THE LUCAS MODEL OF ASSET PRICING: EXPERIMENTS

Elena Asparouhova, Peter Bossaerts, Nilanjan Roy, William Zame

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Why experiments on the Lucas asset pricing model?
Motivation

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- tests with historical data assume equilibrium
  - focus on parametric variations (preferences, consumption, dividends...) of “stochastic Euler equations”
  - weak empirical support
- experiments can inform us about where the model works and where it potentially fails
Motivation
Experimental Setup
Predictions
Results
Pretending To Analyze Historical Data
Conclusion

(Stochastic Euler Equations)

\[
\beta E \left\{ \frac{\partial u_i(c_i(t+1))}{\partial c} \frac{\partial c}{\partial u_i(c_i(t))} \left[ p(t + 1) + d(t + 1) \right] | l(t) \right\} = p(t),
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(Stochastic Euler Equations)

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\]

- Take historical price and consumption data
- Fit equations for a choice of utility and information
Some Objections

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- Why lab test a model that is ‘obviously right’ in the field?
- Why is the model wrong in the field?
- Models are idealizations; the laboratory is an opportunity to test them in an idealized environment.
Objections (c’d)

“The model relies on risk aversion. Nobody should be risk averse in the lab, so the model cannot possibly be right in the lab.”
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- Important message from our work:
  
  *individual ⇔ market*
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- Important message from our work: \textit{individual} $\leftrightarrow$ \textit{market}

- Contrast economic thinking/social choice thinking
How one SHOULD think about the experiments (We think)

We will observe many features that are “defining” for the Lucas model (Pareto efficiency, cross-sectional and intertemporal pricing). Yet at the same time, we observe phenomena that are exactly like in the field: excess volatility, individuals hardly behave as predicted in the theory... without having to invoke design elements that are claimed to be the reason for these phenomena in the field.

Asparouhova, e.a. Lucas Experiments
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  - Individuals hardly behave as predicted in the theory
- ... without having to invoke design elements that are claimed to be the reason for these phenomena in the field
  - Institutions (intermediaries, governments,...), Stochastics (ambiguity, rare events,...), Constraints (incomplete markets, collateral, indivisibilities, ...)

Asparouhova, e.a. | Lucas Experiments
What we learn...

Relative prices are correct, and intertemporally prices move with fundamentals... but fundamentals explain only 18% of price changes (excess volatility). Still, substantial Pareto improvements to autarky. Subject price forecasts are “almost” fulfilled.

Asparouhova, e.a. Lucas Experiments
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Asparouhova, e.a.  Lucas Experiments
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Take away...

Messages:
For theorists: Investigate equilibria where agents make small forecast errors... they look very different from Lucas!
For empiricists: Euler equations might be misguided (because they assume prices are functions of fundamentals only)
For policy: excess volatility does not stand in the way of significant Pareto improvements

Asparouhova, e.a. Lucas Experiments
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Experiments vs. Theory (vs. Reality)

Standard treatment of the Lucas Model starts with Pareto efficient allocations
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- (the equilibrium equations are really first-order conditions of the representative agent that one can construct because of Pareto efficiency!)
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- what economic structure could potentially generate Pareto efficiency... while allowing for heterogeneity across agents?
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- what economic structure could potentially generate Pareto efficiency... while allowing for heterogeneity across agents?
  - impossible to have a complete set of markets
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- (the equilibrium equations are really first-order conditions of the representative agent that one can construct because of Pareto efficiency!)
- what economic structure could potentially generate Pareto efficiency... while allowing for heterogeneity across agents?
  - impossible to have a complete set of markets
  - maybe use dynamic completeness and induce a Radner equilibrium? (Duffie-Huang [1985])
stationary (in dividend levels!), infinite horizon
Setting

- stationary (in dividend levels!), infinite horizon
- two long-lived assets
Setting

- stationary (in dividend levels!), infinite horizon
- two long-lived assets
  - *tree*: pays $0 (bad state) $1 (good state) each period probability $p = 0.5$ (i.i.d.)
  - *bond*: pays $0.50$ each period
two (types of) infinitely lived agents
two (types of) infinitely lived agents
endowments
two (types of) infinitely lived agents
endowments
  type I
    10 trees, 0 bonds
    income: 15 even periods, 0 odd periods
two (types of) infinitely lived agents
endowments
  type I
    • 10 trees, 0 bonds
    • income: 15 even periods, 0 odd periods
  type II
    • 0 trees, 10 bonds
    • income: 15 odd periods, 0 even periods
Why these parameters ??
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- stationary-in-levels (time-invariant) aggregates
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- promote trade (otherwise bubbles – Duffy and Crockett [2013])
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- stationary-in-levels (time-invariant) aggregates
- promote trade (otherwise bubbles – Duffy and Crockett [2013])
- (may restrict shortsales)
How Will Prices Be Formed? Trade Through Continuous Electronic Open Book...
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(Graphical Display Of Book Of Orders)
(Graphical Display Of Book Of Orders)

Tree (4)
Item: Tree

Price: 3.66
Asks
1 unit total
You have no orders at this price

Bond (6)
Item: Bond

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Experimental timeline
Experimental timeline

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Novel Design Solutions

Problems:

- discounting in the lab
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- consumption ("cash") smoothing in the lab
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Solutions:
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- random termination
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Solutions:

- random termination
- pay subjects only cash of last period (intermediate payoffs are forfeited)
Novel Design Solutions

Problems:
- discounting in the lab
- consumption ("cash") smoothing in the lab
- infinite horizon in the lab
- stationarity: end of lab session...

Solutions:
- random termination
- pay subjects only cash of last period (intermediate payoffs are forfeited)
- termination rule: at -10 minutes: reduce to 2-periods ending probabilities = 1/6, 5/6 (exploits separability, iid dividends)
Back To Experimental Timeline
Motivation
Experimental Setup
Predictions
Results
Pretending To Analyze Historical Data
Conclusion
The Economy
Price Formation
Experimental Timeline
More Design

Back To Experimental Timeline

Possible Termination of Session
*If termination--keep CASH
*If continuation--lose CASH, carry over “Trees” and “Bonds”

Period 1

Dividends from initial allocation of “Trees” and “Bonds”

Income

Trade to a final allocation of “Trees,” “Bonds,” and CASH

Period 2

Dividends from carried over allocation of “Trees” and “Bonds”

Income

Trade to a final allocation of “Trees,” “Bonds,” and CASH

Period 3

Possible Termination of Session
*If termination--keep CASH
*If continuation--lose CASH, carry over “Trees” and “Bonds”

Etc.

References
(Radner) Equilibrium

Agents know structure of uncertainty, true probabilities, asset payoffs, own endowments, utility function, current asset prices... and future asset prices. Equilibrium assumes perfect/correct forecasts!
(Radner) Equilibrium

- asset prices $p$ and consumption ("cash") plans $c^I, c^{II}$
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- such that
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  - markets clear
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- *Equilibrium assumes perfect/correct forecasts!*
Prices – Allowing For Heterogeneity

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- cross-sectional
  - tree is less expensive than bond
  - tree expected rate of return higher than bond
    - higher consumption beta
  
  caution: this is an equilibrium prediction
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Asparouhova, e.a. Lucas Experiments
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- intertemporal
  - price levels correlate perfectly and positively with fundamentals
    (dividends of tree)
  - cross-sectional and intertemporal predictions reinforce each other
  - (countercyclical equity premium, or cyclical discount of Tree price relative to Bond price)
Allocations

- **dynamic completeness:**
Allocations

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  - Pareto optimality

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    - diversification: consumption is positively (rank) correlated across states (high, low dividend on tree)
    - (If homothetic utilities: consumption shares are constant across states/periods)
  - (price risk is hedged)
Homogeneous Log Utility, $\beta = 5/6$
Homogeneous Log Utility, $\beta = 5/6$

- Prices and returns – Tree cheaper; Both assets cheaper in Low state; Countercyclical equity premium and pro-cyclical discount

<table>
<thead>
<tr>
<th>State</th>
<th>Tree</th>
<th>Bond</th>
<th>Price</th>
<th>Return</th>
<th>Price</th>
<th>Return</th>
<th>Price</th>
<th>Discount</th>
<th>Equity</th>
<th>Premium</th>
</tr>
</thead>
<tbody>
<tr>
<td>High ($H$)</td>
<td>$2.50$</td>
<td>$3.12$</td>
<td>$0.62$</td>
<td>$3.4%$</td>
<td>$-0.5%$</td>
<td>$3.9%$</td>
<td>$6%$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low ($L$)</td>
<td>$1.67$</td>
<td>$2.09$</td>
<td>$0.42$</td>
<td>$55%$</td>
<td>$49%$</td>
<td>$4%$</td>
<td>$6%$</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
Homogeneous Log Utility, $\beta = 5/6$
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- Holdings and trading: Type I (receives income in Even periods and buys Trees to hedge price risk)

<table>
<thead>
<tr>
<th>Period</th>
<th>Tree</th>
<th>Bond</th>
<th>(Total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Odd</td>
<td>7.57</td>
<td>0.62</td>
<td>(8.19)</td>
</tr>
<tr>
<td>Even</td>
<td>2.03</td>
<td>7.78</td>
<td>(9.81)</td>
</tr>
<tr>
<td>(Trade in Odd)</td>
<td>(+5.54)</td>
<td>(-7.16)</td>
<td>(-1.62)</td>
</tr>
</tbody>
</table>
### Sessions/Replications

<table>
<thead>
<tr>
<th>Session</th>
<th>Place</th>
<th>Replication Periods</th>
<th>Subject Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Caltech</td>
<td>4 (14, 1, 7)</td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>Caltech</td>
<td>2 (13, 4, 9)</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>UCLA</td>
<td>*3 (12, 3, 6)</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>UCLA</td>
<td>*2 (14, 6, 8)</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>Caltech</td>
<td>*2 (12, 2, 10)</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>Utah</td>
<td>*2 (15, 6, 9)</td>
<td>24</td>
</tr>
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</table>

(Overall) 15 (80, 1, 10)

(Starred sessions ended with prematurely halted replication)
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<th>Periods (Total, Min, Max)</th>
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<tr>
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<td>4</td>
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Asparouhova, e.a.  Lucas Experiments
Tree cheaper; Both assets cheaper in low state; But discount counter-cyclical.
Tree cheaper; Both assets cheaper in low state; But discount counter-cyclical

<table>
<thead>
<tr>
<th>Data</th>
<th>Tree Price</th>
<th>Bond Price</th>
<th>Discount (Bond - Tree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.75</td>
<td>3.25</td>
<td>0.50</td>
</tr>
<tr>
<td>St. Dev.</td>
<td>0.41</td>
<td>0.49</td>
<td>0.40</td>
</tr>
<tr>
<td>High (State)</td>
<td>2.91</td>
<td>3.34</td>
<td>0.43</td>
</tr>
<tr>
<td>Low (State)</td>
<td>2.66</td>
<td>3.20</td>
<td>0.54</td>
</tr>
<tr>
<td>Difference across states</td>
<td>0.24</td>
<td>0.14</td>
<td>-0.11</td>
</tr>
</tbody>
</table>

Asparouhova, e.a. Lucas Experiments
Discount (of tree price) and price differential across states are positively correlated.
Discount (of tree price) and price differential across states are positively correlated

- Correlation is between the average (per replication) difference between bond and tree price, and the average (per replication) difference of prices (of a security) between high and low states.

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<tr>
<th>Correlation</th>
<th>Tree</th>
<th>Bond</th>
</tr>
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<tbody>
<tr>
<td>(St. Err.)</td>
<td>0.80</td>
<td>0.52</td>
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<tr>
<td></td>
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Prices move with fundamentals – but noisily
Prices move with fundamentals – but noisily

Asparouhova, e.a.  Lucas Experiments
Apparent trend is not significant once allowing for influence of state (change)
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Table 10: OLS regression of changes in period-average transaction prices. (* = significant at p = 0.05.)

<table>
<thead>
<tr>
<th>Explanatory Variables</th>
<th>Tree Price Change</th>
<th>Bond Price Change</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Estim. (95% Conf. Int.)</td>
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</tr>
<tr>
<td>Change in State Dummy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(None=0; High-to-Low=-1, Low-to-High=+1)</td>
<td>0.19* (0.08, 0.29)</td>
<td>0.10 (-0.03, 0.23)</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.18</td>
<td>0.04</td>
</tr>
<tr>
<td>Autocor. (s.e.=0.13)</td>
<td>0.18</td>
<td>-0.19</td>
</tr>
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Asparouhova, e.a. Lucas Experiments
Results in Returns
**Table 7: Average returns across securities and states (High or Low aggregate dividend).**

<table>
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<th>State</th>
<th>Tree</th>
<th>Bond</th>
<th>Equity</th>
<th>Premium</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>12.8 (%)</td>
<td>15.9</td>
<td>-3.1</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>17.8</td>
<td>16.1</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Difference</td>
<td>-5.0</td>
<td>-0.2</td>
<td>-4.8</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>16.1</td>
<td>16.0</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>
Significant smoothing and diversification across states – to extent that consumption shares are constant (mixed-effects two-factor ANOVA)
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<table>
<thead>
<tr>
<th>Type</th>
<th>States</th>
<th></th>
<th></th>
<th>Periods</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
<td>Low</td>
<td>Odd</td>
<td>Even</td>
<td></td>
</tr>
<tr>
<td>Type I</td>
<td>14.93 (19.75)</td>
<td>7.64 (4.69)</td>
<td>7.69 (2.41)</td>
<td>13.91 (20.65)</td>
<td></td>
</tr>
<tr>
<td>Type II</td>
<td>15.07 (10.25)</td>
<td>12.36 (15.31)</td>
<td>14.72 (20)</td>
<td>11.74 (5)</td>
<td></td>
</tr>
</tbody>
</table>

ANOVA $p$: Factors 0.09 0.27
Interaction 0.23

(Autarky cash holdings in parentheses)
A closer look at trading

Subjects did not hedge price risk (much) – they did not expect prices to move with fundamentals? (Significant correlation between prices and fundamentals cannot easily be detected in 10-15 rounds)

If agents do not expect prices to move with fundamentals, the resulting equilibrium is VERY different from Lucas model!

... but very much like in our experiments (stochastic drift, etc.)

Asparouhova, e.a.

Lucas Experiments
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- ... but very much like in our experiments (stochastic drift, etc.)
Prices when agents do not expect prices to move with fundamentals
Prices when agents do not expect prices to move with fundamentals

(Consumption share of Type I agent fluctuates between 39 and 44%.)

Asparouhova, e.a. Lucas Experiments
Analysis of price expectations

Adam, Marcet and Nicolini (2012) also point out that even with only small mistakes in expectations about prices (assuming everyone knows underlying dividend processes!), equilibrium prices may look very different from the Lucas equilibrium—much more like in "the real world." But Adam, Marcet and Nicolini (2012) do not point out that equilibrium allocations could still be pretty much the same as in the Lucas equilibrium—and close to optimal!... because our agents trade consistent with their expectations, and their expectations are almost self-fulfilling?
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... because our agents trade consistent with their expectations, and their expectations are almost self-fulfilling?
Individual choices are all over...

Table 12: End-Of-Period Asset Holdings Of Three Type I Subjects. Initial allocations: 10 Trees, 0 Bonds. Data from one replication in the first Caltech session.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Trees</th>
<th>Bonds</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>34</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>71</td>
<td>23</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>4</td>
</tr>
</tbody>
</table>

5 The Expected and the Anomalous

With respect to the predictions of the Lucas model, our experiments generate findings that are expected – smoothing of individual consumption across states and time, correlation of individual consumption with aggregate consumption, even to the extent that consumption shares are independent of state and period – and findings that seem anomalous – excessive volatility of prices and absence of price hedging by subjects.

Co-existence of excessive volatility with the absence of price hedging might be surprising: it would seem that excessive volatility would signal especially clearly to subjects that they ought to hedge against price risk. However, this need not be so; the particular kind of excessive volatility that we see in the experimental data might well lead subjects to conclude that there is no need to hedge against price risk.

To see why this might be so, recall first that the predictions of the Lucas model and indeed the very definition of Radner equilibrium depend on the assumption that agents have perfect foresight and in particular that the beliefs of subjects about the dividend process and the price process are exactly correct. Because these processes...
Individual choices are all over...

Table 12: End-Of-Period Asset Holdings Of Three Type I Subjects. Initial allocations: 10 Trees, 0 Bonds. Data from one replication in the first Caltech session.

<table>
<thead>
<tr>
<th>Subject</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trees:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>10</td>
<td>13</td>
<td>15</td>
<td>19</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bonds:</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>15</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>4</td>
</tr>
</tbody>
</table>

(So, individuals are not “representative” of what happens at the market level!)
<table>
<thead>
<tr>
<th>GMM Tests...</th>
</tr>
</thead>
</table>

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GMM Tests...

- using *returns* and aggregate consumption data (only!)
GMM Tests…

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- using traditional instruments
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- assuming power utility (wlog because we only have two states each period)
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We should:
GMM Tests...

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We should:

- reject (prices too volatile; discount on tree is countercyclical)
GMM Tests...

- using *returns* and aggregate consumption data (only!)
- using traditional instruments
- assuming power utility (wlog because we only have two states each period)

We should:

- reject (prices too volatile; discount on tree is countercyclical)
- find significant risk aversion
Results Sensitive To Instruments!

<table>
<thead>
<tr>
<th>Instruments</th>
<th>$2$ test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(p value for)</td>
</tr>
<tr>
<td>constant, $1$</td>
<td>0.86</td>
</tr>
<tr>
<td>lagged consumption growth</td>
<td>(0.003)</td>
</tr>
<tr>
<td>constant, $1$</td>
<td>0.86</td>
</tr>
<tr>
<td>lagged consumption growth</td>
<td>(0.029)</td>
</tr>
<tr>
<td>high state dummy, $1$</td>
<td>0.86</td>
</tr>
<tr>
<td>low state dummy, $1$</td>
<td>(0.002)</td>
</tr>
</tbody>
</table>

The GMM test of over-identifying restrictions is suspect, though. Two instruments, the lagged return on the Tree and Bond, are actually “weak” instruments, in the sense that they are uncorrelated, even independent, over time, both with themselves and with consumption growth. (Details can be obtained from the authors upon request.) As such, the corresponding moment conditions reduce to those with a constant as instrument. That is, these moment conditions do not provide additional restrictions beyond the ones imposed by the moment conditions constructed with the constant as instrument. Effectively, the number of degrees of freedom in the $2$ test is not $6$, but only $2$.

To determine the impact of these weak instruments, we ran a second test, re-estimating the model with only the constant and lagged consumption as instruments. The second panel of Table 15 displays the results. As expected, the estimation results hardly change. The test of over-identifying restrictions still fails to reject, however. Consequently, the effect of the weak instruments is nil; they could as well be deleted, but adding them does not change the conclusions.

The GMM test with traditional instruments does not exploit all restrictions of the model. In particular, expected returns are predicted to be different across states (high/low Tree dividend; see Table 2), but consumption growth can only capture the change in the state, and not the value of the state. In historical data from the field,
Results Sensitive To Instruments!

Table 15: GMM Estimation And Testing Results For Three Different Sets Of Instruments.

<table>
<thead>
<tr>
<th>Instruments</th>
<th>$\beta$</th>
<th>$\gamma$</th>
<th>$\chi^2$ test</th>
</tr>
</thead>
<tbody>
<tr>
<td>constant 1, lagged consumption growth,</td>
<td>0.86</td>
<td>-0.01</td>
<td>7.124</td>
</tr>
<tr>
<td>lagged asset returns</td>
<td>(0.003)</td>
<td>(0.917)</td>
<td>(0.310)</td>
</tr>
<tr>
<td>constant 1, lagged consumption growth</td>
<td>0.86</td>
<td>-0.18</td>
<td>0.731</td>
</tr>
<tr>
<td>low state dummy, lagged consumption growth</td>
<td>(0.029)</td>
<td>(0.162)</td>
<td>(0.694)</td>
</tr>
<tr>
<td>high state dummy, lagged consumption growth</td>
<td>0.86</td>
<td>0.16</td>
<td>14.349</td>
</tr>
<tr>
<td>low state dummy, lagged consumption growth</td>
<td>(0.002)</td>
<td>(0.001)</td>
<td>(0.006)</td>
</tr>
</tbody>
</table>
Conclusions

The cross-sectional pricing implications of the Lucas model are born out in the experimental data. The intertemporal variation (predictability) in asset prices is far less than predicted (given cross-sectional differences). Prices exhibit excessive volatility. Subjects seem to have anticipated this and therefore reduce their demands to hedge against price risk; still, these anticipations are inconsistent in equilibrium (prices will – and do – depend on tree dividends even if this is not anticipated...).

Nevertheless, the risk sharing properties of the Lucas equilibrium emerge: allocations are OK even if prices are excessively volatile.
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The Future

What happens in the "long run"? (Incentive problems!)

Security design (to facilitate learning of future prices)

Introducing redundant securities such as options

Replacing consol bond with shorter-maturity options

(optimal maturity of fixed-income securities?)

The role of emotions

To what extent are emotions part of the neoclassical math? (Prediction errors.) To what extent do they explain the variance of price changes not captured by the neoclassical model (> 80%)?

Contagion?

Introducing money...

Introduce "rational bubbles"
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