A Dynamic General Equilibrium Approach to Asset Pricing Experiments

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Abstract

We use laboratory experiments to test a consumption-based general equilibrium model of asset pricing, which posits that agents buy and sell assets for the purpose of intertemporally smoothing consumption. Such asset pricing models are widely used by macroeconomists and finance researchers but have not yet been subjected to experimental testing. In the experiments we induced several features which, according to the theory, determine asset prices, such as risk and time preferences and the process for income and dividend payments. Our analysis indicates that intertemporal consumption-smoothing strongly inhibits the formation and magnitude of asset price bubbles, a stark departure from most recent asset pricing experiments. In fact, when subjects are motivated to smooth consumption, assets trade at a discount relative to their expected value and markets are thick; when this condition is eliminated in an otherwise identical economy, assets trade at a premium in thin markets.

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1 Introduction

The consumption-based general equilibrium approach to asset pricing, as pioneered in the work of Stiglitz (1970), Lucas (1978) and Breeden (1979), is a workhorse model in the literature on financial asset pricing in macroeconomics, or macrofinance. This approach relates asset prices to individual risk and time preferences, dividends, aggregate disturbances and other fundamental determinants of an asset’s value. While this class of theoretical models has been extensively tested using archival field data, the evidence to date has not been too supportive of the models’ predictions. For instance, estimated or calibrated versions of the standard model generally under-predict the actual premium in the return to equities relative to bonds, the so-called “equity premium puzzle” (Hansen and Singleton (1983), Mehra and Prescott (1985), Kocherlakota (1996)), and the actual volatility of asset prices is typically much greater than the model’s predicted volatility based on changes in fundamentals alone – the “excess volatility puzzle” (Shiller (1981), LeRoy and Porter (1981)).

A difficulty with testing the model using field data is that important parameters like individual risk and time preferences, the dividend process, endowments, and other determinants of asset prices are unknown and have to be calibrated, approximated or estimated in some fashion. An additional difficulty is that the available field data, for example data on aggregate consumption, are measured with error (Wheatley (1988)) or may not approximate well the consumption of asset market participants (Mankiw and Zeldes (1991)). A typical approach is to specify some dividend process and calibrate preferences using micro-level studies that may not be directly relevant to the domain or frequency of data examined by the macrofinance researcher.

Choosing a different path, we designed a laboratory experiment to test predictions of a consumption-based general equilibrium model of asset pricing. In the experiment we controlled income, dividends, and a common discount rate, we precisely measured individual consumption and asset holdings, and we were able to estimate each individual’s risk preferences separately from those implied by his market activity, providing us with a clearer picture of the environment in which agents made asset pricing decisions. We also reliably induced heterogeneity in agent types as a treatment variable to create a clear motivation for subjects to engage in trade, whereas the theoretical literature frequently presumes a representative agent and derives equilibrium asset prices at which the equilibrium volume of trade is zero. The degree of control we maintained in the experiment presents an opportunity to diagnosis the causes of specific deviations from theory which are not identifiable using field data alone.

There already exists a literature testing asset price formation in the laboratory, but the design of those experiments departs in significant ways from the macrofinance literature. The early experimental literature (e.g., Forsythe, Palfrey and Plott (1982), Plott and Sunder (1982) and Friedman, Harrison and Salmon (1984)) considered markets comprised of a known, finite number of 2-3 period cycles. Each subject was assigned a type that determined his endowment of cash and assets at the beginning of a cycle as well as his deterministic (but non-constant) dividend stream. Each period began with trade in the asset among subjects, and ended with the payment of type-dependent dividends for each unit of the asset held. The general finding from this literature is that market prices effectively aggregate private information about dividends and tend to converge toward rational expectations values. While such results are in line with the efficient markets view of asset pricing, the primary motivation for exchange was heterogeneity in the value of dividends rather than intertemporal consumption-smoothing as in the framework we study.

In later, highly influential work by Smith, Suchanek, and Williams (SSW) (1988), a simple four-state i.i.d. dividend process was made common for all subjects. A finite number of trading periods ensured that the fundamental value of the asset declined at a constant rate over time. There was no induced motive for subjects to engage in any trade at all. Nevertheless, SSW observed substantial trade in the asset, with prices

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1See, e.g., Campbell (2003) and Lengwiler (2004) for surveys
typically starting out below the fundamental value, then rapidly soaring above the fundamental value for a sustained duration of time before collapsing near the end of the experiment. The “bubble-crash” pattern of the SSW design has been replicated by many authors under a variety of different treatment conditions, and has become the primary focus of the large and growing experimental literature on asset price formation (key papers include Porter and Smith (1995), Lei et al. (2001), Dufwenberg, et al. (2005), Haruvy et al. (2007) and Hussam et al. (2008); for a review of the literature, see chapters 29 and 30 in Plott and Smith (2008)).

Despite many treatment variations (e.g., incorporating short sales or futures markets, computing expected values for subjects, implementing a constant dividend, inserting “insiders” with previous experience in bubbles experiments, using professional traders in place of students as subjects), the only reliable means to significantly reduce the bubble-crash pattern in the SSW environment has been to repeat the experiment several times with the same group of subjects.

We move in a direction more closely aligned with the theory and predictions of the macrofinance literature, and in doing so we hope to begin a dialogue between macrofinance researchers and experimentalists. Our design enables us to address a number of issues related to asset pricing and intertemporal decision-making while incorporating several important insights gained from the experimental asset pricing literature. One way we departed from the existing experimental literature is to induce “consumption” at the end of each period. In previous designs subjects were loaned a large quantity of experimental currency units (“francs”) at the beginning of a session which had to be repaid at the end, after which their remaining franc balances were converted to dollars at a linear exchange rate. This feature differs from the sequence of budget constraints faced by agents in standard intertemporal asset pricing models, and may promote high asset prices. In our design, subjects received an exogenous franc income at the beginning of each new period. Dividends were paid on assets held and then trade in the asset took place. End-of-period franc balances were converted to dollars and stored in the subjects’ payment accounts, so that at the end of each period all francs disappeared entirely from the system; assets were durable “trees” and francs were perishable “fruit” in the language of Lucas (1978).

In one of our treatments the franc-to-dollar exchange rate was concave, so that long-lived assets became a vehicle for intertemporally smoothing consumption. This feature is a critical component of most macrofinance models as well as in experimental studies of intertemporal consumption/savings decisions (e.g., Noussair and Matheny (2000), Lei and Noussair (2002), Ballinger et al. (2003) and Carbone and Hey (2004)), but it is absent from the experimental asset pricing literature referenced above. Our study thus provides an important bridge between these two literatures. In a second treatment the franc-to-dollar exchange rate was linear. Since our dividend process was common to all subjects, in this treatment there was no induced reason for subjects to trade in the asset, thus connecting a macrofinance economy with the laboratory asset bubble design of SSW. Through treatment variation we sought to enhance our understanding of whether and when asset price bubbles arise in a framework of interest to researchers in macroeconomics and finance.

A third feature of our design is that through induced time discounting we facilitated the stationarity associated with an infinite horizon, a common feature of consumption-based asset pricing models. By contrast, in the SSW design a finite horizon is implemented with no discounting and a constantly declining fundamental value of the asset. We induced discounting by introducing a constant probability that assets would become worthless at the end of each period. Thus from the decision-maker’s perspective, francs today

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2There is also a recent experimental literature testing capital-asset pricing models (CAPM), e.g., Bossaerts and Plott (2002), Asparouhova, Bossaerts, and Plott (2003), Bossaerts, Plott and Zame (2007). These markets differ substantially from the macrofinance models that motivate our study because they involve static repetition of a one-period economy.

3Lugovskyy, Puzzello, and Tucker (2010) implement the SSW framework using a tatonnement institution instead of the double auction and report a significant reduction of bubbles.

4Camerer and Weigelt (1993) used such a device to study asset price formation within the heterogeneous dividends framework
are worth more than identical francs tomorrow, not because the subject is impatient but because future earnings are less likely to be realized. One minus the continuation probability has a natural interpretation as firm bankruptcy risk (i.e., the firm issuing the asset goes bankrupt and the asset becomes worthless). If subjects are risk neutral our indefinite horizon economies feature the same steady state equilibrium price and shareholdings as their infinite horizon analogues. We also study the consequences of departures from risk neutrality. This analysis is both theoretical and empirical, as we elicit a measure of risk tolerance from subjects in most of our experimental sessions using the Holt-Laury (2002) paired lottery choice instrument. To our knowledge no prior study has seriously investigated risk preferences in combination with a multi-period asset pricing experiment. Our evidence on risk preferences, elicited from participants who have also determined asset prices in a dynamic general equilibrium setting, should be of interest to macrofinance researchers investigating the “puzzles” in the asset pricing literature; for example, the equity premium puzzle and the related risk-free rate puzzle depend on assumptions made about risk attitudes (see Campbell 2003).

Our experiment has yielded a number of interesting results. The presence of “bankruptcy risk” in the linear exchange rate environment (where, as in SSW, there is no motivation for asset trade) does not suffice to eliminate asset price “bubbles;” indeed, we often observe sustained deviations of prices above fundamentals in this environment. However, the frequency, magnitude, and duration of these bubbles are substantially mitigated when we induce a concave exchange rate (utility function); in fact, assets tend to trade at a discount relative to expected value in this environment. The higher prices in the linear economies appear to be driven by a concentration of shares among the most risk-tolerant subjects in the market. In contrast, under the concave exchange rate most subjects actively trade shares in each period to smooth their consumption in the manner predicted by theory, so shares were less concentrated. Thus market thin-ness and high prices appear to be endogenous features of speculative markets in our design. We conclude that the frequency, magnitude, and duration of asset price bubbles can be greatly reduced by the presence of an incentive to intertemporally smooth consumption in an otherwise identical economy.

2 A simple asset pricing framework

We adopt a heterogeneous agent asset pricing framework based on Lucas’s (1978) one-tree model. In line with the theory, we assume subjects in the experiment are risk-neutral expected utility maximizers so that the infinite horizon model we present here shares a (unique) steady-state equilibrium with the stochastic horizon economy we actually implement in the lab. In Section 5 we relax this assumption and consider how the model is impacted by departures from risk neutrality.

We consider an economy where time, $t$, is discrete and there are two agent types, $i = 1, 2$, who participate in an infinite sequence of markets. There is a fixed supply of the infinitely durable asset (trees), each unit of which yields some stochastic dividend $d_t$ (fruit) each period. Dividends are paid in units of the single non-storable consumption good at the beginning of each period. Let $s^i_t$ denote the number of asset shares agent $i$ owns at the beginning of period $t$, and let $p_t$ be the price of the asset in period $t$. In addition to dividend payments, agent $i$ receives an exogenous endowment of the consumption good $g^i_t$ at the beginning of every period; his initial endowment of shares is denoted $s^i_1$.

Agent $i$ seeks to maximize:

$$\max_{\{c^i_t\}_{t=1}} E_1 \sum_{t=1}^{\infty} \beta^{t-1} u^i(c^i_t),$$

subject to

$$c^i_t \leq g^i_t + d_t s^i_t - p_t (s^i_{t+1} - s^i_t)$$

referred earlier. Their main finding is that asset prices converge slowly and unreliably to predicted levels from below.
and a transversality condition. Here, $c_i^t$ denotes consumption of the single perishable good by agent $i$ in $t$, $u'(\cdot)$ is a strictly monotonic, strictly concave, twice differentiable utility function, and $\beta \in (0,1)$ is the (common) discount factor. The budget constraint is satisfied with equality by monotonicity. We will impose no borrowing and no short sale constraints on subjects in the experiment, but the economy will be parameterized in such a way that these restrictions only bind out-of-equilibrium. Substituting the budget constraint for consumption in the objective function, and using asset shares as the control, we can restate the problem as:

$$\max_{(s_{i+1}^t)_{i=1}^{\infty}} \sum_{t=1}^{\infty} \beta^{t-1}u'(y_i^t + d_is_i^t - p_t(s_{i+1}^t - s_i^t)).$$

The first order condition for each time $t \geq 1$, suppressing agent superscripts for notational convenience, is:

$$u'(c_t)p_t = E_t u'(c_{t+1})(p_{t+1} + d_{t+1}).$$

Rearranging we have the asset pricing equation:

$$p_t = E_t \mu_{t+1}(p_{t+1} + d_{t+1})$$

where $\mu_{t+1} = \beta \frac{u'(c_{t+1})}{u'(c_t)}$, a term that is referred to variously as the stochastic discount factor, the pricing kernel, or the intertemporal marginal rate of substitution. If we assume, for example, that $u(c) = \frac{c^{\gamma}}{1-\gamma}$ (the commonly studied CRRA utility), we have $\mu_{t+1} = \beta \left(\frac{c_{t+1}}{c_t}\right)^\gamma$. Notice from equation (1) that the price of the asset depends on 1) individual risk parameters such as $\gamma$; 2) the rate of time preference $r$, which is implied by the discount factor $\beta = 1/(1+r)$; 3) the income process; and 4) the dividend process, which is assumed to be known and common to both agents.

In our experiments units of the consumption good are referred to as “francs”, which also serve as the numeraire for endowment income, asset prices and dividends. Shares of the asset are simply referred to as “assets”. The utility function $u'(c)$ serves as a map from subject $i$’s end-of-period franc balance (consumption) to U.S. dollars. Dollars accumulate across periods and are paid in cash at the end of the experiment. After the francs for a given period are converted to dollars they disappear from the system, as the consumption good is not storable. In all sessions of the experiment we restrict the aggregate endowment of francs and assets to be constant across periods.£ We also set the dividend equal to a constant value, that is, $d_t = \bar{d}$ for all $t$, so that a constant steady state equilibrium price exists.© Under the constant dividend assumption, applying some algebra to equation (1) yields:

$$p^* = \frac{\bar{d}}{E_t \frac{u'(c_t)}{\beta u'(c_{t+1})} - 1}.$$  

This equation applies to each agent, so if one agent expects consumption growth or decay they all must do so in equilibrium. Since the aggregate endowment is constant, strict monotonicity of preferences implies that there can be no growth or decay in consumption for all individuals in equilibrium. Thus it must be the case that in a steady state competitive equilibrium each agent perfectly smoothes his consumption, that is, $c_i^t = c^t_{i+1}$, so equation (2) simplifies to the standard fundamental price equation:

$$p^* = \frac{\beta}{1-\beta} \bar{d}.$$  

£The absence of income growth rules out the possibility of “rational bubbles”.

©If the dividend is stochastic, it is straightforward to show that a steady state equilibrium price does not exist. Instead, the price will depend (at a minimum) upon the current realization of the dividend. See Mehra and Prescott (1985) for a derivation of equilibrium pricing in the representative agent version of this model with a finite-state Markovian dividend process. We adopt the simpler, constant dividend framework since our primary motivation was to induce an economic incentive for exchange in a standard macrofinance setting. Porter and Smith (1995) show that implementing constant dividends in the SSW design does not substantially reduce the incidence or magnitude of price bubbles.
3 Experimental design

We conducted sixteen laboratory sessions of a 6-fold replica of the economy introduced above. Thus in each session there were twelve subjects, six of each induced type, for a total of 192 subjects. The endowments of the two subject types and their utility functions are given in the table below.

<table>
<thead>
<tr>
<th>Type</th>
<th>No. Subjects</th>
<th>$s_i$</th>
<th>${y^i_t}$</th>
<th>$u^i(c)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>1</td>
<td>110 if $t$ is odd, 44 if $t$ is even</td>
<td>$\delta^1 + \alpha^1 c^\phi^1$</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>4</td>
<td>24 if $t$ is odd, 90 if $t$ is even</td>
<td>$\delta^2 + \alpha^2 c^\phi^2$</td>
</tr>
</tbody>
</table>

Thus for each period $t$ in each session, the franc endowment $y^i_t$ for each type $i = 1, 2$ followed a known deterministic two-cycle. Subjects were informed that the aggregate endowment of income and shares shares would remain constant throughout the session, but otherwise were only privy to information regarding their own income process, shareholdings, and induced utility functions. Utility parameters in all treatments were chosen so that, in equilibrium, each subject would earn $1 per period. The utility function was presented to each subject as a table converting his end–of–period franc balance into dollars (this schedule was also represented graphically). By inducing agents to hold certain utility functions, we were able to exert some degree of control over individual preferences and provide a rationale for trade in the asset.

We adopt a $2 \times 2$ experimental design where the treatment variables are the induced utility functions (concave or linear) and the asset dividend ($\bar{d} = 2$ or $\bar{d} = 3$). In our baseline, concave treatments we set $\phi^i < 1$ and $\alpha^i \phi^i > 0$. Given our two-cycle income process, it is straightforward to show that steady state shareholdings must also follow a two-cycle between the initial share endowment, $s^i_{odd} = s^i_1$, and

$$s^i_{even} = s^i_{odd} + \frac{y^i_{odd} - y^i_{even}}{\bar{d} + 2p}.$$  \hspace{1cm} (4)

Notice that in equilibrium subjects smooth consumption by buying asset shares during high income periods and selling asset shares during low income periods. In the treatment where $\bar{d} = 2$, the equilibrium price is $p^* = 10$. Thus in equilibrium a type 1 subject holds 1 share in odd periods and 4 shares in even periods, and a type 2 subject holds 4 shares in odd periods and 1 share in even periods. In the treatment where $\bar{d} = 3$, the equilibrium price is $p^* = 15$. In equilibrium, type 1 subjects cycle between 1 and 3 shares, while type 2 subjects cycle between 4 and 2 shares. In autarky (no asset trade), each subject earns $1 every two periods which is only one-half of equilibrium earnings, so the incentive to smooth consumption was reasonably strong.

Our primary variation on the baseline concave treatments was to set $\phi^i = 1$ for both agent types so that there was no longer an incentive to smooth consumption. In these linear treatments, $\alpha^1 = 0.0122$, $\alpha^2 = 0.0161$, and $\delta^1 = \delta^2 = 0$.

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7Specifically, $\phi^1 = -1.195$, $\alpha^1 = -311.34$, $\delta^1 = 2.6074$, $\phi^2 = -1.3888$, $\alpha^2 = -327.81$, and $\delta^2 = 2.0627$.

8In these linear treatments, $\alpha^1 = 0.0122$, $\alpha^2 = 0.0161$, and $\delta^1 = \delta^2 = 0$. 

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we can re-write $U = \sum_{t=1}^{\infty} \beta^{t-1} u(c_t)$ as

$$U = \sum_{t=1}^{\infty} \beta^{t-1} y_t + (d + \hat{p}) s_1 + \sum_{t=2}^{\infty} \beta^{t-2} [\beta d - (1 - \beta) \hat{p}] s_t.$$  \hfill (5)

Notice that the first two right-hand side terms in (5) are constant, because they consist entirely of exogenous, deterministic variables. If $\hat{p} = p^*$, the third right-hand term in (5) is equal to zero regardless of future shareholdings, $\{s_t\}_{t=2}^{\infty}$, so clearly this is an equilibrium price where the corresponding individual equilibrium shareholdings are restricted to sum to the aggregate endowment of shares in each period. If $\hat{p} > p^*$, the third right-hand term is negative, so each agent would like to hold zero shares, but this cannot be an equilibrium since excess demand would be negative. If $\hat{p} < p^*$, this same term is positive, so each agent would like to buy as many shares as his no borrowing constraint would allow in each period, thus resulting in positive excess demand. Thus $p^*$ is the unique steady state equilibrium price in the case of linear utility.

In all sessions of our experiment we imposed the following trading constraints on subjects:

$$y_t^i + d_t s_t^i - p_t(s_{t+1}^i - s_t^i) \geq 0,$$

$$s_t^i \geq 0,$$

where the first constraint is no borrowing, and the second is no short sales. These constraints do not impact the fundamental price in either treatment or steady-state equilibrium shareholdings in the concave treatment. They do restrict the set of equilibrium shareholdings in the linear treatment, which without these constraints must merely sum to the aggregate share endowment. No borrowing or short sales are standard restrictions on out-of-equilibrium exchange in market experiments, particularly when establishing a baseline in a novel environment as we do in this paper.

3.1 Inducing time discounting (or bankruptcy risk)

An important methodological issue is how to induce time discounting and the stationarity associated with an infinite horizon. We follow Camerer and Weigelt (1993) and address this issue by converting the infinite horizon economy to one with a stochastic number of trading periods. Subjects participate in a number of “sequences,” with each sequence consisting of a number of trading periods. Each trading period lasts for three minutes during which time units of the asset can be bought and sold by all subjects in a centralized marketplace (more on this below). At the end of each period subjects take turns rolling a six-sided die. If the die roll results in a number between 1 and 5 inclusive, the current sequence continues with another three minute trading period. Each individual’s asset position at the end of period $t$ is carried over to the start of period $t+1$, and the common, fixed dividend amount $d$ is paid on each unit carried over. If the die roll comes up 6, the sequence of trading periods is declared over and all subjects’ assets are declared worthless. Thus, the probability that assets continue to have value in future trading periods is $5/6 (.833)$, which is our means to implement time discounting, i.e., $\beta = 5/6$. We demonstrate in section 5 that this indefinite horizon economy has the same steady state price and equilibrium shareholdings as the infinite horizon economy, provided subjects are risk neutral. We also consider the consequences for prices and allocations when subjects deviate from risk neutrality.

The fact that the asset may become worthless at the conclusion of any period has a natural interpretation as bankruptcy risk, where the (exogenous) dividend-issuing firm becomes completely worthless with constant probability. This type of risk is not present in any existing experimental asset pricing models aside from Camerer and Weigelt’s (1993) study. For instance, in SSW the main risk that agents face is price risk – uncertainty about the future price of assets – as it is known that assets are perfectly durable and will continue
to pay a stochastic dividend (with known support) for $T$ periods, after which time all assets will cease to have value. However, participants in naturally occurring financial markets face both price risk and bankruptcy risk, as recent events have made quite clear (these two risks are related, obviously, when bankruptcy is a possibility). It is therefore of interest to examine asset pricing in environments where both types of risk are present; for instance, it is possible that bankruptcy risk might interact with indigenous subject risk aversion to inhibit the formation of asset price bubbles.

To give subjects experience with the possibility that their assets might become worthless, our experimental sessions were set up so that there would likely be several sequences of trading periods. We recruited subjects for a three hour block of time. We informed them they would participate in one or more “sequences,” each consisting of an indefinite number of “trading periods” for at least one hour after the instructions had been read and all questions answered. Following one hour of play (during which time one or more sequences were typically completed), subjects were instructed that the sequence they were currently playing would be the last one played, i.e., the next time a 6 was rolled the session would come to a close. This design ensured that we would get a reasonable number of trading periods, while at the same time limited the possibility that the session would not finish within the 3-hour time-frame for which subjects had been recruited. Indeed, we never failed to complete the final sequence within three hours. The expected mean (median) number of trading periods per sequence in our design is 6 (4), respectively. The realized mean (median) were 5.3 (4) in our sessions. On average there were 3.3 sequences per session.

D.2.2 The trading mechanism

Another methodological issue is how to implement asset trading. Equilibrium models simply combine first-order conditions for portfolio choices with market clearing conditions to obtain equilibrium prices, but do not specify the actual mechanism by which prices are determined and assets are exchanged. Here we adopt the double auction mechanism as it is well known to reliably converge to competitive equilibrium outcomes in a wide range of experimental markets. We use the double auction module found in Fischbacher’s (2007) z-Tree software. Specifically, prior to the start of each three minute trading period $t$, each subject $i$ was informed of his initial asset position, $s_i^t$, and the number of francs he would have available for trade in the current period, equal to $y_i^t + s_i^t \bar{d}$. The dividend, $\bar{d}$, paid per unit of the asset held at the start of each period was made common knowledge to subjects (via the experimental instructions), as was the discount factor $\beta$. After all subjects clicked a button indicating they understood their beginning-of-period asset and franc positions, the first three minute trading period was begun. Subjects could post buy or sell orders for one unit of the asset at a time, though they were instructed that they could sell as many assets as they had available, or buy as many assets as they wished so long as they had sufficient francs available. During a trading period, standard double auction improvement rules were in effect: buy offers had to improve on (exceed) existing buy offers and sell offers had to improve on (undercut) existing sell offers before they were allowed to appear in the order book visible to all subjects. Subjects could also agree to buy or sell at a currently posted price at any time by clicking a button. In that case, a transaction was declared and the transaction price was shown to all participants. The agreed upon transaction price in francs was paid from the buyer to the seller and one unit of the asset was transferred from the seller to the buyer. The order book was cleared, but

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9There is also some dividend risk but it is relatively small given the number of draws relative to states.

10In the event that we did not complete the final sequence by the three hour limit, we instructed subjects at the beginning of the experiment that we would bring all of them back to the laboratory as quickly as possible to complete the final sequence. Subjects would be paid for all sequences that had ended in the current session, but would be paid for the continuation sequence only when it had been completed. Their financial stake in that final sequence would be derived from at least 25 periods of play, which makes such an event very unlikely (about %1) but quite a compelling motivator to get subjects back to the lab.
subjects could (and did) immediately begin reposting buy and sell orders. A history of all transaction prices in the trading period was always present on all subjects’ screens, which also provided information on asset trade volume. In addition to this information, each subject’s franc and asset balances were adjusted in real time in response to any transactions.

3.2 Subjects, payments and timing

Subjects were primarily undergraduates from the University of Pittsburgh. No subject participated in more than one session. At the beginning of each session, the 12 subjects were randomly assigned a role as either a type 1 or type 2 agent, so that there were 6 subjects of each type. Subjects remained in the same role for the duration of the session. They were seated at visually isolated computer workstations and were given written instructions that were also read aloud prior to the start of play in an effort to make the instructions public knowledge. As part of the instructions, each subject was required to complete two quizzes to test comprehension of his induced utility function, the asset market trading rules and other features of the environment; the session did not proceed until all subjects had answered these quiz questions correctly. Copies of the instructions and quizzes are available at http://www.pitt.edu/~jduffy/assetpricing. Subjects were recruited for a three hour session, but a typical session ended after two hours. Subjects earned their payoffs from every period of every sequence played in the session. Mean (median) payoffs were $22.45 ($21.84) per subject in the linear sessions and $18.26 ($18.68) in the concave sessions, including a $5 show-up payment but excluding the Holt-Laury elicitation payment. Payments were higher in the linear sessions because it was a zero-sum market (whereas social welfare was uniquely optimized in the steady-state equilibrium in the concave sessions).

At the end of each period \( t \), subject \( i \)'s end-of-period franc balance was declared his consumption level, \( c_i^t \), for that period; the dollar amount of this consumption holding, \( u'(c_i^t) \), accrued to his cumulative cash earnings (from all prior trading periods), which were paid at the completion of the session. The timing of events in our experimental design is summarized below:

<table>
<thead>
<tr>
<th>( t )</th>
<th>dividends paid: ( s_i^t \bar{d} + y_i^t )</th>
<th>3-minute trading period</th>
<th>consumption takes place</th>
<th>die role: ( t + 1 ) continue to ( t + 1 ) w.p. 5/6, else end</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3-minute trading period</td>
<td>using a double auction</td>
<td>to trade assets and francs</td>
<td>( c_i^t = s_i^t \bar{d} + y_i^t ) + ( \sum_{k=1}^{K_i^t} p_{t,k}^t (s_{t,k}^t - s_{t,k-1}^t) ) (if 0, continue to ( t + 1 ))</td>
</tr>
</tbody>
</table>

In this timeline, \( K_i^t \) is the number of transactions completed by \( i \) in period \( t \), \( p_{t,k}^t \) is the price governing the \( k \)th transaction for \( i \) in \( t \), and \( s_{t,k}^i \) is the number of shares held by \( i \) after his \( k \)th transaction in period \( t \). Thus \( s_{t,0}^i = s_i^t \) and \( s_{t,K_i^t}^i = s_{t+1}^i \). Of course, this summation does not exist if \( i \) did not transact in period \( t \); in this “autarkic” case, \( c_i^t = s_i^t \bar{d} + y_i^t \). In equilibrium, sale and purchase prices are predicted to be identical over time and across subjects, but under the double auction mechanism they can differ within and across periods and subjects.

Following completion of the last sequence of trading periods, beginning with Session 7 we asked subjects to participate in a further brief experiment involving the Holt-Laury (2002) paired lottery choice instrument. This is a commonly-used individual decision-making experiment that takes about 5-10 minutes to complete. It provides subjects with an additional monetary payment and provides us with a measure of each individual subject’s risk attitudes which we can use to better comprehend their behavior in the asset pricing/consumption smoothing task. This second part of the experiment was not announced in advance;
4 Experimental findings

We conducted sixteen experimental sessions. Each session involved twelve subjects with no prior experience in our experimental design (192 subjects total). The treatments used in these sessions are summarized in the table below.

<table>
<thead>
<tr>
<th>Session</th>
<th>$d$</th>
<th>$u(c)$</th>
<th>Holt-Laury test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>concave</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>concave</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>linear</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>linear</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
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<td>linear</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>concave</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>linear</td>
<td>Yes</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>concave</td>
<td>Yes</td>
</tr>
<tr>
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<td>concave</td>
<td>Yes</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
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</tr>
<tr>
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</tr>
<tr>
<td>12</td>
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</tr>
<tr>
<td>13</td>
<td>3</td>
<td>linear</td>
<td>Yes</td>
</tr>
<tr>
<td>14</td>
<td>3</td>
<td>concave</td>
<td>Yes</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td>concave</td>
<td>Yes</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>linear</td>
<td>Yes</td>
</tr>
</tbody>
</table>

A Holt-Laury (2002) test for risk tolerance was implemented after the market experiment in sessions 7-16, after it became apparent that indigenous risk preferences may have played a decisive role in the following results. We denote our four treatments as C2, C3, L2, and L3. We report on several findings of interest.

Finding 1 In the concave utility treatment ($\phi^i < 1$), observed transaction prices at the end of the session were generally less than or equal to $p^* = \frac{2}{1-\phi^i} \bar{d}$.

Figure 1 displays median prices by period for all sessions. The graphs on the top (bottom) row represent prices in the concave (linear) utility sessions, $\bar{d} = 2$ on the left and $\bar{d} = 3$ on the right. Solid dots represent the first period of a new indefinite trading sequence. To facilitate comparison across sessions, prices have been transformed to a percentage deviation from the predicted equilibrium price (e.g., a price of -40% in panel (a), where $\bar{d} = 2$, reflects a price of 6 in the experiment, whereas a price of -40% in panel (b), where $\bar{d} = 3$, reflects a price of 9 in the experiment).

Of the eight concave utility sessions depicted in panels (a) and (b), half end relatively close to the asset’s fundamental price (7%, 0%, 0%, -13%) while the others finish far below it (-30%, -40%, -47%, -60%). In two sessions (8 and 9) there were sustained departures above the fundamental price, but in both cases the “bubbles” were self-correcting. It is important to emphasize that these corrections were wholly endogenous rather than forced by a known finite horizon as in SSW.

Finding 2 In the linear induced utility sessions ($\phi^i = 1$) trade in the asset did occur, at volumes similar to the concave sessions. Observed transaction prices were significantly higher in the linear sessions.
On average there were 24 shares traded per period in both linear and concave sessions. Prices were much higher in the linear sessions, particularly by the end of the sessions. Focusing on the median price in the final period of each session, if we pool across dividend treatments the average of these prices in the linear sessions was 14.88 vs. 9.50 in the concave sessions. A (two-tailed) Mann-Whitney rank sum test of the null hypothesis that the two sets of prices come from the same distribution is rejected at the 0.0169 level.

Of course it is more appropriate to treat prices from the $d = 2$ sessions differently from $d = 3$ sessions, so we next consider prices as percentage deviations from the fundamental price as in Figure 1. On average the linear sessions were 27% above the fundamental price in the final period of the session, while the concave sessions were 18% below it. Thus the difference is still quite large, but no longer significant at the 5% level (p-value is 0.1412).

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11 We focus on transaction prices in the final period for two reasons. First, in a relatively complicated market experiment like this one there is the potential for significant learning over time. Thus prices in the final period reflect the actions of subjects most experienced with the trading institution, realizations of the continuation probability, and the behavior of other subjects. Second, during the latter half of the experiment prices in the linear sessions were either trending upward or flat, while prices in the concave sessions were trending downward or flat, so the price difference between concave and linear sessions would have likely been even greater had our experiment lasted longer. Thus final prices best reflect learning and long-term trends in these markets. If we instead take the average of the median transaction price per period during the second half of each session, the mean price across linear sessions is 21% above the fundamental price, while it is 18% below in the concave sessions. Thus the difference is still quite large, but no longer significant at the 5% level (p-value is 0.1412).
sessions were 23% below the fundamental price. This difference is significant at the 0.0350 level. Breaking down these equilibrium-normalized prices by the four treatments, the mean final period price is 65% in L2 vs. -18% in C2, and -12% in L3 vs. -28% in C3. The difference between C2 and L2 is significant (p-value = 0.0209), the difference between C3 and L3 is not (p-value = 0.5637).

There is a significant treatment effect of dividend size on deviations from equilibrium in the linear sessions (p-value = 0.0433) but not in the concave sessions (p-value = 0.5637). We offer a hypothesis and supporting evidence for this difference between the linear treatments. First, we note that the mean within-session price change was actually 1.5 times greater in L3 than L2 (4.5 vs. 3 francs), so the difference in final equilibrium-normalized prices between L2 and L3 stems from a substantial difference in initial prices. The mean of median first period prices in L2 was 13.5 francs vs. 8.75 francs in L3; by way of comparison, the mean of median first period prices in the concave treatments were similar (10.38 in C2 and 9.25 in C3). In the description of Finding 5 we detail our implementation of a Holt-Laury paired choice lottery following each market experiment, beginning with Session 7. For now, we note that each subject had the option to choose a high-variance or low-variance lottery at ten decision nodes, and we define a subject’s Holt-Laury score as his number of high-variance choices; the higher the Holt-Laury score, the more risk-tolerant the subject. In Finding 5, we report that a subject’s Holt-Laury score had a significant and substantial positive influence on the number of shares he acquired in the linear (but not in the concave) sessions.

Figure 2 displays the mean Holt-Laury score in a session against its median initial price (note that we only have Holt-Laury scores from ten sessions). There is a strong positive relationship between the two; sessions with greater average risk tolerance among its subjects tend to initiate much higher prices. Running a simple linear regression on the pooled data, the estimated coefficient on the Holt-Laury variable is 4.19 with an associated p-value of 0.002 and $R^2$ of 0.73; the fitted line has been plotted in the figure. It also appears to be the case that more asymmetric distributions of risk tolerance between types account for most deviations from the fitted line; including the squared difference between a session’s mean HL score and the mean HL score of its type 2 subjects brings the $R^2$ of the above regression up to 0.97 (the full regression result is reported in Table 1 of the Appendix). Thus it appears to be the case that the difference in prices between L2 and L3 is due entirely to the difference in the distribution of risk preferences in these sessions (it remains a puzzle why L3 prices do not initiate higher than L2 prices after controlling for risk). We believe this result supports our decision to pool equilibrium-normalized prices within the linear and concave
treatments and report a significant difference in median final prices between the linear and concave sessions.

**Finding 3** *In the concave utility treatment, there is strong evidence that subjects used the asset to intertemporally smooth their consumption.*

Figure 3 shows the per capita shareholdings of type 1 subjects by period (the per capita shareholdings of type 2 subjects is 5 minus this number). Dashed vertical lines denote the first period of a sequence, dashed horizontal lines mark equilibrium shareholdings (the bottom line in odd periods of a sequence, the top line in even periods). Recall that equilibrium shareholdings follow a perfect two-cycle, increasing in high income periods and decreasing in low income periods. As Figure 3 indicates, a two-cycle pattern (at least in sign) is precisely what occurred in each and every period on a per capita basis. The two sessions with the most pronounced deviations from predicted per capita trades, sessions 8 and 9, were the sessions that produced sustained deviations above the fundamental price.

The average trade by type 1 subjects across concave sessions is to buy 1.63 shares in odd periods and sell 1.71 shares in even periods. In contrast, in the linear sessions type 1 subjects buy 0.28 shares in odd periods and sell 0.23 shares in even periods on average. So while there is a small degree of consumption-smoothing taking place in the linear sessions (on a per capita basis, subjects sell shares in low income periods and buy shares in high income periods in 6 of 8 sessions), it is clear that induced concavity is driving the consumption-smoothing apparent in Figure 3 rather than cyclic income alone.

We can also confirm a strong degree of consumption-smoothing at the individual level. Consider the proportion of periods a subject smooths consumption; that is, the proportion of periods that a type 1 (2) subject buys (sells) shares if the period is odd, and sells (buys) shares if the period is even. Figure 4 displays the cumulative distribution across subjects of this proportion, pooled by whether the session had linear or concave induced utility functions. Half of the subjects in the concave sessions smoothed consumption in at least 80% of the periods, compared to only 2% of the subjects in the linear sessions who smoothed consumption so frequently. Nearly 90% of the subjects in the concave sessions smoothed consumption in at least half of the periods, vs. 30% of the subjects in the linear sessions. It may be useful to note that because three-quarters of the subjects in the linear sessions smoothed consumption less than 50% of the time does not imply the presence of anti-smoothing behavior; many of these subjects did not actively trade shares in many periods. It is clear from the figure that subjects in the concave sessions were actively trading in most periods, and had a strong tendency to smooth their consumption.

To date, the limited experimental evidence on whether subjects can engage in consumption-smoothing has not been encouraging (see, e.g., Noussair and Matheny (2000)); we appear to have developed a design where consumption-smoothing comes rather naturally to most subjects.

**Finding 4** *In the linear utility treatment, the asset was hoarded by just a few subjects.*

In the linear treatment subjects have no induced motivation to smooth consumption and thus no induced reason to trade at $p^*$ under the assumption of risk neutrality. However, we observe substantial trade in these sessions, with roughly half of the subjects selling nearly all of their shares, and a small number of subjects accumulating most of the shares. Figure 5 displays the cumulative distribution of mean individual shareholdings during the final two periods of the final sequence of each session, aggregated by linear vs. concave. We average across the final two periods due to the consumption-smoothing identified in Finding

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12 Since each subject begins period $t$ with $s_i^t$ and finishes the period with $s_i^{t+1}$, all vertical lines but the first also correspond to shares that were bought in the final period of the previous sequence but which expired without paying a dividend.

13 In these figures, the period numbers shown are aggregated over all sequences played. The actual period number of each individual sequence starts with period 1, which is indicated by the dashed vertical lines.

14 We use the final sequence with a duration of at least two periods.
Figure 3: Shares in Concave Utility Sessions
Figure 4: Individual Consumption-Smoothing

Figure 5: Distribution (by Treatment) of Mean Shareholdings During the Final Two Periods

3; use of final period data would bias upward the shareholdings of subjects in concave sessions. We consider the final two periods rather than averaging shares over the final sequence or over the entire session because it can take several periods within a sequence for a subject to achieve a targeted position due to the budget constraint. Forty-three percent of subjects in the linear sessions held an average of 0.5 shares or less during the final two periods, compared to just 9% of subjects who held so few shares in the concave sessions. At the
other extreme, 16% of subjects in the linear sessions held an average of at least 6 shares during the final two periods, while only 4% of subjects in the concave sessions held so many shares. Thus subjects in the linear sessions were five times more likely to hold ‘few’ (< 1) shares and four times more likely to hold ‘many’ (≥ 6) shares as subjects in the concave sessions, while subjects in the concave sessions were more than twice as likely to hold an intermediate quantity (87% vs. 41%).

A useful summary statistic for the distribution of shares is the Gini coefficient, a measure of inequality that equals zero when each subject holds an identical quantity of shares and equals one when a subject owns all shares. The mean Gini coefficient for mean shareholdings in the final two periods in the linear sessions is 0.63, compared to 0.37 in the concave sessions (Mann-Whitney p-value 0.0008). For benchmark purposes, the Gini coefficient in autarky is 0.3; the difference in the distribution of Gini coefficients between autarky and mean shareholdings during the final two periods in the concave sessions is marginally significant (p-value 0.0727). As mentioned above, this treatment difference in inequality increases during the session. We compute the mean shares per subject held during each session, omitting shares in the first period of each horizon with an odd number of periods to account for consumption-smoothing in the concave sessions. The mean Gini coefficient of this statistic is 0.37 in the linear sessions and 0.33 in the concave sessions, a difference which is not statistically significant (p-value 0.3998). So it appears to be the case that the tendency of some subjects to hoard shares of the asset is inhibited by induced consumption-smoothing, while the tendency for all subjects to hold some shares of the asset is enhanced by induced consumption-smoothing.

An interesting regularity is that exactly two subjects in each linear session held at least 6 shares of the asset on average during the final two periods. Thus the subjects identified in the right tail of the distribution in Figure 5 were divided evenly between the linear sessions. The proportion of shares held by the largest two shareholders during the final two periods averaged 61% across the linear sessions, compared to 38% in the concave sessions. Applying the Mann-Whitney rank sum test, the distribution of shares held by the largest two shareholders in the linear sessions is significantly different from this distribution in the concave sessions (p-value = 0.0135). To benchmark these statistics, in autarky the two largest shareholders would hold 27% of the shares in all sessions. If a C2 (C3) session adopted the risk-neutral steady state equilibrium, 17% (20%) of the shares would be held by the two largest shareholders on average during the final two periods.

**Finding 5** In the linear sessions there is a strong and significant positive relationship between a subject’s number of high-variance choices in the Holt-Laury paired choice lottery and his end-of-session shareholdings, but not in the concave sessions. In the concave sessions there is a significant negative relationship between a subject’s distance from risk-neutrality and the expected value of his net transactions, which does not hold during the linear sessions. Thus risk-neutral subject tend to make the most sound trading decisions in the concave sessions, but get “caught up” in the linear session bubbles.

After running the first six sessions of this experiment it seemed likely to us that the indigenous risk preferences of subjects were a substantial influence on asset prices and the distribution of shareholdings, particularly in the linear sessions. It is intuitive that over the course of a linear session sequence the price of an asset would be bid up by subjects with the highest risk tolerance, causing shareholdings to become concentrated among these subjects. Thus beginning with session 7 we ran a Holt-Laury paired choice lottery instrument after the market experiment. Subjects faced a series of ten choices between two lotteries. In session 7, the safe lottery A paid either $2 or $1.60, and the risky lottery B paid either $3.85 or $0.10. In all later sessions, we scaled up these payoffs by a factor of 3, so that the scale of the test was roughly equal to the expected value of an equilibrium sequence in the market experiment. For choice \( n \), the probability of getting the high payoff in the chosen lottery was \((0.1)n\). One of the choices was selected at random after all decisions were made, that lottery was played (with computer-generated probabilities), and the subject was
paid according to the outcome. A risk-neutral subject would choose high-variance lottery B six times. We refer to a subject’s HL score as the number of times he selected lottery B. The mean HL score in the final nine sessions was 3.9. Roughly 16% of the subjects had an HL score of at least 6, and 30% had a score of at least 5, a distribution reasonably consistent with the experimental literature for lotteries of this scale. The mean HL score in session 7 (which was not scaled by a factor of 3) was 5.0, so we elected to adjust each HL score in this session down by 1 to make it more comparable to scores in the other sessions (Holt-Laury and others report a significant impact of payoff scale on the distribution of risk preferences). The analysis which follows is robust to keeping the original scores in session 7.

For pooled linear and concave treatments, we ran a random effects regression of HL scores on average shareholdings during the final two periods of each session. This specification was necessary since the distribution of HL scores in each session was endogenous (e.g., a subject with HL score 6 might be the least risk-averse subject in one session but only the third least risk-averse in another). In the linear case, the estimated coefficient on the HL score was 0.46 and its associated p-value was 0.033 (the full regression results are presented in Table 2 of the Appendix). Thus the model predicts that for every two additional high-variance choices in the Holt-Laury experiment, the subject will hold nearly one additional share of the asset by the end of the period. This is a large impact, as there are only 2.5 shares per capita in these economies. On the other hand, in the concave case the estimated coefficient on the HL score is -0.10 with an associated p-value of 0.407 (full results reported in Table 3). The estimated coefficients and p-values in these regressions are nearly identical to those in the analogous fixed effects regressions. Thus only in the linear sessions is HL score a useful predictor of final shareholdings: The more risk-tolerant a subject relative to his session cohort, the more shares he tends to own by the end of the experiment.

To corroborate the result in the linear sessions, we consider the Holt-Laury rank of the two largest shareholders during the final two periods of the session. The rank of the subject with the highest HL score is 12, the rank of the subject with the second-highest HL score is 11, and so on. Ties are assigned the average position within the tie; e.g., if the second-highest score is 6 and it is shared by two subjects, each of them is assigned a rank of 10.5. The mean Holt-Laury rank of the two “hoarders” in each session (as described in Finding 4) is 8.3, and their median rank is 9.5. The probability that the average rank of two hoarders across five sessions is at least 8.3 if they are drawn at random from the Holt-Laury rank distribution is bounded from above by 0.047, which further confirms the strong relationship between shareholdings and the relative size of the HL score within-session.

Finally, we consider the relationship between HL score and the expected value of a subject’s net transactions. For subject \(i\) in period \(t\), let \(h_i^t\) be his net shares acquired and \(f_i^t\) be his net francs acquired. Recalling that \(p^*\) is the fundamental price, let \(v_i^t = f_i^t + h_i^t p^*\). Thus \(v\) is the net change in expected value of the subject’s asset and cash position during the trading period. Consider for the moment behavior in linear sessions. Ignoring positions held for speculative purposes across periods, a risk-neutral subject who does not lose money on within-period speculation will always take a positive expected value position; that is, if the price is below the fundamental price he’ll be a buyer, and if the price is above he’ll be a seller. We’ll consider non-risk-neutral behavior formally in the following section, but intuitively, for prices below the fundamental price, we expect risk-neutral and risk-seeking subjects to take positive expected value positions while risk-averse subjects may potentially take negative expected value positions depending on the price and their degree of risk-aversion. Similarly, for prices above the fundamental price, we expect risk-neutral and risk-averse subjects to take positive expected value positions while risk-seeking subjects may potentially take negative expected value positions. Thus during a session with exposure to a wide range of prices, we

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15 This computation assumes there are no ties in Holt-Laury rank, which of course is not possible with twelve subjects and only 10 possible HL scores. If one of the hoarders is tied with another subject in HL score it pulls his rank downward.
should expect a risk-neutral subject to take a higher expected value position relative to other subjects in his session, and the further from risk-neutrality a subject gets, the lower his expected value position.

For the concave sessions, because most subjects are consumption-smoothers we have to adjust for the fact that there are generally more odd periods than even periods. We do this by calculating $v$ separately for odd and even periods, taking the period average of each, adding the them together and dividing by two. This gives us the mean net addition to expected value for a subject in each period. We run a quadratic random effects regression of HL score on the mean net expected value function for the concave sessions (regression results reported in Table 4 in the Appendix). The coefficient on the HL score is 2.08 (p-value 0.012) and the coefficient on the squared HL term is -0.195 (p-value 0.029). Thus the fitted curve is concave in HL score as we would expect, and has a peak at a HL score of 5.3, which is nearly risk-neutral. Running this model for the linear sessions we get much smaller and highly insignificant coefficients (see Table 4).

Thus it appears to be the case that risk-neutral subjects take net positions of greater expected value than other subjects in the concave sessions. They also tend to earn more than other subjects, as is apparent in Figure 6 (the maximum of the fitted curve is for an HL score of 5.7; regression results reported in Table 6), so the net increases in expected value are not coming at the expense of consumption-smoothing. The farther a subject from risk-neutrality, the lower the expected value of his net positions. However, this result does not carry over to the linear sessions. In fact, earnings are decreasing in HL score in these sessions, although the difference is small. Risk-neutral subjects are among the most risk-tolerant subjects in their sessions, so naturally they tend to accumulate shares during the session. But they often get caught up in a bubble as they compete with other risk-tolerant subjects for shares of the asset. This circumstance seems somewhat analogous to overbidding on Ebay, where conventional wisdom suggests participants often overpay just to “win” the auction.

![Figure 6: Earnings in the Concave Sessions by Holt-Laury Score](image)
5 Indigenous (homegrown) risk preferences

It is not a simple task to even define optimal behavior for non-risk-neutral subjects in this experiment. Beyond the difficulty of structuring subjects’ expectations about future prices, it is not clear what is the best way to deal with wealth effects. As Rabin (2000) points out, the degree of risk-aversion exhibited by subjects over small stakes in laboratory settings cannot be rationalized by lifetime expected utility optimization because it would imply an implausibly high degree of risk-aversion in high stakes lotteries; most rational subjects should behave risk-neutrally in the lab. So if the subjects we have identified as risk-averse do not maximize expected utility over all decisions (both inside and outside the lab), should we nevertheless expect them to maximize expected utility over a sequence of decisions within the lab?\footnote{Benjamin, Brown, and Shapiro (2006) report that the degree of small stakes risk-aversion exhibited in the lab is negatively correlated with cognitive ability, further casting doubt on the likelihood that risk-averse subjects are dynamic expected utility optimizers.}

Our first goal is to describe how a rational risk-averse subject would behave. Let \( m_t = u(c_t) \) and \( M_t = \sum_{s=0}^{t} m_s \) be the sum of dollars a subject has earned through period \( t \) of the current sequence, given initial wealth \( m_0 \). At this point \( m_0 \) is quite general, and may be equal to zero or include some combination of the show-up fee, cumulative earnings within or across sequences, or even individual wealth. Superscripts indexing individual subjects are suppressed for notational convenience. Let \( v(x) \) be a subject’s indigenous utility over \( x \) dollars, and suppose this function is strictly concave, strictly monotonic, and twice differentiable. Then the subject’s expected value of participating through the current sequence is

\[
V = \sum_{t=1}^{\infty} \beta^{t-1} (1 - \beta) v(M_t).
\]  

Using \( s_t \) as the control, the first order conditions with respect to \( s_{t+1} \) for \( t \geq 1 \) can be written as

\[
u'(c_t) p_t \sum_{s=0}^{\infty} \beta^{s-t} E_t\{v'(M_s)\} = \sum_{s=0}^{\infty} \beta^{s-t+1} E_t\{v'(M_{s+1}) u'(c_{t+1}) (d + p_{t+1})\} \]

For simplicity, let us assume that subjects have myopic expectations with respect to future prices; in particular, each subject expects the price in all future periods to equal the current price with probability one. Thus supposing the price is expected to be constant and equal to \( p \), a subject’s first-order condition reduces to:

\[
p = \frac{d}{u'(c_t)} \frac{\frac{\gamma}{\gamma}}{\frac{1}{1 - \gamma}} - 1
\]

Notice the similarity of (8) to (2). This is not a coincidence; if indigenous risk preferences are linear, the indigenous marginal utility of wealth is constant, and applying a little algebra to (8) produces (2). This justifies our earlier claim that the infinite horizon economy and its stochastic horizon economy analogue share the same steady-state equilibrium provided that subjects are risk-neutral.

We begin with the case where induced utility is linear (that is, treatments L2 and L3), so \( u(c) = \alpha c \). Then by (8) prices can be constant only if \( v'(M_{t+1}) = k v'(M_t) \) for all \( t \), where \( k \in (0,1) \) is a constant rate of decay of marginal utility (this condition provides an interior solution, which must be unique by strict concavity). Thus (8) reduces to

\[
p = \frac{k \beta}{1 - k \beta} d.
\]

Suppose subjects have indigenous risk preferences of the CRRA class, i.e., \( v(m) = \frac{1}{1 - \gamma} m^{1 - \gamma} \), where \( \gamma \in (0,1) \). Then \( k = \left( \frac{m_t}{m_{t+1}} \right)^\gamma \). Substituting this expression into (9) and applying some algebra, we obtain the condition:

\[
m_{t+1} = gm_t,
\]

\[\]
where \( g = \left[ \frac{(\dd + \phi)}{p} \right]^{\frac{1}{\dd + \phi}} \) is the optimal growth rate of wealth during the sequence from period 2 forward. If \( p = p^* \) then \( g = 1 \), so consumption is zero after the first period at the interior solution. Since we assume subjects cannot borrow against future income, a risk-averse subject facing constant price \( p^* \) thus adopts the corner solution in which he sells all of his assets in the first period and simply consumes his income in subsequent periods (this is also true for \( p > p^* \), in which case \( g < 1 \)).

For \( p < p^* \) we have \( g > 1 \), so the subject prefers that his wealth grows over time at a constant rate. This growth rate is decreasing in the indigenous risk-aversion of the subject (\( \gamma \) and price. Thus, a more risk-averse subject facing higher prices prefers more of his earnings in the sequence up-front (and a less risk-averse subject facing lower prices prefers to invest more in future consumption). Wealth eventually explodes, as the curvature of the subject’s utility function becomes approximately linear at “high” levels of consumption; that is, he behaves like a risk-neutral subject once he’s accumulated sufficient wealth, and would prefer to go long on assets at the current price if he were allowed to borrow. Note that it is not possible for all subjects to behave as expected utility maximizers at a constant price, because aggregate income in the experiment is constant in each period. Eventually demand will outpace supply, causing prices to rise towards \( p^* \).

Now suppose induced preferences are concave rather than linear, that is, \( u(c) = \delta + \alpha c^\phi \). We have already determined that if the subject increases his wealth at a constant rate, then \( \frac{\sum_{t=0}^{\infty} g^t - c^\phi_t}{\sum_{t=0}^{\infty} g^t - c^\phi_t} = \frac{1 - k\beta}{k\beta} \), where \( k \in (0, 1) \) is the decay rate of marginal utility. Suppose initial wealth is zero (as explained below, this assumption gives dynamic optimization the best chance to fit the data). If wealth grows at a constant rate \( g > 1 \), then \( \frac{u'(c_t)}{u'(c_{t+1})} = g^{-\phi} \) for all \( t \). Therefore the expected marginal rate of substitution is constant, and since \( \phi < -1 \) it must be greater than 1. Thus increasing wealth at a constant rate also provides a solution to (8) in the case of concave induced preferences. However, since the marginal rate of substitution must be larger in the concave case (it is equal to one in the linear case), then for any \( p < p^* \), \( k \) must be larger in the concave case, as well. Thus a subject in a session with concave induced preferences who expects constant price \( p < p^* \) should attempt to increase his wealth at a constant rate, but less quickly than he would at the same price in a session with linear induced preferences.

Result 1 – Rational Indigenous Risk-aversion. An indigenously risk-averse subject who believes with certainty he faces a constant price \( p \geq p^* \) will immediately sell all asset shares and stay out of the market in all treatments. If this subject faces a constant price \( p < p^* \), he prefers for his wealth to grow at a constant rate. Thus there does not exist a steady-state equilibrium with risk-averse subjects and \( p < p^* \), because demand must eventually exceed supply. For a given price \( p < p^* \), the rate of wealth increase is larger under induced linear preferences than under induced concave preferences.

How quickly should wealth grow for a typically risk-averse subject at a commonly observed below-fundamental price? Consider a type 1 subject with indigenous CRRA preference parameter \( \gamma = 0.5 \) (this subject would have an HL score of 4 in our experiment, which was the mean number of high-variance choices). Suppose this subject naively believes prices will be a constant 10.5 forever (there were three linear sessions which remained below the fundamental price, all in L3, and in two of these sessions prices remained between 10 and 11 in most periods). If this subject has as little as $4.30 of accumulated earnings (recall his show-up fee alone is $5) and uses this number as his reference wealth level (that is, \( m_0 = 4.30 \)), he should use his entire endowment income to purchase shares. Thus there should have been enormous excess demand in the low-price L3 sessions and rapidly increasing prices.

So for risk-averse dynamic optimization to have any hope of explaining the data at all, risk-averse subjects must re-initialize wealth to zero at the beginning of each sequence. But even in this case, although a type 1 subject should sell his only share of the asset in the first period if \( p = 10.5 \), by the third period he should
be a buyer, and by the fifth period he should hold ten shares. At the relatively stable below-fundamental prices reported in the three low-price L3 sessions (one of these sessions had steadily increasing prices, but the rate of increase was 1 franc per three periods), if subjects were CRRA expected utility maximizers we should have observed a majority of them trying to purchase large quantities of shares, quickly pushing prices higher.

But what if risk-averse subjects ignore wealth effects entirely, even within a sequence? Suppose again the price is expected to remain a constant 10.5 with probability one, and consider the remainder of the sequence as a compound lottery. Then the expected value (in francs) of a \( d = 3 \) asset for a subject with \( \gamma = 0.5 \) is 10.41. Thus a subject with an average degree of small-stakes risk aversion who ignores wealth effects should be nearly indifferent to buying or selling shares at the most common prices observed in the low-price L3 sessions. Therefore myopic risk-aversion can rationalize the fact that most subjects sell off their shares at prices far below the fundamental price, even before factoring in consideration of price risk.

For the case of concave induced preferences, again we observe relatively stable below-fundamental prices in several sessions; subjects apparently do not attempt to accumulate wealth over time in these sessions, either (which would cause an increase in prices). An intuitive myopic strategy which can sustain stable low prices would be for subjects to equate the expected marginal cost of a trade to the expected marginal benefit. Thus a type 1 subject in the first period of a sequence would equate the marginal cost (in utils) of buying \( \Delta \) shares at price \( p \) in the current period with the expected marginal benefit of those shares in the subsequent period (these shares return a dividend plus the option value of re-sale). Assuming CRRA utility, the subject would choose \( \Delta \) such that:

\[
\delta + \alpha \left( y_2 + s_1 d + \Delta (d + p) \right) = \beta (d + p) \left( y_1 + s_1 d - \Delta p \right)
\]

The equation for a type 2 agent is similar, except this subject would set the marginal benefit of selling shares in the current period equal to the expected marginal cost in the subsequent period.

For a subject with \( \gamma = 0.5 \) facing a constant price of 10.5 in a C3 session, if he is type 1 then in the first period he would prefer to buy 2.83 shares, while if he is type 2 he would prefer to sell 2.69 shares. In the second period, if he is type 1 he would prefer to sell 2.67 shares, while if he is type 2 he would prefer to buy 2.81 shares. So there is a preference to accumulate shares under this myopic procedure as in dynamic optimization. However, because asset shares in our experiment can only be held in discrete quantities, each subject will prefer to cycle between buying and selling two shares throughout the sequence (if a subject is instead dynamically optimizing utility in the sequence, wealth effects dictate that his desired shareholdings will eventually explode, despite the fact that shares are discrete). In fact, myopic behavior varies little with indigenous risk preference; a risk-neutral type 1 subject would prefer to buy 2.86 shares in the first period and sell 2.64 in the second, while a very risk-averse subject with \( \gamma = 1.1 \) would prefer to buy 2.81 shares in the first period and sell 2.69 in the second. So each myopic subject facing a price of 10.5 would cycle between buying and selling two shares regardless of his indigenous risk preferences. It turns out that for any of the prices observed in the experiment (held constant), the size of myopic trades varies little by type and by indigenous risk preference (the size of the trade does vary to some degree with price). Therefore, if subjects are behaving myopically, virtually any price can be supported as a myopic equilibrium; regardless of the distribution of risk preferences, myopic behavior will result in supply equaling demand, or very close to it, so there will be no pressure on prices to change.

In summary, rational risk-averse subjects facing a constant below-fundamental price should attempt to increase their wealth at a constant rate over time, which should cause prices to increase towards \( p^* \). However, we observe several sessions in both linear and concave treatments where prices remain well below
the fundamental price. We present two simple models of myopic behavior, one for linear sessions and one for concave, which can rationalize stable prices below $p^*$. The linear sessions are characterized by thin markets where two (of twelve) subjects accumulate most of the assets. The model of linear myopic behavior, which provides a threshold price (conditional on indigenous risk preferences) for buying/selling as many shares as possible, implies that most subjects will stay out of a market even at the low prices observed in the L3 sessions, while the several remaining subjects will buy as many shares as possible. The concave sessions are characterized by thick markets where subjects smooth consumption across periods in relatively stable quantities. The model of concave myopic behavior can sustain most below-fundamental prices as equilibria, because trading quantities are very insensitive to indigenous risk preferences and similar (but of opposite sign) across types. It is interesting to note that Finding 5 is consistent with the hypothesis implied by these models of myopia that behavior in the concave sessions, unlike the linear ones, will not vary significantly with estimated indigenous risk preferences.

6 Conclusion

Our research design provides an important bridge between the literature on experimental methods and experimental asset pricing models, and the literature on equilibrium asset pricing models used by macroeconomic/business cycle and finance researchers. To date there has been little communication between these two fields. Our work integrating methods and models from both fields will enable both literatures to speak to a broader audience.

What we learn specifically in our attempt to integrate these segmented literatures is that an induced incentive to consumption-smooth can serve as a powerful brake on asset prices. If we very loosely define a bubble as a sustained deviation above an asset’s fundamental price, half of our laboratory economies with no induced incentive to trade experienced bubbles, and in three-quarters of these sessions the bubble exhibited no signs of collapse. Indeed, in half of the bubble sessions the median price of the asset towards the end of the experiment was more than double the fundamental price and was continuing to rise. In contrast, when consumption-smoothing was induced in an otherwise identical economy only one-quarter of the sessions bubbled, and in these sessions the median price of the asset collapsed to the fundamental price by the end of the experiment. Thus bubbles were less frequent, of lesser magnitude, and of shorter duration when we induced consumption-smoothing in an otherwise identical economy.

These results may offer some preliminary guidance as to which naturally occurring markets are most prone to experience large asset price bubbles. We might reasonably expect that markets with a high concentration of speculators are the most likely to bubble, while markets with a large number of participants who trade at least in part on intrinsic preferences are less likely to do so (in our study market depth itself appears to be a function of what motivates agents to trade). Of course in our current design we do not observe economies with mixtures of intrinsic and non-intrinsic participants, so at this point we merely offer the possibility that laboratory experiments may provide the basis for such a characterization in the future.

We anticipate that our basic research design can be extended in at least three distinct directions. First, the design can be moved a step closer to the environments used in the macrofinance literature; specifically, by adding a Markov process for dividends, and/or a known, constant growth rate in endowment income. The purpose of such treatments would be to explore the robustness of our present findings in the deterministic setting to stochastic or growing environments. A further step would be to induce consumption-smoothing through overlapping generations rather than via cyclic income and a concave exchange rate; how would a finite horizon at the individual subject level (while maintaining an indefinite horizon at the market level) impact asset prices?
In another direction, it would be useful to clarify the impact of features of our experimental design relative to the much-studied experimental design of Smith, Suchanek, and Williams (1988). For example, one could study a finite horizon, lump-of-money, linear (induced) utility design as in SSW, but where there exists a constant probability of firm bankruptcy as in our present design. Would the interaction of a finite horizon and firm bankruptcy inhibit bubbles relative to the SSW design, or is an induced economic incentive to trade necessary to prevent a small group of speculators from effectively setting asset prices across a broad range of economies?

Finally, it would be interesting to design an experiment to rigorously test for within-session risk-preferences and wealth effects. In our present design we observe little evidence that risk-averse subjects (classified by the Holt-Laury paired choice lottery instrument) attempt to increase their shareholdings over time in the linear induced utility treatment in sessions where prices are relatively a constant, a contradiction of time-consistent rational risk aversion. This result is perhaps not surprising; if subjects exhibit a different degree of risk aversion in small stakes laboratory gambles than they apply to ‘large’ economic decisions (i.e., the Rabin (2000) critique), then perhaps it should be expected that they exhibit myopic risk aversion over a sequence of small stakes gambles rather than maximize expected utility globally over the sequence. To our knowledge this hypothesis has not been directly tested. In fact, most laboratory studies of risk preferences explicitly eliminate the possibility of laboratory wealth effects on subject behavior. Modifying our present design, subjects could face a sequence of decisions to buy or sell assets directly with the experimenter at a constant price with a constant risk of bankruptcy, i.e., we can study individual risk preferences in a stationary, competitive market. Will risk-averse subjects (as identified by the HL procedure) tend to increase their shareholdings as their earnings in the experiment accumulate, as dictated by CRRA preferences, or will their decisions be more myopic? This is an important question, because empirical macroeconomic studies are some times calibrated to a distribution of CRRA preferences commonly estimated in laboratory studies. Our present paper suggests the possibility that the wealth effects implied by CRRA utility are not observed for many subjects. While CRRA seems to fit laboratory data on static decisions reasonably well (for a given magnitude of the stakes involved), it is possible that an alternative model of risk-aversion is preferable for dynamic decisions. The relationship of dynamic financial decision-making to a subject’s elicited static degree of risk aversion has the potential to lead to many exciting new results.
References


## Appendix - Regression Results

### Table 1: Linear Regression of Mean HL Score on Median First Period Prices

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<th>SS</th>
<th>df</th>
<th>MS</th>
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<tr>
<td>Model</td>
<td>94.00233</td>
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<td>47.001165</td>
<td>Prob &gt; F = 0.0000</td>
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<tr>
<td>Residual</td>
<td>3.3216693</td>
<td>7</td>
<td>0.4795265</td>
<td>R-squared = 0.9775</td>
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<tr>
<td>Total</td>
<td>97.32392</td>
<td>9</td>
<td>10.8139111</td>
<td>Root MSE = 0.9634</td>
</tr>
</tbody>
</table>

|                | Coef. | Std. Err. | t     | P>|t| | [99% Conf. Interval] |
|----------------|-------|-----------|-------|-----|----------------------|
| hllevadfq      | 1.18187 | 1.445256 | 0.8000 | 7.361817 | 14.60152 |
| _cons          | -7.86664 | 1.244665 | -6.3500 | -7.22982 | -1.843483 |

### Table 2: R.E. Regression of HL Scores on Final Shareholdings in Linear Sessions

|                | Coef. | Std. Err. | z     | P>|z| | [99% Conf. Interval] |
|----------------|-------|-----------|-------|-----|----------------------|
| hl             | 4.579467 | 2.158381 | 2.13 | 0.033 | 0.032065 | 9.158939 |
| _cons         | 56.15329 | 10.01782 | 5.60 | 0.375 | -1.402699 | 2.328510 |

<table>
<thead>
<tr>
<th></th>
<th>sigma_u</th>
<th>sigma_e</th>
<th>rho</th>
<th>(Fraction of variance due to u_i)</th>
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</thead>
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<td>3.3157167</td>
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<td>0.0000</td>
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### Table 3: R.E. Regression of HL Scores on Final Shareholdings in Concave Sessions

|                | Coef. | Std. Err. | z     | P>|z| | [99% Conf. Interval] |
|----------------|-------|-----------|-------|-----|----------------------|
| hl             | -0.962082 | 1.1650705 | -0.83 | 0.407 | -3.256162 | 1.325399 |
| _cons         | 2.847254 | 0.4658383 | 6.11 | 0.000 | 1.934531 | 3.759978 |

<table>
<thead>
<tr>
<th></th>
<th>sigma_u</th>
<th>sigma_e</th>
<th>rho</th>
<th>(Fraction of variance due to u_i)</th>
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<td>1.6286249</td>
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<td>0.0000</td>
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</table>
Table 4: R.E. Quadratic Regression of HL Scores on Net Expected Value Positions in Concave Sessions

| Variable          | Std. Err. | z  | P>|t| | 95% Conf. Interval |
|-------------------|-----------|----|------|-------------------|
| b1                | 2.06459   | 8316107 | 2.61 | 0.012 | 4546832 - 3714517 |
| b2                | -1.953846 | 0.091952 | -2.19 | 0.027 | -3.730154 - 0.725152 |
| _cons             | -1.377782 | 1.704868 | 1.20 | 0.232 | -7.888617 - 4.742839 |
| sigma_u           | 0         |     |     |       |                 |
| sigma_e           | 3.5726936 |       |     |       |                 |
| rho_U             | 0         | (Fraction of variance due to u_i) |

Table 5: R.E. Quadratic Regression of HL Scores on Net Expected Value Positions in Linear Sessions

| Variable          | Std. Err. | z  | P>|t| | 95% Conf. Interval |
|-------------------|-----------|----|------|-------------------|
| b1                | 0.0301019 | 0.127498 | 0.03 | 0.998 | 1.356865 - 1.297064 |
| b2                | 0.032395  | 0.065130 | 0.05 | 0.961 | -1.278522 - 1.349113 |
| _cons             | 0.1997112 | 1.330851 | -0.15 | 0.877 | -2.998379 - 3.198467 |
| sigma_u           | 0         |     |     |       |                 |
| sigma_e           | 3.4191594 |       |     |       |                 |
| rho_U             | 0         | (Fraction of variance due to u_i) |

Table 6: F.E. Quadratic Regression of HL Scores on Period Earnings in Concave Sessions

| Variable          | Std. Err. | t  | P>|t| | 95% Conf. Interval |
|-------------------|-----------|----|------|-------------------|
| var1              | 1.523488  | 0.017133 | 1.36 | 0.176 | 0.228486 - 2.818486 |
| var2              | -0.013366 | 0.008251 | -1.51 | 0.135 | -0.316467 - 0.004535 |
| _cons             | 0.365246  | 1.704212 | 2.26 | 0.024 | 0.451066 - 0.158485 |
| sigma_u           | 0.10695612|       |     |       |                 |
| sigma_e           | 0.3305127 |       |     |       |                 |
| rho_U             | 0.0947224 | (Fraction of variance due to u_i) |

F test that all u_i=0: F(4, 53) = 1.25 Prob > F = 0.3069