Complex Economic Systems in Macro & Finance
Empirical Validation and Laboratory Experiments

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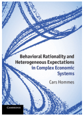
Outline

1. Asset pricing model with heterogeneous beliefs
2. Empirical Validation (Chapter 7)
3. Laboratory Experiments (Chapter 8)
   - cobweb experiments
   - asset pricing experiments
4. Heterogeneous Expectations Model
5. Positive versus Negative Feedback
6. Conclusions

Some References

- Hommes, C.H., (2013), Behavioral Rationality and Heterogeneous Expectations in Complex Economic Systems, Cambridge.



- Hommes, C. and in't Veld, D. (2014), Behavioral heterogeneity and the financial crisis, CeNDEF Working Paper, Univ. of Amsterdam
- Assenza, T., Bao, T., Hommes, C.H. and Massaro, D. (2014), Experiments on expectations in macroeconomics and finance, In: Duffy, J. (Eds.), *Research in Experimental Economics*, Volume 17, Emerald Press

Asset Pricing Model with Four Belief Types

(zero costs; memory one lag)
example.

$$\begin{array}{lllllll} g_1 & = & 0 & b_1 & = & 0 & \text{fundamentalists} \\ g_2 & = & 0.9 & b_2 & = & 0.2 & \text{trend + upward bias} \\ g_3 & = & 0.9 & b_3 & = & -0.2 & \text{trend + downward bias} \\ g_4 & = & R = 1.01 & b_4 & = & 0 & \text{trend chaser} \end{array} \tag{1}$$

$$Rx_t = \sum_{h=1}^{4} n_{h,t}(g_h x_{t-1} + b_j)$$

$$n_{h,t+1} = \exp\left(\frac{\beta}{a\sigma^2}(g_h x_{t-2} + b_h - Rx_{t-1})(x_t - Rx_{t-1})\right)/Z_t, \qquad h = 1, 2, 3,$$

Four Belief Types

Rational Route to Randomness:

- $\beta < \beta^*$: fundamental steady state globally stable
- $\beta = \beta^*$: **Hopf bifurcation** of steady state
- $\beta^* < \beta < \beta^{**}$: periodic and quasi-periodic price fluctuations on attracting invariant circle
- high values of β: strange attractors
- $\beta = \infty$: convergence to (locally unstable) fundamental steady state

Theoretical Question:

Is the system close to *homoclinic orbits* and chaos,
when the intensity of choice β is high?

Bifurcation diagram and largest Lyapunov exponent plot

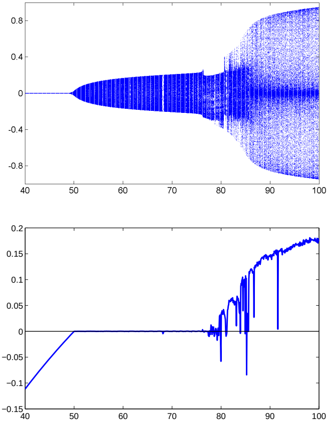


Figure : Bifurcation diagram (top panel) and largest Lyapunov exponent plot (bottom panel) for 4-type model.

Chaotic and noisy chaotic time series, and strange attractor

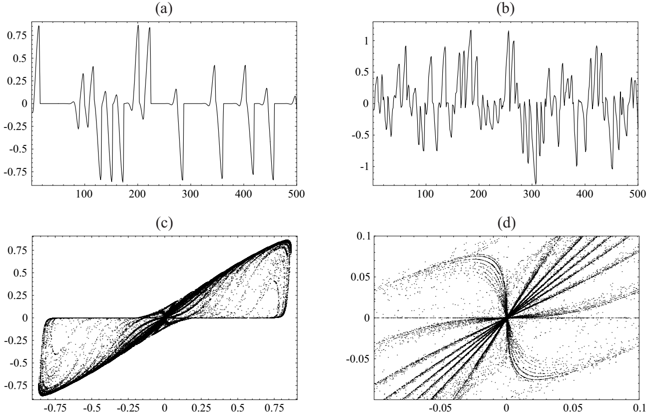


Figure : Chaotic (top left) and noisy chaotic (top right) time series of asset prices in adaptive belief system with four trader types. Strange attractor (bottom left) and enlargement of strange attractor (bottom right).

Forecasting errors

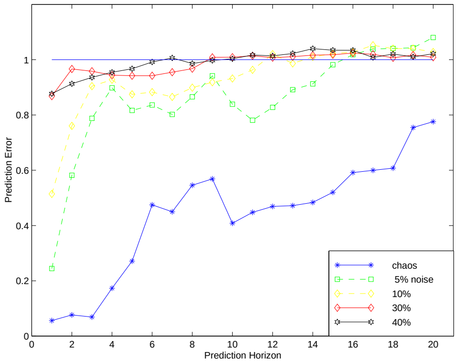
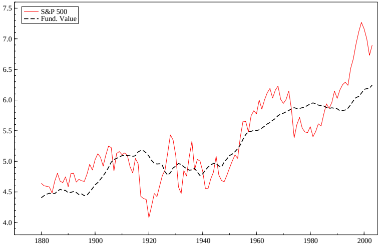
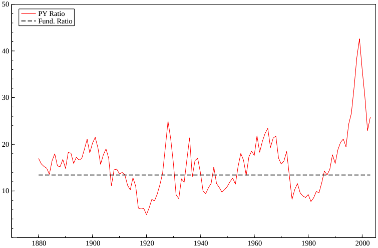


Figure : Forecasting errors for nearest neighbor method applied to chaotic returns series (lowest graph) as well as noisy chaotic returns series, for time horizons $1 - 20$ and for different noise levels, in ABS with four trader types.

Empirical Validation: S&P500 and PE ratios, 1871–2003

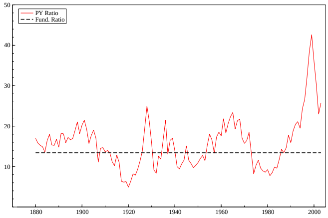




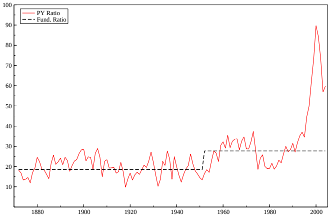
log S&P500 and fundamental

Price-to-Earnings

Empirical Validation: PE and PD ratios S&P500, 1871–2003

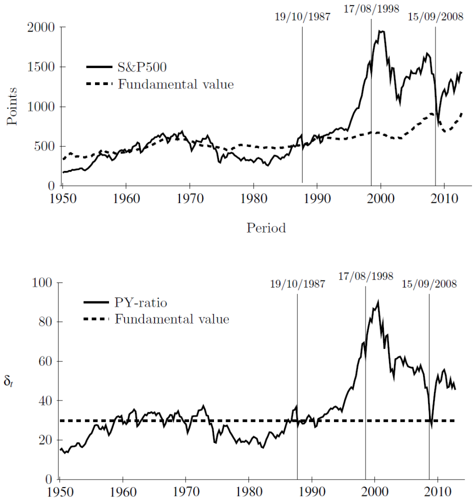


Price-to-Earnings



Price-to-Dividends

S&P 500, 1950-2012 + benchmark fundamental $p_t^* = \frac{1+g}{1+r} y_t$ (g constant growth rate dividends)



BH-Model and risk premium

market clearing (with zero net supply)

$$\sum_{h=1}^{H} n_{h,t} \frac{E_{h,t}[p_{t+1} + y_{t+1}] - (1+r)p_t}{aV_t[R_{t+1}]} = 0$$

equilibrium pricing equation

$$p_t = \frac{1}{1+r} \sum_{h=1}^{H} n_{h,t} E_{h,t}(p_{t+1} + y_{t+1}), \text{ or } r = \sum_{h=1}^{H} n_{h,t} \frac{E_{h,t}[p_{t+1} + y_{t+1} - p_t]}{p_t},$$

estimation:

required rate of return r = risk free interest rate + **risk premium**

Stochastic cash flow with constant growth rate

$\log y_t$ Gaussian random walk with drift:

$$\log y_{t+1} = \mu + \log y_t + \upsilon_{t+1}, \qquad \upsilon_{t+1} \sim \text{i.i.d. } N(0, \sigma_\upsilon^2),$$

This implies

$$\frac{y_{t+1}}{y_t} = e^{\mu + \upsilon_{t+1}} = e^{\mu + \frac{1}{2}\sigma_\upsilon^2} e^{\upsilon_{t+1} - \frac{1}{2}\sigma_\upsilon^2} = (1+g)\varepsilon_{t+1},$$

where $g = e^{\mu + \frac{1}{2}\sigma_\upsilon^2} - 1$ and $\varepsilon_{t+1} = e^{\upsilon_{t+1} - \frac{1}{2}\sigma_\upsilon^2}$, which implies $E_t(\varepsilon_{t+1}) = 1$.
all types **correct beliefs** about cash flows

$$E_{h,t}[y_{t+1}] = E_t[y_{t+1}] = (1+g)y_t E_t[\varepsilon_{t+1}] = (1+g)y_t.$$

RE fundamental benchmark for constant growth cash flow

$$p_t = \frac{1}{1+r} E_t(\mathbf{p}_{t+1} + \mathbf{y}_{t+1})$$

"no bubble" condition implies unique bounded RE **fundamental price** p_t^*:
(discounted sum of expected future dividends)

$$p_t^* = \frac{E_t(y_{t+1})}{1+r} + \frac{E_t(y_{t+2})}{(1+r)^2} + \ldots \quad = \frac{1+g}{1+r} y_t + \frac{(1+g)^2}{(1+r)^2} y_t + \ldots \quad = \frac{1+r}{r-g} y_t.$$

fundamental price to cash flow ratio

$$\delta_t^* = \frac{p_t^*}{y_t} = \frac{1+r}{r-g} = m$$

Reformulation BH-model in terms of price to cash flows

equilibrium pricing equation

$$p_t = \frac{1}{1+r}\sum_{h=1}^{H} n_{h,t} E_{h,t}(p_{t+1} + y_{t+1})$$

in terms of **price-to-cash flows** $\delta_t = p_t / y_t$

$$\delta_t = \frac{1}{R^*}\{1 + \sum_{h=1}^{H} n_{h,t} E_{h,t}[\delta_{t+1}]\}, \qquad R^* = \frac{1+r}{1+g}$$

Heterogeneous Beliefs in terms of price-to-cash flows

deviation price-to-cash flow from fundamental

$$x_t = \delta_t - m = \delta_t - \frac{1+g}{r-g}$$

belief of type h about price-to-cash flow:

$$E_{ht}[\delta_{t+1}] = E_t[\delta_t^*] + f_h(x_{t-1}, ..., x_{t-L}) = m + f_h(x_{t-1}, ..., x_{t-L})$$

pricing equation in **deviations** from fundamental

$$R^* x_t = \sum_{h=1}^{H} n_{ht} f_h(x_{t-1}, ..., x_{t-L}), \qquad R^* = \frac{1+r}{1+g}$$

Evolutionary Fitness Measure

realized net profits in period t

$$U_{ht} = \pi_{ht} = R_t z_{h,t-1} = (p_t + y_t - Rp_{t-1})\frac{E_{h,t-1}[p_t + y_t - Rp_{t-1}]}{aV_{t-1}[p_t + y_t - Rp_{t-1}]}$$

Assume (in analogy with BH)

$$V_{t-1}[p_t + y_t - Rp_{t-1}] = V_{t-1}[p_t^* + y_t - Rp_{t-1}^*] = y_{t-1}^2 \eta^2$$

fitness in deviations from fundamental

$$U_{ht} = \pi_{ht} = \frac{(1+g)^2}{a\eta^2}(x_t - R^* x_{t-1})(E_{h,t-1}[x_t - R^* x_{t-1}])$$

Two-types: Fundamentalists versus trend

Two trader types, with forecasting rules

$$
\begin{array}{rcllr}
f_{1t} & = & \phi_1 x_{t-1}, & 0 \leq \phi_1 < 1 & \textbf{fundamentalists} \\
f_{2t} & = & \phi_2 x_{t-1}, & \phi_2 > 1, & \text{trend extrapolators}
\end{array}
$$

Fractions of the Two Types

fractions of belief types are updated in each period according to discrete choice model (BH 1997,1998)

$$n_{h,t} = \frac{\exp[\beta \pi_{h,t-1}]}{\sum_{k=1}^{H} \exp[\beta \pi_{k,t-1}]} = \frac{1}{1 + \sum_{k \neq h} \exp[-\beta \Delta \pi_{t-1}^{h,k}]},$$

where $\beta > 0$ is **intensity of choice** and
$\Delta \pi_{t-1}^{h,k} = \pi_{h,t-1} - \pi_{k,t-1}$ **difference in realized profits** types h and k
In 2-type case, **fraction of type 1**:

$$n_t = \frac{1}{1 + \exp\{-\beta^* [(\phi_1 - \phi_2) x_{t-3} (x_{t-1} - R^* x_{t-2})]\}}$$

Estimation of two type model

in deviations from fundamental; synchronous updating; Boswijk et al., JEDC 2007

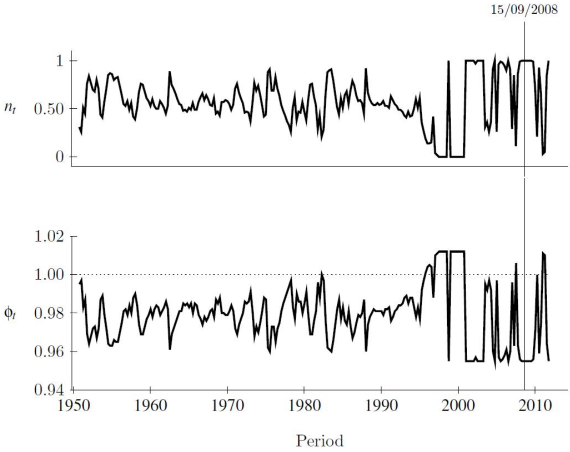
$$R^* x_t = n_t \phi_1 x_{t-1} + (1 - n_t)\phi_2 x_{t-1} + \epsilon_t \qquad R^* = \frac{1+r}{1+g} \approx 1.074$$

- $\phi_1 = 0.762$: **fundamentalists**, mean reversion
- $\phi_2 = 1.135$ **trend extrapolators**
- $\beta \approx 10$

$$\phi_t = \frac{n_t \phi_1 + (1 - n_t)\phi_2}{R^*} \qquad \textbf{market sentiment}$$

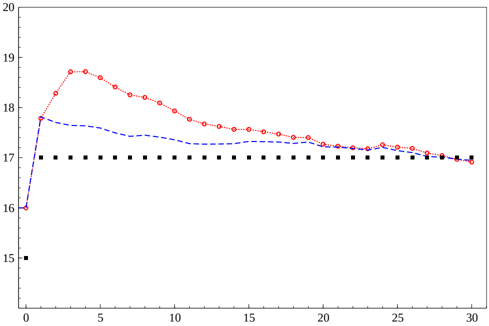
- $\phi_t < 1$: mean reversion;
- $\phi_t > 1$: explosive, trend following

Fraction Fundamentalists & Market Sentiment



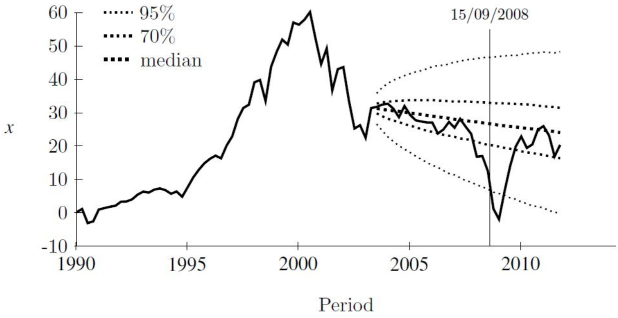
Explanation: dot com bubble triggered by economic fundamentals and **strongly amplified** by trend following behavior

Average Response to Fundamental shock (2000 runs)



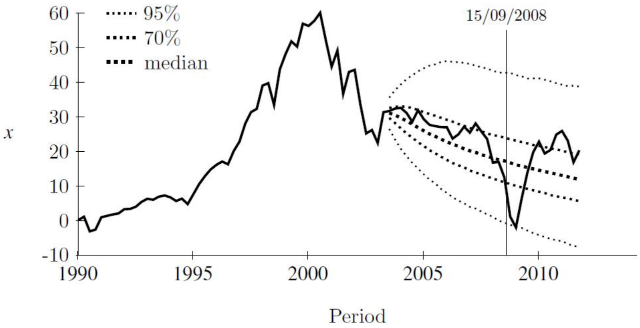
short term **overreaction** and long term **mean reversion**

Financial Crisis Extreme Event in Linear RE Model



Quantiles of 2000 simulated predictions of the PE-ratio in deviations from fundamental

Financial Crisis not Extreme in Nonlinear Switching Model



Quantiles of 2000 simulated predictions of the PE-ratio
in deviations from fundamental

Conclusions

Asset Pricing Model with Heterogeneous Beliefs

- rational route to randomness as β increases, with temporary **bubbles** and **crashes**
  - weak correlation of beliefs: **stable** price behavior;
  - strong coordination of beliefs: **unstable** price dynamics
- counter-examples to Friedman hypothesis:
  fundamentalists do **not** drive out "irrational" **technical analysts**, driven by short run profits
- empirical validation: explanation of bubbles and crashes
- consistent with **learning-to-forecast** laboratory experiments

Laboratory Experiments in Macro and Finance

- study behavior in **controlled** laboratory environment
- **empirical foundation** for individual decision rules for ABMs to **discipline** wilderness of bounded rationality
- **individual** (micro) as well as **aggregate** (macro) behavior
- testing **complex systems**;
  emergent macro behavior through interactions at micro level

Lucas, JPE, 1986 on Learning and Experiments

"Recent theoretical work is making it increasingly clear that the **multiplicity of equilibria** ... can arise in a wide variety of situations involving sequential trading, in competitive as well as finite agent games. All but a few of these equilibria are, I believe, behaviorally uninteresting: They do not describe **behavior that collections of adaptively behaving people** would ever hit on. I think an appropriate **stability theory** can be useful in weeding out these uninteresting equilibria ... But to be useful, stability theory must be more than simply a fancy way of saying that one does not want to think about certain equilibria. I prefer to view it as an **experimentally testable hypothesis**, as a special instance of the adaptive laws that we believe govern all human behavior."

Deviations from Rationality & Heterogeneity

Muth (1961) [emphasis added]

Allowing for **cross-sectional differences** *in expectations is a simple matter, because their* **aggregate affect is negligible** *as long as the deviation from the rational forecast for an individual firm is* **not strongly correlated with those of the others**. *Modifications are necessary only if* **the correlation of the errors is large** *and depends systematically on other explanatory variables.*

key issues:

- are individual expectations **coordinated**?
- if so, do individuals coordinate on a **rational** or a **boundedly rational** aggregate outcome?

This should be tested **empirically** and in **laboratory experiments**

Learning to Forecast Experiments

Empirical test for expectations at micro and macro level

- Which **forecasting rules** do **individuals** use?
  Are expectations **heterogeneous** or do individuals **coordinate**?
- If so, do they coordinate on **RE** or **learning equilibrium**?
- Which **theory of expectations** and learning fits the **aggregate** as well as **individual** experimental data?
- How do **micro** and **macro** behaviour depend on **expectations feedback structure**?

Learning to Forecasts Laboratory Experiments

- individuals **only** have to forecast price, **ceteris paribus**, e.g. with all other behavior assumed to be **rational**, demand/supply derived from profit/utility **maximization**
- computerized trading yields market equilibrium price, consistent with **benchmark model**, e.g.
  - cobweb model
  - asset pricing model
  - New Keynesian macro model
- **advantage**: clean data on expectations
- **Challenge**: universal theory of heterogeneous expectations

Learning to Forecast Experiments (Ctd)

Subjects' task and incentive (professional forecasters)

- forecasting a price for 50 periods
- **better** forecasts yield **higher** earnings

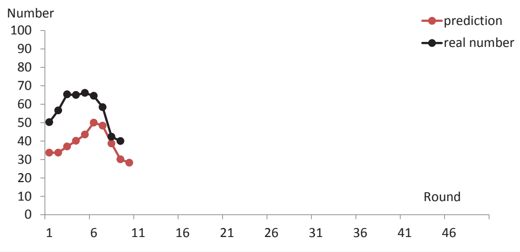
Subjects know

- only **qualitative information** about the market
- price p_t derived from equilibrium between **demand** and **supply**
- type of expectations feedback: **positive** or **negative**
- **past information**: at time t participant h can see **past prices (up to p_{t-1}), own past forecasts (up to $p_{t,h}$) and own earnings (up to $e_{t-1,h}$)**

Subjects do not know

- exact equilibrium **equation**, e.g. $p_t = f(\bar{p}^e_{t+1})$ or $p_t = f(\bar{p}^e_t)$
- exact **demand schedule** of themselves and others
- number and **forecasts of other** participants

Example Computer Screen Experiment



Round	Prediction	Real value
1	33,70	50,23
2	33,70	56,63
3	37,00	65,32
4	40,10	65,00
5	43,50	66,12
6	50,00	64,53
7	48,35	58,35
8	38,70	42,35
9	30,10	40,01
10	28,25	

Total earnings:	Earnings this period:	Remaining time:
10357	1298	00

What is your prediction this period?
Your prediction must be between 0 and 100

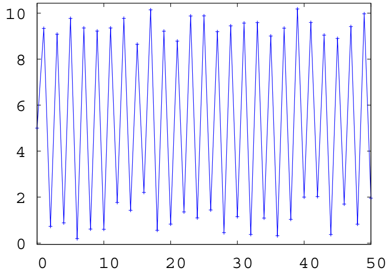
Prediction:

Cobweb Experimental Setting

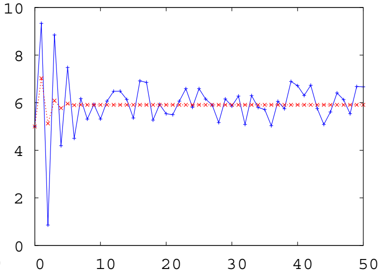
- one-period ahead
- negative feedback; supply driven
- **profit maximization**
- agents **do not know** demand and supply
- **market clearing**

$$p_t = D^{-1}(\sum_{i=1}^{K} S_\lambda(p^e_{i,t})) = \frac{a - \sum_{i=1}^{K} S_\lambda(p^e_{i,t})}{d} + \epsilon_t$$

Cobweb Experiment Simulation Benchmarks



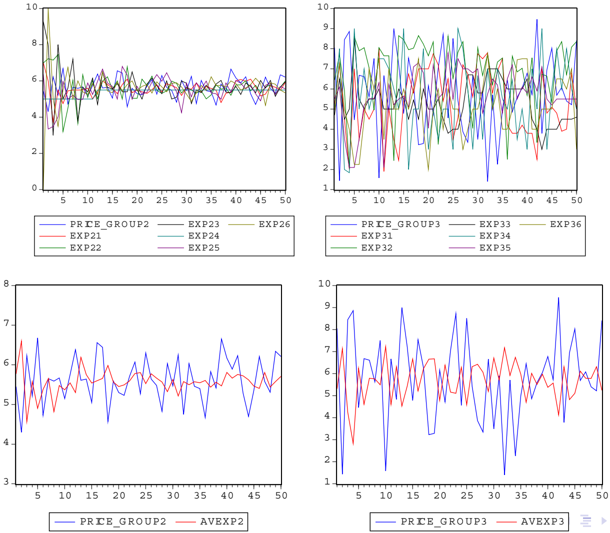
naive expectations



sample average learning

Cobweb Experiment

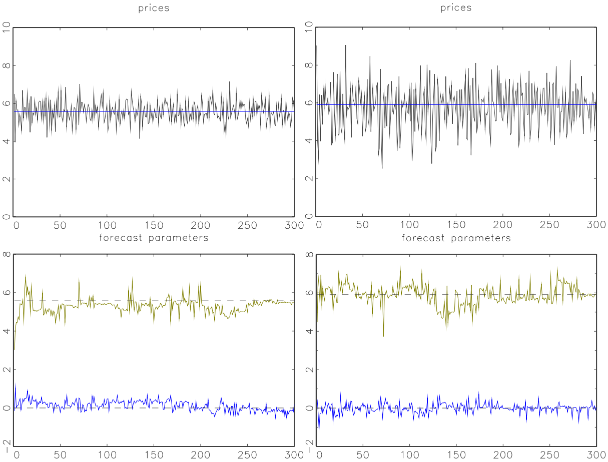
stable treatment | unstable treatment



Cobweb GA Simulations ($p_{i,t+1} = \alpha_i + \beta_i(p_t - \alpha_i)$)

Hommes and Lux, *Macroeconomic Dynamics* 2012

stable treatment | unstable treatment



Asset Pricing Experimental Setting

- **asset pricing experiment** (with/without robot trader)
  - two-period ahead
  - positive feedback
  - mean-variance **utility maximization** and **market clearing**
  - mean dividend $\bar{y} = 3$ and interest rate $r = 0.05$ are **known** **fundamental price** $p^f = \bar{y}/r = 60$ is **not known** (but can be computed)

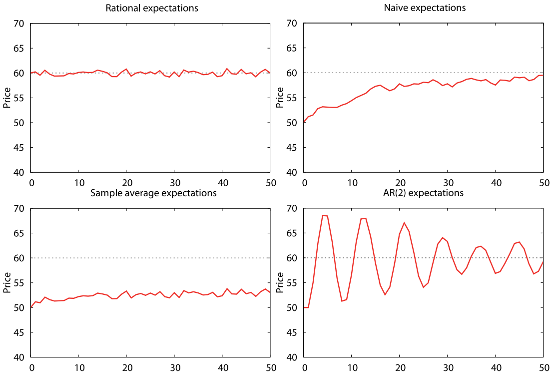
$$p_t = \frac{1}{1+r}\left((1-n_t)\frac{p^e_{t+1,1} + \cdots + p^e_{t+1,6}}{6} + n_t\, p^f + \bar{y} + \varepsilon_t\right)$$

Two Other Experimental Settings

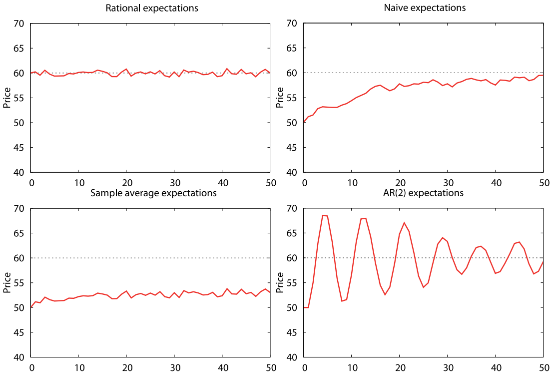
- **positive** versus **negative** feedback; one-period ahead $p_t = f(p_t^e)$:
  - **positive** feedback: linear, slope $+0.95$;
  - **negative** feedback: linear, slope -0.95.
- **New Keynesian Macromodel**: aggregate inflation and output depend on individual forecasts of **both** inflation and output (and monetary policy rule):

$$(\pi_t, y_t) = F(\pi_{t+1}^e, y_{t+1}^e)$$

Asset Pricing Experiment Simulation Benchmarks



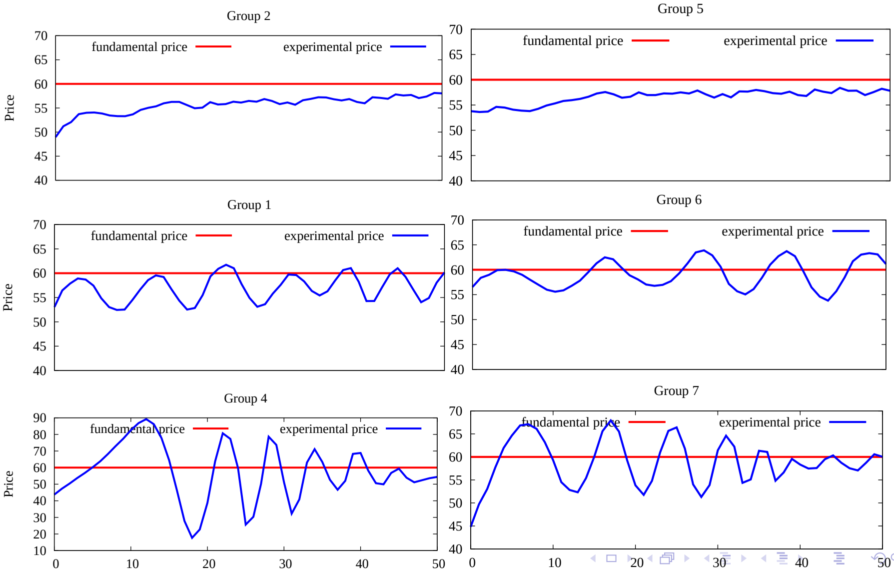
Asset Pricing Experiment Simulation Benchmarks



AR2 // anchor and adjustment rule

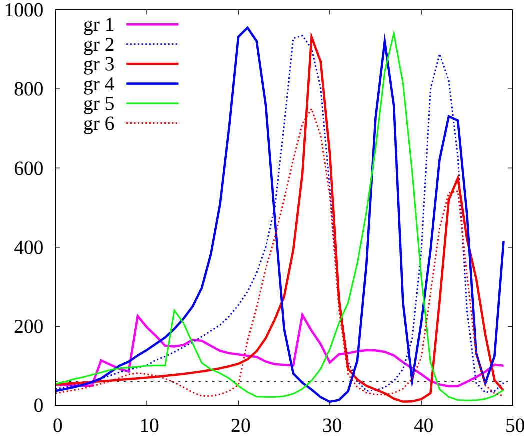
$$p^e_{t+1} = 30 + \frac{3}{2}p_{t-1} - p_{t-2} = (60 + p_{t-1})/2 + (p_{t-1} - p_{t-2})$$

Asset Pricing Experiment (with Robot Trader)



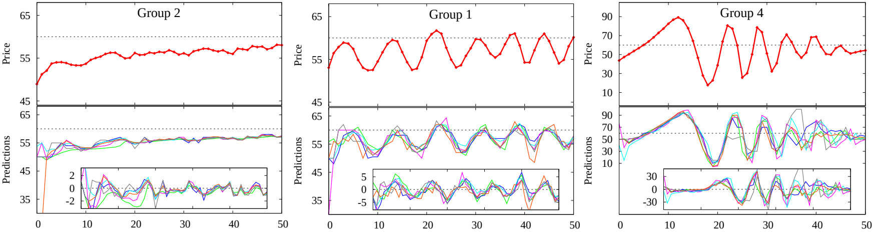
Asset Pricing Experiments (without Robot Trader)

(Hommes et al., JEBO 2008)



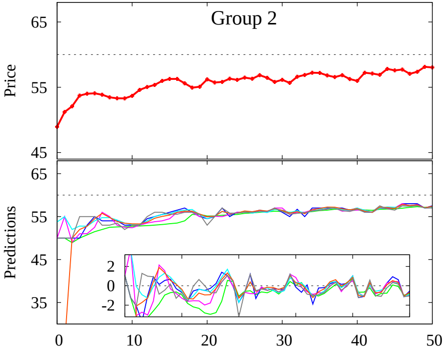
Asset Pricing Experiment

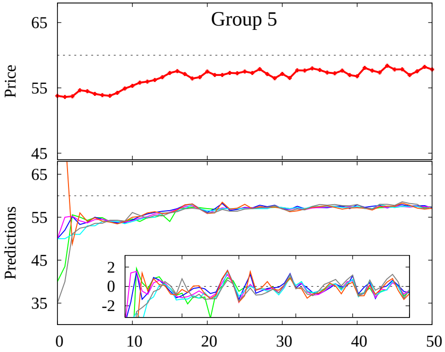
Strong coordination of individual forecasts and errors



Groups with (Almost) Monotonic Convergence

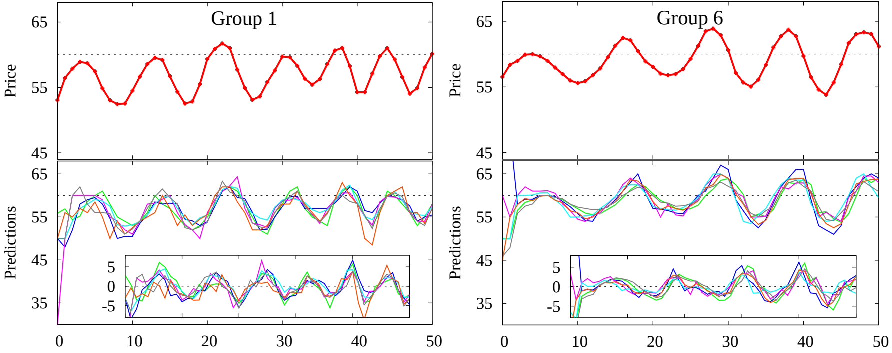
prices, individual predictions and individual errors





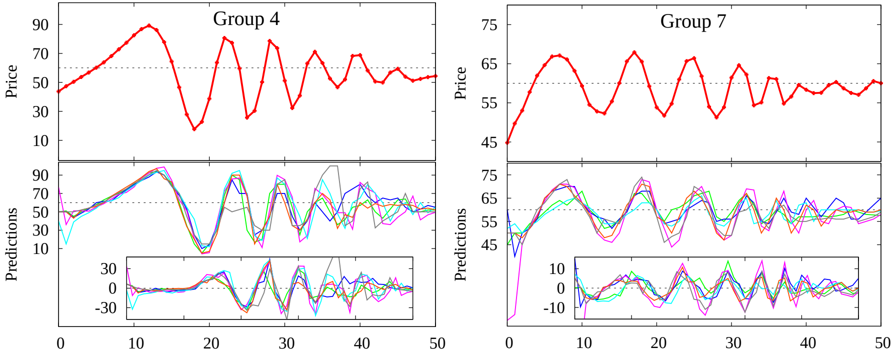
2 Groups with Perpetual Oscillations

prices, individual predictions and individual errors



2 Groups with Damping Oscillations

prices, individual predictions and individual errors



Summary Results Asset Pricing Experiment

Results are inconsistent with rational, fundamental forecasting

One would like to explain:

- **three qualitatively different patters**
    - (almost) monotonic convergence
    - constant oscillations
    - damping oscillations
- **coordination of agents in their predictions**
- **no homogeneous expectations model fits these experiments need heterogeneous expectations model**

Estimation of Individual Predictions

...for the last 40 periods

- in converging groups agents use **adaptive expectations**

$$p^e_{t+1} = w\, p_{t-1} + (1-w)\, p^e_t$$

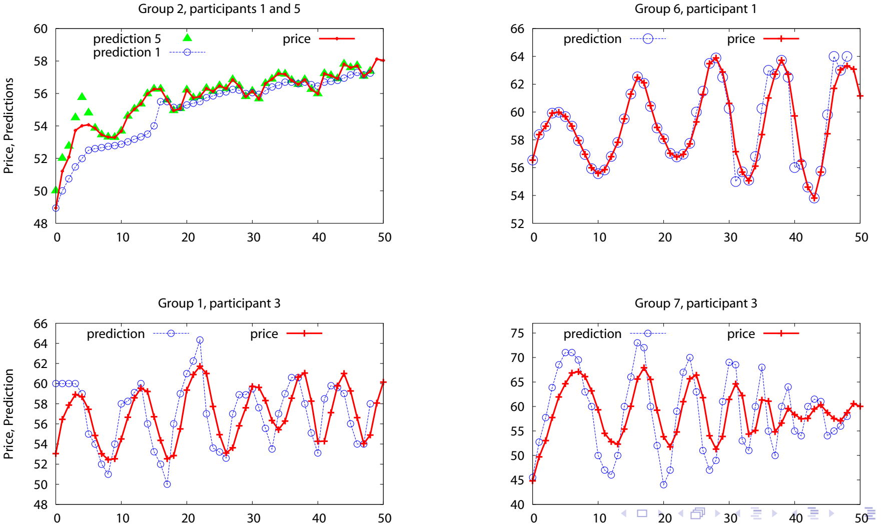
- often agents used **simple linear rules**
  anchor and adjustment rule

$$\begin{array}{ll} p^e_{t+1} = & \alpha + \beta_1\, p_{t-1} + \beta_2\, p_{t-2} \\ \text{e.g.} & (60 + p_{t-1})/2 + (p_{t-1} - p_{t-2}) \\ \text{or} \quad \text{LAA} & (p^{av}_{t-1} + p_{t-1})/2 + (p_{t-1} - p_{t-2}) \end{array}$$

  in particular **trend-extrapolating rules**

$$p^e_{t+1} = p_{t-1} + \gamma\,(p_{t-1} - p_{t-2}) \qquad 0.4 \le \gamma \le 1.3$$

Examples of Individual Predictions and Switching



Heterogeneous Expectations Heuristics Switching Model

Anufriev and Hommes, AEJ:Micro 2012

- agents choose from a number of simple **forecasting heuristics**
- **adaptive learning**: some parameters of the heuristics are updated over time, e.g. anchor $\equiv$ average
- **performance based reinforcement learning:**
  (extension of Brock and Hommes, *Econometrica* 1997)
  agents evaluate the **performances** of all heuristics, and tend to **switch** to more successful rules; **impacts are evolving** over time

Four forecasting heuristics

- adaptive rule

$$\text{ADA} \qquad p^e_{1,t+1} = 0.65\, p_{t-1} + 0.35\, p^e_{1,t}$$

- weak trend-following rule

$$\text{WTR} \qquad p^e_{2,t+1} = p_{t-1} + 0.4\,(p_{t-1} - p_{t-2})$$

- strong trend-following rule

$$\text{STR} \qquad p^e_{3,t+1} = p_{t-1} + 1.3\,(p_{t-1} - p_{t-2})$$

- anchoring and adjustment heuristics with learnable anchor

$$\text{LAA} \qquad p^e_{4,t+1} = 0.5\, p^{av}_{t-1} + 0.5\, p_{t-1} + (p_{t-1} - p_{t-2})$$

Evolutionary Switching with Asynchronous Updating

- performance measure of heuristic i is

$$U_{i,t-1} = -\left(p_{t-1} - p^e_{i,t-1}\right)^2 + \eta\, U_{i,t-2}$$

parameter $\eta \in [0,1]$ – the **strength of the agents' memory**

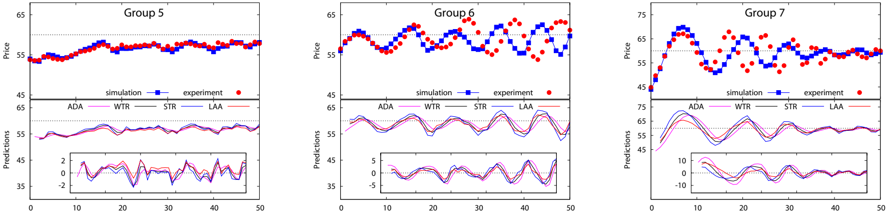
- **discrete choice model with asynchronous updating**

$$n_{i,t} = \delta\, n_{i,t-1} + (1-\delta)\,\frac{\exp(\beta\, U_{i,t-1})}{\sum_{i=1}^{4} \exp(\beta\, U_{i,t-1})}$$

parameter $\delta \in [0,1]$ – the inertia of the traders
parameter $\beta \geq 0$ – the intensity of choice

Simulated Paths (50 periods ahead)

Parameters: $\beta = 0.4, \eta = 0.7, \delta = 0.9$



Stochastic Simulations (one step ahead forecast)

Anufriev and Hommes (2012)

- uses **past experimental data**
- **same information** as participants in experiments

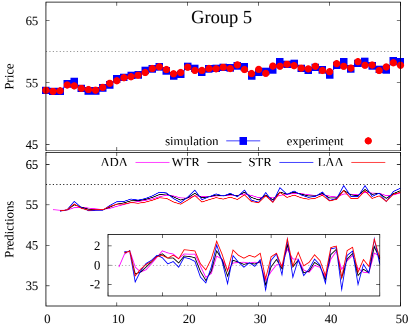
Parameters fixed at: $\beta = 0.4, \eta = 0.7, \delta = 0.9$

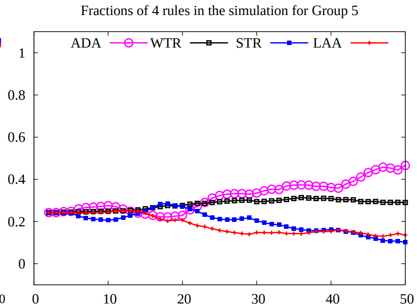
- initial fractions **equal**, i.e. $n_{ht} = 0.25$
- initial prices **as in experiments**

Group 5 (Convergence)

experimental prices
simulated prices, predictions and errors

Parameters: $\beta = 0.4, \eta = 0.7, \delta = 0.9$

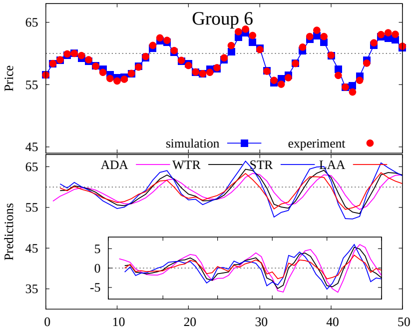


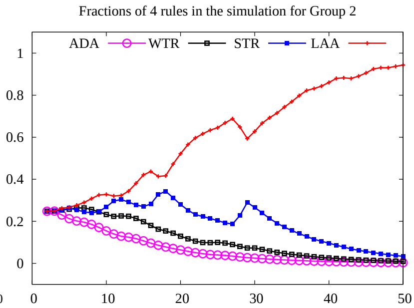


Group 6 (Constant Oscillations)

experimental prices
simulated prices, predictions and errors

Parameters: $\beta = 0.4, \eta = 0.7, \delta = 0.9$

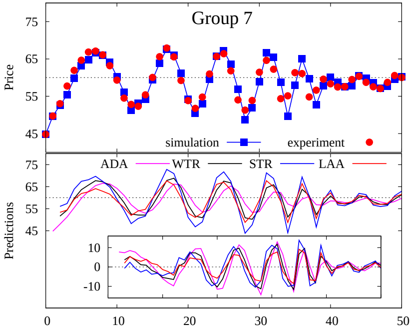


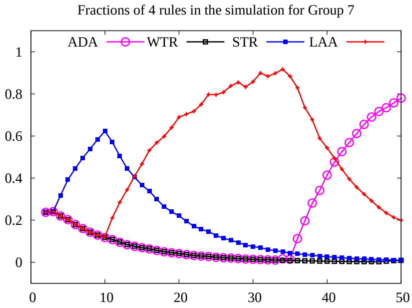


Group 7 (Damping Oscillations)

experimental prices
simulated prices, predictions and errors

Parameters: $\beta = 0.4, \eta = 0.7, \delta = 0.9$





Muth (1961) on Deviations from Rationality
[emphasis added]

Allowing for **cross-sectional differences** *in expectations is a simple matter, because their* **aggregate affect is negligible** *as long as the deviation from the rational forecast for an individual firm is* **not strongly correlated with those of the others**. *Modifications are necessary only if the* **correlation of the errors is large** *and depends systematically on other explanatory variables.*

key issues:

- are individual expectations **coordinated**?
- if so, do individuals coordinate on a **rational** or a **boundedly rational** aggregate outcome?

This can be tested in **Learning to Forecast Experiments**

Positive versus Negative Feedback Experiments

Heemeijer et al. (JEDC 2009); Bao et al. (JEDC 2012

- **negative feedback** (strategic substitute environment)

$$p_t = 60 - \frac{20}{21}[\sum_{h=1}^{6} \frac{1}{6} p^e_{ht}] - 60] + \epsilon_t$$

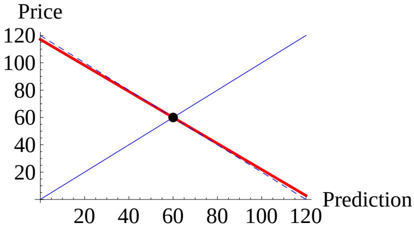
- **positive feedback** (strategic complementarity environment)

$$p_t = 60 + \frac{20}{21}[\sum_{h=1}^{6} \frac{1}{6} p^e_{ht} - 60] + \epsilon_t$$

- **different types of shocks** ϵ_t: small resp. large permanent shocks
- **common feature**: same RE equilibrium
- **only difference**: sign in the slope of linear map $+0.95$ vs -0.95

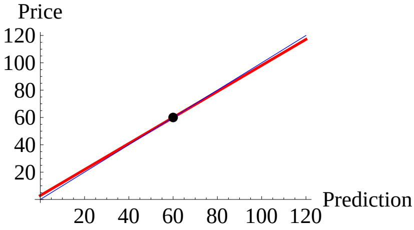
Feedback Mappings in LtFE

Negative feedback



$$p_t = 60 - \frac{20}{21}\left(\overline{p_t^e} - 60\right) + \varepsilon_t$$

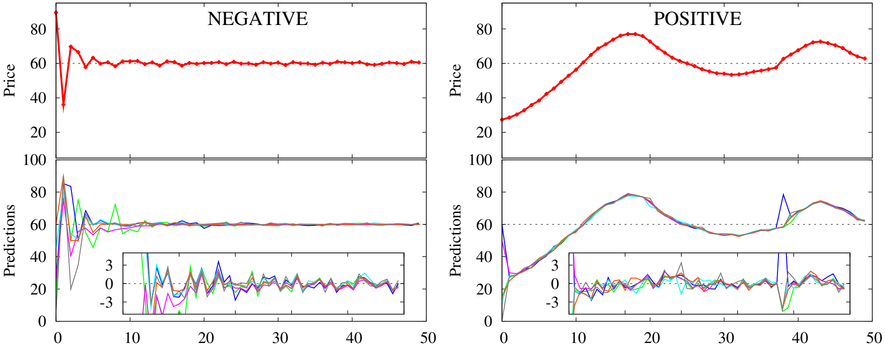
Positive feedback



$$p_t = 60 + \frac{20}{21}\left(\overline{p_t^e} - 60\right) + \varepsilon_t$$

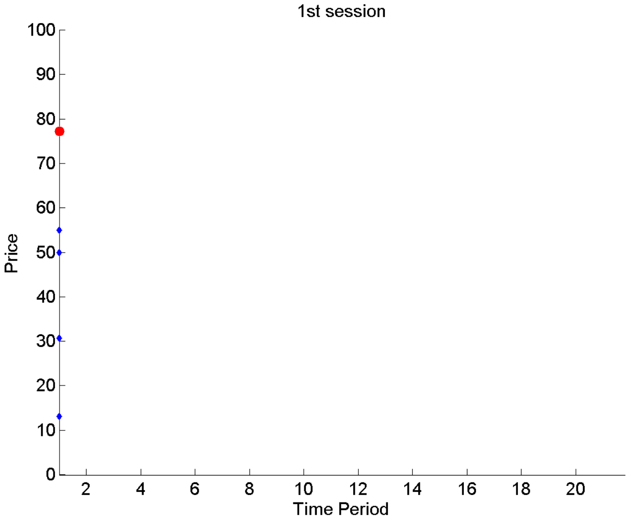
Negative vs. Positive Feedback Experiments

Prices, Individual Predictions and Errors



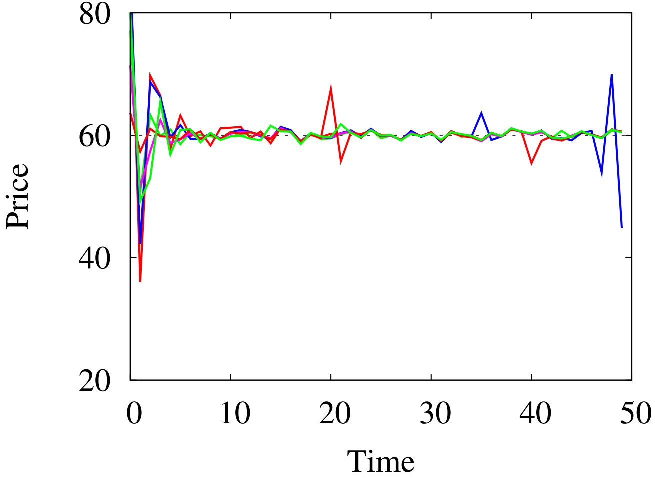
Positive Feedback: coordination on “wrong” price

Negative Feedback Experiment: Session 1

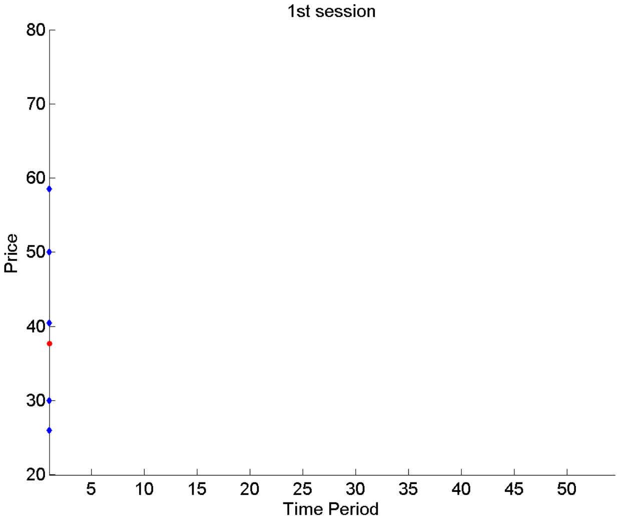


Price in Experiments with Negative Feedback (6 groups)

(Heemeijer et al., JEDC 2009)

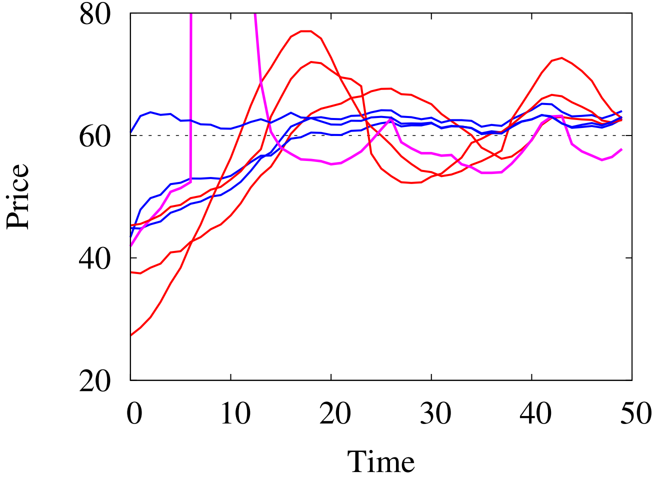


Positive Feedback Experiment: Session 1



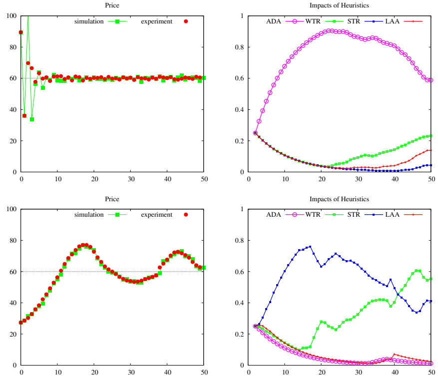
Prices in Experiments with Positive Feedback (7 groups)

(Heemeijer et al., JEDC 2009)



Positive vs Negative Feedback; Small Shocks Heuristics Switching Model Simulations

prices strategy frequencies

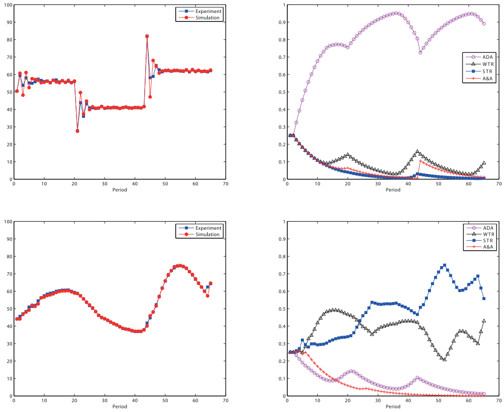


positive feedback: trend-followers amplify fluctuations

Positive/Negative Feedback; Large Shocks

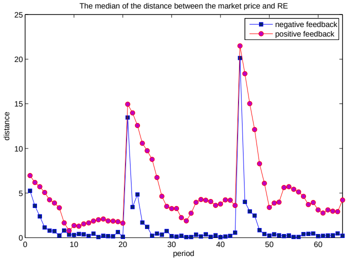
Bao et al., JEDC 2012

prices strategy frequencies

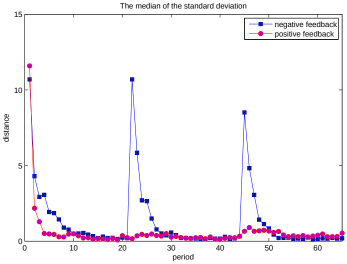


Positive/Negative Feedback; Large Shocks

distance to RE price



degree of heterogeneity



positive feedback: quick coordination on 'wrong' price

negative feedback: slower coordination on correct RE price

Conclusion: Empirical and Exper. Data consistent with Behavioral Rationality & Heterogeneous Expectations

- simple **heterogeneous expectations heuristics switching model** fits experimental **micro** and **macro** data quite nicely
- **heterogeneity** and **heuristics switching** explains
  - path dependence
  - different behaviour in different feedback systems
  - different behaviour in aggregate variables of same economy
- agents are **behaviorally rational** at the individual level: they use simple heuristics such as **adaptive expectations**, **trend following rules** and **anchor and adjustment rules**
- **positive feedback** markets are 'irrational' due to coordination on 'wrong' price and **survival** of (almost) **self-fulfilling trend following strategies**

If you have questions ...

read the book!

or ask now ...

Thank you very much!!