

Bayesian sequential least-squares estimation for the drift of a Wiener process

Erik Ekström*, Ioannis Karatzas† and Juozas Vaicenavicius‡

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Abstract

Given a Wiener process with unknown and unobservable drift, we seek to estimate this drift as effectively but also as quickly as possible, in the presence of a quadratic penalty for the estimation error and of a linear cost per unit of observation time. In a Bayesian framework, this question reduces to choosing judiciously a stopping time for an appropriate diffusion process in natural scale; we provide structural properties of the solution for the corresponding problem of optimal stopping. In particular, regardless of the prior distribution, the continuation region is monotonically shrinking in time. Moreover, conditions on the prior distribution that guarantee a one-sided boundary are provided.

1 Introduction

Imagine trying to estimate a quantity about which there is considerable uncertainty, and which cannot be observed directly. Instead, one has access to a stream of observations that this unobservable quantity affects and, based on this stream, tries to find an estimator of the unobservable quantity which is “optimal” in the sense of least-squares. However, access to this stream of information is costly: one pays a fixed, positive cost per unit of time, for as long as information is being obtained. How does one resolve the dilemma inherent in this situation, which calls for balancing the conflicting requirements of fidelity in estimation and of cost minimization?

We study here an instance of this problem in a highly idealized and stylized form. Namely, we assume that the unobservable quantity is a square-integrable random variable

*Department of Mathematics, Uppsala University, 75106 Uppsala, Sweden (email: ekstrom@math.uu.se)

†Department of Mathematics, Columbia University, 2990 Broadway, New York, NY 10027, USA (email: ikl@columbia.edu); and INTECH Investment Management, One Palmer Square, Suite 441, Princeton, NJ 08542, USA (email: ikaratzas@intechjanus.com). Support from the National Science Foundation under grant NSF-DMS-14-05210 is gratefully acknowledged.

‡Department of Information Technology, Uppsala University, 75106 Uppsala, Sweden (email: juozas.vaicenavicius@it.uu.se)

X , and that one observes sequentially the stochastic process

$$Y(t) = Xt + W(t), \quad 0 \leq t < \infty. \quad (1.1)$$

Here W is a standard Brownian motion, independent of the random variable X . Moreover, adopting a Bayesian methodology, we assume that X has a known “prior” distribution μ which has finite second moment and is *non-atomic*; that is, we exclude the trivial case where μ is a one-point distribution. We posit that, at any given time $t \in [0, \infty)$, one has access to the observations

$$\sigma\{Y(s), 0 \leq s \leq t\};$$

we call the right-continuous augmentation $\mathbb{F}^Y = \{\mathcal{F}^Y(t)\}_{0 \leq t < \infty}$ of the family of σ -algebras $(\sigma\{Y(s), 0 \leq s \leq t\})_{0 \leq t < \infty}$ the so-called *observations filtration*, and set $\mathcal{F}^Y(\infty) := \sigma(\bigcup_{0 \leq t < \infty} \mathcal{F}^Y(t))$.

We denote by \mathcal{T}^Y the collection of stopping times of this filtration \mathbb{F}^Y ; to wit, the collection of random variables $\tau : \Omega \rightarrow [0, \infty)$ with $\{\tau \leq t\} \in \mathcal{F}^Y(t)$ for every $t \in [0, \infty)$. Based on the flow of information \mathbb{F}^Y , we construct the least-squares estimate

$$\widehat{X}(t) = \mathbb{E}[X | \mathcal{F}^Y(t)], \quad 0 \leq t < \infty$$

of the unobserved variable. In this work we seek to compute the minimal expected cost

$$C_* = \inf_{\tau \in \mathcal{T}^Y} C(\tau), \quad C(\tau) := \mathbb{E}[(X - \widehat{X}(\tau))^2 + c\tau], \quad (1.2)$$

and to determine whether it is attained by some stopping time $\tau_* \in \mathcal{T}^Y$. Here $c > 0$ is a given real constant, representing the cost of one unit of delay in the estimation procedure. The positivity of this constant, along with the obvious bound $C_* \leq C(0) = \text{Var}(X) < \infty$, implies that we may restrict attention in (1.2) to stopping times τ with $\mathbb{E}(\tau) < \infty$.

2 Preliminaries on the conditional mean and variance processes

In this section, we recall a general result regarding the conditional mean and variance processes from the theory of filtering. We build then on this result in order to unveil the structure of our problem at hand, as well as the stochastic dynamics of the processes that are crucial for its analysis.

2.1 Projecting onto the observations filtration

We first recall the conditional distribution of X given observations on the process Y . For a proof we refer to [1, Proposition 3.16].

Proposition 2.1. Consider a function $q : \mathbb{R} \rightarrow \mathbb{R}$ satisfying the integrability condition

$$\int_{\mathbb{R}} |q(u)| \mu(du) < \infty.$$

Then, for any $t \geq 0$, we have

$$\mathbb{E}[q(X) | \mathcal{F}^Y(t)] = \frac{\int_{\mathbb{R}} q(u) \exp\{uy - u^2t/2\} \mu(du)}{\int_{\mathbb{R}} \exp\{uy - u^2t/2\} \mu(du)}.$$

On the strength of Proposition 2.1, we have

$$\widehat{X}(t) := \mathbb{E}[X | \mathcal{F}^Y(t)] = G(t, Y(t)) \quad (2.1)$$

for the conditional expectation of X given the observations up to time $t \in (0, \infty)$, where

$$G(t, y) := \frac{\int_{\mathbb{R}} u \exp\{uy - u^2t/2\} \mu(du)}{\int_{\mathbb{R}} \exp\{uy - u^2t/2\} \mu(du)} = \int_{\mathbb{R}} u \mu_{t,y}(du) \quad (2.2)$$

and

$$\mu_{t,y}(du) := \frac{\exp\{uy - u^2t/2\} \mu(du)}{\int_{\mathbb{R}} \exp\{uy - u^2t/2\} \mu(du)}. \quad (2.3)$$

This measure $\mu_{t,y}$ is the conditional (“posterior”) distribution of X at time t , given the values $Y(u)$, $0 \leq u < t$ and $Y(t) = y$ of the observation process up to that time. We have a similar computation for the conditional variance

$$\text{Var}(X | \mathcal{F}^Y(t)) = \mathbb{E}[(X - \widehat{X}(t))^2 | \mathcal{F}^Y(t)] = \mathbb{E}[X^2 | \mathcal{F}^Y(t)] - \widehat{X}^2(t) = H(t, Y(t))$$

of X given the observations up to time $t \in (0, \infty)$, where

$$\begin{aligned} H(t, y) &:= \frac{\int_{\mathbb{R}} u^2 \exp\{uy - u^2t/2\} \mu(du)}{\int_{\mathbb{R}} \exp\{uy - u^2t/2\} \mu(du)} - \left(\frac{\int_{\mathbb{R}} u \exp\{uy - u^2t/2\} \mu(du)}{\int_{\mathbb{R}} \exp\{uy - u^2t/2\} \mu(du)} \right)^2 \\ &= \int_{\mathbb{R}} u^2 \mu_{t,y}(du) - \left(\int_{\mathbb{R}} u \mu_{t,y}(du) \right)^2 = \int_{\mathbb{R}} (u - G(t, y))^2 \mu_{t,y}(du). \end{aligned} \quad (2.4)$$

It is straightforward from (2.2), (2.4) that the quantities $G(t, y)$, $H(t, y)$ are, respectively, the center of gravity and the second central moment of the measure $\mu_{t,y}$ in (2.3); to wit,

$$G(t, y) = \mathbb{E}[X | Y(u), 0 \leq u < t; Y(t) = y], \quad H(t, y) = \text{Var}[X | Y(u), 0 \leq u < t; Y(t) = y].$$

The function G of (2.2) is strictly increasing in its spatial variable, has partial derivatives of all orders on $(0, \infty) \times \mathbb{R}$, and satisfies on this strip the *Backwards Burgers equation*

$$\partial G + \frac{1}{2} D^2 G + G \cdot DG = 0. \quad (2.5)$$

On the other hand, the gradient of the function G , i.e., the function

$$H = DG$$

of (2.4), is positive on the strip $(0, \infty) \times \mathbb{R}$ and satisfies there the equation

$$\partial H + \frac{1}{2} D^2 H + G \cdot DH + H^2 = 0. \quad (2.6)$$

Here and throughout, we are denoting by $\partial \equiv \partial/\partial t$ the partial derivative with respect to the temporal argument t , and by $D^k \equiv \partial^k/\partial y^k$ the partial derivative of order $k = 1, 2, \dots$ with respect to the spatial argument, in this case y .

Remark 2.2. (*Bijections.*) Let now \mathcal{I}_μ denote the interior of the smallest closed interval containing the support of the probability measure μ , i.e.,

$$\mathcal{I}_\mu = (\inf(\mathcal{S}_\mu), \sup(\mathcal{S}_\mu)) \quad \text{with} \quad \mathcal{S}_\mu := \text{supp}(\mu). \quad (2.7)$$

Then, for any given $t \in [0, \infty)$, the function

$$G_t(\cdot) \equiv G(t, \cdot) : \mathbb{R} \rightarrow \mathcal{I}_\mu$$

defined in (2.2) is a strictly increasing, continuous bijection (see also [3]). The strict increase of this function $G_t(\cdot)$ implies that $Y(t) = G_t^{-1}(\widehat{X}(t))$ holds for $0 \leq t < \infty$. To wit, the observation processes Y and the least-squares estimate process \widehat{X} are bijections of each other pointwise in time, and thus generate the same filtration.

In particular, $G_t^{-1}(x)$ is the unique value of the observation process $Y(t)$ at time t , that yields $\widehat{X}(t) = x$.

Remark 2.3. (*The Widder Transform.*) The derivation of the parabolic backwards partial differential equations (2.5), (2.6) is facilitated by the observation that G is itself the logarithmic gradient $G = D \log F$ of the function

$$F(t, y) := \int_{\mathbb{R}} \exp \left\{ uy - \frac{t}{2} u^2 \right\} \mu(du), \quad (t, y) \in (0, \infty) \times \mathbb{R} \quad (2.8)$$

that appears in the denominators of (2.2), (2.4). It is checked easily that this function, the so-called *Widder Transform* of the prior distribution μ , solves the backward heat equation

$$\partial F + \frac{1}{2} D^2 F = 0.$$

Conversely, as shown by Widder [14] and Robbins & Siegmund [10], every positive solution of this backward heat equation can be written in the form (2.8), in terms of an appropriate measure μ on $\mathcal{B}(\mathbb{R})$. For a probabilistic treatment and development of the relevant theory, see Section 3.4.B in [7].

For technical convenience, we shall impose henceforth the following integrability condition:

Assumption 2.4. For some real number $a > 0$, the prior distribution μ satisfies

$$\int_{\mathbb{R}} \exp\{au^2\} \mu(du) < \infty. \quad (2.9)$$

Assumption 2.4 is a rather mild requirement in the sense that, for any $t > 0$, the integrability condition (2.9) is satisfied by the posterior distribution $\mu_{t,y}$ of any prior μ . The assumption allows us to extend the definition of $\mu_{t,y}$ in (2.3) above, to include points of the type $(0, y)$; and the resulting $\mu_{0,y}$ coincides with the posterior distribution in a scenario with prior distribution

$$\xi(du) := \frac{\exp\{au^2/2\} \mu(du)}{\int_{\mathbb{R}} \exp\{au^2/2\} \mu(du)},$$

conditional on observing $Y(a) = y$. Consequently, the points $(0, y)$ can be regarded as interior points for a shifted problem started instead at time $-a$; it is therefore clear that, for instance, (2.5) holds then on the whole domain $[0, \infty) \times \mathbb{R}$.

2.2 Dynamics under the observations filtration

The process

$$\widehat{W}(t) := Y(t) - \int_0^t \widehat{X}(s) ds = \int_0^t (X - \widehat{X}(s)) ds + W(t), \quad 0 \leq t < \infty, \quad (2.10)$$

known as the *innovation process* in the theory of filtering, is clearly adapted to the observations filtration \mathbb{F}^Y . It is also a Brownian motion of this filtration, as it is continuous, an \mathbb{F}^Y -martingale, and has the right quadratic variation; for instance, see [1, Proposition 2.30 on p. 33].

We write $\mathbb{F}^{\widehat{W}} = (\mathcal{F}^{\widehat{W}}(t))_{0 \leq t < \infty}$ for the right-continuous augmentation of the filtration $\sigma\{\widehat{W}(s) : 0 \leq s \leq t\}$, $0 \leq t < \infty$ that this process generates; similarly, we shall use the notation $\mathbb{F}^{\widehat{X}} = (\mathcal{F}^{\widehat{X}}(t))_{0 \leq t < \infty}$ for the right-continuous augmentation of the filtration generated by \widehat{X} , the process in (2.1), and $\mathbb{F}^Y = (\mathcal{F}^Y(t))_{0 \leq t < \infty}$ for the right-continuous augmentation of the filtration generated by the observation process Y . Clearly, and in light of Remark 2.2, we have the comparisons $\mathbb{F}^{\widehat{W}} \subseteq \mathbb{F}^Y = \mathbb{F}^{\widehat{X}}$.

We deduce now from (2.1), (2.10) the representation for the observations process

$$dY(t) = \widehat{X}(t) dt + d\widehat{W}(t) = G(t, Y(t)) dt + d\widehat{W}(t) \quad (2.11)$$

as the solution of a stochastic differential equation driven by the innovations process \widehat{W} , with initial condition $Y(0) = 0$. Because of the smoothness of the function G , this equation admits a pathwise unique, strong solution, so we deduce the filtration identities

$$\mathbb{F}^{\widehat{W}} = \mathbb{F}^Y = \mathbb{F}^{\widehat{X}}. \quad (2.12)$$

On the other hand, with the notation $G_t(\cdot) = G(t, \cdot)$ already introduced in Remark 2.2, we let

$$\Psi(t, x) := DG(t, G_t^{-1}(x)) = H(t, G_t^{-1}(x)). \quad (2.13)$$

An application of Itô's formula to (2.1) yields, in conjunction with (2.5) and (2.11), a stochastic differential equation for the conditional mean process \widehat{X} of (2.1), namely,

$$d\widehat{X}(t) = \Psi(t, \widehat{X}(t)) d\widehat{W}(t), \quad \widehat{X}(0) = \mathbb{E}(X) = \int_{\mathbb{R}} u \mu(du). \quad (2.14)$$

The function Ψ of (2.13), the dispersion of the stochastic differential equation right above, can be expressed as

$$\Psi(t, x) = H(t, G_t^{-1}(x)) = \text{Var}[X \mid \widehat{X}(u), 0 \leq u < t; \widehat{X}(t) = x],$$

and a bit more generally

$$\Psi(t, \widehat{X}(t)) = H(t, G_t^{-1}(\widehat{X}(t))) = H(t, Y(t)) = \text{Var}[X \mid \mathcal{F}^Y(t)]. \quad (2.15)$$

Furthermore, it is checked with the help of (2.5), (2.6) that the function $\Psi > 0$ of (2.13) satisfies on the strip $(0, \infty) \times \mathcal{I}_\mu$ the fully nonlinear, backwards parabolic equation

$$\partial\Psi + \Psi^2 \left(\frac{1}{2} D^2\Psi + 1 \right) = 0. \quad (2.16)$$

Once again, we denote differentiation with respect to the temporal argument by ∂ , and differentiation with respect to the spatial argument by D .

Finally, we recall from [3, Proposition 3.6] the following result about the function Ψ .

Proposition 2.5 (Properties of the dispersion function Ψ).

1. $\partial\Psi \leq 0$; consequently, by (2.16), $D^2\Psi \geq -2$.
2. If μ is compactly supported, then the function Ψ is bounded.

3 Optimal Stopping

The above considerations show that the optimal stopping problem (1.2) can be cast in the form

$$\inf_{\tau \in \mathcal{T}} \mathbb{E} \left[\Psi(\tau, \widehat{X}(\tau)) + c\tau \right]. \quad (3.1)$$

Here Ψ is the function of (2.13), the process \widehat{X} satisfies the dynamics of (2.14), and \mathcal{T} stands for the collection of stopping times of the filtration $\mathbb{F}^{\widehat{X}} = \mathbb{F}^{\widehat{W}} = \mathbb{F}^Y$, as in (2.12).

It is a noteworthy feature of this problem, that the same function Ψ of (2.13) appears both as the dispersion of the diffusion \widehat{X} in (2.14), *and* as the cost function for this new formulation of the optimal stopping problem in (3.1). This feature makes the problem rather special, and aids considerably its analysis in Sections 4, 5.

Proposition 3.1. *For any stopping time $\tau \in \mathcal{T}$ we have*

$$\mathbb{E}[\Psi(\tau, \widehat{X}(\tau))] = \text{Var}(X) - \mathbb{E} \left[\int_0^\tau \Psi^2(s, \widehat{X}(s)) ds \right]. \quad (3.2)$$

Proof. From (1.1) and the strong law of large numbers for Brownian motion, we have $\lim_{t \rightarrow \infty} (Y(t)/t) = X$, a.e.; in other words, the random variable X is $\mathcal{F}^Y(\infty)$ -measurable. As a result, the P.Lévy martingale convergence theorem gives $\lim_{t \rightarrow \infty} \mathbb{E}(X^k | \mathcal{F}^Y(t)) = \mathbb{E}(X^k | \mathcal{F}^Y(\infty)) = X^k$ a.e., for $k = 1, 2$; therefore also

$$\lim_{t \rightarrow \infty} \Psi(t, \widehat{X}(t)) = \lim_{t \rightarrow \infty} \left(\mathbb{E}(X^2 | \mathcal{F}^Y(t)) - \left(\mathbb{E}(X | \mathcal{F}^Y(t)) \right)^2 \right) = 0$$

on the strength of (2.15). Now it follows from the dynamics in (2.14), the partial differential equation in (2.16), and elementary stochastic calculus, that the positive process

$$\begin{aligned} M(t) &:= \Psi(t, \widehat{X}(t)) + \int_0^t \Psi^2(s, \widehat{X}(s)) ds \\ &= \text{Var}(X) + \int_0^t \Psi(s, \widehat{X}(s)) D\Psi(s, \widehat{X}(s)) d\widehat{W}(s), \quad 0 \leq t < \infty \end{aligned}$$

is a local martingale. It is thus also a supermartingale, and consequently

$$\mathbb{E} \left(\Psi(\tau, \widehat{X}(\tau)) + \int_0^\tau \Psi^2(s, \widehat{X}(s)) ds \right) \leq \text{Var}(X)$$

holds by the optional sampling theorem for every stopping time $\tau \in \mathcal{T}$; this includes $\tau = \infty$, so we have also

$$\mathbb{E} \int_0^\infty \Psi^2(s, \widehat{X}(s)) ds \leq \text{Var}(X).$$

We shall show presently that, as claimed in (3.2), these last two displayed inequalities hold actually as equalities.

In order to see these things, let us start from the observation that the representation

$$\widehat{X}(\tau) = \mathbb{E}(X) + \int_0^\tau \Psi(s, \widehat{X}(s)) d\widehat{W}(s) \quad (3.3)$$

from (2.14) holds for every stopping time $\tau \in \mathcal{T}$, including $\tau = \infty$: the martingale \widehat{X} and the submartingale \widehat{X}^2 are both uniformly integrable. Thus, the representation

$$X - \widehat{X}(\tau) = \int_\tau^\infty \Psi(s, \widehat{X}(s)) d\widehat{W}(s)$$

holds, as does the analogue

$$\text{Var}(X | \mathcal{F}^Y(\tau)) = \mathbb{E} \left[(X - \widehat{X}(\tau))^2 | \mathcal{F}^Y(\tau) \right] = \Psi(\tau, \widehat{X}(\tau)) = \mathbb{E} \left(\int_\tau^\infty \Psi^2(s, \widehat{X}(s)) ds \mid \mathcal{F}^Y(\tau) \right)$$

of (2.15); this, in turn, leads to

$$\mathbb{E}\left[\text{Var}(X \mid \mathcal{F}^Y(\tau))\right] = \mathbb{E}(X - \widehat{X}(\tau))^2 = \mathbb{E}\Psi(\tau, \widehat{X}(\tau)) = \mathbb{E}\int_{\tau}^{\infty} \Psi^2(s, \widehat{X}(s)) \, ds.$$

In addition, (3.3) gives

$$\text{Var}\left(\mathbb{E}(X \mid \mathcal{F}^Y(\tau))\right) = \text{Var}(\widehat{X}(\tau)) = \mathbb{E}\int_0^{\tau} \Psi^2(s, \widehat{X}(s)) \, ds.$$

From these computations, and from a classical identity about variances, we deduce

$$\begin{aligned} \text{Var}(X) &= \mathbb{E}\left[\text{Var}(X \mid \mathcal{F}^Y(\tau))\right] + \text{Var}\left(\mathbb{E}(X \mid \mathcal{F}^Y(\tau))\right) \\ &= \mathbb{E}\left(\Psi(\tau, \widehat{X}(\tau)) + \int_0^{\tau} \Psi^2(s, \widehat{X}(s)) \, ds\right), \end{aligned}$$

that is, our claim (3.2). With the choice $\tau = \infty$, these considerations give the identity $\mathbb{E}\int_0^{\infty} \Psi^2(s, \widehat{X}(s)) \, ds = \text{Var}(X)$, as claimed. \square

Equation (3.2) shows that the optimal stopping problem of (1.2)/(3.1) is equivalent to the problem

$$v := \inf_{\tau \in \mathcal{T}} \mathbb{E}\left[\int_0^{\tau} (c - \Psi^2(s, \widehat{X}(s))) \, ds\right]. \quad (3.4)$$

3.1 Markovian Framework

To study the optimal stopping problem in its new form (3.4), we first embed it into a Markovian framework, by allowing the diffusion \widehat{X} to start at any given point $(t, x) \in [0, \infty) \times \mathcal{I}_{\mu}$. More precisely, we define the function $v : [0, \infty) \times \mathcal{I}_{\mu} \rightarrow (-\infty, 0]$ via

$$v(t, x) := \inf_{\tau \in \mathcal{T}} \mathbb{E}\left[\int_0^{\tau} (c - \Psi^2(t+s, \widehat{X}^{t,x}(t+s))) \, ds\right], \quad (3.5)$$

where the process $\widehat{X} = \widehat{X}^{(t,x)}$ is given by

$$\begin{cases} d\widehat{X}(t+s) = \Psi(t+s, \widehat{X}(t+s)) \, d\widehat{W}(s) \\ \widehat{X}(t) = x. \end{cases}$$

Since $\tau = 0$ is an admissible stopping time, the value function v in (3.5) is non-positive: $v \leq 0$. On the other hand, it is clear from (3.1), (3.2) that $v(t, x) \geq -\text{Var}(X) > -\infty$, so v is also real-valued, as indicated.

In accordance with standard optimal stopping theory, we introduce the so-called continuation region

$$\mathcal{C} := \{(t, x) \in [0, \infty) \times \mathcal{I}_{\mu} : v(t, x) < 0\}$$

and its complement, the stopping region

$$\mathcal{D} := \{(t, x) \in [0, \infty) \times \mathcal{I}_{\mu} : v(t, x) = 0\}.$$

Moreover, for a given starting point (t, x) , we denote by

$$\tau^{(t,x)} := \inf \{s \geq 0 : (t+s, \widehat{X}^{(t,x)}(t+s)) \in \mathcal{D}\}$$

the first hitting time of the stopping region. Then we know (for instance, [5], [13], [12], [4]) that the function $v : [0, \infty) \times \mathcal{I}_\mu \rightarrow [0, \infty)$ of (3.5) is upper-semicontinuous, and that for each $(t, x) \in [0, \infty) \times \mathcal{I}_\mu$ the stopping time $\tau^{(t,x)}$ attains the infimum there, i.e.,

$$v(t, x) = \mathbb{E} \left[\int_0^{\tau^{t,x}} \left(c - \Psi^2(t+s, \widehat{X}^{(t,x)}(t+s)) \right) ds \right].$$

Remark 3.2. It is clear from the formulation (3.5) that immediate stopping ($\tau^{(t,x)} = 0$) is optimal, if the inequality

$$c \geq \sup_{(t,x) \in [0, \infty) \times \mathcal{I}_\mu} \Psi^2(t, x) = \sup_{x \in \mathcal{I}_\mu} \Psi^2(0, x) \quad (3.6)$$

holds; here, the equality follows from Proposition 2.5. A bit more generally, if

$$c \geq \sup_{x \in \mathcal{I}_\mu} \Psi^2(T_c, x)$$

holds for some $T_c \in (0, \infty)$, then the strip $[T_c, \infty) \times \mathcal{I}_\mu$ belongs to the stopping region \mathcal{D} .

3.2 A very simple special case: The Gaussian distribution

As an illustration, let us consider the Gaussian prior distribution μ with mean $m \in \mathbb{R}$ and variance $\sigma^2 \in (0, \infty)$, i.e.,

$$\mu(du) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp \left\{ -\frac{(u-m)^2}{2\sigma^2} \right\} du,$$

a special case of the Kalman-Bucy filter. Here we have $\mathcal{I}_\mu = \mathbb{R}$, and the functions F , G , H and Ψ take the respective forms

$$F(t, y) = \frac{1}{\sqrt{2\pi\sigma^2}\sqrt{1+\sigma^2t}} \exp \left\{ -\frac{1}{2\sigma^2} \left(\frac{(m+\sigma^2y)^2}{1+\sigma^2t} - m^2 \right) \right\}$$

$$G(t, y) = \frac{m+\sigma^2y}{1+\sigma^2t}, \quad H(t, y) = \Psi(t, x) = \frac{\sigma^2}{1+\sigma^2t} =: \xi(t).$$

Now, the function $t \mapsto c - \xi^2(t)$ is negative for $t \in [0, \frac{1}{\sqrt{c}} - \frac{1}{\sigma^2})$ if $\sqrt{c} < \sigma^2$, and it is everywhere non-negative if $\sqrt{c} \geq \sigma^2$. With

$$\tau_* := \left(\frac{1}{\sqrt{c}} - \frac{1}{\sigma^2} \right)^+,$$

it follows from Remark 3.2 that the above constant τ_* is an optimal (albeit trivial!) stopping time in (3.4).

In [2], a similar result is obtained in the case when W is a fractional Brownian motion.

4 A Time-Homogeneous case: the Bernoulli Distribution

Let us now consider the Bernoulli prior distribution

$$\mu = (1 - p)\delta_{-\beta} + p\delta_{\beta}$$

with symmetric support, where $p \in (0, 1)$ and $\beta \in (0, \infty)$. Since the problem is translation invariant (in the prior), and since we embed the problem so that we consider all possible starting points simultaneously, the solution below also covers the case of any (not necessarily symmetric) Bernoulli distribution.

In this case we have $\mathcal{I}_{\mu} = (-\beta, \beta)$, as well as

$$G(t, y) = \beta \frac{p e^{\beta y} - (1 - p) e^{-\beta y}}{p e^{\beta y} + (1 - p) e^{-\beta y}}, \quad \text{thus} \quad H(t, y) = \beta^2 - G^2(t, y)$$

and

$$\Psi(t, x) = \beta^2 - x^2 =: \psi(x).$$

We note that we are here at the opposite extreme of the example in subsection 3.2: All these are functions of only the spatial variable; and the last of them does not even depend on the parameter $p \in (0, 1)$.

The stopping problem (3.4) thus takes the form

$$v(x) = \inf_{\tau \in \mathcal{T}} \mathbb{E} \left[\int_0^{\tau} \left(c - \psi^2(\widehat{X}(t)) \right) dt \right] \quad (4.1)$$

where \widehat{X} is a diffusion in natural scale, with state-space $\mathcal{I}_{\mu} = (-\beta, \beta)$ and initial condition $x \in \mathcal{I}_{\mu}$:

$$\begin{cases} d\widehat{X}(t) = \psi(\widehat{X}(t)) d\widehat{W}(t) \\ \widehat{X}(0) = \beta(2p - 1) =: x \in \mathcal{I}_{\mu}. \end{cases} \quad (4.2)$$

We note that for $\beta^4 \leq c$, the integrand in (4.1) is non-negative, and hence the trivial stopping time $\tau_* \equiv 0$ is optimal.

Thus, we assume from now onwards that

$$c > \beta^4;$$

then $c - \psi^2(x)$ is negative for $|x| < \gamma$ with

$$\gamma := \sqrt{\beta^2 - \sqrt{c}},$$

zero for $|x| = \gamma$, and positive for $\gamma < |x| < \beta$. Conjecturing that an optimal stopping rule is of the type

$$\tau_a^* := \inf \{ t \geq 0 : |\widehat{X}(t)| \geq a \} \quad (4.3)$$

for some constant $a \in (\gamma, \beta)$, general optimal stopping theory leads to the following free-boundary problem:

To find a constant $a \in (\gamma, \beta)$ and an evenly symmetric function $u : (-\beta, \beta) \rightarrow (-\infty, 0]$ of class $\mathcal{C}^1((-\beta, \beta)) \cap \mathcal{C}^2((-\beta, \beta) \setminus \{-a, a\})$, such that

$$\begin{cases} u(x) < 0, & (\psi^2(x)/2)u''(x) + c - \psi^2(x) = 0; & x \in [0, a), \\ u(x) = 0, & c - \psi^2(x) > 0; & x \in [a, \beta); \end{cases} \quad (4.4)$$

and then to argue that the function u coincides with the minimum expected cost v in (4.1).

In the two paragraphs that follow we shall show that this problem admits a unique solution, which coincides with the value function v of (4.1) and can be computed explicitly.

4.1 Verification

Indeed, if such a function u with the above properties exists, the process

$$N := u(\widehat{X}) - u(x) - \int_0^\cdot \frac{1}{2}(\psi^2 u'')(\widehat{X}(t))dt = \int_0^\cdot (\psi u')(\widehat{X}(t))d\widehat{W}(t)$$

is a local martingale. The function $\psi u'$ is continuous, and supported on the compact interval $[-a, a]$, thus bounded. Therefore, for any stopping time $\tau \in \mathcal{T}$ with $\mathbb{E}(\tau) < \infty$, we have

$$\mathbb{E}(N^2(\tau)) = \mathbb{E} \int_0^\tau (\psi u')^2(\widehat{X}(t))dt \leq \|\psi u'\|_\infty^2 \mathbb{E}(\tau) < \infty.$$

As a consequence, $N(\cdot \wedge \tau)$ is a square-integrable martingale, and $\mathbb{E}(N(\tau)) = 0$ holds, leading to

$$u(x) = \mathbb{E}[u(\widehat{X}(\tau))] - \mathbb{E} \int_0^\tau \frac{1}{2}(\psi^2 u'')(\widehat{X}(t))dt \leq \mathbb{E} \int_0^\tau (c - \psi^2(\widehat{X}(t))) dt \quad (4.5)$$

on account of the inequalities $u \leq 0$, $(\psi^2/2)u'' + c - \psi^2 \geq 0$ from (4.4).

We repeat now the above reasoning for the stopping time τ_a^* defined in (4.3). This satisfies the property $\mathbb{E}(\tau_a^*) < \infty$, as is checked by considering the diffusion process \widehat{X} of (4.2) on the interval $[-a, a]$ as its state-space, and recalling Proposition 5.5.32 (i) in [7]. For this stopping time, both inequalities summoned to justify the last comparison in (4.5) hold as equalities, and thus so does (4.5) itself:

$$u(x) = \mathbb{E} \int_0^{\tau_a^*} (c - \psi^2(\widehat{X}(t))) dt. \quad (4.6)$$

Now (4.5) and (4.6) show that the stopping time τ_a^* is optimal for the problem of (4.1), among all stopping times with finite expectation. As we argued in the discussion following (1.2), these are the only relevant times for the stopping problem under consideration, and we are done: $u(x) = v(x)$ holds for every $x \in \mathcal{I}_\mu$.

In particular, there can exist at most one solution to the free-boundary problem.

4.2 Construction

For a given constant $a \in (0, \infty)$, the recipe

$$u(x) := 2 \int_x^a \left(\int_y^a \frac{\psi^2(\xi) - c}{\psi^2(\xi)} d\xi \right) dy, \quad 0 \leq x \leq a \quad (4.7)$$

defines a function that satisfies the equation $(\psi^2(x)/2)u''(x) + c - \psi^2(x) = 0$ in (4.4), as well as the “smooth-fit” conditions” $u(a) = u'(a-) = 0$.

We extend this function by even symmetry to all of $[-a, a]$. For the resulting extension to have the claimed smoothness, we need the condition $u'(0+) = 0$, namely

$$\int_0^a \frac{d\xi}{\psi^2(\xi)} = \frac{a}{c}. \quad (4.8)$$

Now, the function $Q(x) := \int_0^x \psi^{-2}(y)(c - \psi^2(y)) dy$, $0 < x < \beta$ satisfies $Q(0) = 0$, decreases strictly on $(0, \gamma)$, and increases strictly to infinity on (γ, β) . It attains its overall minimum at $x = \gamma$, namely,

$$Q(\gamma) = \int_0^\gamma \frac{c - \psi^2(\xi)}{\psi^2(\xi)} d\xi < 0.$$

Therefore, there exists a unique number $a \in (\gamma, \beta)$ that satisfies $Q(a) = 0$, i.e., (4.8).

With the constant a thus chosen, $c - \psi^2(x) > 0$ holds for every $x \in [a, \beta)$; setting

$$u(x) := 0, \quad x \in (a, \beta) \quad (4.9)$$

and extending again by even symmetry, we obtain a function u defined via (4.7), (4.9) on all of $\mathcal{I}_\mu = (-\beta, \beta)$; this function satisfies all the requirements of the free-boundary problem in (4.4). From what we have proved so far, the function u emerges as the unique solution of this problem, as well as the minimum expected cost in (4.1); that is, $v \equiv u$.

5 Structural properties

In contrast to the two examples discussed above, the typical situation is that the stopping and continuation regions are not so easily described. Thus, general methods to determine their structural properties are of considerable interest.

For this purpose, the following monotonicity result will prove useful. It is based on the observation, that the term Ψ^2 appearing in the integrand in (3.5) coincides with the instantaneous quadratic variation rate of the underlying process \widehat{X} (we extend the function Ψ to be equal to zero outside $[0, \infty) \times \mathcal{I}_\mu$). This suggests a time-change of the martingale \widehat{X} in the manner of Dambis-Dubins-Schwarz (e.g., Theorem 3.4.6 and Problem 3.4.7 in [7]). We follow the construction given in [6], where two diffusion processes in natural scale with the same starting point, but with different dynamics, are constructed as time-changes of the *same* Brownian motion.

Theorem 5.1. *Assume that two distributions μ_i , $i = 1, 2$ are given and that the corresponding variance functions Ψ_i in (2.13) satisfy $\Psi_1(t, x) \geq \Psi_2(t, x)$ for all $(t, x) \in [0, \infty) \times \mathbb{R}$. Then the corresponding value functions v_i , $i = 1, 2$ of (3.5) satisfy $v_1(t, x) \leq v_2(t, x)$ for all $(t, x) \in [0, \infty) \times \mathbb{R}$.*

Proof. It suffices to show that $v_1(0, x) \geq v_2(0, x)$; the case of a general time variable is similar. For $x \in \mathbb{R}$, let B be a one-dimensional Brownian motion with $B(0) = x$. Let $\tau_i(\cdot)$, $i = 1, 2$, be the unique stopping time solution (see [6]) of the integral equation

$$\tau_i(t) = \int_0^t \Psi_i^2(\theta, B(\tau_i(\theta))) d\theta, \quad 0 \leq t < \infty.$$

Then the process $X_i(t) := B(\tau_i(t))$, $0 \leq t < \infty$, is a solution of the stochastic integral equation

$$X_i(s) = x + \int_0^s \Psi_i(u, X_i(u)) dB_i(u), \quad 0 \leq s < \infty$$

for some Brownian motion B_i . Consequently, the distribution of $\{X_i(s), s \geq 0\}$ coincides with the distribution of $\{\widehat{X}_i^{(0,x)}(s), s \geq 0\}$, for $i = 1, 2$.

Furthermore, it follows from [6, Lemma 10] that

$$\tau_1(t) \geq \tau_2(t) \tag{5.1}$$

holds for all $t \geq 0$. Now, let γ_2 be a stopping time (of the right-continuous augmentation of the filtration generated by the process X_2) which minimizes

$$\mathbb{E} \left[c\gamma - \int_0^\gamma \Psi_2^2(s, X_2(s)) ds \right] = \mathbb{E} [c\gamma - \tau_2(\gamma)]$$

over all stopping times γ . Define

$$\gamma_1 := \inf\{s \geq 0 : \tau_1(s) > \tau_2(\gamma_2)\}$$

so that $\tau_1(\gamma_1) = \tau_2(\gamma_2)$, and note that (5.1) implies that $\gamma_1 \leq \gamma_2$. Then γ_1 is a stopping time for the process X_1 , but not necessarily an optimal one. Consequently,

$$\begin{aligned} v_2(0, x) &= \mathbb{E} \left[c\gamma_2 - \int_0^{\gamma_2} \Psi_2^2(s, X_2(s)) ds \right] = \mathbb{E} [c\gamma_2 - \tau_2(\gamma_2)] \\ &\geq \mathbb{E} [c\gamma_1 - \tau_1(\gamma_1)] = \mathbb{E} \left[c\gamma_1 - \int_0^{\gamma_1} \Psi_1^2(s, X_1(s)) ds \right] \geq v_1(0, x), \end{aligned}$$

which completes the proof. \square

As we have seen, the structure of the stopping region \mathcal{D} depends crucially on the prior distribution μ ; however, we note the following consequence of Theorem 5.1, which provides a very general structural result with respect to the temporal parameter.

Corollary 5.2. (Contracting continuation region.) *The function $t \mapsto v(t, x)$ is non-decreasing, for every fixed $x \in \mathcal{I}_\mu$. Consequently, the t -section of the stopping region, namely,*

$$\mathcal{D}_t := \{x \in \mathcal{I}_\mu : (t, x) \in \mathcal{D}\},$$

is increasing in time: $\mathcal{D}_{t_1} \subseteq \mathcal{D}_{t_2}$ for $0 \leq t_1 \leq t_2$.

Proof. Consider two time points t_i , $i = 1, 2$ with $t_1 < t_2$, and define $\Psi_i(t, x) = \Psi(t_i + t, x)$ for $(t, x) \in [0, \infty) \times \mathcal{I}_\mu$. Since, on the strength of Proposition 2.5, the function $\Psi(\cdot, x)$ is decreasing, we have $\Psi_1(t, x) \geq \Psi_2(t, x)$ for each $(t, x) \in [0, \infty) \times \mathcal{I}_\mu$. It then follows from Theorem 5.1 that the corresponding value functions satisfy $v_1(0, x) \leq v_2(0, x)$, which is equivalent to $v(t_1, x) \leq v(t_2, x)$.

Thus $x \in \mathcal{D}_{t_1}$ (i.e., $v(t_1, x) = 0$) leads to $v(t_2, x) = 0$, i.e., to $x \in \mathcal{D}_{t_2}$. \square

Corollary 5.3. (Comparison with the Bernoulli distribution.) *For $\beta > 0$, let $a = a(\beta) > 0$ be the optimal stopping boundary-point for the Bernoulli distribution with support $\{-\beta, \beta\}$ as determined in Section 4. For a “prior” distribution μ , recall the notation of (2.7).*

(i) *Assume that $\mathcal{S}_\mu \subseteq [-\beta, \beta]$. Then $\mathcal{C} \subseteq [0, \infty) \times (-a, a)$.*

(ii) *Assume that $\mathcal{S}_\mu \subseteq (-\infty, -\beta] \cup [\beta, \infty)$, with $\mathcal{S}_\mu \cap (-\infty, -\beta] \neq \emptyset$ and $\mathcal{S}_\mu \cap [\beta, \infty) \neq \emptyset$. Then $\mathcal{C} \supseteq [0, \infty) \times (-a, a)$.*

Proof. It is straightforward to check that among all distributions with support contained in $[-\beta, \beta]$ and expected value $x \in [-\beta, \beta]$, the Bernoulli distribution

$$\frac{\beta - x}{2\beta} \delta_{-\beta} + \frac{\beta + x}{2\beta} \delta_\beta \tag{5.2}$$

is the one with the largest variance. Consequently, if $\mathcal{S}_\mu \subseteq [-\beta, \beta]$, then $\Psi(t, x) \leq \beta^2 - x^2 = \psi(x)$. Therefore, (i) follows from Theorem 5.1.

Similarly, among all distributions μ with $\mathcal{S}_\mu \cap (-\beta, \beta) = \emptyset$ and with expected value $x \in (-\beta, \beta)$, the one with the smallest variance is the Bernoulli distribution in (5.2). Consequently, $\Psi(t, x) \geq \beta^2 - x^2$ for all $x \in \mathcal{I}_\mu$, and (ii) follows as above, on account of Theorem 5.1. \square

We restrict now attention to sub-classes of prior distributions, for which further structural properties can be derived. We first have the following well-known result from optimal stopping theory (see for instance [8, Remark, page 217]).

Lemma 5.4. *Assume that $\Psi^2(t, x) > c$ at some point $(t, x) \in [0, \infty) \times \mathcal{I}_\mu$. Then $(t, x) \in \mathcal{C}$.*

Proof. By the continuity of the function Ψ^2 , there exists a real number $\varepsilon > 0$ and a rectangle $\mathcal{R} = [t_1, t_2) \times (a, b) \subseteq [0, \infty) \times \mathcal{I}_\mu$ with $(t, x) \in \mathcal{R}$, and $\Psi^2 - c > \varepsilon$ on \mathcal{R} . Denoting by

$$\tau_{\mathcal{R}} := \inf \{s \geq 0 : (t + s, \widehat{X}(t + s)) \notin \mathcal{R}\},$$

we have

$$v(t, x) \geq \mathbb{E} \left[\int_0^{\tau_{\mathcal{R}}} \left(c - \Psi^2(t + s, \widehat{X}(t + s)) \right) ds \right] \leq -\varepsilon \mathbb{E}[\tau_{\mathcal{R}}] < 0,$$

which shows that $(t, x) \in \mathcal{C}$. □

We provide next conditions, under which the stopping region is one-sided. We shall use the notation $\bar{\mathcal{I}}_\mu = \mathcal{I}_\mu \cup \{a, b\}$, where $a = \inf(\mathcal{S}_\mu)$ and $b = \sup(\mathcal{S}_\mu)$ are the (possibly infinite) boundary points of \mathcal{I}_μ , as in (2.7).

Proposition 5.5. (One-sided stopping region.) *Assume that, for every fixed time $t \geq 0$, the function $x \mapsto \Psi(t, x)$ (equivalently, the function $y \mapsto H(t, y)$) is non-decreasing. Then the following statements hold.*

(i) *There exists a non-decreasing function $b : [0, \infty) \rightarrow \bar{\mathcal{I}}_\mu$ such that the optimal continuation region is of the form*

$$\mathcal{C} = \{(t, x) \in [0, \infty) \times \mathcal{I}_\mu : x > b(t)\}.$$

(ii) *With $\Psi(t, \infty) := \lim_{x \rightarrow \infty} \Psi(t, x)$, let*

$$T := \inf \{t \geq 0 : \Psi^2(t, \infty) \leq c\}.$$

Then $b(t) \in \mathcal{I}_\mu$ for all $t < T$, and $b(t) = \sup(\mathcal{S}_\mu)$ for $t \geq T$, as in (2.12).

(iii) *If $x \mapsto \Psi(t, x)$ is strictly increasing for all $t \geq 0$, then the function $b : [0, \infty) \rightarrow \bar{\mathcal{I}}_\mu$ is continuous.*

Proof. (i) Without loss of generality, we consider the initial time $t = 0$. We consider two points $(0, x_1)$ and $(0, x_2)$ with $x_1, x_2 \in \mathcal{I}_\mu$ and $x_1 < x_2$. By comparison results for solutions of stochastic integral equations (see for instance [9, Theorem IX.3.7]), we obtain $\widehat{X}^{0, x_1}(s) \leq \widehat{X}^{0, x_2}(s)$ for all times $s \geq 0$. Therefore,

$$\mathbb{E} \left[\int_0^\tau \left(c - \Psi^2(s, \widehat{X}^{0, x_1}(s)) \right) ds \right] \geq \mathbb{E} \left[\int_0^\tau \left(c - \Psi^2(s, \widehat{X}^{0, x_2}(s)) \right) ds \right]$$

holds for any stopping time τ . Taking the infimum over all stopping times τ yields $v(0, x_1) \geq v(0, x_2)$. In particular, if $v(0, x_1) < 0$, then also $v(0, x_2) < 0$, which shows that \mathcal{C} has the claimed form. The monotonicity of b is immediate from Corollary 5.2.

(ii) With $t \geq T$, we have $\Psi(t + s, \cdot) \leq c$ for all $s \geq 0$ by Proposition 2.5(1), and the claim follows from Remark 3.2. For $t < T$, on the other hand, there are points $x \in \mathcal{I}_\mu$ with $\Psi(t, x) > c$, so the respective claim follows from Lemma 5.4.

(iii) The upper semi-continuity of v and the monotonicity of b imply $b(t) = b(t+)$ for all $t \geq 0$.

Next assume that $x \mapsto \Psi(t, x)$ is strictly increasing, and that $b(t_1-) < b(t_1)$ for some $t_1 > 0$. Since $(t_1, b(t_1)) \in \mathcal{D}$, it follows from Lemma 5.4 that $\Psi^2(t_1, b(t_1)) \leq c$.

Consequently, there exists an $\epsilon > 0$ and a rectangle $\mathcal{R} = (t_0, t_1) \times (x_1, x_2)$ with $t_0 < t_1$ and $b(t_1-) \leq x_1 < x_2 \leq b(t_1)$ such that $\mathcal{R} \subseteq \mathcal{C}$ and $\Psi^2 \leq c - \epsilon$ on \mathcal{R} . Moreover, $v(t_0, x_1) \leq v < 0$ on \mathcal{R} . For a starting point $(t, x) \in \mathcal{R}$, define

$$\tau_{\mathcal{R}}^{t,x} := \inf\{s \geq 0 : (t+s, \widehat{X}^{t,x}(t+s)) \notin \mathcal{R}\}$$

to be the first exit time from \mathcal{R} . Then

$$\begin{aligned} v(t, x) &= \mathbb{E} \left[\int_0^{\tau_{\mathcal{R}}^{t,x}} (c - \Psi^2(t+s, \widehat{X}^{t,x}(t+s))) ds \right] \\ &\geq \mathbb{E} \left[1_{\{\tau_{\mathcal{R}}^{t,x} \geq t_1-t\}} \int_0^{t_1-t} (c - \Psi^2(t+s, \widehat{X}^{t,x}(t+s))) ds \right] \\ &\quad + v(t_0, x_1) \mathbb{P}(\tau_{\mathcal{R}}^{t,x} < t_1-t) \\ &\geq \epsilon(t_1-t) \mathbb{P}(\tau_{\mathcal{R}}^{t,x} \geq t_1-t) + v(t_0, x_1) \mathbb{P}(\tau_{\mathcal{R}}^{t,x} < t_1-t). \end{aligned}$$

Here the first term is of size $\epsilon(t_1-t)$ for t close to t_1 , whereas the probability $\mathbb{P}(\tau_{\mathcal{R}}^{t,x} < t_1-t)$ is of order $o(t_1-t)$ as $t \rightarrow t_1$. Consequently, for each $x \in (x_1, x_2)$ there exists t close to t_1 such that $v(t, x) > 0$, which is a contradiction. This proves that $b(t_1-) = b(t_1)$, so b is continuous. \square

Remark 5.6. There is an analogue of Proposition 5.5 for problems in which the function $x \mapsto \Psi(t, x)$ is non-increasing for every fixed $t \geq 0$. Arguing exactly as above, this condition implies the existence of a non-increasing boundary b such that

$$\mathcal{C} = \{(t, x) : x < b(t)\}.$$

5.1 A case with a one-sided stopping region: the absolute value of a normal distribution

Let us consider a case where the prior belief is represented by the absolute value of a normally distributed random variable with mean 0 and variance σ^2 , i.e.,

$$\mu(du) = \sqrt{\frac{2}{\pi\sigma^2}} \exp\left\{-\frac{u^2}{2\sigma^2}\right\} du, \quad u \geq 0.$$

Then $\mathcal{I} = (0, \infty)$, and determined computation gives

$$H(t, y) = \frac{\sigma^2}{1 + \sigma^2 t} \left(1 - z \frac{\varphi(z)}{\Phi(z)} - \frac{\varphi^2(z)}{\Phi^2(z)} \right) \Big|_{z=Z(t,y)}, \quad \text{for } Z(t, y) := \frac{\sigma^2 y}{\sigma \sqrt{1 + t\sigma^2}}$$

and

$$\varphi(b) = \frac{1}{\sqrt{2\pi}} \exp\{-b^2/2\}, \quad \Phi(a) = \int_{-\infty}^a \varphi(b) db$$

for the function of (2.4). Note that this function satisfies

$$\lim_{y \rightarrow \infty} H(t, y) = \frac{\sigma^2}{1 + \sigma^2 t}$$

for $t \geq 0$, very much in accordance with section 3.2. Furthermore, $\Psi(t, \cdot)$ is increasing if and only if $H(t, \cdot)$ is increasing, and

$$DH(t, y) = \frac{\sigma \varphi(z)}{\Phi^5(z) \sqrt{1 + t\sigma^2 t}} \left(z^2 - 1 + 3z \frac{\varphi(z)}{\Phi(z)} + 2 \frac{\varphi^2(z)}{\Phi^2(z)} \right) \Big|_{z=Z(t,y)}.$$

To see that $DH \geq 0$, we follow an argument from [11]. It suffices to check that

$$f(z) := z^2 + 3z \frac{\varphi(z)}{\Phi(z)} + 2 \frac{\varphi^2(z)}{\Phi^2(z)} = \left(z + 2 \frac{\varphi(z)}{\Phi(z)} \right) \left(z + \frac{\varphi(z)}{\Phi(z)} \right) \geq 1.$$

Straightforward calculations give

$$\begin{aligned} f'(z) &= 2 \left(\frac{\varphi(z)}{\Phi(z)} + z \right) \left(1 - z \frac{\varphi(z)}{\Phi(z)} - \frac{\varphi^2(z)}{\Phi^2(z)} \right) + \frac{\varphi(z)}{\Phi(z)} (1 - f(z)) \\ &> \frac{\varphi(z)}{\Phi(z)} (1 - f(z)) \end{aligned} \quad (5.3)$$

at all points z . However, it is clear that $\lim_{z \rightarrow \infty} f(z) = \infty$, and using the expansion

$$\Phi(z) = \frac{\varphi(z)}{-z} \left(1 - \frac{1}{z^2} + o(1/z^2) \right)$$

for $z < 0$ yields $\lim_{z \rightarrow -\infty} f(z) = 1$. Therefore, if there is a finite root of the equation $f(z) = 1$, then there exists a finite z_0 with $f(z_0) \leq 1$ and $f'(z_0) = 0$, which contradicts (5.3). Therefore, $f \geq 1$ so $DH \geq 0$.

It now follows from Proposition 5.5 that the continuation region is one-sided and given by

$$\mathcal{C} = \{(t, x) \in [0, T) \times (0, \infty) : x > b(t)\}$$

for some continuous, non-decreasing function $b : [0, T) \rightarrow [0, \infty)$ with $b(T) := \lim_{t \uparrow T} b(t) = \infty$, where $T = \frac{1}{\sqrt{c}} - \frac{1}{\sigma^2}$.

6 Symmetric prior distributions

In this section we consider the special case when μ is symmetric around the origin with $\mathcal{I}_\mu = (-a, a)$ in (2.7), for some $a \in (0, \infty]$. Then the functions Ψ and v are also symmetric around the origin, in the sense that $\Psi(t, x) = \Psi(t, -x)$ and $v(t, x) = v(t, -x)$. Consequently, the optimal stopping problem can be re-written in terms of the reflected diffusion $Z = Z^{t,x} = |\widehat{X}^{t,x}|$ as

$$v(t, x) = \inf_{\tau \in \mathcal{T}} \mathbb{E} \left[\int_0^\tau \left(c - \Psi^2(t+s, Z^{t,x}(t+s)) \right) ds \right], \quad (t, x) \in [0, \infty) \times [0, a]. \quad (6.1)$$

Proposition 6.1. *Assume that μ is symmetric around the origin.*

(i) *Assume that, for every fixed time $t \geq 0$, the function $\Psi(t, \cdot) : [0, a] \rightarrow [0, \infty)$ is non-decreasing. Then there exist a point $t_0 \geq 0$ and a non-decreasing boundary $b : [t_0, \infty) \rightarrow [0, a]$ such that*

$$\mathcal{C} = ([0, t_0) \times \mathcal{I}_\mu) \cup \{(t, x) \in [t_0, \infty) \times \mathcal{I}_\mu : |x| > b(t)\}.$$

(ii) *Assume that, for every fixed time $t \geq 0$, the function $\Psi(t, \cdot) : [0, a] \rightarrow [0, \infty)$ is non-increasing. Then there exists a non-increasing boundary $b : [0, \infty) \rightarrow [0, a]$ such that*

$$\mathcal{C} = \{(t, x) \in [0, \infty) \times \mathcal{I}_\mu : |x| < b(t)\}.$$

Proof. Without loss of generality, we consider the initial time $t = 0$. For $x \geq 0$, let (\tilde{Z}, L) be the unique continuous process such that $L(0) = 0$, L is non-decreasing, $Z(0) = x$, $Z(s) \geq 0$ and

$$\begin{cases} d\tilde{Z}(s) = \Psi(s, \tilde{Z}(s)) d\widehat{W}(s) + dL(s) \\ \int_0^t 1_{\{\tilde{Z}(s)=0\}} dL(s) = L(t). \end{cases}$$

Then \tilde{Z} is the reflected version of \widehat{X} , and the processes $\{Z(s), s \geq 0\}$ and $\{\tilde{Z}(s), s \geq 0\}$ coincide in law. Moreover, by comparison we have that $x_1 \leq x_2$ implies that $\tilde{Z}^{x_1}(t) \leq \tilde{Z}^{x_2}(t)$ for all t . The proof then follows the proof of Proposition 5.5. \square

6.1 Symmetric Gaussian mixtures

We end the article with a study of the case when the prior is given by a symmetric Gaussian mixture. More precisely, let μ be given by

$$\mu(du) = \frac{1}{2\sigma\sqrt{2\pi}} \left(\exp \left\{ -\frac{(u-m)^2}{2\sigma^2} \right\} + \exp \left\{ -\frac{(u+m)^2}{2\sigma^2} \right\} \right) du$$

with $m \in (0, \infty)$ and $\sigma > 0$, i.e. a mixture of two Gaussians $N(m, \sigma)$ and $N(-m, \sigma)$ (again, due to translation invariance, the symmetry of the prior about the origin is not essential for the example). Then

$$\begin{aligned} F(t, y) = & \frac{1}{2\sqrt{2\pi\sigma^2}\sqrt{1+\sigma^2t}} \left(\exp \left\{ -\frac{1}{2\sigma^2} \left(\frac{(m+\sigma^2y)^2}{1+\sigma^2t} - m^2 \right) \right\} \right. \\ & \left. + \exp \left\{ -\frac{1}{2\sigma^2} \left(\frac{(-m+\sigma^2y)^2}{1+\sigma^2t} - m^2 \right) \right\} \right), \end{aligned}$$

and straightforward calculations yield

$$H(t, y) = \frac{\sigma^2}{1+\sigma^2t} + \frac{4m^2}{(1+\sigma^2t)^2} \left(\exp \left\{ \frac{my}{1+\sigma^2t} \right\} + \exp \left\{ \frac{-my}{1+\sigma^2t} \right\} \right)^{-2}.$$

It follows that $\Psi(t, \cdot)$ is decreasing on $[0, \infty)$ and satisfies

$$\Psi(t, 0) = \frac{\sigma^2}{1 + \sigma^2 t} + \frac{4m^2}{(1 + \sigma^2 t)^2}, \quad \Psi(t, \infty) = \frac{\sigma^2}{1 + \sigma^2 t}.$$

Consequently, by (ii) of Proposition 6.1, there exists a non-increasing boundary $b : [0, \infty) \rightarrow [0, \infty]$ such that

$$\mathcal{C} = \{(t, x) \in [0, \infty) \times \mathcal{I}_\mu : |x| < b(t)\}.$$

Furthermore, $b(t) = \infty$ for $t \in [0, (c^{-1/2} - \sigma^{-2})^+)$ and $b(t) = 0$ for

$$t \geq \frac{1}{2\sqrt{c}} \left(1 - 2\sigma^{-2}\sqrt{c} + \sqrt{1 + 16m^2\sigma^{-4}c^{1/2}} \right)^+.$$

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We dedicate this paper to Dr. Beneš on the occasion of his upcoming 90th birthday, with affection and respect.

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