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**Price discovery with fallible choice**

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# Chapter 7

## Summary

General equilibrium theory can state conditions for the existence, uniqueness and optimality of the Walrasian equilibrium, but it cannot satisfactorily explain how this equilibrium can be achieved. Experimental economists, on the other hand, claim that it only takes a few, uninformed, traders and a Continuous Double Auction (CDA) to obtain results that are approximately equal to the Walrasian equilibrium. For instance, Anderson et al. (2004) reports experiments in which human subjects trade in the examples proposed by Scarf (1960). Its results are remarkable: trading by human subjects closely approximates the Walrasian equilibrium in the stable example; in the unstable examples there is orbiting of prices in the direction that is predicted by tâtonnement theory. This suggests that we may learn something profound about equilibrium discovery by studying experimental price formation.

This thesis aims to contribute to our understanding of equilibrium discovery by replicating experimental trading with the help of algorithms. It seeks behavioral explanations of price formation that acknowledge disequilibrium and the fallibility of human choice. We want to know how human traders behave and how this affects equilibrium discovery. How do they propose prices? Which opportunities do they perceive? If traders recognize alternative actions, how do they select a preferred option? Are their strategies ecologically rational, i.e. do they survive competition with alternative strategies?

Chapter 1 gives a general introduction to and an overview of our research.

Chapter 2 reviews different theories of price formation. For this, we largely draw on stability theory because our research takes place in the context of a general equilibrium model. We find that assumptions with respect to comprehensive choice, price taking and the central role of aggregate excess demand do not serve our purpose. We therefore prefer to study the subject matter of stability theory from the perspective of experimental economics and agent based modeling.

In chapter 3 we discuss the experiments of Anderson et al.. These are of great interest for our goal because (i) trading at all prices in a CDA is sufficiently realistic; (ii) the Scarf economies constitute a harsh environment for theories of price formation, to which Anderson et al. have added the requirement that one commodity takes on the role of money; (iii) since there are two markets, trading at all prices can shift the stable state away from the Walrasian equilibrium; (iv) convergence of human trading

to the Walrasian equilibrium is contingent on the initial allocation; and (v) orbits (if any) provide an additional way of discriminating between rival explanations. Prof. Anderson has kindly provided the data of two sessions (that apply the stable and the counter clockwise treatment). The data provide us with 9799 individual decisions for replication. We also use them to derive stylized facts that characterize human trading.

Chapter 4 introduces our simulation platform FACTS (short for Fallible Agents' Commodity Trading System). We examine how human traders propose prices as part of the calibration of FACTS. According to economic theory, monopolistic competition is the appropriate way for understanding disequilibrium behavior. In the Scarf economies this means that traders will propose prices that maximize their expected utility, conditional on subjective beliefs that a proposed price will be accepted. This, however, is not how the subjects of Anderson et al. behave. Instead they appear to anchor their reservation prices by their current price expectations. This is reminiscent of price taking, albeit in a more active form, because traders face incomplete and false signals. With respect to the calibration of price expectations, different criteria favor different algorithms. The algorithm that best predicts human actions, eBAS, derives price expectations from bid / ask spreads. Algorithms that estimate so-called "no arbitrage" prices generate robust convergence. The ZIP-algorithm of Cliff (1997) causes prices to orbit systematically in the unstable Scarf economies in the direction that is predicted by tâtonnement theory. A meditated choice leads us to prefer the eGD-algorithm that derives "no arbitrage" prices from so-called Gjerstad-Dickhaut beliefs: (i) algorithms that perform well in one-step-ahead predictions but fail to achieve convergence in the stable Scarf economy ignore an essential part of human behavior; (ii) the eBAS-algorithm is overly sensitive to haggling;<sup>1</sup> (iii) theoretically, the notion of "no arbitrage" prices provides the best basis for price expectations; (iv) the eGD-algorithm can be improved whereas the eBAS-algorithm cannot. Perhaps the most important result of the calibration of expectation formation is an understanding of how the algorithms can be improved. Our robots do not generate enough transactions and beliefs over time become insensitive to new information. These issues are related and can be fixed. After improving the number of transactions, algorithms that manage reservation prices based on a utility target can be expected to benefit more than others. This is due to the fact that human trading largely is non-speculative: traders buy what they need and sell what they can spare. Having more transactions then means that robot traders will learn that they can achieve higher levels of utility.

Chapter 5 argues that human choice is fallible. Fallible choice can be seen as a variety of bounded rationality that allows traders to be persistently biased. Continuing the calibration of FACTS, we study the selection of preferred actions from sets of perceived alternatives. Here we restrict ourselves to decisions of human traders that have been recognized as feasible actions by the eGD-algorithm. For ranking alternatives we consider expected utility maximization, cumulative prospect theory, entropy-sensitive preferences (ESP) and simple rules of thumb for prioritizing feasible

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<sup>1</sup>The success of eBAS, in terms of one-step-ahead predictions, is due to its flexibility and not to it capturing some essential characteristic of expectation formation.

actions.<sup>2</sup> We find that the latter predict human trading behavior best. In addition, we model arbitrage by applying the theory of mental accounting. This imposes many constraints on the set of perceived opportunities and induces myopia. The overall prediction of human behavior slightly improves as a result of admitting arbitrage behavior based on mental accounting.

Chapter 6 tests the robustness of the results of selected calibrations by giving traders the opportunity to learn which strategy works best for them. Our approach to learning is a mixture of replicator dynamics and reinforcement learning. Here, the main results are that (i) monopolistic competition is strongly dominated in the stable and counter clockwise treatments by reservation prices based on expected prices; (ii) rules of thumb for prioritizing feasible actions strongly dominate other methods of selecting an alternative from a set of perceived opportunities; and, unexpectedly, (iii) that ZIP is ecologically rational for the formation of price expectations.

Appendix A addresses market failure. This occurs if available Pareto improvements cannot be implemented through trading. Our initial simulations quickly ran into market failure, due to the initialization of price expectations (randomly selected from the price simplex) and to quantity setting based on expected utility maximization.

In appendix B, we provide more details with respect to FACTS. We explain how robot traders perceive opportunities for action and how these can be represented as lotteries. Here we also derive the rules of thumb for prioritizing actions. Furthermore, this appendix describes the algorithms for learning prices. We have adapted existing algorithms to the context of the Scarf economies, and in some cases made improvements. We have added variations and new algorithms.

Appendix C describes a price adjustment process that was part of the development of FACTS. Here, the auctioneer *assumes* that each trader has preferences that can be described by a Cobb-Douglas utility function. A trader's response to previously quoted prices suffices to identify these hypothetical preferences. The unique equilibrium prices of the associated Cobb-Douglas economy feed into the next iteration. We prove global convergence for CES economies in which traders have utility functions ranging from Leontief to Cobb-Douglas utility functions.

Looking back at the explanation of convergence in the stable Scarf economy we offer some reflections:

- Algorithms that generate economically meaningful prices unfortunately do not perform well in achieving convergence. However, we may expect algorithms based on a utility target to do better after robot traders generate more transactions.
- Traders learn from observing prices, but they can also learn a lot from scrutinizing the opportunities that are available to them: chapter 3 demonstrates that sophisticated traders in the unstable Scarf economies can deduce the Walrasian equilibrium prices without even having to trade. However, if traders use rules of thumb for prioritizing feasible actions then this explanation seems less likely.

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<sup>2</sup>ESP introduce a trade-off between expected value and uncertainty. This trade-off provides a simple explanation of paradoxes of choice. We show that ESP fits the framework of choice theory after the axiom of independence is slightly weakened.

- In the Scarf economies, deviations from the equilibrium price in one market do not affect demand in the other market. A localized impact of "false" prices could offer an explanation for the limited shift of the competitive equilibrium in the stable Scarf economy. However, our simulations suggest otherwise.
- Plott et al. (2013) proposes that prices in the stable Scarf economy converge because trading occurs along a Marshallian path, i.e. as if buyers and sellers have been ordered according to their reservation prices. We think it is unclear how a Marshallian path can be achieved: traders cannot coordinate on private reservation prices, and this may even be not incentive compatible.
- Marshall (1961) suggests another mechanism that seems more promising. According to Marshall, traders first determine how much they want to spend on each commodity, given (expected) prices. Then they determine reservation prices that take their previous transactions into account. If someone previously has paid too much on average, then he now wants to pay less than the expected price in order to compensate the difference. This kind of behavior feeds corrections back into the market where the "mistake" was made (which is distinct from utility targets and monopolistic competition).