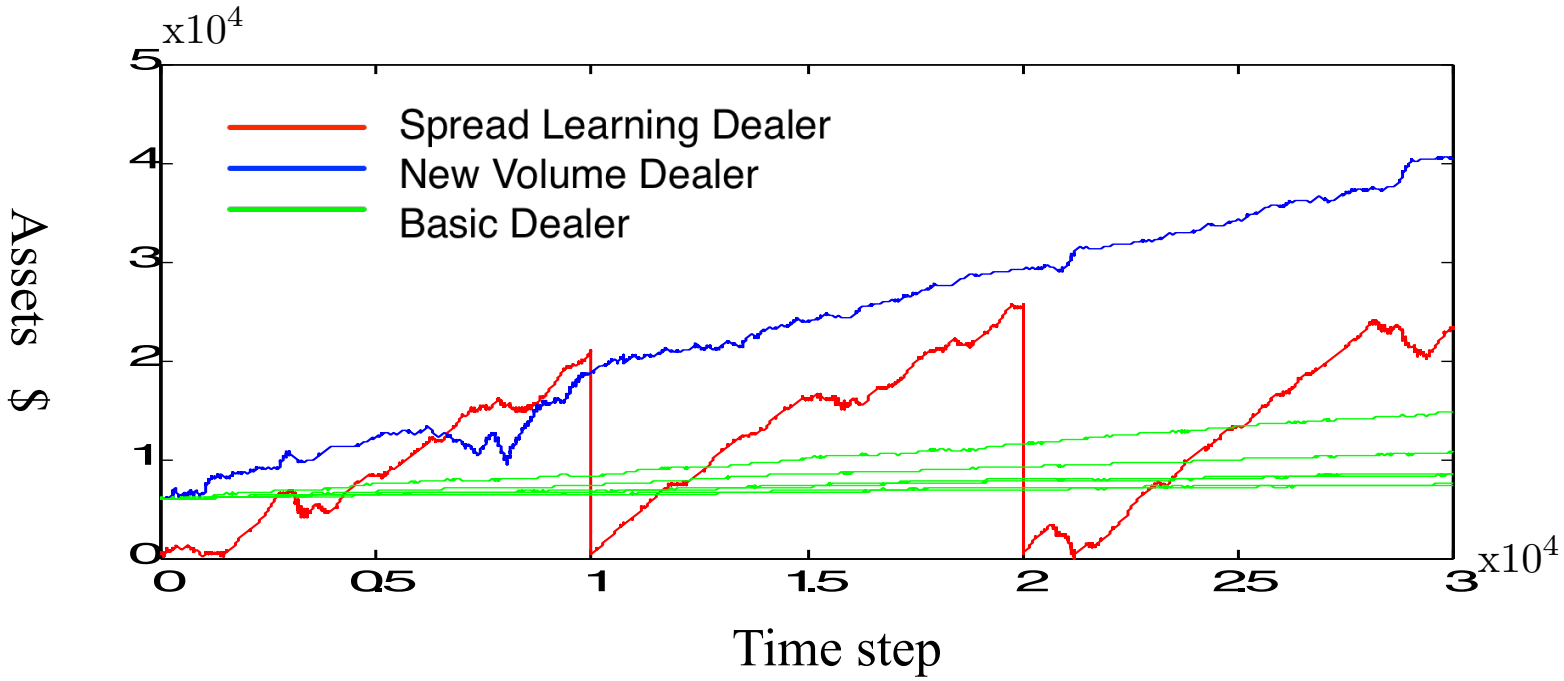
Skeptic: if undercutting successful

$n + 1$:

Skeptic: close the position by undercutting on other side by 2τ

$K_{n+1} = K_n - 1 + S_{min} - 4\tau$.

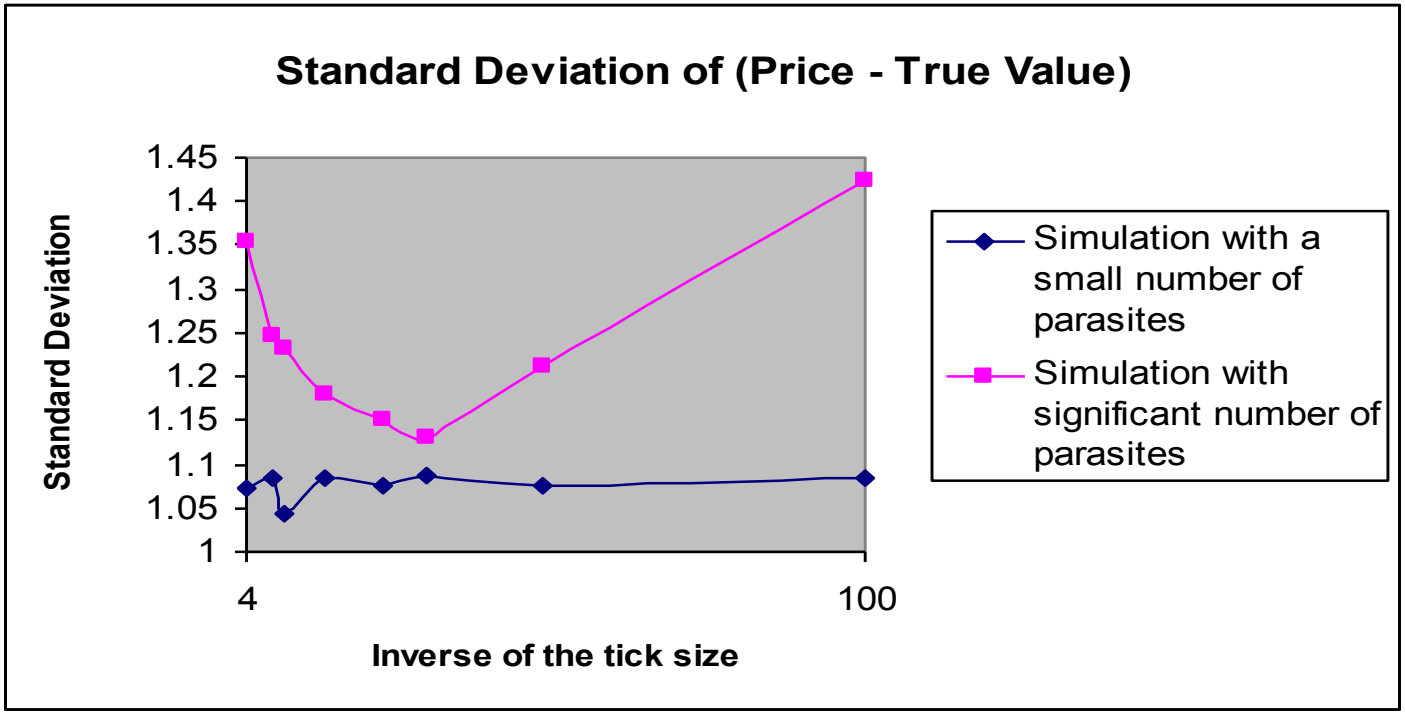
Simulated Strategies Testing



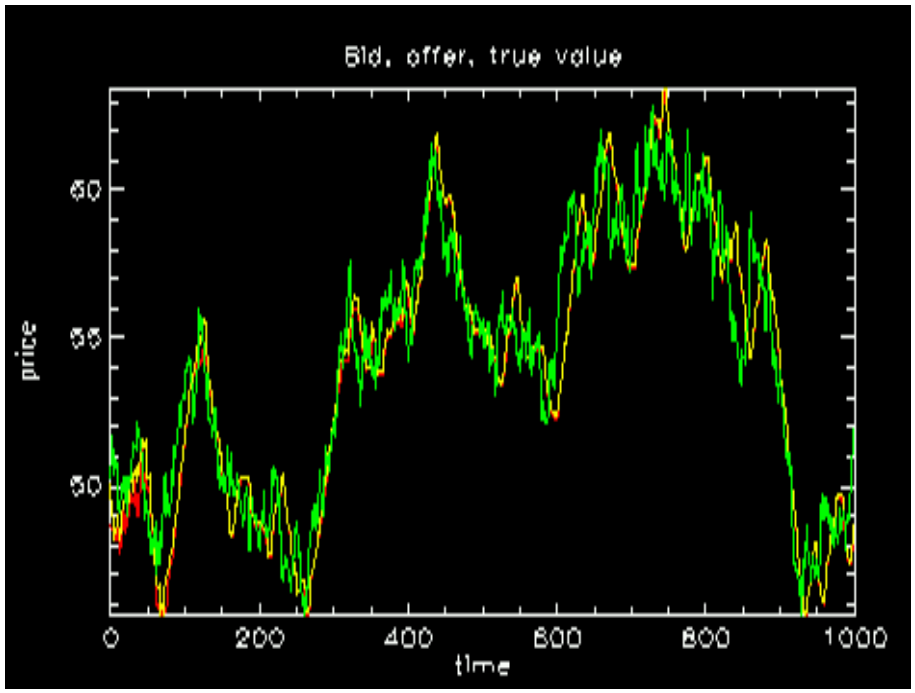
- Spread Learning market maker is the most profitable dealer on the market under many circumstances
- Exceptions: *high volatility, many parasites*

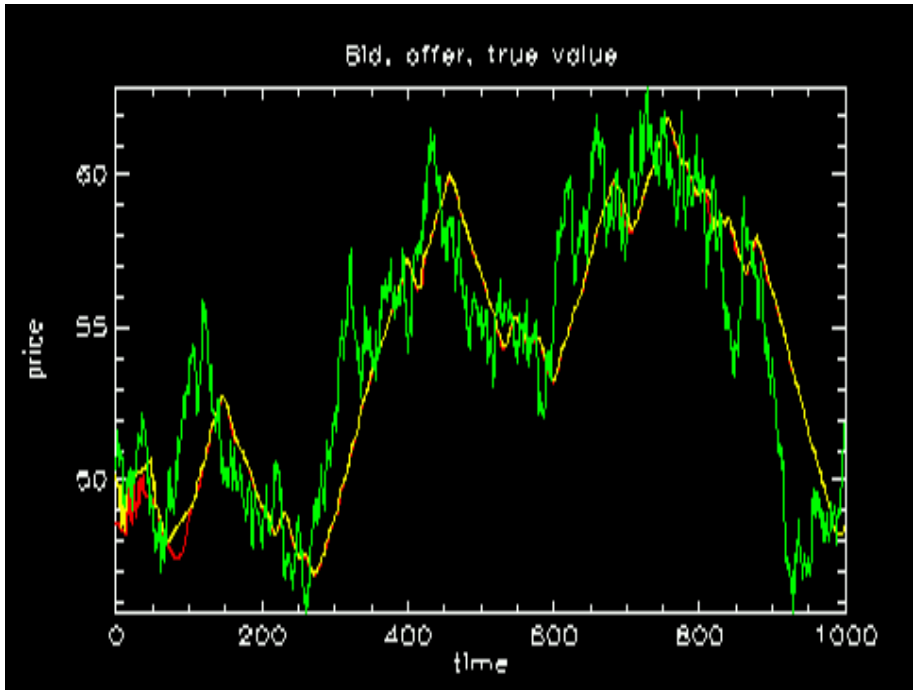
Market Testing: Tick size effects

As tick size is reduced, parasitic strategies increasingly impede price discovery / market's ability to generate useful information



Tick Size Effects, Many Parasites

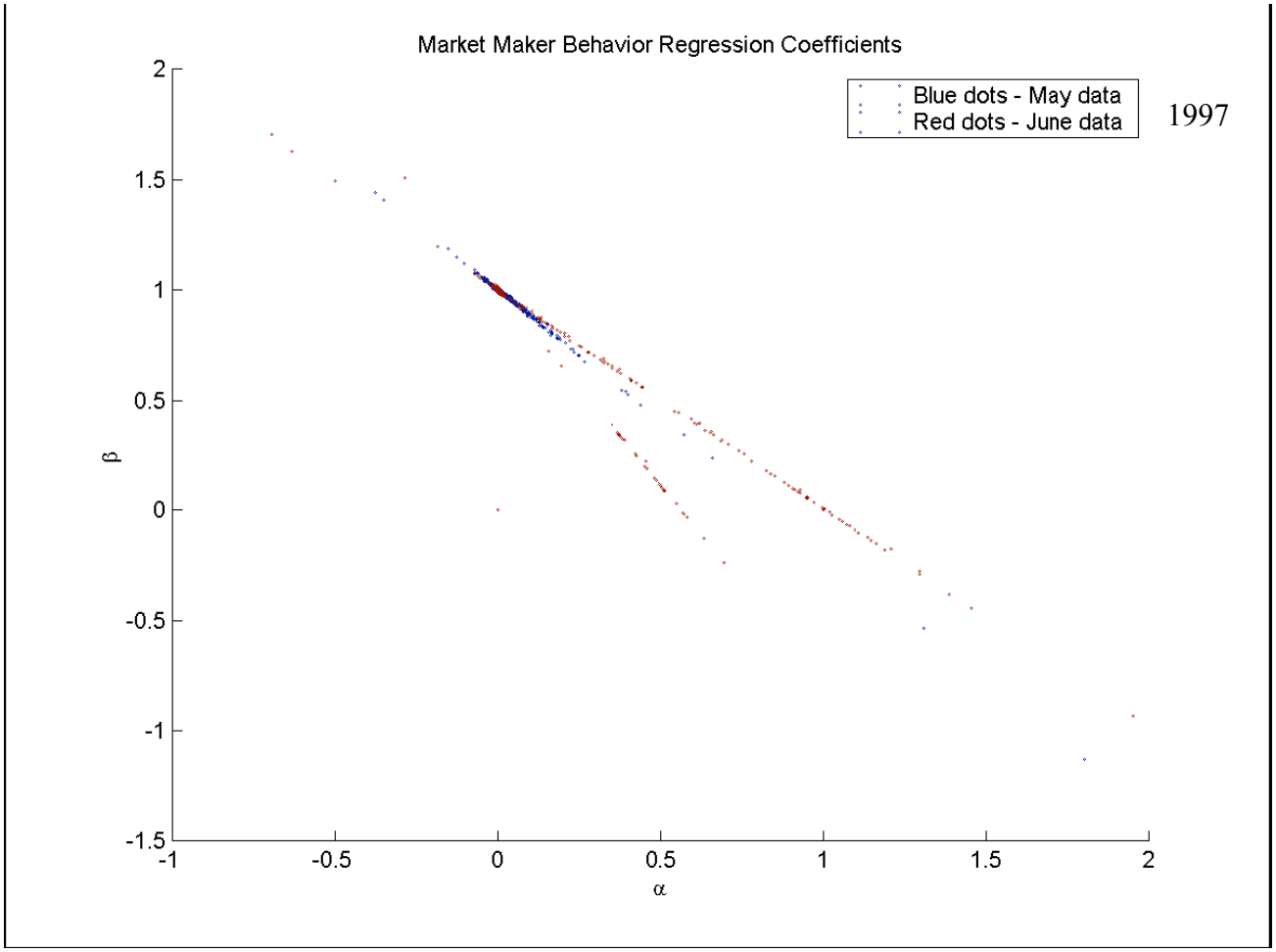




Tick size 1/16

Tick size 1/100

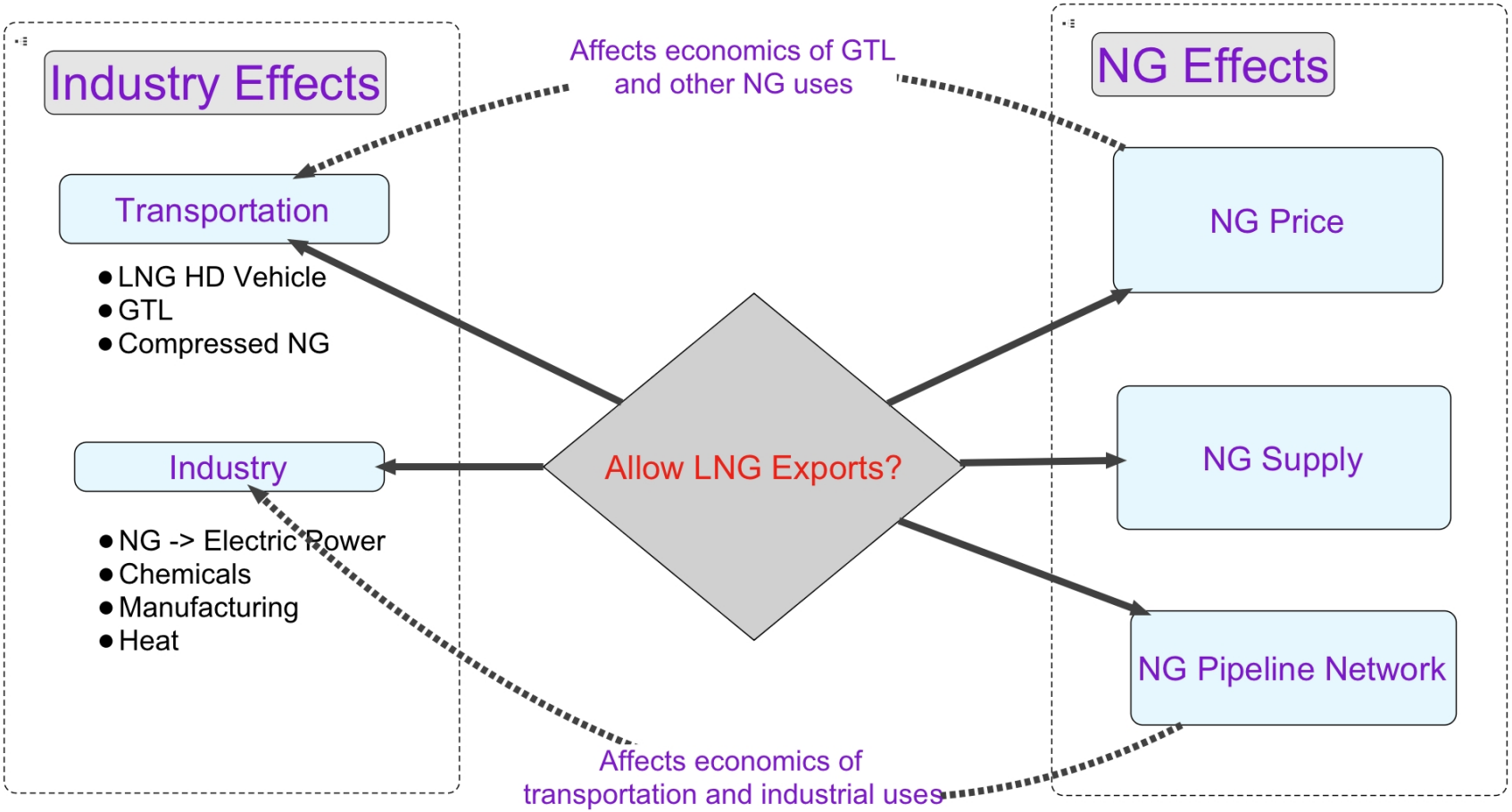
Market Testing: Strategy Phase Transitions, Tick Size Reduction



GTP+ Orig. Model Calibration

- Calibrated the model to
    - Individual strategies
    - Aggregate market parameters
- Simulated strategies are able to replicate the real-world ones (with precision up to 60-70%)
- Tested against existence of real-world patterns, such as presence of fat tails and spread clustering
- Created self-calibrating software to use data as it comes in

Applications to Energy Markets Natural Gas (NG)



Summary of Findings

1. Decimalization (tick size reduction) will negatively impact the price discovery process.
2. Ambiguous investor wealth effects may be observed. (Investors' average wealth may actually decrease in the simulation, but the effect is not statistically significant).
3. Phase transitions will occur in the space of market-maker strategies.
4. Spread clustering may be more frequent with tick size reductions.
5. Parasitic strategies may become more effective as a result of tick size reductions.
6. Volume will increase, potentially ranging from 15% to 600%.

Comparisons with Data

Tick size was officially reduced from a 1/16th to $.01 (in phases) in March, 2001.

Nasdaq economists captured actual data from this transition and put the findings in their Economic Research study report.

BiosGroup compared our model's results with the findings from the Nasdaq report.

Comparisons with Data (Cont.)

5 of the 6 likely outcomes actually occurred.

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Conclusions

- GTP
  - Help in individual strategies development
  - Provide quantitative approach for generating aggregated (market)strategies when data is unavailable or is non-probabilistic
- Defensive forecasting
  - Test the market behavior.
- ABMs
  - Simulate GTP protocols.
- Applicable to financial, energy, and other markets.