

# Statistical Arbitrage and Securities Prices

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This article introduces the concept of a *statistical arbitrage opportunity* (SAO). In a finite-horizon economy, a SAO is a zero-cost trading strategy for which (i) the expected payoff is positive, and (ii) the conditional expected payoff in each final state of the economy is nonnegative. Unlike a *pure arbitrage opportunity*, a SAO can have negative payoffs provided that the *average* payoff in each final state is non-negative. If the pricing kernel in the economy is path independent, then no SAOs can exist. Furthermore, ruling out SAOs imposes a novel martingale-type restriction on the dynamics of securities prices. The important properties of the restriction are that it (1) is model-free, in the sense that it requires no parametric assumptions about the true equilibrium model, (2) can be tested in samples affected by selection biases, such as the peso problem, and (3) continues to hold when investors' beliefs are mistaken. The article argues that one can use the new restriction to empirically resolve the joint hypothesis problem present in the traditional tests of the efficient market hypothesis.

In a fairly general environment, this article proposes a novel martingale-type restriction on the dynamics of securities prices. This restriction has a number of important properties. Most notably, the restriction may be viewed as model-free because it requires no parametric assumptions about the true equilibrium model. To derive the restriction, we rely on the concept of statistical arbitrage, a generalization of pure arbitrage.

A *pure arbitrage opportunity* (PAO) is a zero-cost trading strategy that offers the possibility of a gain with no possibility of a loss. As is well known, the existence of PAOs is incompatible with a competitive equilibrium in asset markets. The fundamental theorem of the financial theory establishes a link between the absence of PAOs and the existence of a positive *pricing kernel* which supports securities prices.

While the absence of PAOs is a necessary condition for any equilibrium model, this condition alone often yields pricing implications that are too weak to be practically useful. For example, when valuing options in incomplete markets, the no-arbitrage bounds on option prices are typically very wide. To strengthen pricing implications, several recent articles

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have suggested to further restrict the set of available investment opportunities and/or the set of admissible pricing kernels.

Cochrane and Saá-Requejo (2000) propose to rule out not only PAOs but also “good deals” (GDs), or investment opportunities with high Sharpe ratios. Following Hansen and Jagannathan (1991), Cochrane and Saá-Requejo show that precluding GDs imposes an upper bound on the pricing kernel volatility and yields tighter pricing implications when markets are incomplete. Bernardo and Ledoit (2000) propose to rule out *approximate arbitrage opportunities* (AAOs), or investment opportunities which offer high gain-loss ratios, where gain (loss) is the expectation of the positive (negative) part of the excess payoff computed under a benchmark risk-neutral measure. They demonstrate that restricting the maximum gain-loss ratio implies, loosely stated, that an admissible pricing kernel cannot deviate too far from the benchmark pricing kernel.

In this article we propose a different approach to restrict the set of admissible pricing kernels. In this approach we do not preclude opportunities whose attractiveness—as measured by the Sharpe ratio, the gain-loss ratio, or other criteria—exceeds some ad hoc threshold. Nor do we need to make parametric assumptions about a benchmark pricing kernel. Instead we impose an arguably weak assumption on a *functional form* of admissible pricing kernels and show that this assumption has striking implications for securities prices. The idea of our approach can be best explained for a simple special case.

Consider a finite-horizon economy with a single asset. The asset is traded in a frictionless market on dates  $t = 0, 1, \dots, T$ . The asset's price is  $v_t$ , and  $I_t = (v_0, \dots, v_t)$  is the price history through time  $t$ . Let  $Z_t$  denote the value of a general derivative security with a payoff  $Z_T = Z(I_T)$ . The absence of PAOs implies that there exists a positive pricing kernel  $m_T$  such that

$$E[Z_s m_s | I_t] = Z_t m_t, \quad t < s \leq T, \quad (1)$$

where  $m_t = E[m_T | I_t]$  and the risk-free rate is assumed to be zero.

Generally the pricing kernel  $m_T$  may depend on the complete price history, or  $m_T = m(I_T)$ . Except for the positivity constraint, the function  $m(I_T)$  has to satisfy no other conditions. This means that the function  $m(I_T)$  could be economically rather “unreasonable.” For example, values of the pricing kernel for two “close” price histories are allowed to be arbitrarily far apart. Such a pricing kernel, however, is unlikely to describe anyone's marginal utility function.

In this article we argue that, in many important situations, the economics of the problem imposes an additional structure on admissible pricing kernels. Specifically, suppose that the preferences of the representative investor are given by the utility function  $U(v_T)$ . Then the pricing kernel is a function of  $v_T$  only, or  $m_T = m(v_T)$ . It turns out that the fact that the

pricing kernel is *path independent* considerably reduces the set of investment opportunities that can exist in the economy.

We show that a pricing kernel  $m(v_T) > 0$  exists if and only if no *statistical arbitrage opportunities* (SAOs) are available. Here, a SAO is a zero-cost trading strategy for which (1) the expected payoff is positive,  $E[Z_T | I_t] > 0$ , and (2) for each  $v_T$ , the expected payoff *conditional* on the asset's final price being  $v_T$  is nonnegative,  $E[Z_T | I_t^{v_T}] \geq 0$ , where  $I_t^{v_T} = (v_0, \dots, v_t; v_T)$  is the *augmented* information set, which in addition to  $I_t$  also includes the knowledge of the final price. Unlike a PAO, a SAO is allowed to have negative payoffs, provided that the *average* payoff for each  $v_T$  is nonnegative.

The concept of a SAO is useful because ruling out SAOs induces a new powerful restriction on securities prices. To demonstrate it, let  $h_t(v_T)$  denote the conditional risk-neutral density of the asset's final price. Suppose that an empiricist observes a price history  $I_T$  with the final price  $v_T = v$ . Then securities prices deflated by the risk-neutral density evaluated at the final price must follow a martingale process:<sup>1</sup>

$$E\left[\frac{Z_s}{h_s(v)} \middle| I_t^v\right] = \frac{Z_t}{h_t(v)}, \quad t < s < T. \quad (2)$$

Intuitively, the restriction in Equation (2) states the following. Suppose that the empiricist observes many repetitions of the same environment and selects only those price histories that result in the same final price  $v_T = v$ . Then, in the selected histories, the ratio  $Z_t/h_t(v)$  must change over time unpredictably.

The unusual feature of the restriction is that it involves conditioning on future information.<sup>2</sup> To test the restriction, the empiricist needs to know the asset's price at time  $T$ . The empiricist cannot conduct testing in "real time"—she must wait until the final price is revealed. Note also that the restriction assumes that the risk-neutral density  $h_t(v_T)$  is available to the empiricist. Despite the fact that the risk-neutral density is not directly observable in financial markets, it is implicit in securities prices. In particular, it can be estimated from prices of traded options, such as standard European calls with different strikes. Consequently the new restriction in Equation (2) is best suited for applications where liquid option markets exist.

Three important properties of the restriction in Equation (2) deserve mentioning. First and most significantly, the restriction is completely preference independent. In other words, the utility function  $U(v_T)$  can be

<sup>1</sup> An additional technical assumption will be made to ensure that the term inside the conditional expectation operator in Equation (2) is well-defined for all price histories.

<sup>2</sup> In an important article, Bossaerts (1999a) demonstrates that conditioning on future price outcomes can be useful in testing asset pricing models. Our article builds on many of his insights, as will be discussed shortly.

arbitrary and the restriction in Equation (2) must still hold. This might seem counterintuitive. One would conjecture that no meaningful restriction on securities prices can exist if the utility function is allowed to be arbitrary, because almost any price dynamics can be generated. This article shows, however, that this conjecture is untrue. Under an arguably weak assumption that preferences are path independent, there is an easily verifiable “structure” in securities prices, for *all* preferences.

This implies that the restriction in Equation (2) can be used to resolve the joint hypothesis problem ubiquitous in tests of the efficient market hypothesis (EMH). Traditional tests of the EMH rely on the restriction in Equation (1) and require one to precommit to a specific pricing kernel or, equivalently, an equilibrium model. As a result, if tests are rejected, this could be because the market is truly inefficient or because the incorrect equilibrium model has been assumed. In contrast, the restriction in Equation (2) requires no parametric assumptions about the true equilibrium model. Rejection of the restriction in Equation (2) means that the market cannot be efficient for *any* model with a path-independent pricing kernel.

Second, the restriction in Equation (2) can be used in samples which come with various selection biases. To see this more clearly, suppose that the empiricist has collected a dataset in which not all price histories are present; say, the dataset includes only those histories for which the asset's final price is greater than initial price,  $v_T \geq v_0$ . Such a deliberate selection bias will generally cause rejection of the restriction in Equation (1), even if the true pricing kernel  $m_T$  were known. Of interest is that the selection bias will *not* affect the restriction in Equation (2). This is because the restriction involves conditioning on the final price.

As a more empirically relevant illustration, consider the so-called *peso problem*. The peso problem arises when a rare but influential event could have reasonably happened but did not happen in the sample. A typical example of this problem is when investors have correctly anticipated the possibility of a crash, but the sample includes no crash. In the presence of the peso problem, the restriction in Equation (2) can still be tested, while the restriction in Equation (1) cannot.

Third, the restriction in Equation (2) continues to hold even when investors' beliefs are mistaken. Specifically, suppose that investors have incorrect expectations about the distribution of  $v_T$ . However, they continue to update their expectations in a rational way. Then, under a certain condition, the restriction in Equation (2) must still hold.

To summarize, the new restriction permits a nonparametric test of whether investors are rational or not, for a broad class of preferences and beliefs. The test works even in the presence of selection biases.

It should be emphasized that the analogue of the restriction in Equation (2) obtains in a fairly general environment. In particular, there can be multiple assets, trading can take place continuously or at discrete

intervals, markets can be incomplete, and the information flow can be represented by general filtrations. A general version of the restriction essentially looks like Equation (2), except that  $v_T$  is replaced with a state variable  $\xi_t$  that describes uncertainty in the economy. The state variable  $\xi_t$  may include prices of traded assets as well as additional economic factors. Assuming that the pricing kernel  $m_T$  is a function of the final state  $\xi_T$  only, we show that no SAOs can exist, where a SAO is a zero-cost trading strategy with a positive expected payoff and nonnegative conditional expected payoffs for each  $\xi_T$ . We argue that the assumption of a path-independent pricing kernel is satisfied by many popular asset pricing models, including CAPM, the consumption-based models, the multifactor pricing models, the Epstein–Zin–Weil model, the Black–Scholes model, and others. Consequently, in all these models, not only PAOs but also more general SAOs cannot exist.

It is important to point out that a special case of the restriction in Equation (2) was originally developed in Bossaerts (1999a, 1999b). His motivation is different from ours. While we are primarily interested to learn how securities prices are affected by *risk preferences*, Bossaerts focuses on the effects of *incorrect beliefs*. He introduces an extension of EMH where investors are rational but may have mistaken beliefs. The extension is termed *efficiently learning market* (ELM). Using the fundamental property of Bayesian beliefs, Bossaerts shows that, in ELM under *risk neutrality* and a certain condition on beliefs, there exists a set of novel restrictions on securities prices. His restrictions involve conditioning on future information and deflating securities prices by posterior beliefs evaluated at the eventual outcome.<sup>3</sup>

In this article we argue that there is an interesting *equivalence* relationship between preferences and beliefs. The equivalence relationship means that, in economies populated by rational investors, the same securities prices can result from either risk aversion or biased beliefs, or some combination of the two. In particular, for every economy in which investors are risk averse but have correct beliefs, there is another economy in which investors are risk neutral but have biased beliefs, such that the two economies support the same securities prices. An outside empiricist, who only uses market data, *cannot* distinguish the two economies.

The remainder of the article is organized as follows. The theory is presented in Sections 1 and 2. To develop intuition, Section 1 considers a finite-state economy with discrete trading. This section introduces the concept of a SAO and derives the new restriction on securities prices, first for EMH and then for ELM. Section 2 considers a general continuous-time economy. This section also presents the equivalence relationship

<sup>3</sup> Bossaerts (1999a, 1999b) also propose results for the risk-averse case. Those results, however, assume that investors' preferences are known.

between preferences and beliefs. Section 3 discusses empirical implications. Section 4 concludes. The appendix contains proofs of all results.

## 1. Basic Model

In this section we develop the theory under a number of simplifying assumptions. These assumptions are relaxed in Section 2.

### 1.1 The economy

We consider a finite-horizon economy modeled as follows.

**Information structure.** There are a finite number of trading dates, indexed by  $t = 0, 1, \dots, T$ . At time  $t$ , the state of the economy is represented by a random variable  $\xi_t$ . The history of states up to time  $t$  determines the market information set  $I_t = (\xi_1, \dots, \xi_t)$ . We will distinguish between “elementary” and “final” states. The elementary state  $I_T \in \mathcal{I}_T$  provides a complete description of uncertainty from time 1 to  $T$ , while the final state  $\xi_T \in \Xi_T$  describes the price relevant uncertainty on the final date.

For example, one can interpret  $\xi_t$  as the value of the market portfolio at time  $t$ , with  $I_T$  representing the complete time-series path. More generally,  $\xi_t$  may represent a vector of values of traded assets and other economic factors (such as stochastic volatility or interest rates). The structure for state variables can be very general, but for now we assume that  $\xi_t$  is a discrete random variable that takes on a finite number of different values.

**Securities market.** There is a finite number of primary assets that are traded in a frictionless and competitive market. At time  $t$ , their prices depend on the state  $\xi_t$ . For simplicity, we assume that the risk-free rate is zero.

By trading primary assets, investors can generate various payoffs at time  $T$ . Specifically, consider a self-financing trading strategy that pays a random, path-dependent payoff  $Z_T = Z(I_T)$ . Let  $Z_t$  denote the value of such a generic payoff at time  $t$ .<sup>4</sup> (The set of available final payoffs is denoted  $\mathcal{Z}$ . The set  $\mathcal{Z}$  is a linear space, that is, if payoffs  $Z_T^{(1)}, Z_T^{(2)} \in \mathcal{Z}$ , then the payoff  $\alpha Z_T^{(1)} + \beta Z_T^{(2)} \in \mathcal{Z}$  for all constants  $\alpha$  and  $\beta$ . If the market is complete then  $\mathcal{Z} = \mathcal{R}^N$ , where  $N$  is the dimension of  $\mathcal{I}_T$ .)

Alternatively,  $Z_t$  can be interpreted as the time  $t$  price of a general European-style derivative security with a path-dependent payoff  $Z(I_T)$ .

<sup>4</sup> Formally, suppose that there are  $n$  primary assets and let  $d_t = (d_t^1, \dots, d_t^n)$  and  $p_t = (p_t^1, \dots, p_t^n)$  denote their dividends and (ex-dividend) prices at time  $t$ . One of the assets may represent a risk-free bond. A self-financing trading strategy (dynamic portfolio) is a nonanticipating process  $\theta_t = (\theta_t^1, \dots, \theta_t^n)$ , where  $\theta_t^i$  represents the number of shares of asset  $i$  held at time  $t$ , such that  $\theta_{t-1} \cdot (p_t + d_t) = \theta_t \cdot p_t$  for all  $t \geq 1$ . The value process of the strategy is defined as  $Z_t = \theta_t \cdot p_t$ .

**Probability distributions.** Let  $F_t(I_T) = F(I_T | I_t)$  denote the *objective* probability of the elementary state  $I_T$  conditional on the market information at time  $t$ . Similarly  $G_t(I_T)$  and  $H_t(I_T)$  are the conditional *subjective* and *risk-neutral* probabilities, respectively. Expectations with respect to the three probability measures are denoted as  $E[\cdot]$ ,  $E^S[\cdot]$ , and  $E^N[\cdot]$ .

The objective probabilities  $F_t(I_T)$  reflect the *true* (or *physical*, or *large-sample*) frequencies with which elementary states  $I_T$  occur. The subjective probabilities  $G_t(I_T)$  represent the investors' *beliefs* regarding the distribution of  $I_T$ . In general, investors may not know the true frequencies of various outcomes. Therefore we allow for the possibility that  $G_t(I_T) \neq F_t(I_T)$ .

The risk-neutral probabilities are also known as the *state prices* or *Arrow–Debreu prices*. Intuitively the risk-neutral probability  $H_t(I_T)$  is equal to the price of a security that pays one dollar in state  $I_T$  and zero in all other states. The risk-neutral probabilities allow securities prices to be expressed as expected values of their payoffs. The price of a security with a payoff  $Z(I_T)$  is

$$Z_t = E^N[Z(I_T) | I_t] = \sum_{I_T} Z(I_T) H_t(I_T).$$

As is well known, the set of risk-neutral probabilities always exists if the market is arbitrage-free [Harrison and Kreps (1979)]. This set is unique if the market is complete [Harrison and Pliska (1981)]. However, we do not insist on market completeness.

Besides distributions of *elementary* states, we will also need distributions of *final* states. Therefore, let  $f_t(\xi_T)$ ,  $g_t(\xi_T)$ , and  $h_t(\xi_T)$  denote the conditional objective, subjective, and risk-neutral probabilities of the final state  $\xi_T$ . In the continuous-state case, we will refer to  $f_t(\cdot)$ ,  $g_t(\cdot)$ , and  $h_t(\cdot)$  as the objective, subjective, and risk-neutral densities.

**EMH versus ELM.** In what follows, we distinguish between two cases of investors' rationality. The first one is the *efficient market hypothesis*, which is defined by the following two conditions:

- (i) **Rational learning.** This means that, when new information arrives to the market, investors update their beliefs by applying the rules of conditional probability, that is, Bayes' law. Intuitively this condition states that investors beliefs change over time unpredictably:

$$G_t(I_T) = E^S[G_s(I_T) | I_t], \quad t \leq s \leq T. \quad (3)$$

- (ii) **Correct beliefs.** This means that, when making investment decisions, investors weigh potential future outcomes using

frequencies with which these outcomes will actually occur. In other words, this condition states that the objective and subjective probabilities coincide:

$$F_t(I_T) = G_t(I_T) \quad \text{and} \quad E[\cdot | I_t] = E^S[\cdot | I_t].$$

EMH is a special case of the *efficiently learning market*, considered in Bossaerts (1999a).<sup>5</sup> He argues that of the two conditions underlying EMH, it is the condition of rational learning that reflects the essence of rationality. In contrast, the possibility of biased expectations is not an indication of irrationality. In ELM, Bossaerts maintains (i), but relaxes (ii).

**Pricing kernel.** The risk-neutral probability  $H_t(I_T)$  is related to the subjective probability  $G_t(I_T)$  via the *pricing kernel*.<sup>6</sup> The pricing kernel is a strictly positive random variable  $m_T > 0$  such that

$$H_t(I_T) = \frac{m_T}{m_t} G_t(I_T), \quad \text{where } m_t := E^S[m_T | I_t].$$

In general, the pricing kernel is a function of the elementary state, or  $m_T = m(I_T)$ . In this article, however, we focus on the important class of economies for which the pricing kernel depends on the final state  $\xi_T$ , but not the complete history  $I_T$ . Therefore we impose

**Assumption 1.** *The pricing kernel is path independent, or  $m_T = m(\xi_T)$ .*

Path independence of the pricing kernel is the main economic assumption of our analysis. We discuss this assumption in detail in Section 3.1 and argue that it is satisfied by many important asset pricing models, including CAPM, the consumption-based models, the multifactor pricing models, the Epstein–Zin–Weil model, the Black–Scholes model, and others.<sup>7</sup>

A simple setting where Assumption 1 holds is the following. Consider a pure-endowment economy with a single risky asset (the market portfolio). The asset's price  $v_t$  follows an exogenous process. Also traded is the risk-free bond, which is in zero net supply. The representative investor maximizes the expected value of a von Neumann–Morgenstern utility function  $U(v_T)$ . The utility function  $U$  is twice continuously differentiable with

<sup>5</sup> A remark on terminology. The classical definition of EMH in Fama (1970) does not explicitly identify conditions (i) and (ii). Still, most financial economists interpret EMH as meaning the *rational expectations equilibrium*.

<sup>6</sup> In the consumption-based models,  $m_T/m_t$  is also referred to as the *intertemporal marginal rate of substitution* (IMRS).

<sup>7</sup> In Assumption 1, path independence is stated with respect to the final date  $T$ . If, in addition to this assumption, it is also assumed that the state  $\xi_t$  follows a Markov process (i.e.,  $\Pr(I_T | I_t) = \Pr(I_T | \xi_t)$  for all  $I_T, I_t, \xi_t$ ), then the pricing kernel is path independent for all  $t \leq T$ , or  $m_t = m(\xi_t, t)$ . Section 3.1 demonstrates that many pricing models have this property.

$U' > 0$  and  $U'' \leq 0$ . In this case, the pricing kernel  $m_T = U'(v_T)$  depends on the final state  $\xi_T = v_T$ , but not on the complete history  $I_T = (v_0, \dots, v_T)$ . We will often use this simple setting for illustration purposes. However, it should be reiterated that Assumption 1 is satisfied in much more general equilibrium frameworks.

In view of Assumption 1, we can write

$$h_t(\xi_T) = \frac{m(\xi_T)g_t(\xi_T)}{m_t}, \quad \text{where } m_t = \sum_{\xi_T} m(\xi_T)g_t(\xi_T). \quad (4)$$

The pricing kernel  $m(\xi_T)$  can be interpreted as the state price per unit probability for a payoff in the state  $\xi_T$ . When investors are risk neutral,  $m(\xi_T) \equiv 1$ . When they are risk averse,  $m(\xi_T) \neq 1$ , reflecting the fact that investors value differently gains in “good” and “bad” states. For example, one dollar when the aggregate wealth is low may be worth to investors more than when the aggregate wealth is high.

## 1.2 Case of EMH

We first consider the case of EMH when the objective and subjective probabilities coincide. Then in Section 1.3, we allow investors to have subjective beliefs that differ from the objective probabilities.

Under EMH, securities prices satisfy the standard restriction that

$$E[m_s Z_s | I_t] = m_t Z_t, \quad t < s \leq T. \quad (5)$$

To test this restriction, one needs to know the pricing kernel. In reality, however, the pricing kernel is unobservable and, as a result, tests of EMH based on Equation (5) suffer from a joint hypothesis problem. Rejections may emerge because the market is truly inefficient or because an incorrect pricing kernel has been assumed.

One of the objectives of this article is to derive a restriction on securities prices which is independent of the pricing kernel. Central to our approach is the idea of statistical arbitrage.

**1.2.1 Statistical arbitrage.** A SAO is a generalization of a PAO. A PAO is a zero-cost trading strategy that offers the positive expected payoff with no possibility of a loss.

**Definition 1.** A zero-cost trading strategy with a payoff  $Z_T = Z(I_T)$  is called a PAO if

- (i)  $E[Z_T | I_0] > 0$ , and
- (ii)  $Z_T \geq 0$ , for all  $I_T$ .

From Harrison and Kreps (1979), a pricing kernel  $m(I_T) > 0$  exists if and only if there are no PAOs. This result is often referred to as the first fundamental theorem of asset pricing.

A SAO is a zero-cost trading strategy for which the expected payoff is positive and the conditional expected payoff in each final state  $\xi_T$  is nonnegative. Formally, let  $I_t^{\xi_T} := (I_t; \xi_T) = (\xi_1, \dots, \xi_t; \xi_T)$  denote the *augmented* information set, which in addition to the market information at time  $t$ , also includes the knowledge of the final state of the economy.

**Definition 2.** A zero-cost trading strategy with a payoff  $Z_T = Z(I_T)$  is called a SAO if

- (i)  $E[Z_T | I_0] > 0$ , and
- (ii)  $E[Z_T | I_0^{\xi_T}] \geq 0$ , for all  $\xi_T$ .

Unlike a PAO, a SAO can have negative payoffs in some elementary states  $I_T$ , as long as the average payoff for each  $\xi_T$  is nonnegative. Implicit in the definition of a SAO is the assumption that there are many different histories  $I_T$  corresponding to a given final state  $\xi_T$ , meaning that a path-dependent strategy may have uncertain payoffs in  $\xi_T$ . It is clear that any PAO is a SAO, but the reverse is not true.

The concept of a SAO is useful because of the following duality result.

**Proposition 1.** A pricing kernel  $m(\xi_T) > 0$  exists if and only if there are no statistical arbitrage opportunities.

Proposition 1 differs from the first fundamental theorem in that the pricing kernel is restricted to be path independent. Path independence implies that not only PAOs but also more general SAOs cannot exist. In the following subsection we will show that the absence of SAOs has important pricing implications. In particular, we will derive a new restriction on the *dynamics* of securities prices. Before that, however, we want to point out that the concept of a SAO could be useful in a *static* environment as well.

Consider, for example, Hakansson (1978). He studies a single-period model with several assets when investors' preferences depend on the market return but not returns of individual assets. In such a model he shows that state securities on the market portfolio are the only securities needed to achieve the full allocational efficiency. That is, a complete market would lead to exactly the same allocations and prices.

Suppose now that  $\xi_T$  denotes the market return and that  $I_T$  is a vector of individual returns. In other words,  $\xi_T$  represents a "metastate" that includes many elementary states  $I_T$ . Then a SAO can be defined as a zero-cost portfolio for which the expected payoff  $E[Z_T | I_0]$  is positive and the expected payoff in each metastate  $E[Z_T | I_0^{\xi_T}]$  is nonnegative. Since preferences only depend on  $\xi_T$ , Proposition 1 implies that no SAOs can exist. This confirms the general intuition of Hakansson: conditional on the

market return, uncertainty about distribution of individual returns should not be priced.

**1.2.2 Preference-independent restriction.** We first present intuition and then derive the result formally. Consider three dates  $t = 0, 1$ , and  $2$ . For fixed  $x$ , let  $\delta^x$  denote the Arrow–Debreu security which at  $t = 2$  pays \$1 if the final state of the world is  $\xi_2 = x$  and zero otherwise. The security’s price at time  $t$  is equal to the risk-neutral probability  $h_t(x)$ . Consider two strategies that both invest one dollar in  $\delta^x$ : the first strategy buys  $1/h_0(x)$  shares at  $t = 0$ , while the second strategy buys  $1/h_1(x)$  shares at  $t = 1$ . The payoffs of the strategies are

$$Z^I = \begin{cases} \frac{1}{h_0(x)}, & \xi_2 = x \\ 0, & \xi_2 \neq x, \end{cases} \quad Z^{II} = \begin{cases} \frac{1}{h_1(x)}, & \xi_2 = x \\ 0, & \xi_2 \neq x. \end{cases}$$

The strategies have the same zero payoff in all states  $\xi_2 \neq x$ . This means that they must also pay the same expected payoff conditional on  $\xi_2 = x$ . Because, if not, either  $(Z^I - Z^{II})$  or  $(Z^{II} - Z^I)$  will be a SAO. Therefore

$$E[Z^I \mid I_0^x] = E[Z^{II} \mid I_0^x],$$

or

$$E\left[\frac{1}{h_1(x)} \mid I_0^x\right] = \frac{1}{h_0(x)}.$$

The last equation states that if we consider an Arrow–Debreu security which eventually matures in-the-money, then the inverse of its price follows a martingale process. The result must hold for *all* pricing kernels  $m(\xi_2) > 0$ .

To generalize the above argument, we consider another Arrow–Debreu security  $\delta^y$ , which pays \$1 in state  $\xi_2 = y$  and zero in other states. As before, two strategies are compared. The first strategy at  $t = 0$  sells one share of  $\delta^y$  and uses the proceeds to purchase shares of  $\delta^x$ . The second strategy is similar to the first one, except the trading takes place at the intermediate period  $t = 1$ . The payoffs of the strategies are

$$Z^I = \begin{cases} \frac{h_0(y)}{h_0(x)}, & \xi_2 = x \\ -1, & \xi_2 = y \\ 0, & \xi_2 \neq x, y, \end{cases} \quad Z^{II} = \begin{cases} \frac{h_1(y)}{h_1(x)}, & \xi_2 = x \\ -1, & \xi_2 = y \\ 0, & \xi_2 \neq x, y. \end{cases}$$

Again, an important feature of the two strategies is that their payoffs are the same for all states  $\xi_2 \neq x$ . Therefore there will be no SAO only if both strategies have the same expected payoff conditional on  $\xi_2 = x$ , implying that

$$E\left[\frac{h_1(y)}{h_1(x)} \mid I_0^x\right] = \frac{h_0(y)}{h_0(x)}.$$

This restriction states that the change in the ratio of the Arrow–Debreu prices  $h_1(y)/h_1(x)$  is unpredictable in price histories for which the final state is  $\xi_2 = x$ .

A similar argument can be used to show that for a general security with a payoff  $Z(I_2)$  at  $t = 2$ ,

$$E \left[ \frac{Z_1}{h_1(x)} \middle| I_0^x \right] = \frac{Z_0}{h_0(x)}.$$

We are now ready to state the result formally. Let  $x \in \Xi_T$  denote a possible final state and let  $T' < T$ . We assume that the following condition is satisfied.

**Assumption 2.** *For all histories  $I_{T'}$ , the risk-neutral probability  $h_{T'}(x) > 0$ .*

**Proposition 2.** *Suppose that EMH and Assumptions 1 and 2 hold. Then securities prices deflated by the risk-neutral probability of the final state  $h_t(x)$  are martingale processes under the objective probability measure and with respect to the augmented information set  $I_t^x$ . That is,*

$$E \left[ \frac{Z_s}{h_s(x)} \middle| I_t^x \right] = \frac{Z_t}{h_t(x)}, \quad t < s \leq T'. \quad (6)$$

Assumption 2 is a technical assumption, which ensures that the ratio inside the conditional expectation operator in Equation (6) is always well defined. Its purpose is to preclude situations when at some point  $s \leq T'$  investors learn that state  $x$  cannot possibly happen and thus  $h_s(x) = 0$ . In the previous analysis of the two trading strategies, Assumption 2 guarantees that the price of the Arrow–Debreu security  $\delta^x$  is positive for all intermediate states  $\xi_1$  so that the second strategy can always be implemented.<sup>8</sup> Later on we will illustrate the role of Assumption 2 in the context of specific examples.

Proposition 2 says that, if of many repetitions of the same environment, an empiricist selects histories that result in the same final state  $\xi_T = x$ , then in those histories the ratio  $Z_t/h_t(x)$  must change over time unpredictably. The unusual feature of the new restriction in Equation (6) is that it involves conditioning on future information. The empiricist cannot test the restriction in “real time”—she must wait until the final state is revealed. Note also that the restriction assumes that the risk-neutral probability  $h_t(x)$  is available to the empiricist. Despite the fact that the risk-neutral probabilities are not directly observable in financial markets, they are implicit in prices of derivative securities. In Section 3.2 we will

<sup>8</sup> We state Assumption 2 slightly differently from the “no early exclusion” assumption in Bossaerts (1999a, 1999b), but the two serve the exactly same purpose.

discuss how the risk-neutral probabilities can be estimated from prices of traded call options with different strikes.

As mentioned earlier, an important property of the new restriction is that it makes no reference to the pricing kernel. This means that one can be completely agnostic about the true equilibrium model and still be able to test EMH provided that Assumptions 1 and 2 are satisfied.

Another important property is that the restriction in Equation (6) can be used in samples that come with various selection biases. Specifically, let  $A \subset \Xi_T$  denote a subset of final states. Suppose that the empiricist has a sample of histories  $I_T^j (j = 1, \dots, J)$  with final states  $x^j \in A$ . By Proposition 2, the quantity

$$\frac{1}{J} \sum_{j=1}^J \left( \frac{Z_s^j}{h_s^j(x^j)} - \frac{Z_t^j}{h_t^j(x^j)} \right)$$

must be insignificantly different from zero for all  $t < s \leq T'$ . Note that this must be the case for *all* subsets  $A$ , because the expectation in Equation (6) is *conditioned* on the final state.<sup>9</sup> For example, if  $\xi_T$  represents the market return, then  $A$  can be a subset of returns that fall within the specific interval  $[r_l, r_h]$ . This is useful for the case of the peso problem. The peso problem refers to a situation when rare but influential outcomes (say, very extreme returns) have not happened in the sample.<sup>10</sup>

Consider the following illustration of this problem. Suppose that every year there is a 5% chance of a market crash. (Let us say, a crash is defined as a 20% one-day decline.) Investors know the probability of a crash and correctly incorporate it in securities prices. If crashes are independent, then on average one crash occurs every 20 years. Suppose now that the empiricist studies a random 20-year sample of data. Then there is a 36% chance that the sample will include no crash. For such a sample, the empiricist will conclude that investors are too pessimistic (because ex post realized returns are too high). On the other hand, with a probability of 26%, the sample may include two or more crashes. In this case, investors will appear to the empiricist as too optimistic. In both cases, the EMH restriction in Equation (5) will be rejected, even if the true pricing kernel is known to the empiricist.

Clearly the peso problem is merely a small sample problem. Unfortunately it may require unrealistically long data series to overcome this problem using the traditional approaches (and assuming that the data-generating process is stationary — which may be objectionable as well). However, with the help of Proposition 2, even short series can be analyzed because the peso problem does not affect the restriction in Equation (6).

<sup>9</sup> We implicitly assume that Assumption 2 is satisfied for all  $x \in A$ .

<sup>10</sup> The peso problem is analyzed in, for example, Bekaert, Hodrick, and Marshall (1995). Other biases may result from backfilling, censoring, and survivorship. See Brown, Goetzmann, and Ross (1995).

In the next subsection, we argue that the new restriction satisfies yet another important property: it continues to hold even when investors' beliefs are mistaken.

### 1.3 Extension to ELM

Suppose that investors' beliefs may be different from objective probabilities,  $F_t(I_T) \neq G_t(I_T)$ . In this more general setting, we can still follow the approach of Section 1.2. The notions of a PAO and a SAO, however, must now be redefined in terms of subjective expectations  $E^S[\cdot]$  instead of objective expectations  $E[\cdot]$ . The restriction in Equation (6) becomes

$$E^S \left[ \frac{Z_s}{h_s(x)} \middle| I_t^x \right] = \frac{Z_t}{h_t(x)}, \quad t < s \leq T'. \quad (7)$$

The problem with the restriction in Equation (7) is that it involves expectation under the subjective probabilities and therefore is of little use to an empiricist who observes securities prices sampled with the objective frequencies. It turns out, however, that there is a broad class of economies for which it is possible to "remove" the superscript from the expectation operator  $E^S[\cdot]$  in Equation (7). This class of economies has been introduced in Bossaerts (1999a).

As mentioned earlier, Bossaerts extends EMH to a more general ELM, where investors are rational but may have potentially biased beliefs. He demonstrates that, in ELM under *risk neutrality* and the assumption of *correct conditional beliefs* (to be formulated shortly), securities prices satisfy a set of novel restrictions.<sup>11</sup>

By following his approach, we can extend Proposition 2 to the case of ELM. Bossaerts restricts the set of possible beliefs in the following way. Suppose that beliefs are partitioned into two components: initial beliefs (priors) and beliefs conditional on the final state  $\xi_T$  (likelihood functions). Then he assumes that initial beliefs can be arbitrary but conditional beliefs must be correct. Formally, let  $\lambda_t(\xi_{t+1}; \xi_T)$  denote the objective transition probability of state  $\xi_{t+1}$  conditional on the history  $I_t$  and the final state  $\xi_T$ . That is,

$$\lambda_t(\xi_{t+1}; \xi_T) = \Pr(\xi_{t+1} | I_t^{\xi_T}).$$

The subjective transition probability  $\lambda_t^S(\xi_{t+1}; \xi_T)$  is defined in a similar fashion.

**Assumption 3.** *Investors' conditional beliefs are correct. That is,*

$$\lambda_t(\xi_{t+1}; \xi_T) = \lambda_t^S(\xi_{t+1}; \xi_T), \quad \text{for all } \xi_{t+1}, \xi_T, \text{ and } I_t.$$

<sup>11</sup> For empirical applications based on his theory, see Bondarenko (1997), Bossaerts (1999a, 1999b), Bondarenko and Bossaerts (2000), Bossaerts and Hillion (2001).

The economic interpretation for Assumption 3 is that intermediate states  $\xi_t (t < T)$  are “signals” about the final state  $\xi_T$  and that, even though investors may not know the correct distribution of final states, they do understand how the signals are generated for each realization  $\xi_T$ .

Assumption 3 is not completely innocuous. It puts a fair amount of structure on possible beliefs. Specifically, it assigns all “incorrectness” of beliefs to priors; conditional beliefs are restricted to be correct. It turns out, however, that many interesting applications exist where it can be natural to partition beliefs into biased priors and correct conditional beliefs. Two examples are provided in Sections 1.5 and 2.3. One should also keep in mind that Assumption 3 is an integral part of the standard EMH. However, EMH requires priors to be correct as well.

**Proposition 3.** *Suppose that ELM and Assumptions 1–3 hold. Then security prices deflated by the risk-neutral probability of the realized final state  $h_t(x)$  are martingale processes under the objective probability measure and with respect to the augmented information set  $I_t^x$ . That is,*

$$E \left[ \frac{Z_s}{h_s(x)} \middle| I_t^x \right] = \frac{Z_t}{h_t(x)}, \quad t < s \leq T'. \quad (8)$$

The only difference between Proposition 2 and Proposition 3 is that in the latter EMH is replaced with more general ELM. Proposition 3 states that biases in initial beliefs do not affect the restriction in Equation (6), provided that the assumption of correct conditional beliefs is satisfied. Clearly, Proposition 2 is a special case of Proposition 3, since under EMH, Assumption 3 is satisfied trivially.

Proposition 3 extends the original results obtained in Bossaerts (1999a, 1999b) in two ways. First, for the risk-neutral case, the restriction in Equation (8) is slightly more general than the corresponding restrictions in Bossaerts (1999a, 1999b). In the first article, Bossaerts considers a security whose liquidation value can take only two values,  $v_T \in \{0, v\}$ . The security’s price is thus  $v_t = v h_t(v)$ . He shows that the *inverse* of the price of the security that matures in-the-money (i.e., for which  $v_T = v$ ) is a martingale:

$$E \left[ \frac{1}{v_s} \middle| I_t^v \right] = \frac{1}{v_t}.$$

To derive this result from Proposition 3, consider a risk-free bond with payoff  $Z(v_T) = 1$ . Applying the restriction in Equation (8) to the bond’s price  $Z_t = 1$ , we obtain

$$E \left[ \frac{1}{h_s(v)} \middle| I_t^v \right] = \frac{1}{h_t(v)}.$$

In the second article, Bossaerts considers a general asset whose liquidation value  $v_T$  is a continuous random variable. The restriction on the asset's price  $v_T$  follows from Proposition 3 by taking the final payoff  $Z(v_T) = v_T$ :

$$E\left[\frac{v_s}{h_s(v)} \middle| I_t^v\right] = \frac{v_t}{h_t(v)}, \quad (9)$$

where  $v$  is the final value of the asset.

Proposition 3 proves the martingale property not only for the price of the *underlying* asset  $v_t$  as in Equation (9), but for the price of a general *derivative* security  $Z_t$ . Moreover, Proposition 3 restricts the dynamics of the whole risk-neutral distribution, not just its mean, as is the case with Equation (9). Specifically, the restriction in Equation (8) implies that

$$E\left[\frac{h_s(\xi_T)}{h_s(x)} \middle| I_t^x\right] = \frac{h_t(\xi_T)}{h_t(x)}, \quad \text{for all } \xi_T. \quad (10)$$

Second and more significantly, Proposition 3 extends the results in Bossaerts (1999a, 1999b) to the risk-averse case.<sup>12</sup> With the help of Proposition 3, one can now test the rationality of asset pricing without worrying that investors' preferences or beliefs are misspecified.

An interesting implication of Proposition 3 is that risk aversion and biases in beliefs appear to have similar effects on securities prices. In Section 2 we will confirm this intuition. We will show that there exists an "equivalence" relationship between the two, in the sense that the same equilibrium prices can be explained by either risk aversion or biased beliefs.

We conclude this subsection with a comment on why extending EMH to ELM is important. One situation when beliefs may deviate from the objective frequencies occurs when investors deal with unique and nonrepetitive events. The Gulf War, the Asian crisis, the Russian debt default, the long-term capital management meltdown are examples of events that had dramatic effects on the world's financial markets and which were very difficult to anticipate in advance. Under EMH, however, market participants are assumed to correctly predict the frequencies of all such historic events, which is arguably unrealistic.

EMH is often defended on the ground that, even if beliefs are *sometimes* biased, it is sufficient if beliefs are correct *on average*. This is not true. One can construct an example of a risk-neutral economy where (1) half of

<sup>12</sup> As mentioned earlier, Bossaerts (1999a, 1999b) proposes results for the risk-averse case as well. In those, the pricing kernel is assumed to be known. To obtain a martingale restriction, securities prices are first risk-adjusted using the pricing kernel and then deflated by the subjective probability  $g_t(x)$ . Proposition 3 shows that if  $g_t(x)$  is replaced with  $h_t(x)$ , then any reference to the pricing kernel disappears. An added advantage of the restriction based on the *risk-neutral* probabilities, as opposed to the *subjective* ones, is that the former can be derived from prices of traded securities. In contrast, beliefs are difficult to observe or estimate.

the time investors are too optimistic about assets' returns, (2) half of the time they are too pessimistic, (3) investors' expectations are correct on average, and (4) returns are predictable, in contradiction to EMH. It is not enough that expectations are correct most of the time, or on average — EMH requires expectations to be correct at *all* times. In many cases, this is a strong requirement.

#### 1.4 Two rationality restrictions

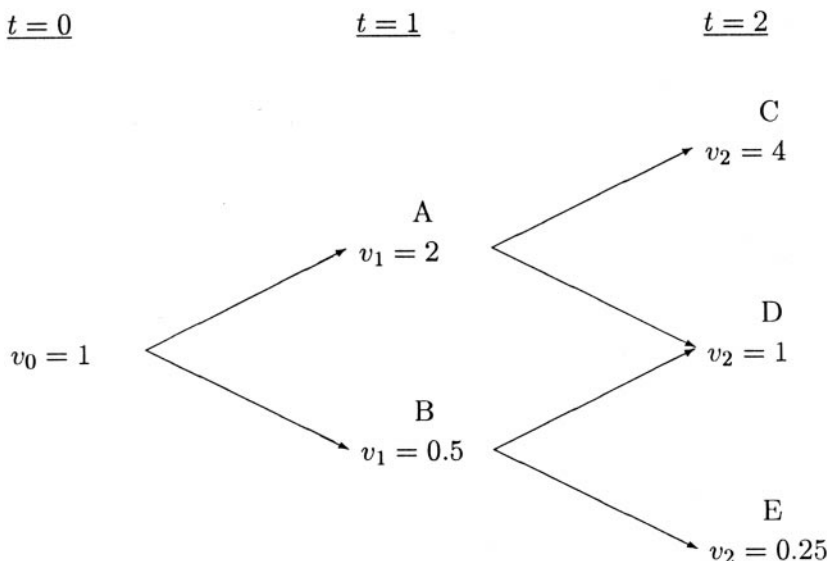
As follows from the previous subsections, there are two alternative approaches for testing the rationality of asset pricing. The first one is based on the standard EMH restriction in Equation (5). However, an empiricist can follow this approach only if (1) the true pricing kernel is known, (2) the sample is free of selection biases, and (3) investors' beliefs are correct.

The second approach is based on the new martingale restriction in Equation (8). In this approach, the empiricist does not have to make parametric assumptions about the pricing kernel or investors' preferences, the sample can be affected by the peso problem and other selection biases, and investors' beliefs can be incorrect. In fact, preferences and beliefs may even change from one history to another. The second approach works if Assumptions 1–3 are satisfied (recall that Assumption 3 is required for the first approach as well) and if the risk-neutral probabilities  $h_t(\xi_T)$  can be estimated from prices of traded securities.

The two rationality restrictions will be violated when investors are irrational, that is, when the condition in Equation (3) does not hold.<sup>13</sup> Recently it has become fashionable to explain anomalies of EMH through suboptimal forms of learning motivated by the psychology literature. While there is only one way to learn optimally, there are many possible rules of inefficient learning, corresponding to various behavior biases (such as overconfidence, representativeness, conservatism, self-attribution, disposition, limited memory, and framing). In Section 2.3, we will consider an example where investors underreact or overreact to news. By imposing additional structure on the state variable, we will argue that, when investors underreact (overreact), the following *supermartingale* (*submartingale*) restriction holds:

$$E \left[ \frac{Z_s^p}{h_s(x)} \mid I_t^x \right] \quad < (>) \quad \frac{Z_t^p}{h_t(x)},$$

<sup>13</sup> There is another distinction between the two approaches. Under EMH, the existence of a positive pricing kernel  $m_T$  that satisfies the standard restriction in Equation (5) is only *necessary* for the condition in Equation (3). This is because, in an incomplete market, a particular choice of  $m_T$  may differ from the *true* pricing kernel and be disconnected from marginal rates of substitution in the economy. In contrast, one can show that, if ELM and Assumptions 1–3 hold, then the new restriction in Equation (8) is both *necessary* and *sufficient* for Equation (3).



**Figure 1**  
The dynamics of the asset's price  $v_t$  in two-step binomial tree.

where  $Z_t^p > 0$  denotes the price of a security with a *nonnegative* final payoff  $Z_T^p \geq 0$ . The restriction is independent of the pricing kernel and obtains under ELM and Assumptions 1–3.

### 1.5 Binomial tree example

In this subsection we illustrate Proposition 3 with the help of a simple example. The example is the standard binomial tree model of Cox, Ross, and Rubinstein (1979). Consider a pure-endowment economy with a single risky asset. There are three dates  $t = 0, 1$ , and 2. The asset's price  $v_t$  follows a binomial process shown in Figure 1. The initial price is  $v_0 = 1$  and in each period the price either doubles or halves. Each period, the objective, subjective, and risk-neutral probabilities of an “up” movement are  $p$ ,  $q$ , and  $r$ , respectively. The asset pays no dividends. Also traded is the risk-free bond. The bond is in zero net supply and the risk-free rate is zero.

Given the asset's prices, the risk-neutral probability of an “up” movement is  $r = \frac{1}{3}$ . Suppose that investors preferences are given by the utility function  $U(v) = -1/v$ . Then the subjective probability of an “up” movement is  $q = \frac{2}{3}$ .<sup>14</sup> We first consider the case of EMH and then the more general case of ELM.

<sup>14</sup> Consider the *constant relative risk aversion* (CRRA) utility function  $U(v) = v^{1-\gamma}/(1-\gamma)$  with  $0 < \gamma \neq 1$ . Then the objective probability of the “up” movement satisfies

$$q2^{1-\gamma} + (1-q)2^{\gamma-1} = 1.$$

When  $\gamma = 2$ , this implies that  $q = \frac{2}{3}$ .

**1.5.1 Correct beliefs.** Under EMH, beliefs are correct and  $p = q = \frac{2}{3}$ . Let  $\delta = \delta^D$  denote an Arrow–Debreu security which at time 2 pays \$1 in state D and nothing in states C and E. The price of the Arrow–Debreu security is

$$\begin{aligned} \text{at } t=0 : \quad \delta_0 &= \frac{4}{9}, \\ \text{at } t=1 : \quad \delta_1 &= \begin{cases} \frac{2}{3}, & \text{in state A,} \\ \frac{1}{3}, & \text{in state B.} \end{cases} \end{aligned}$$

Consider now two trading strategies which both start with initial endowment of \$1 and invest in the Arrow–Debreu security  $\delta$ . In the first strategy, we purchase the Arrow–Debreu security at  $t=0$ , resulting in a total of  $n_1 = \frac{9}{4}$  shares of  $\delta$ . In the second strategy, we wait one period and purchase the Arrow–Debreu security at  $t=1$ . In this case, the number of shares of  $\delta$  depends on the state at  $t=1$ : with probability  $p = \frac{2}{3}$ , the state is A and we buy  $n_2 = \frac{3}{2}$  shares; with probability  $1-p = \frac{1}{3}$ , the state is B and we buy  $n_2 = 3$  shares. Note that the expected number of shares is

$$E_0[n_2] = \Pr(A) \cdot \frac{3}{2} + \Pr(B) \cdot 3 = \frac{2}{3} \cdot \frac{3}{2} + \frac{1}{3} \cdot 3 = 2 < n_1,$$

suggesting that at  $t=1$  the second strategy on average results in a greater number of shares of  $\delta$  than the first strategy does. However, when comparing the two strategies, the *unconditional* average number of shares is irrelevant. Instead, what *is* relevant is the average number of shares *provided* that state D is eventually realized:

$$E_0[n_2 | D] = \Pr(A|D) \cdot \frac{3}{2} + \Pr(B|D) \cdot 3 = \frac{1}{2} \cdot \frac{3}{2} + \frac{1}{2} \cdot 3 = \frac{9}{4} = n_1,$$

implying that

$$E_0 \left[ \frac{1}{\delta_1} \mid D \right] = \frac{1}{\delta_0}. \quad (11)$$

In fact, one can check that for any security with a payoff  $Z(v_2)$  at time  $t=2$ ,

$$E_0 \left[ \frac{Z_1}{\delta_1} \mid D \right] = \frac{Z_0}{\delta_0}, \quad (12)$$

in agreement with Proposition 3. In particular, for the asset's price  $v_t$ ,

$$E_0 \left[ \frac{v_1}{\delta_1} \mid D \right] = \frac{1}{2} \cdot \frac{2}{2/3} + \frac{1}{2} \cdot \frac{1/2}{1/3} = \frac{9}{4} = \frac{v_0}{\delta_0}.$$

**Remark 1.** In the above example, Equations (11) and (12) will continue to hold for *any* utility function  $U(v)$ . This is because the choice of the utility function only affects the objective probability  $p = q$ . The choice does not affect the risk-neutral probability  $r$  or securities prices. Furthermore, it is a property of the binomial tree model that frequencies of states A and B conditional on state D being realized are *independent* of  $p$ . In particular,

$$\Pr(A|D) = \Pr(B|D) = \frac{1}{2}. \quad (13)$$

In other words, one can use the restriction in Proposition 3 to test whether securities prices are set under EMH without specifying the utility function. In contrast, the traditional EMH restriction in Equation (5) requires the knowledge of the objective probability  $p$ . For example, the risk premium for the asset's return is

$$E_0 \left[ \frac{v_1 - v_0}{v_0} \right] = \frac{1}{2}(3p - 1).$$

The risk premium depends on  $p$  and thus on the assumed utility function. Only when investors are risk neutral ( $p = q = r = \frac{1}{3}$ ) will the risk premiums for all securities be equal to zero.

**Remark 2.** The binomial tree example allows us to discuss the role of Assumption 2. It is easy to see that Assumption 2 is violated for state C (as well as for state E): if at  $t = 1$  the “down” node B is reached, then state C can never occur, contradicting the assumption. In this case, the intuitive approach used in Section 1.2.2 to derive the new restriction breaks down. To be more specific, let  $\delta^C$  denote the Arrow–Debreu security that pays \$1 in state C. As before, we consider two strategies which invest in  $\delta^C$ , one at  $t = 0$  and the other at  $t = 1$ . This time, however, we are unable to ensure that the two strategies have the same zero payoff in states D and E: when node B is reached, the second strategy will pay a positive amount either in state D or state E, or both. This means we no longer can rank the two strategies independently of the pricing kernel, and Proposition 3 does not obtain.

Consequently, if an empiricist observes historical repetitions of the same binomial tree environment and wishes to test Proposition 3, then she will not be able to use all collected price histories. She will have to select only those histories for which the final state is D. As for histories with the final state C or E, they are unusable for the purpose of testing the restriction of Proposition 3. Fortunately Assumption 2 is rarely violated when more realistic models are considered.

**Remark 3.** It may be instructive to contrast various extensions of arbitrage proposed in the literature. Extensions of arbitrage are useful for deriving sharper pricing implications when markets are *incomplete*.

In incomplete markets, securities prices cannot be uniquely determined by replication. By ruling out certain investment opportunities in addition to PAOs, one can tighten bounds on possible values of securities prices.

In the two-step binomial tree, the set of elementary states  $\mathcal{I}_T$  consists of four elements corresponding to price histories AC, AD, BD, and BE. Therefore, any payoff at  $t = 2$  can be represented by a vector  $(z_1, z_2, z_3, z_4)$  of payoffs in these elementary states.

Consider now the following three payoffs:

$$Z^{(1)} = (0, 0, 0, 1),$$

$$Z^{(2)} = (0, 1 + \varepsilon, -1, 0),$$

$$Z^{(3)} = (0, 1, 0, -\varepsilon),$$

where  $\varepsilon$  denotes an arbitrary small positive number. When the market is complete, the values of these payoffs at  $t = 0$  are uniquely determined via dynamic replication as

$$\frac{4}{9}, \quad \frac{2\varepsilon}{9}, \quad \frac{2 - 4\varepsilon}{9}.$$

Suppose, however, that the asset can no longer be traded at  $t = 1$ . In this case, the market is incomplete and many pricing kernels can exist. Different pricing kernels will assign different time-0 values to  $Z^{(1)}$ ,  $Z^{(2)}$ , and  $Z^{(3)}$ . In what follows, we assume that it costs nothing to form the three payoffs at  $t = 0$  and then check whether this assumption is consistent with the absence of arbitrage and some of its extensions.

Of the three zero-cost investment opportunities, only  $Z^{(1)}$  is a PAO. The other two may result in a loss in some elementary states and therefore they are not inconsistent with the absence of pure arbitrage. It is easy to check that  $Z^{(2)}$  is a SAO, while  $Z^{(3)}$  is not a SAO. (For  $Z^{(2)}$ , expected payoffs conditional on final states C, D, and E are nonnegative. In particular, conditional on the final state being D, histories AD and BD are equally likely and thus  $E_0[Z^{(2)}|\mathbf{D}] = \varepsilon/2 > 0$ .)

Bernardo and Ledoit (2000) introduce an extension of a PAO, called an *approximate arbitrage opportunity* (AAO). An AAO is a zero-cost investment that offers the gain-loss ratio above some prespecified level, where the gain (loss) is the expectation of the positive (negative) part of the payoff computed under the benchmark risk-neutral probabilities. Since PAOs are characterized by an infinite gain-loss ratio, the set of AAOs includes PAOs as a special case. We observe that investment opportunity  $Z^{(3)}$  is an AAO, since its gain-loss ratio is high:

$$\frac{E_0^N[\max(Z^{(3)}, 0)]}{E_0^N[\max(-Z^{(3)}, 0)]} = \frac{1}{2\varepsilon}.$$

On the other hand,  $Z^{(2)}$  is not an AAO, since its gain-loss ratio ( $=1 + \varepsilon$ ) is not particularly large.

Cochrane and Saá-Requejo (2000) introduce the notion of “good deals” (GDs), or investment opportunities with high Sharpe ratios. They show that by ruling out GDs, one can obtain tighter bounds on securities prices. One limitation of their approach is that not all PAOs qualify as GDs. To demonstrate this, we compare the Sharpe ratio of  $Z^{(1)}$  with the Sharpe ratio offered by the asset itself. The latter is given by the Sharpe ratio of zero-cost investment opportunity with the following payoff at  $t = 2$ ,

$$Z^{(4)} = (3, 0, 0, -3/4).$$

Note that the payoff of  $Z^{(4)}$  is equal to  $(v_2 - v_0)$ . Direct computations of the two Sharpe ratios yield

$$\text{SR of } Z^{(1)} = \sqrt{\frac{1}{8}} = 0.35, \quad \text{SR of } Z^{(4)} = \sqrt{\frac{5}{8}} = 0.79.$$

The Sharpe ratio of  $Z^{(1)}$  is low relative to that offered by the market. Thus zero-cost investment opportunity  $Z^{(1)}$  is not a GD, despite being a PAO. Even though  $Z^{(1)}$  never results in a loss and is clearly an attractive investment opportunity, its payoff has a high standard deviation, which implies a low Sharpe ratio. Intuitively the Sharpe ratio penalizes variability of payoffs, even when all payoffs are nonnegative. The following table summarizes the results for the three zero-cost investment opportunities:

|           | PAO | SAO | AAO | GD |
|-----------|-----|-----|-----|----|
| $Z^{(1)}$ | Yes | Yes | Yes | No |
| $Z^{(2)}$ | No  | Yes | No  | No |
| $Z^{(3)}$ | No  | No  | Yes | No |

**1.5.2 Biased beliefs.** Consider now the case of ELM where the subjective probabilities are different from the objective ones. The price dynamics and utility function are kept as before. This means that the risk-neutral and subjective probabilities also do not change,  $r = \frac{1}{3}$  and  $q = \frac{2}{3}$ . However, we are free to choose arbitrary objective probability  $p$ . For example, take  $p = \frac{1}{2}$ , the situation representing optimistic beliefs. It is easy to see that allowing for arbitrary  $p$  does not affect Equations (11) and (12). The reason for this has already been noted in Remark 1: frequencies of states A and B conditional on state D being realized are independent of  $p$ . See Equation (13). This implies that Assumption 3 is *automatically* satisfied if investors know that the underlying model is the standard binomial tree (they are not required to know the *probabilities* of the tree).

To summarize, Equations (11) and (12) obtain in a rather general setting. They hold when investors have arbitrary preferences and beliefs. Preferences, beliefs, and the price dynamics can even change across historical repetitions of the same environment. All we need is that the utility function is path independent and that investors know that the asset's price follows the binomial process.

## 2. General Argument

In this section we state a general version of Proposition 3 for abstract probability spaces. This allows us to relax simplifying assumptions made in the previous section (such as finite number of states, discrete trading, constant risk-free rate, etc.) and to obtain additional theoretical insights. We also propose a more elegant proof of the main result based on the change of measure technique.

### 2.1 Continuous-time setting

Let  $P$ ,  $Q$ , and  $R$  be three equivalent probability measures defined on a common measurable space  $(\Omega, \mathcal{F}_T)$ . The three measures should be interpreted as the objective, subjective, and risk-neutral probability measures, respectively. The information flow to the market is represented by a filtration  $(\mathcal{F}_t, t \in T)$ , where  $T = [0, T]$ . Let  $E_t^P[\cdot] := E^P[\cdot | \mathcal{F}_t]$ ,  $E_t^Q[\cdot] := E^Q[\cdot | \mathcal{F}_t]$ , and  $E_t^R[\cdot] := E^R[\cdot | \mathcal{F}_t]$  denote time  $t$  conditional expectations under the objective, subjective, and risk-neutral probability measures.

The state of the economy at time  $T$  is represented by a  $\mathcal{F}_T$ -measurable random variable  $X$ . In Section 1 we have assumed that the pricing kernel is a function of the final state, but not the whole history. To formulate a similar assumption for general probability measures, we use the following definition.

**Definition 3.** Let  $P_1$  and  $P_2$  be two probability measures equivalent on  $(\Omega, \mathcal{F}_T)$ . We say that  $P_1$  and  $P_2$  are  $X$ -equivalent if the Radon–Nikodym derivative  $dP_1/dP_2$  is  $\sigma(X)$ -measurable, where  $\sigma(X) \subset \mathcal{F}_T$  is the  $\sigma$ -field generated by random variable  $X$ .

Informally, Definition 3 states that the Radon–Nikodym derivative  $dP_1/dP_2$  is a function of  $X$ . We now impose the following analogue of Assumption 1.

**Assumption 4.** The subjective and risk-neutral probability measures  $Q$  and  $R$  are  $X$ -equivalent.

Let  $x$  denote the “outcome” of random variable  $X$ . For fixed  $x$ , define the *augmented* filtration  $(\mathcal{F}_t^x, t \in T)$ , where  $\mathcal{F}_t^x := \mathcal{F}_t \wedge \{X = x\}$ . As before, the augmented filtration in addition to the market information

also includes the knowledge of the final state. Note that  $\mathcal{F}_t^x \subseteq \mathcal{F}_T$ , for all  $t \in \mathcal{T}$ .

Let  $T' < T$  and  $T' := [0, T']$ . Consider a new probability measure  $R^x$  on the measurable space  $(\Omega, \mathcal{F}_{T'})$  constructed from the measure  $R$  as follows:

$$R^x(A) := E^R[I_A | \mathcal{F}_{T'}^x], \quad \text{all } A \in \mathcal{F}_{T'},$$

where  $I_A$  is the indicator function of the event  $A$ , defined for each  $\omega \in \Omega$  by

$$I_A(\omega) := \begin{cases} 1, & \text{if } \omega \in A \\ 0, & \text{if } \omega \notin A. \end{cases}$$

Intuitively the measure  $R^x$  is the risk-neutral probability measure conditional on  $X=x$ . The measure  $R^x$  is absolutely continuous with respect to the measure  $R$  on  $(\Omega, \mathcal{F}_{T'})$ . This simply means that, if  $R(A) = 0$  for some event  $A \in \mathcal{F}_{T'}$ , then  $R^x(A) = 0$ . The following assumption requires that  $R$  is also absolutely continuous with respect to  $R^x$ , so that  $R$  and  $R^x$  are equivalent on  $(\Omega, \mathcal{F}_{T'})$ .

**Assumption 5.** *The probability measure  $R$  is absolutely continuous with respect to the probability measure  $R^x$  on  $(\Omega, \mathcal{F}_{T'})$ .*

Assumption 5 is a generalization of Assumption 2. Intuitively it says that, at any time  $t \leq T'$ , it is impossible to observe an event that rules out the final outcome  $X=x$ . Specifically, for any event  $A \in \mathcal{F}_{T'}$ , such that  $R(A) > 0$ , it must be that  $R^x(A) > 0$ .

Since  $R$  and  $R^x$  are equivalent measures on  $(\Omega, \mathcal{F}_{T'})$ , the Radon–Nikodym derivative of  $R^x$  with respect to  $R$  is a strictly positive random variable. Let  $\eta_{T'}$  denote this Radon–Nikodym derivative (which is  $\mathcal{F}_{T'}$ -measurable):

$$\eta_{T'} := \frac{dR^x}{dR}.^{15}$$

Furthermore, consider any  $\mathcal{F}_T$ -measurable random variable  $Z_T$  and let  $Z_t = E_t^R[Z_T]$  and  $\eta_t = E_t^R[\eta_{T'}]$ . Then the abstract version of Bayes' formula states that

$$E_t^{R^x}[Z_s] = \frac{E_t^R[\eta_s Z_s]}{\eta_t}, \quad \text{for } t < s \leq T'. \quad (14)$$

In a similar fashion,  $P^x$  and  $Q^x$  are defined as the objective and subjective probability measures conditional on  $X=x$ , respectively.

<sup>15</sup> As always, all relations involving random variables should actually be interpreted in an *almost sure* sense, but for convenience we suppress the label “a.s.” everywhere.

Assumption 5 implies that probability measures  $P, Q, R, P^x, Q^x$ , and  $R^x$  are all equivalent on  $(\Omega, \mathcal{F}_{T'})$ .

In Section 1.3 we allowed investors to have arbitrary priors about possible outcomes, but required conditional beliefs to be correct (Assumption 3). With the help of Definition 3, a general version of this assumption is stated as follows:

**Assumption 6.** *The objective and subjective probability measures  $P$  and  $Q$  are  $X$ -equivalent.*

It may not be immediately obvious why Assumption 6 for the continuous-time case is analogous to Assumption 3 for the discrete-time case. However, as established in the proof of Proposition 4, if  $P$  and  $Q$  are  $X$ -equivalent, then  $P^x = Q^x$  for all  $x$ . The latter can be interpreted as the condition that beliefs conditional on the eventual outcome are correct. Moreover, comparison with Assumption 4 reveals an interesting alternative interpretation of Assumption 6. The requirement of correct conditional beliefs is equivalent to the requirement that the belief kernel  $dQ/dP$  is path independent, where the term “belief kernel” has been introduced in Bossaerts (1999b).

**Proposition 4.** *Suppose that Assumptions 4–6 hold. Consider a process  $(Z_t, \mathcal{F}_t, t \in T')$  which is  $R$ -martingale, that is,*

$$E_t^R[Z_s] = Z_t, \quad t < s \leq T'.$$

*Then the process  $(Z_t/\eta_t, \mathcal{F}_t, t \in T')$  is  $P^x$ -martingale, that is,*

$$E_t^{P^x} \left[ \frac{Z_s}{\eta_s} \right] = \frac{Z_t}{\eta_t}, \quad t < s \leq T'. \quad (15)$$

The relation of Proposition 4 to Proposition 3 is clear. Here,  $Z_t$  represents the price of a general security. When investors are rational, the process  $(Z_t, \mathcal{F}_t, t \in T')$  is  $R$ -martingale. Then, by Proposition 4, the process  $(Z_t/\eta_t, \mathcal{F}_t, t \in T')$  must be  $P^x$ -martingale. (Alternatively, we can say that the process  $(Z_t/\eta_t, \mathcal{F}_t^x, t \in T')$  is  $P$ -martingale, where the *augmented* filtration  $\mathcal{F}_t^x$  is used.)

When  $X$  is a discrete random variable, the deflator  $\eta_t$  in Equation (15) becomes the risk-neutral probability of the eventual outcome:

$$\eta_t = \Pr^R(X = x | \mathcal{F}_t) = h_t(x).$$

When  $X$  is a continuous random variable,  $\eta_t$  is the risk-neutral density evaluated at the eventual outcome.

## 2.2 Equivalent economies

In this subsection we argue that there exists an intimate relationship between investors' preferences and beliefs. Suppose that the measurable

space of events  $(\Omega, \mathcal{F}_T)$  and the filtration  $(\mathcal{F}_t, t \in T)$  are fixed. We use the triplet  $M = \{P, Q, R\}$  to represent the original economy, where  $P$ ,  $Q$ , and  $R$  are the objective, subjective, and risk-neutral probability measures on  $(\Omega, \mathcal{F}_T)$ . Suppose that Assumptions 4 and 6 are satisfied in economy  $M$ . Consider another economy  $M' = \{P, Q', R\}$ . In economy  $M'$ , the objective and risk-neutral measures are the same but the subjective measure is replaced with a new measure,  $Q'$ .  $Q'$  can be an arbitrary measure on  $(\Omega, \mathcal{F}_T)$  except for the fact that  $Q'$  must be  $X$ -equivalent to  $P$  (and thus to  $R$ ). In other words, Assumptions 4 and 6 are satisfied in economy  $M'$  as well.

Note that an outside empiricist cannot distinguish  $M'$  from the original economy  $M$ : in both economies, events occur with the same objective frequencies and securities prices are the same. Therefore we say that  $M$  and  $M'$  are *equivalent* economies.

There are many economies equivalent to  $M$ , but two are of particular interest. Let  $M^{RN} = \{P, R, R\}$  and  $M^{CB} = \{P, P, R\}$  denote equivalent economies for which the subjective measure is replaced with  $R$  and  $P$ , respectively. In economy  $M^{RN}$  investors are risk-neutral (the subjective measure coincides with the risk-neutral one), while in economy  $M^{CB}$ , investors have correct beliefs (the subjective measure coincides with the objective one). We refer to  $M^{RN}$  and  $M^{CB}$  as the *equivalent risk-neutral* and *equivalent correct-beliefs* economies.

Intuitively, in the equivalent risk-neutral economy,  $M^{RN}$ , preferences are “incorporated” into beliefs. Moreover, beliefs are risk adjusted in a specific way. Since Assumption 6 is satisfied in all equivalent economies, beliefs conditional on the eventual outcome are correct in  $M^{RN}$ ; only initial beliefs, or priors, need to be changed. In contrast, in the equivalent correct-beliefs economy,  $M^{CB}$ , bias in initial beliefs is “translated” into preferences.

As mentioned earlier, economies  $M$ ,  $M^{RN}$ , and  $M^{CB}$  are observationally indistinguishable, in the sense that the same securities prices may be supported by any of them (as well as numerous other equivalent economies). This has important implications for empirical studies. Suppose that the empiricist verifies that securities prices satisfy the restriction of Proposition 4, but violate the EMH restriction under risk neutrality:

$$E[Z_s | I_t] = Z_t, \quad t < s \leq T. \quad (16)$$

The empiricist will then conclude that investors are rational. However, she will not be able to pinpoint exactly why the restriction in Equation (16) is violated. She may attribute the violation to risk aversion, or biased priors, or some combination of the two.

There is a simple way to interpret equivalent economies. We refer to the Radon–Nikodym derivative  $dR/dP$  as the *empirical kernel* and write

$$\frac{dR}{dP} = \frac{dR}{dQ'} \times \frac{dQ'}{dP},$$

or

$$\text{empirical kernel} = \text{pricing kernel} \times \text{belief kernel}.$$

In all equivalent economies, the empirical kernel is the same. Therefore different choices of the subjective measure  $Q'$  correspond to different decompositions of the empirical kernel into a pricing kernel and a belief kernel. The pricing kernel then determines investors' preferences, while the belief kernel determines their beliefs.<sup>16</sup> In the next section we illustrate the idea of equivalent economies with a numerical example.

Several articles have addressed the issue of distinguishing the effects of beliefs and preferences on securities prices. In particular, Kraus and Sick (1980) and Cuoco and Zapatero (2000) consider parametric models and ask whether investors' beliefs and preferences can be jointly recovered from market data. Our contribution to this literature is that we identify fairly general conditions (Assumptions 4 and 6) under which the answer is No.

One can think of several situations in which distinguishing beliefs from preferences is relevant. First, it has been documented that the equity premium varies with the business cycle: high during recession, low during expansion. One can explain this effect by shifts in (1) preferences (during recession, investors are more risk averse), or (2) beliefs (during recession, investors are more pessimistic). However, can one separate (1) from (2) using market data only?

Second, Bondarenko (2000) estimates the risk-neutral densities (RNDs) implicit in the S&P 500 options and documents that shapes of implied RNDs are related to the recent returns of the index. In particular, on trading days when the index declines, RNDs have higher standard deviation and are more nonlognormal (more skewed and peaked) than when the index advances. One can again consider two possible interpretations for the time-series relations: when the index performs poorly, investors become (1) more risk averse or (2) more pessimistic. When Assumptions 4 and 6 are satisfied, the two interpretations are empirically indistinguishable.

## 2.3 Continuous-time example

In this subsection we illustrate Proposition 4 with the help of a continuous-time example. There is an asset whose liquidation value at

<sup>16</sup> Recall that, in order for Proposition 4 to hold, the empirical kernel must be a function of  $X$  only, a condition which immediately follows from Assumptions 4 and 6.

time  $t$  is a random variable  $v_T$ . The objective distribution of  $v_T$  at time 0 is a normal density with mean  $v_0$  and standard deviation  $\sigma_0$ , that is,  $f_0(v_T) = n(v_T; v_0, \sigma_0)$ , where for all  $\mu$  and  $\sigma$  we use the notation

$$n(v_T; \mu, \sigma) := \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(v_T - \mu)^2}{2\sigma^2}\right).^{17}$$

Investors' initial beliefs are represented by a normal density  $g_0(v_T) = n(v_T; u_0, \eta_0)$ , where  $u_0$  and  $\eta_0$  are the mean and standard deviation of the subjective density. In general,  $(v_0, \sigma_0) \neq (u_0, \eta_0)$ . Investors maximize the expected utility function with constant absolute risk aversion (CARA),

$$U(v_T) = \begin{cases} \frac{1}{\rho}(1 - e^{-\rho v_T}), & \text{if } \rho > 0 \\ v_T, & \text{if } \rho = 0. \end{cases}$$

For a CARA utility function, the risk-neutral density is also normal,  $h_0(v_T) = n(v_T; w_0, \eta_0)$ , with the same standard deviation as that for the subjective density and with risk-adjusted mean

$$w_0 = u_0 - \rho\eta_0^2.$$

As the maturity date approaches, investors learn about the realized liquidation value, denoted by  $v$ . Specifically, they observe continuous flow of signals modeled by the process

$$dS_t = vdt + \eta_s dB_t, \quad S_0 = 0, \quad (17)$$

where  $B_t$  is the standard Brownian motion. This means that, at time  $t$ , investors receive an "incremental" signal  $dS_t$  which is normally distributed with mean  $v$ . The flow of market information is represented by the filtration  $(\mathcal{F}_t, 0 \leq t)$ , where  $\mathcal{F}_t = \sigma(S_t)$ . It is easy to check that at any time  $t$ , all three probability densities (objective, subjective, and risk-neutral) are normal and that they depend on the cumulative signal  $S_t$  but not on the complete path. In particular, for all  $t < T$ , the objective density is  $f_t(v_T) = n(v_T; v_t, \sigma_t)$ , where

$$\begin{aligned} v_t &= \sigma_t^2 \left( \frac{v_0}{\sigma_0^2} + \frac{S_t}{\eta_s^2} \right) = v + \frac{\sigma_t^2}{\sigma_0^2} (v_0 - v) + \frac{\sigma_t^2}{\eta_s} B_t, \\ \frac{1}{\sigma_t^2} &= \frac{1}{\sigma_0^2} + \frac{t}{\eta_s^2}. \end{aligned}$$

<sup>17</sup> In this example, the liquidation value is normally distributed, violating limited liability. However, the example can be reformulated for lognormal densities.

Similarly,  $g_t(v_T) = n(v_T; u_t, \eta_t)$  and  $h_t(v_T) = n(v_T; w_t, \eta_t)$ , where

$$\begin{aligned} u_t &= \eta_t^2 \left( \frac{u_0}{\eta_0^2} + \frac{S_t}{\eta_s^2} \right) = v + \frac{\eta_t^2}{\eta_0^2} (u_0 - v) + \frac{\eta_t^2}{\eta_s^2} B_t, \\ \frac{1}{\eta_t^2} &= \frac{1}{\eta_0^2} + \frac{t}{\eta_s^2}, \\ w_t &= u_t - \rho \eta_t^2. \end{aligned}$$

Since all densities are normal,  $v_t$ ,  $u_t$ , and  $w_t$  can be interpreted as the objective, subjective, and risk-neutral time- $t$  expectations of the liquidation value. In particular,  $w_t$  is the asset's price.

In what follows, we illustrate Proposition 4. Note that Assumptions 4–6 are satisfied in this example. Assumption 4 holds because the utility function is path independent. Assumption 5 holds because at any time  $t < T$  the risk-neutral density  $h_t(v_T)$  is always positive for any given  $v_T$ . Finally, Assumption 6 holds because investors understand how signals are generated conditional on the liquidation value  $v$ , that is, they know Equation (17). We first analyze the risk-neutral case ( $\rho = 0$ ) and then we consider the risk-averse case ( $\rho > 0$ ).

**2.3.1 Risk neutrality.** When  $\rho = 0$ , the subjective density  $g_t(v_T)$  and the risk-neutral density  $h_t(v_T)$  coincide, and we can focus on the former. We observe that, as the maturity date approaches, standard deviations computed from  $f_t(v_T)$  and  $g_t(v_T)$  decrease and means approach  $v$ . Moreover, the initial bias of the subjective density is partly carried forward. Specifically, if  $u_0 \neq v_0$ , then  $u_t$  continues to be a biased estimate of the liquidation value,

$$E_0[u_t - v] = \frac{\eta_t^2}{\eta_0^2} (u_0 - v_0) \neq 0,$$

while, of course,  $E_0[v_t - v] = 0$ . (Recall that all expectations are computed under the objective probability measure.) Another way to illustrate the biasedness of  $u_t$  is to look at the stochastic process that  $u_t$  follows. By Ito's lemma,

$$du_t = \frac{\eta_t^2}{\eta_s^2} ((v - u_t)dt + \eta_s dB_t) \quad \text{and} \quad E_0[du_t] = \frac{\eta_t^2}{\eta_s^2} (v_0 - u_0)dt.$$

We can also look at the dynamics of investors' beliefs. By Ito's lemma,  $g_t(v_T)$  satisfies the following stochastic differential equation:

$$dg_t(v_T) = \frac{g_t(v_T)(v_T - u_t)}{\eta_s^2} ((v - u_t)dt + \eta_s dB_t).$$

When beliefs are biased, the EMH restriction in Equation (16) does not generally hold. In particular, beliefs will change predictably unless the mean of the subjective density is unbiased ( $E_0[dg_t(v_T)] = 0$  only if  $u_0 = v_0$ ).

It is interesting to note that, in this particular example, the EMH restriction holds even when the subjective standard deviation  $\eta_0$  is biased, provided that  $u_0$  is unbiased. For example, suppose that investors view their information as too imprecise ( $\eta_0 > \sigma_0$ ), but they are correct about the mean of the distribution of the liquidation value ( $u_0 = v_0$ ). In this case the EMH restriction will still hold and securities returns will still be unpredictable under the objective density. However, to an empiricist, securities volatilities will appear high relative to the variability of the fundamental uncertainty. (In particular, the diffusion coefficient of the stochastic process for  $u_t$  is greater than that for  $v_t$ , that is,  $\eta_t^2/\eta_s > \sigma_t^2/\eta_s$ .)

Empirically it has been well documented that stock prices exhibit too much volatility when compared to time-series variability of the earnings. This finding is frequently cited as evidence of market irrationality. In our example, however, the excessive volatility is not due to investors' irrationality. Instead, it stems entirely from biases in beliefs.

We now turn to Proposition 4. Let  $r_t(v_T) = r_t(v_T; v) := g_t(v_T)/g_t(v)$  denote the ratio of the time- $t$  values of the subjective density evaluated at  $v_T$  and at the eventual outcome  $v$ . Then

$$r_t(v_T) = \exp\left(\frac{(v - v_T)(v + v_T - 2u_t)}{2\eta_t^2}\right).$$

By Ito's lemma,

$$dr_t(v_T) = \frac{r_t(v_T)}{\eta_s}(v_T - v)dB_t. \quad (18)$$

An important-feature of the above equation is the absence of the drift term. This confirms Proposition 4: for every realization  $v$ , the quantity  $r_t(v_T)$  is a martingale process under the objective probability measure with respect to the augmented information filtration, that is,  $E[dr_t(v_T) | \mathcal{F}_t^v] = 0$ .

Furthermore, consider a derivative security with a payoff  $Z(v_T)$ . If we divide the security's price  $Z_t$  by  $g_t(v)$ , then this will again yield a martingale process with respect to  $\mathcal{F}_t^v$ , that is,  $E[d(Z_t/g_t(v)) | \mathcal{F}_t^v] = 0$ .<sup>18</sup> Specifically, one can verify that

$$d\left(\frac{Z_t}{g_t(v)}\right) = \frac{L_T(v)}{\eta_s}dB_t, \quad \text{where } L_T(v) := \int g_t(v_T)(v_T - v)Z(v_T)dv_T.$$

<sup>18</sup> In fact, the same property holds even when the payoff of the derivative security is path dependent.

For special cases  $Z(v_T) = 1$  and  $Z(v_T) = v_T$  we obtain

$$d\left(\frac{1}{g_t(v)}\right) = \frac{u_t - v}{\eta_s} dB_t, \quad \text{and} \quad d\left(\frac{u_t}{g_t(v)}\right) = \frac{\eta_t^2 + u_t(u_t - v)}{\eta_s} dB_t.$$

**2.3.2 Risk aversion.** When investors are risk averse ( $\rho > 0$ ), the subjective and risk-neutral densities are no longer the same,  $g_t(v_T) \neq h_t(v_T)$ . However, the risk-averse case can be reduced to the risk-neutral one. Following the discussion in Section 2.2, let the filtration  $(\mathcal{F}_t, 0 \leq t)$  be fixed and let the triplet  $M = \{f_0, g_0, h_0\}$  represent the original economy, while the triplet  $M^{RN} = \{f_0, h_0, h_0\}$  represents the equivalent risk-neutral economy. Economy  $M^{RN}$  is the same as  $M$  except the subjective density is now  $g_0^{RN}(v_T) = h_0(v_T)$ .

As explained in Section 2.2, in economy  $M^{RN}$  risk aversion is “incorporated” into initial beliefs. This is done by “risk adjusting” the original subjective density  $g_0(v_T) = n(v_T; u_0, \eta_0)$  to  $g_0^{RN}(v_T) = n(v_T; u_0 - \rho\eta_0^2, \eta_0)$ . Since securities prices are the same in economies  $M$  and  $M^{RN}$  and since  $g_0^{RN}(v_T)$  is still a normal density, all the previous analysis continues to hold for economy  $M^{RN}$ .

In Section 2.2 we also considered the equivalent correct-beliefs economy,  $M^{CB} = \{f_0, f_0, h_0\}$ , for which bias in initial beliefs is “translated” into preferences. In this respect, it may be instructive to ask the question: What kind of the utility function  $U(v_T)$  must investors have in that economy?

Since the objective and risk-neutral densities are normal,  $f_0(v_T) = n(v_T; v_0, \sigma_0)$  and  $h_0(v_T) = n(v_T; w_0, \eta_0)$ , the pricing kernel in economy  $M^{CB}$  is given to within a constant by

$$\ln(m(v_T)) = \frac{v_T^2}{2} \left( \frac{1}{\sigma_0^2} - \frac{1}{\eta_0^2} \right) + v_T \left( \frac{w_0}{\eta_0^2} - \frac{v_0}{\eta_0^2} \right).$$

Following Harrison and Kreps (1979), we note that any economy with a positive pricing kernel can be sustained in a competitive equilibrium with a representative investor simply by taking the preferences that are defined by the price functional of Harrison and Kreps. Not all associated preferences, however, will have an expected utility representation.<sup>19</sup>

In this example, preferences will be represented by a concave utility function  $U(v_T)$  only if the pricing kernel  $m(v_T)$  is monotonically decreasing in  $v_T$ . This can only happen if  $\sigma_0 = \eta_0$  and  $v_0 > w_0$ , which corresponds to a CARA utility function with  $\rho = (v_0 - w_0)/\sigma_0^2$ . In all other cases, preferences admit no expected utility representation.

<sup>19</sup> To admit expected utility representation, a preference relation must satisfy a set of certain conditions. For the case of state-independent utility  $U(v_T)$ , conditions can be found, for example, in Huang and Litzenberger (1988, chap. 1).

**2.3.3 Irrational learning.** We conclude the example by examining what happens when investors' learning is not fully rational. There are many ways that irrationality can be introduced into investors' behavior. The behavioral finance literature often advocates two types of irrational behavior: *underreaction* and *overreaction* [see, e.g., De Bondt and Thaler (1985), Chopra, Lakonishok, and Ritter (1992), Lakonishok, Shleifer, and Vishny (1994), Barberis, Shleifer, and Vishny (1998), Daniel, Hirshleifer and Subrahmanyam (1998)].

Underreaction and overreaction can also be modeled in a number of ways. For example, Bayesian updating in Equation (3) can be replaced by alternative, suboptimal rules. In our setting, a simple way to introduce underreaction and overreaction is the following. We retain the same information structure as before and focus on the risk-neutral case. Investors continue to update their beliefs in a Bayesian fashion, but with one change. They now *misinterpret* the arriving signals. Specifically, we assume that, even though signals continue to be generated by Equation (17), investors update their beliefs using an *incorrect* model,

$$dS_t = vdt + \hat{\eta}_s dB_t,$$

where the diffusion coefficient  $\hat{\eta}_s$  is different from its true counterpart  $\eta_s$ . Note that such a specification is inconsistent with rationality. This is because investors can easily estimate the true variability of signals  $\eta_s$ , but they use the incorrect model with  $\hat{\eta}_s$  instead. Note also that Assumption 6 is now violated.

We interpret the case when  $\hat{\eta}_s < \eta_s$  as overreaction. In this case, investors (mistakenly) perceive signals as very precise. As a result, investors overadjust their beliefs. In contrast, when  $\hat{\eta}_s > \eta_s$ , investors underreact: they understate the informativeness of signals and update beliefs too slowly.

Because investors misinterpret the precision of signals, Equation (18) must be replaced by

$$\frac{dr_t(v_T)}{r_t(v_T)} = \frac{(v_T - v)^2}{2\hat{\eta}_s^2} \left( \frac{\eta_s^2}{\hat{\eta}_s^2} - 1 \right) dt + \frac{\eta_s}{\hat{\eta}_s^2} (v_T - v) dB_t. \quad (19)$$

When  $\hat{\eta}_s = \eta_s$ , the drift term disappears and Equation (19) reduces to Equation (18). However, when  $\hat{\eta}_s \neq \eta_s$ , the drift is nonzero. This implies that the process  $r_t(v_T)$  is no longer a martingale with respect to the augmented filtration  $\mathcal{F}_t^v$ . In particular,  $E[dr_t(v_T) | \mathcal{F}_t^v] < 0$  in the case of underreaction, while  $E[dr_t(v_T) | \mathcal{F}_t^v] > 0$  in the case of overreaction. Furthermore, let  $Z_t^p > 0$  denote the price of a security whose final payoff

$Z^p(v_T)$  is nonnegative for all  $v_T$ . (For example,  $Z_t^p$  may represent the price of a vanilla call or put option written on  $v_T$ .) Then

$$E \left[ d \left( \frac{Z_t^p}{h_t(v)} \right) \middle| \mathcal{F}_t^v \right] < (>) 0,$$

when investors underreact (overreact). This result has an interesting implication. Suppose that the empiricist studies securities prices and rejects the restriction of Equation (15), suggesting that investors' learning cannot be fully rational, for *any* choice of preferences and initial beliefs. She will then be able to verify whether the rejection is due to overreaction, underreaction, or neither by testing the following *supermartingale* and *submartingale* restrictions:

$$\text{Underreaction: } E \left[ \frac{Z_s^p}{h_s(v)} \middle| \mathcal{F}_t^v \right] < \frac{Z_t^p}{h_t(v)}. \quad (20)$$

$$\text{Overreaction: } E \left[ \frac{Z_s^p}{h_s(v)} \middle| \mathcal{F}_t^v \right] > \frac{Z_t^p}{h_t(v)}. \quad (21)$$

The above restrictions are still preference and belief independent.<sup>20</sup>

### 3. Discussion

In this section we first discuss the role of Assumption 1 and then suggest how the new theoretical restriction can be tested empirically.

#### 3.1 Is Assumption 1 restrictive?

Path independence of the pricing kernel is a key assumption in our analysis. The assumption may seem restrictive but, in reality, it is not. To demonstrate this, we provide several examples of popular models that satisfy Assumption 1 (Assumption 4 in the general case). In these models the pricing kernel  $m_t = m(\xi_t)$  depends on the state variable  $\xi_t$ , but not the whole history  $I_t$ . Often the state variable  $\xi_t$  is either the aggregate consumption  $c_t$  or the value of the market portfolio  $v_t$ .

**3.1.1 Black–Scholes model.** In this model, the market portfolio follows a geometric Brownian motion. The objective price process is

$$\frac{dv_t}{v_t} = \mu dt + \sigma dB_t,$$

<sup>20</sup> See also Bossaerts and Hillion (2001). They propose another model of irrational learning, termed the *variable reversal delay* model. To measure underreaction and overreaction, Bossaerts and Hillion use inequalities similar to Equations (20) and (21).

where  $\mu$  and  $\sigma$  are constants, and  $B_t$  is the standard Brownian motion. As is well known, prices of derivative securities in this model are supported by the following pricing kernel:

$$m_t = m(v_t) = v_t^{-\gamma}, \quad (22)$$

where  $\gamma = (\mu - r_f)/\sigma^2 > 0$  is the coefficient of relative risk aversion and  $r_f$  is the risk-free rate.<sup>21</sup> The pricing kernel is path independent. This means that for a general derivative on the market portfolio  $v_t$  (exotic, path dependent), the new restriction must hold:

$$E \left[ \frac{Z_s}{h_s(v)} \middle| \mathcal{F}_t^v \right] = \frac{Z_t}{h_t(v)}, \quad t < s < T,$$

where the risk-neutral density is

$$\begin{aligned} h_t(v) &= h(v, T; v_t, t) \\ &= \frac{1}{2\pi\sigma\sqrt{\tau}} \frac{1}{v} \exp \left( -\frac{(\ln v/v_t - (r_f - \frac{1}{2}\sigma^2)\tau)^2}{2\sigma^2\tau} \right), \quad \tau = T - t. \end{aligned}$$

(Clearly Assumption 1 is also satisfied in a discrete time setting, where the price process is modeled by the standard binomial tree.)

**3.1.2 The Bates model.** An interesting extension of the Black–Scholes model is Bates (2001). He studies a jump-diffusion economy with “crash-averse” investors. The pricing kernel in this economy takes the form

$$m_t = v_t^{-\gamma} e^{Y_c n_t},$$

where  $\gamma > 0$ ,  $n_t$  is the number of jumps over  $[0, t]$ , and  $Y_c > 0$  is the parameter of crash aversion.<sup>22</sup>

Let  $\xi_t = (v_t, n_t)$ , then the pricing kernel is path independent and no SAOs can exist. Moreover, the risk-neutral density  $h_t(\xi_T)$  can be computed explicitly in this model. Therefore we can apply the new martingale restriction in Proposition 4 to a general option  $Z_t$  written on process  $\xi_t$ . For example,  $Z_t$  may represent the jump insurance contract considered in Bates (2001).

<sup>21</sup> For simplicity, we omit irrelevant constant multiples in all formulas for pricing kernels.

<sup>22</sup> The representative investor’s utility function depends on  $v_T$  and the number of jumps  $n_T$ . Specifically, the utility function is

$$U(v_T, n_T) = e^{Y_c n_T} \begin{cases} \frac{1}{1-\gamma} v_T^{1-\gamma}, & \text{if } \gamma \neq 0 \\ \ln v_T, & \text{if } \gamma = 0, \end{cases}$$

**3.1.3 Consumption-based models.** Intertemporal asset pricing models often assume that the representative investor maximizes the expectation of a time-separable utility function:

$$\max E_t \left[ \sum_{j=t+1}^{\infty} \delta^j U(c_j, t) \right], \quad (23)$$

where  $\delta$  is the time discount factor and  $U(\cdot, t)$  is a strictly concave utility function. In these models, path independence of the pricing kernel immediately follows from time separability. To see this, recall that the pricing kernel can be found from the first-order conditions to the portfolio problem:

$$m_t = U_c(c_t, t). \quad (24)$$

Therefore the pricing kernel  $m_t$  depends on  $c_t$ , but not on consumption in earlier periods. An important special case of the specification in Equation (23) is the consumption capital asset pricing model (CCAPM) with the CRRA preferences. For this model, the pricing kernel is simply

$$m_t = c_t^{-\gamma}.$$

Some consumption-based models make additional assumptions that allow us to replace  $c_t$  in Equation (24) with other variables. One example is Rubinstein (1976). He demonstrates that the pricing kernel in Equation (22) arises in a more general setting. In particular, the market portfolio  $v_t$  is not restricted to follow a geometric Brownian motion.

It should be mentioned that the path-independence assumption is also satisfied in various extensions (modifications) of Equation (23). In these specifications, (1) the time horizon can be finite (with a possibility of a terminal bequest); (2) time can be continuous; (3)  $c_t$  can represent a *vector* of several consumption goods. (Additional variables, which have been suggested in the literature, include leisure, government spending, and the stock of durable goods.)

Another way to extend the specification in Equation (23) is to rewrite the utility function at time  $t$  as  $U(c_t, y_t, t)$ , where  $y_t$  is an additional state variable. One important example is habit formation models, in which  $y_t$  represents the time-varying “habit” or subsistence level. To be specific, consider two specifications of habit formation of many proposed in the literature. Abel (1990) and Campbell and Cochrane (1999) develop models of *external* habit. In these models the pricing kernel  $m_t$  is path independent with the state variable  $\xi_t = (c_t, y_t)$ .<sup>23</sup> In particular, in Campbell and Cochrane (1999),

$$m_t = U_c(c_t, y_t) = (c_t - y_t)^{-\gamma}.$$

<sup>23</sup> Note that since habit  $y_t$  is a function of past consumption  $c_{t-1}, c_{t-2}, \dots$ , the pricing kernel  $m_t$  depends on past consumption through habit  $y_t$ . However,  $m_t$  depends *not* on the exact sequence of past consumption, but only on a “summary statistics”  $y_t$ .

**3.1.4 Epstein–Zin–Weil model.** The standard CCAPM with the CRRA preferences has one well-known limitation. In this model a single parameter  $\gamma$  controls both the elasticity of intertemporal substitution and the coefficient of relative risk aversion. Epstein and Zin (1989, 1991) and Weil (1989) propose a more flexible model that allows us to disentangle intertemporal substitution from risk aversion. Their objective function is defined recursively by

$$U_t = \{(1 - \delta)c_t^\rho + \delta(E_t[U_{t+1}^{\theta\rho}])^{1/\theta}\}^{1/\rho},$$

where  $0 \neq \rho < 1$ , and  $\theta > 0$ . The resulting pricing kernel depends both on consumption  $c_t$  and the value of the market portfolio  $v_t$ :

$$m_t = c_t^{\theta(\rho-1)} v_t^{\theta-1}.$$

The Epstein–Zin–Weil model nests CCAPM with the CRRA preferences ( $\theta = 1$ ) and the log utility CAPM ( $\theta = 0$ ). The pricing kernel  $m_t$  depends on  $c_t$  for  $\theta = 1$ , on  $v_t$  for  $\theta = 0$ , and on  $c_t$  and  $v_t$  for all other values of  $\theta$ . In any case, the pricing kernel is path independent with  $\xi_t = (c_t, v_t)$ .

**3.1.5 Multifactor arbitrage models.** In a general continuous-time multifactor model, the expected return on any security is given by

$$E_t[dp_t/p_t] = \alpha dt + \beta_1 d\lambda_{1t} + \cdots + \beta_k d\lambda_{kt},$$

where  $\lambda_{1t}, \dots, \lambda_{kt}$  represent  $k$  common factors. In this model the pricing kernel is

$$m_t = \exp(a + b_1 \lambda_{1t} + \cdots + b_k \lambda_{kt}),$$

where  $a, b_1, \dots, b_k$  are constants. The pricing kernel is path independent with  $\xi_t = (\lambda_{1t}, \dots, \lambda_{kt})$ .

The list of examples can be continued but the message is clear: Many important models in finance fit in our framework. In all examples, there is a state variable with respect to which the pricing kernel is path independent. This in turn implies that certain investment opportunities (namely, SAOs) cannot exist in equilibrium and that securities prices must satisfy the new martingale restriction.

Our setting is general in several other respects. First, the analysis does not depend on the existence of the representative investor. All the above models assume that the representative investor exists. However, we do not need that preferences and beliefs of heterogeneous investors aggregate in some meaningful way. Recall that a positive pricing kernel always exists provided that securities prices admit no pure arbitrage. In general, this pricing kernel does not have to correspond to a von Neumann–Morgenstern utility function. Nevertheless, if the pricing

kernel is path independent, then more general SAOs must be ruled out as well.

Second, our setting allows for incomplete markets. In incomplete markets, securities prices can be supported by many pricing kernels. If among admissible pricing kernels there is at least one that is path independent, then SAOs cannot exist and the new restriction holds.

Finally, we impose no specific structure on the state variable  $\xi_T$ . This means that  $\xi_T$  could, in principle, be redefined to include the complete description of all intermediate states  $\xi_t$ . In other words, we could choose  $\xi_T$  to contain as much information as the elementary state  $I_T$  does. In this extreme case, there would be no difference between a PAO and a SAO, and Proposition 1 would reduce to the standard result by Harrison and Kreps (1979). However, in all situations when  $\xi_T$  contains strictly less information than  $I_T$ , the concept of a SAO is more general than that of a PAO. Therefore, ruling out SAOs has stronger pricing implications.

There is, of course, a cost to defining the state variable  $\xi_T$  too broadly. When  $\xi_T$  contains more information, it will be more difficult to recover the risk-neutral probability  $h_t(\xi_T)$  from prices of traded securities. Still, the new restriction is useful even when  $h_t(\xi_T)$  is not observable.

Suppose that one has in mind a specific parametric model with a path-independent pricing kernel. Then ruling out SAOs imposes additional testable implications that have been largely overlooked in the literature. Moreover, the new restriction has important advantages even in a *parametric* setting. In particular, the new restriction can be used in samples affected by selection biases.

### 3.2 Empirical application

We implement the methodology of this article in Bondarenko (2002) using the S&P 500 index futures options data. We report that over the period from 1987 to 2000, a number of option strategies appear to be highly profitable. In particular, selling unhedged put options one month before maturity would have resulted in extraordinary high and statistically significant average excess returns. For at-the-money (ATM) puts, the average return over the studied period is about  $-40\%$  per month. For deeply out-of-the-money (OTM) puts, the average return approaches  $-100\%$  per month. In other words, puts appear to be grossly overpriced, at least from the point of view of Equation (16) for EMH under risk neutrality.

Do these findings indicate that investors are irrational? Are there true inefficiencies in option markets? Before answering these questions affirmatively, three explanations should be investigated:

**Explanation 1: risk premium.** According to this explanation, high prices of puts are *expected* and reflect normal risk premium under some

equilibrium model. Even though the canonical models (such as CAPM or the Rubinstein model) cannot explain option prices, maybe there is another model that can. In this true model, investors strongly dislike negative returns of the S&P 500 index and are willing to pay hefty premiums to hedge their portfolios against declines.

**Explanation 2: the peso problem.** To understand this explanation, suppose that market crashes (similar to that of October 1987) occur on average once in five years. Suppose also that investors correctly incorporate a probability of another crash in option prices. However, since only one major market crash has actually happened over the 14-year period, the ex post realized returns of the index are different from investors' ex ante beliefs. According to this explanation, puts only *appear* overpriced. The mispricing would have disappeared if data for a much longer period were available.

**Explanation 3: biased beliefs.** According to this explanation, investor's beliefs are mistaken. Investors, however, still process information rationally. This is the case of the more general ELM. OTM puts were expensive because investors assigned too high probabilities to negative returns of the index. Perhaps memories of the 1987 stock market crash were still fresh and, even though the *true* probability of another extreme decline was small, investors continued to overstate that probability.

Proposition 4 allows us to test whether Explanations 1–3 can explain the historical put returns. Specifically, we assume that the pricing kernel is of the form  $m_t = m(v_t, t)$ , where  $v_t$  denotes the value of the S&P 500 index.<sup>24</sup> Recall that to test the new martingale restriction, we need to know the risk-neutral density (RND),  $h_t(v_T)$ . We estimate RND from prices of standard call options as follows.

Consider a European-style call option with strike price  $K$  and maturity date  $T$  written on  $v_T$ . The option price  $C_t(K)$  is equal to the expected present value of the payoff under the RND  $h_t(v_T)$ :

$$C_t(K) = e^{-r_f(T-t)} \int_0^\infty \max(v_T - K, 0) h_t(v_T) dv_T,$$

where  $r_f$  is the risk-free rate over period  $[t, T]$ .

<sup>24</sup> Note that in this application we focus on a very short horizon ( $T=1$  month). This means that other theory-motivated state variables discussed in Section 3.1 are not likely to be important. In particular, time series for the aggregate consumption  $c_t$  or habit  $y_t$  are very smooth at monthly frequency. Moreover, since the pricing kernel is allowed to explicitly depend on  $t$ , the long-term dependence of the pricing kernel on  $c_t$  and  $y_t$  can be incorporated.

Differentiating the above equation twice with respect to  $K$ , we obtain the relationship first discovered in Ross (1976), Banz and Miller (1978), Breeden and Litzenberger (1978):

$$h_t(v_T) = e^{-r_f(T-t)} \frac{\partial^2 C_t(K)}{\partial K^2} \Big|_{K=v_T}.$$

The relationship states that RND is proportional to the second partial derivative of call price with respect to strike evaluated at  $K = v_T$ . In liquid option markets, it is not uncommon to observe 30 and more concurrently traded call contracts with different strikes  $K$  and the same maturity  $T$ . Given a collection of these options, it is possible to accurately estimate the function  $C_t(K)$  and its second derivative. In the literature, a number of estimation methods are now available. See Jackwerth (1999) for a recent survey. We estimate RNDs using the method recently developed in Bondarenko (2000).

After RNDs are obtained from option prices, we test the restriction in Proposition 4 and strongly reject it. The rejection means that the put pricing anomaly cannot be explained by *any* asset pricing model with the path-independent pricing kernel  $m(v_t, t)$ , even if investors have mistaken beliefs and the sample is affected by selection biases. In fact, only a very small portion of the put mispricing can be attributed to risk aversion, the peso problem, and biased beliefs.<sup>25</sup> Moreover, by testing the restriction in Equation (20), we argue that put prices are consistent with *underreaction*.

### 3.1 Conclusion

In this article, we introduce the concept of a SAO. In a finite-horizon economy, a SAO is a zero-cost trading strategy for which (i) the expected payoff is positive, and (ii) the conditional expected payoff in each final state of the economy is nonnegative.

We show that when the pricing kernel is path independent, then no SAOs can exist. Furthermore, precluding SAOs imposes a novel martingale-type restriction on the dynamics of securities prices. It states that securities prices deflated by the risk-neutral density evaluated at the eventual outcome must follow a martingale. The restriction extends the results in Bossaerts (1999a, 1999b). Important properties of the restriction are that it (1) requires no parametric assumptions on investors' preferences; (2) can be tested in samples affected by selection biases, such as the

<sup>25</sup> Our findings do not rule out two other possibilities: (a) the pricing kernel is path dependent, and (b) the pricing kernel is path independent but is a function of other state variables in addition  $v_t$  (a natural candidate here would be stochastic volatility). Neither possibility, however, has received enough attention in the literature. First, as argued in Section 3.1, standard equilibrium models usually produce path-independent kernels. Second, there is currently no accepted *equilibrium* model in which preferences of the representative investor depend on volatility. To be able to explain the put anomaly, one might need to develop new theoretical models that allow for (a) or (b).

peso problem; and (3) continues to hold even when investors' beliefs are mistaken (provided that conditional beliefs are correct).

The new restriction allows one to resolve the joint hypothesis problem present in the traditional tests of the efficient market hypothesis. In order to test the restriction, one must first estimate the risk-neutral density from market prices of traded options. Consequently the methodology is best suited for applications where well-developed liquid option markets exist. One such application is proposed in Bondarenko (2002).

The concept of a SAO can also be useful in a *parametric* setting. Suppose that one has in mind a specific model with a path-independent pricing kernel. Then ruling out SAOs imposes additional testable implications that have been largely overlooked in the literature. Compared to the standard approaches, the new restriction has the important advantage that it is robust to selection biases.

An interesting extension of our approach is securities valuation in incomplete markets. In incomplete markets, many possible pricing kernels can exist and perfect replication of a derivative security with primary assets is impossible. This means that one can assign to the derivative security a range of possible values, all consistent with the absence of PAOs. The resulting no-arbitrage bounds, however, are often too wide to be practically useful. One way to obtain tighter pricing bounds is to rule out more general SAOs. We leave this topic for future research.

## Appendix

**Proof of Proposition 1.** (1) If there is a pricing kernel  $m(\xi_T) > 0$ , then no SAOs can exist. Indeed, consider a strategy with a payoff  $Z_T = Z(I_T) \in \mathcal{Z}$  that satisfies conditions (i) and (ii) in Definition 2, that is,  $E[Z_T | I_0] > 0$  and  $E[Z_T | I_0^{\xi_T}] \geq 0$ , for all  $\xi_T$ . Then the initial value of this strategy  $Z_0$  cannot be zero, because

$$\begin{aligned} Z_0 = E[m(\xi_T)Z_T | I_0] &= \sum_{\xi_T} E[m(\xi_T)Z_T | I_0^{\xi_T}] \Pr(\xi_T | I_0) \\ &= \sum_{\xi_T} m(\xi_T) E[Z_T | I_0^{\xi_T}] \Pr(\xi_T | I_0) > 0, \end{aligned}$$

where the last inequality follows from

$$E[Z_T | I_0] = \sum_{\xi_T} E[Z_T | I_0^{\xi_T}] \Pr(\xi_T | I_0) > 0.$$

(2) Conversely, suppose that there are no SAOs. For an arbitrary path-dependent trading strategy with an initial value  $Z_0$  and a final payoff  $Z_T = Z(I_T) \in \mathcal{Z}$ , we construct the "associated" path-independent strategy with the same initial value  $\tilde{Z}_0 = Z_0$  and the payoff defined as

$$\tilde{Z}_T = \tilde{Z}(\xi_T) := E[Z_T | I_0^{\xi_T}].$$

By construction, the two strategies have the same expected payoffs at  $t = 0$ :

$$E[Z_T | I_0] = \sum_{\xi_T} E[Z_T | I_0^{\xi_T}] \Pr(\xi_T | I_0) = \sum_{\xi_T} \tilde{Z}(\xi_T) \Pr(\xi_T | I_0) = E[\tilde{Z}_T | I_0].$$

Let  $\tilde{\mathcal{Z}}$  denote the set of associated path-independent payoffs  $\tilde{Z}_T$  corresponding to all path-dependent payoffs  $Z_T \in \mathcal{Z}$ . While payoffs  $Z_T \in \mathcal{Z}$  are defined on the set of elementary states  $\mathcal{I}_T$ , payoffs  $\tilde{Z}_T \in \tilde{\mathcal{Z}}$  are defined on the set of final states  $\Xi_T$ .

We now note that if a path-dependent strategy is a SAO on  $\mathcal{I}_T$ , then its associated path-independent strategy is a PAO on  $\Xi_T$ . The absence of SAOs on  $\mathcal{I}_T$  therefore implies the absence of PAOs on  $\Xi_T$ . By the standard argument [see Harrison and Kreps (1979)], there exists a function  $m(\xi_T) > 0$  that correctly prices all path-independent payoffs  $\tilde{Z}_T \in \tilde{\mathcal{Z}}$ ,

$$E[\tilde{Z}_T m(\xi_T) | I_0] = \tilde{Z}_0.$$

This function  $m(\xi_T)$  then also supports all path-dependent payoffs  $Z_T \in \mathcal{Z}$ , because

$$\begin{aligned} E[m(\xi_T) Z_T | I_0] &= \sum_{\xi_T} m(\xi_T) E[Z_T | I_0^{\xi_T}] \Pr(\xi_T | I_0) \\ &= \sum_{\xi_T} m(\xi_T) \tilde{Z}_T \Pr(\xi_T | I_0) = E[m(\xi_T) \tilde{Z}_T | I_0] = \tilde{Z}_0 = Z_0. \end{aligned}$$

Therefore,  $m(\xi_T) > 0$  is a proper pricing kernel. ■

**Proof of Proposition 2.** We first consider the case when the security's final payoff is a function of  $\xi_T$  only and then the general case when the payoff may depend on the whole history  $I_T$ .

(1) At time  $t+1$ , the objective probability will depend on the realized state  $\xi_{t+1}$ , that is,  $f_{t+1}(\xi_T) = f_{t+1}(\xi_T; \xi_{t+1})$ . Let  $\lambda_t(\xi_{t+1}; \xi_T)$  denote the time- $t$  objective transition probability of state  $\xi_{t+1}$  conditional on  $I_t^{\xi_T}$  (i.e., conditional on history  $I_t$  and the fact that the final state is  $\xi_T$ ). Then  $f_{t+1}(\xi_T; \xi_{t+1})$  can be computed using Bayes' law as follows:

$$f_{t+1}(\xi_T; \xi_{t+1}) = \frac{f_t(\xi_T) \lambda_t(\xi_{t+1}; \xi_T)}{\sum_{\xi_{t+1}} f_t(\xi_T) \lambda_t(\xi_{t+1}; \xi_T)} = \frac{\Pr(\xi_{t+1}, \xi_T | I_t)}{\Pr(\xi_{t+1} | I_t)}.$$

In view of Equation (4), the risk-neutral probability

$$h_{t+1}(\xi_T; \xi_{t+1}) = \frac{m(\xi_T)}{m_{t+1}} f_{t+1}(\xi_T; \xi_{t+1}).$$

Therefore

$$\frac{h_{t+1}(\xi_T; \xi_{t+1})}{h_{t+1}(x; \xi_{t+1})} = \frac{m(\xi_T) f_t(\xi_T) \lambda_t(\xi_{t+1}; \xi_T)}{m(x) f_t(x) \lambda_t(\xi_{t+1}; x)} = \frac{h_t(\xi_T) \lambda_t(\xi_{t+1}; \xi_T)}{h_t(x) \lambda_t(\xi_{t+1}; x)}. \quad (25)$$

Note that Assumption 2 ensures that for all  $\xi_{t+1}$ , the quantity  $\lambda_t(\xi_{t+1}; x)$  is always greater than zero. Using Equation (25), we obtain that

$$\begin{aligned} E \left[ \frac{h_{t+1}(\xi_T)}{h_{t+1}(x)} \middle| I_t^x \right] &= \sum_{\xi_{t+1}} \frac{h_{t+1}(\xi_T; \xi_{t+1})}{h_{t+1}(x; \xi_{t+1})} \lambda_t(\xi_{t+1}; x) \\ &= \sum_{\xi_{t+1}} \frac{h_t(\xi_T)}{h_t(x)} \frac{\lambda_t(\xi_{t+1}; \xi_T)}{\lambda_t(\xi_{t+1}; x)} \lambda_t(\xi_{t+1}; x) \\ &= \frac{h_t(\xi_T)}{h_t(x)} \sum_{\xi_{t+1}} \lambda_t(\xi_{t+1}; \xi_T) = \frac{h_t(\xi_T)}{h_t(x)}. \end{aligned}$$

By the law of iterated expectations, for  $t < s < T'$ ,

$$E \left[ \frac{h_s(\xi_T)}{h_s(x)} \middle| I_t^x \right] = \frac{h_t(\xi_T)}{h_t(x)}. \quad (26)$$

Suppose now that the security's final payoff is a function of  $\xi_T$ , that is,  $Z_T = Z(\xi_T)$ . Then the security's price at time  $t$  is

$$Z_t = \sum_{\xi_T} Z(\xi_T) h_t(\xi_T).$$

Using Equation (26), we obtain that

$$\begin{aligned} E \left[ \frac{Z_s}{h_s(x)} \middle| I_t^x \right] &= E \left[ \sum_{\xi_T} Z(\xi_T) \frac{h_s(\xi_T)}{h_s(x)} \middle| I_t^x \right] = \sum_{\xi_T} Z(\xi_T) E \left[ \frac{h_s(\xi_T)}{h_s(x)} \middle| I_t^x \right] \\ &= \sum_{\xi_T} Z(\xi_T) \frac{h_t(\xi_T)}{h_t(x)} = \frac{Z_t}{h_t(x)}. \end{aligned}$$

(2) When the security's payoff depends on the whole history, that is,  $Z_T = Z(I_T)$ , the proof is essentially the same. This time, however, we need to establish an analogue of Equation (26) for the elementary state  $I_T = (\xi_1, \dots, \xi_T)$ .

Recall that  $F_t(I_T)$  and  $H_t(I_T)$  denote the conditional objective and risk-neutral probabilities of the elementary state  $I_T$ . At time  $t+1$ , the objective probability  $F_{t+1}(I_T) = F_{t+1}(I_T; \xi_{t+1})$  depends on the state  $\xi_{t+1}$ :

$$F_{t+1}(I_T; \xi_{t+1}) = \frac{F_t(I_T) \iota_{t+1}(\xi_{t+1}; I_T)}{\sum_{I'_T} F_t(I'_T) \iota_{t+1}(\xi'_{t+1}; I'_T)} = \frac{\Pr(\xi_{t+1}, I_T | I_t)}{\Pr(\xi_{t+1} | I_t)},$$

where  $\iota_t(y; I_T)$  is the indicator function equal to one if the  $t$ th component of vector  $I_T$  is  $y$  (i.e.,  $\xi_t = y$ ) and zero otherwise. The risk-neutral probability  $H_{t+1}(I_T; \xi'_{t+1})$  can be written as

$$\frac{H_{t+1}(I_T; \xi_{t+1})}{h_{t+1}(x; \xi_{t+1})} = \frac{H_t(I_T)}{h_t(x)} \frac{\iota_{t+1}(\xi_{t+1}; I_T)}{\lambda_t(\xi_{t+1}; x)}. \quad (27)$$

Therefore

$$\begin{aligned} E \left[ \frac{H_{t+1}(I_T)}{h_{t+1}(x)} \middle| I_t^x \right] &= \sum_{\xi_{t+1}} \frac{H_{t+1}(I_T; \xi_{t+1})}{h_{t+1}(x; \xi_{t+1})} \lambda_t(\xi_{t+1}; x) \\ &= \frac{H_t(I_T)}{h_t(x)} \sum_{\xi_{t+1}} \iota_{t+1}(\xi_{t+1}; I_T) = \frac{H_t(I_T)}{h_t(x)}. \end{aligned}$$

This implies that, for  $t < s < T'$ ,

$$E \left[ \frac{H_s(I_T)}{h_s(x)} \middle| I_t^x \right] = \frac{H_t(I_T)}{h_t(x)}.$$

Since the security's time- $t$  price is

$$Z_t = \sum_{I_T} Z(I_T) H_t(I_T),$$

we obtain that

$$E \left[ \frac{Z_s}{h_s(x)} \middle| I_t^x \right] = \sum_{I_T} Z(I_T) \left[ \frac{H_s(I_T)}{h_s(x)} \middle| I_t^x \right] = \sum_{I_T} Z(I_T) \frac{H_t(I_T)}{h_t(x)} = \frac{Z_t}{h_t(x)}.$$

■

**Proof of Proposition 3.** The proof of Proposition 3 is a slight modification of the proof of Proposition 2. In part (1), the ratio of risk-neutral probabilities in Equation (25) must now be expressed in terms of the *subjective* transition probabilities instead of the *objective* ones. However, by Assumption 3 we have  $\lambda_t^S(\xi_{t+1}; \xi_T) = \lambda_t(\xi_{t+1}; \xi_T)$ . In this case, Equation (25) becomes.

$$\frac{h_{t+1}(\xi_T; \xi_{t+1})}{h_{t+1}(x; \xi_{t+1})} = \frac{h_t(\xi_T) \lambda_t^S(\xi_{t+1}; \xi_T)}{h_t(x) \lambda_t^S(\xi_{t+1}; x)} = \frac{h_t(\xi_T) \lambda_t(\xi_{t+1}; \xi_T)}{h_t(x) \lambda_t(\xi_{t+1}; x)},$$

and the rest of the proof is the same.

Similarly, in part (2), Equation (27) must now be replaced by

$$\frac{H_{t+1}(I_T; \xi_{t+1})}{h_{t+1}(x; \xi_{t+1})} = \frac{H_t(I_T)}{h_t(x)} \frac{u_{t+1}(\xi_{t+1}; I_T)}{\lambda_t^S(\xi_{t+1}; x)} = \frac{H_t(I_T)}{h_t(x)} \frac{u_{t+1}(\xi_{t+1}; I_T)}{\lambda_t(\xi_{t+1}; x)}.$$

(Note that the indicator function  $u_{t+1}(\xi_{t+1}; I_T)$  is the same for both the objective and subjective probabilities.) Then the rest of the proof follows through. ■

**Proof of Proposition 4.** (1) We first prove that Assumptions 4 and 6 imply that.

$$P^x = Q^x = R^x, \quad \text{all } x.$$

Recall that the measures  $P$ ,  $Q$ , and  $R$  are equivalent on  $(\Omega, \mathcal{F}_T)$ . Let  $\phi_T$  denote the Radon–Nikodym derivative of  $R$  with respect to  $Q$ :

$$\phi_T := \frac{dR}{dQ}.$$

For any  $\mathcal{F}_{T'}$ -measurable random variable  $Z$  and for  $t \leq T'$  we have

$$\begin{aligned} E^{R^x}[Z | \mathcal{F}_t] &= E^R[Z | \mathcal{F}_t^x] = \frac{E^Q[\phi_T Z | \mathcal{F}_t^x]}{E^Q[\phi_T | \mathcal{F}_t^x]} = \frac{\phi_T(x) E^Q[Z | \mathcal{F}_t^x]}{\phi_T(x)} \\ &= E^Q[Z | \mathcal{F}_t^x] = E^{Q^x}[Z | \mathcal{F}_t], \end{aligned}$$

where we use the fact that the Radon–Nikodym derivative  $\phi_T > 0$  is a *constant* when  $X = x$  (by Assumption 4). Since the above equation holds for all  $\mathcal{F}_{T'}$ -measurable random variables  $Z$ , the measures  $Q^x$  and  $R^x$  must coincide on  $(\Omega, \mathcal{F}_{T'})$ , or  $Q^x = R^x$ . In a similar fashion, it follows from Assumption 6 that  $P^x = Q^x$ .

(2) Consider now any random process  $(Z_t, \mathcal{F}_t, t \in T')$  which is  $R$ -martingale. Then, for  $t < s \leq T'$ ,

$$E_t^{P^x} \left[ \frac{Z_s}{\eta_s} \right] = E_t^{Q^x} \left[ \frac{Z_s}{\eta_s} \right] = E_t^{R^x} \left[ \frac{Z_s}{\eta_s} \right] = \frac{E_t^R[\eta_s Z_s / \eta_s]}{E_t^R[\eta_s]} = \frac{Z_t}{\eta_t},$$

where the third equality follows from Equation (14). To complete the proof, we also need to check the integrability condition on  $Z_s / \eta_s$ . Since  $(Z_t, \mathcal{F}_t, t \in T')$  is  $R$ -martingale,

$$E_t^{P^x} \left[ \left| \frac{Z_s}{\eta_s} \right| \right] = E_t^{P^x} \left[ \frac{|Z_s|}{\eta_s} \right] = \frac{E_t^R[|Z_s|]}{\eta_t} < \infty.$$

The last two conditions imply that the process  $(Z_t / \eta_t, \mathcal{F}_t, t \in T')$  is  $P^x$ -martingale. ■

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