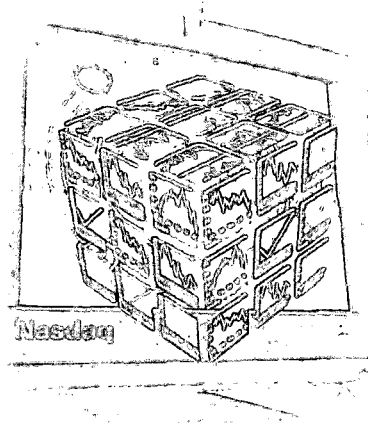


# A NASDAQ MARKET SIMULATION

INSIGHTS ON A MAJOR MARKET FROM  
THE SCIENCE OF COMPLEX ADAPTIVE SYSTEMS



**VINCENT DARLEY**

President & CEO of Eurobios, UK

**ALEXANDER V OUTKIN**

Los Alamos National Laboratory, USA

 **World Scientific**

# Contents

<i>Preface</i>	vii
1. Foresight, Unpredictability and Strategies	1
1.1 Introduction . . . . .	1
1.2 What is Agent-Based Modeling? . . . . .	8
1.3 Nasdaq Market Overview . . . . .	12
1.4 Nasdaq Simulation Model Overview . . . . .	13
1.5 Existing Market Modeling and Simulation Work . . . . .	15
1.5.1 Complexity and Agent-Based Modeling . . . . .	16
1.5.2 Financial Markets and Agent-Based Modeling . . . . .	17
1.5.3 Artificial Intelligence, Machine Learning, and Other Approaches to Modeling Agent Strategies . . . . .	19
2. Market Dynamics — Analytical Results	21
2.1 Introduction . . . . .	21
2.2 Spreads in Markets . . . . .	23
2.3 Summary of the Glosten-Milgrom Model . . . . .	23
2.3.1 GM Model, Information, and Bayesian Updates . . . . .	24
2.3.2 Convergence Times . . . . .	26
2.3.3 Tick-Size Effects . . . . .	26
2.4 Extension of the GM Model to Multinomial Prices . . . . .	27
2.4.1 The Mathematical Formulas for the Multinomial Case . . . . .	28
2.4.2 Updating the Probability in the Recursive Case . . . . .	28
2.4.3 Setting the Bid-Ask Prices . . . . .	30
2.4.4 The Binomial Case . . . . .	31

2.5	Multinomial Additions . . . . .	32
2.5.1	Convergence of Beliefs . . . . .	34
2.6	Extension of GM to Incorporate Inventory . . . . .	34
2.6.1	Convergence of Beliefs . . . . .	35
2.7	Price Dynamics . . . . .	36
3.	Agent-Based Model and Simulation Results . . . . .	39
3.1	Introduction . . . . .	39
3.2	Model Overview . . . . .	41
3.2.1	Market . . . . .	41
3.2.2	Strategies . . . . .	42
3.2.3	Evolutionary Selection of Strategies and Learning Strategies . . . . .	46
3.3	An Outline of the Computer Model . . . . .	48
3.4	Results . . . . .	50
3.4.1	Tick Size Effects on Price Discovery . . . . .	50
3.4.2	Explanations of Observed Results . . . . .	56
3.4.2.1	Effects of Parasitism . . . . .	56
3.4.2.2	Effects of Tick Size . . . . .	57
3.5	Aggregate Behavior of the Market . . . . .	58
3.6	Fat Tails . . . . .	59
3.6.1	Herding Effects . . . . .	60
3.6.2	Range of Fat Tails . . . . .	62
3.7	Spread Clustering . . . . .	63
3.8	Other Results . . . . .	65
3.9	Profitability of Market Makers' Strategies . . . . .	65
3.10	Informational Content of the Trades . . . . .	66
3.11	Market Structure Analysis . . . . .	66
3.12	Market's Predictability . . . . .	66
3.13	Effects of Market Infrastructure . . . . .	67
3.14	Effects of Learning and Evolution . . . . .	67
3.15	Conclusions . . . . .	69
4.	Spread Clustering . . . . .	71
4.1	Introduction . . . . .	71
4.2	Spread Clustering . . . . .	72
4.2.1	Spread Clustering with Learning and Basic Inventory Market Makers . . . . .	72

4.2.2	Spread Clustering with Other Dealer Types . . . . .	74
4.3	Are the Spread Clustering Results Meaningful? Pros and Cons . . . . .	76
4.3.1	Real World Relevance of the Spread Clustering Results . . . . .	76
4.3.2	Possible Criticism . . . . .	77
4.4	Validity of the Observed Clustering Effects . . . . .	77
4.5	Possible Reasons for Observed Clustering of Spread Sizes . . . . .	79
4.6	Conclusions . . . . .	80
5.	Learning, Evolution and Tick Size Effects . . . . .	81
5.1	Types of Reinforcement-Learning Dealers . . . . .	81
5.2	The Reinforcement-Learning Framework and Incentive Structure . . . . .	84
5.3	Learning in the Market . . . . .	86
6.	Calibration . . . . .	89
6.1	Introduction . . . . .	89
6.2	Results . . . . .	90
6.3	Calibration Methodology . . . . .	92
6.3.1	Calibrating to the Trading Volume Distribution . . . . .	92
6.3.2	Calibration on the Individual Level . . . . .	92
6.4	Quantitative Behaviors: Calibrating Simulated Strategies Against Real-World Strategies . . . . .	93
6.4.1	Parameter Discovery for Basic Dealers . . . . .	95
6.4.2	Parameter Discovery for Volume Dealers . . . . .	97
6.4.2.1	Time series comparisons . . . . .	97
6.4.2.2	Statistical analysis . . . . .	99
6.4.3	Identification of Analytic Parasites . . . . .	100
6.4.4	Results – Basic Dealers . . . . .	101
6.4.5	Results – Volume Dealers and Parasitic Dealers . . . . .	103
6.5	Wealth Effects Analysis . . . . .	108
6.6	Conclusions . . . . .	110
7.	Phase Transitions in the Market . . . . .	111
7.1	Data Preparation . . . . .	111
7.1.1	Time Series Regularization Procedure . . . . .	111

7.1.2	Price Response to the Number of Transactions and Their Volume . . . . .	112
7.2	Phase Transitions Analysis . . . . .	114
7.3	Conclusions . . . . .	115
8.	Validation: After Decimalization and the Tick-Size Change . . . . .	119
8.1	Introduction . . . . .	119
8.2	Comparing Predictions with the Actual Decimalization Results . . . . .	121
8.2.1	Negative Effects on the Price Discovery Process . . . . .	121
8.2.2	Possible Volume Increases . . . . .	122
8.2.3	Ambiguous Investor Wealth Effects . . . . .	123
8.2.4	Phase Transitions in the Space of Market-Maker Strategies . . . . .	124
8.2.5	Spread Clustering . . . . .	124
8.2.6	More Effective Parasitic Strategies . . . . .	124
8.3	Conclusions and Directions for the Future . . . . .	125
9.	Future Developments of the Model . . . . .	127
9.1	Qualitative Scenario Investigation . . . . .	127
9.2	Macrostructure Explanation . . . . .	128
9.3	Risk Analysis . . . . .	128
9.4	Agent Soup of the Day . . . . .	128
Appendix A:	The Agent-Based Model Software . . . . .	131
A.1	Graphical User Interface . . . . .	132
A.2	Menus . . . . .	135
A.3	Charts . . . . .	136
A.3.1	Market and Pricing Charts . . . . .	136
A.3.2	Market Maker Performance . . . . .	139
A.3.3	Investor Performance . . . . .	139
A.4	Interacting with the Market . . . . .	140
A.5	Batch Mode . . . . .	141
A.6	Basic Description of Object Simulation Framework . . . . .	142
	<i>Bibliography</i> . . . . .	145
	<i>Index</i> . . . . .	151