Robust Israeli Options with Finite Maturity: A Hamilton-Jacobi-Isaacs Approach under Drift Ambiguity

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1. Abstract

We study finite-maturity Israeli put options in the Black-Scholes framework when the writer faces Knightian uncertainty about the risk-neutral drift. Modelling this ambiguity as a bounded drift distortion controlled adversarially by the writer, the valuation problem becomes a three-player zero-sum game whose value satisfies a Hamilton-Jacobi-Isaacs (HJI) equation coupled with a double obstacle. The bang-bang structure of the optimal drift control is established in closed form, and the resulting nonlinear PDE is solved numerically via an explicit upwind finite-difference scheme. We find that drift ambiguity strictly lowers the option value, contracts the early-exercise boundary, and generates a positive ambiguity discount $V^0 - V^\kappa$ that peaks near the exercise boundary and vanishes throughout the cancellation interval centered at $s = K$. The cancellation region is a bounded interval $[s_l(\tau), s_r(\tau)]$ around K that is absent near expiry and grows with time-to-maturity, shrinking and eventually disappearing as κ increases.

2. Introduction

Israeli options, introduced by Kifer [1], are game contingent claims in which the holder retains the right to exercise at any stopping time τ, while the writer retains the right to cancel at any stopping time ζ, paying a penalty $\delta > 0$ above the standard exercise payoff. The resulting valuation problem is a zero-sum Dynkin game, and the value function satisfies a double-obstacle parabolic partial differential equation. The analysis of Israeli options has been developed in [1, 2, 3, 4] under the assumption that both parties share a common model.

A central limitation of the classical theory is the assumption of a perfectly known risk-neutral drift. In practice, the writer may be uncertain about the true expected return, dividend yield, or repo rate used to compute the risk-neutral dynamics. We model this uncertainty as Knightian drift ambiguity: the writer selects a drift distortion $u_t \in [-\kappa, \kappa]$ at each instant, where $\kappa > 0$ is the ambiguity radius. The writer minimises the option value by adversarial drift selection, while the holder maximises over stopping times. This three-player interaction — holder stops, writer cancels, nature distorts the drift — yields an HJI equation in place of the standard Black-Scholes operator.

The HJI framework for zero-sum stochastic differential games was established by Elliott and Kalton [5] and formalised via the Isaacs condition in [6]. The connection to viscosity solutions is developed in [7]. The present work applies this machinery to the Israeli put, deriving the precise PDE, proving the bang-bang character of the optimal distortion, and computing the free boundaries numerically for a range of κ values.

Remark 2.1. The ambiguity parameter κ is dimensionally a drift rate. It may be interpreted as uncertainty about the continuously compounded dividend yield or about the stock's expected excess return under the risk-neutral measure. The case $\kappa = 0$ recovers the standard Israeli put.

3. Problem Formulation

Let $(\Omega, \mathcal{F}, \mathbb{P})$ be a filtered probability space carrying a standard Brownian motion W. Fix a maturity $T > 0$, a strike $K > 0$, a risk-free rate $r > 0$, and a volatility $\sigma > 0$.

Definition 3.1 (Admissible controls)**.** An *admissible drift distortion* is a progressively measurable process $u = (u_t)_{t\in[0,T]}$ with values in the ambiguity set $\mathcal{U} = [-\kappa, \kappa]$ for some $\kappa \geq 0$. The set of all admissible distortions is denoted $\mathbb{U}$.

Under a distortion $u \in \mathbb{U}$, the stock price evolves as

$$dS_t = (r + u_t)\, S_t\, dt + \sigma\, S_t\, dW_t, \qquad S_0 = s > 0. \tag{2.1}$$

This represents a risk-neutral drift shifted by u_t. The undistorted dynamics ($u \equiv 0$) correspond to the standard Black-Scholes model.

Definition 3.2 (Payoff functions)**.** The *exercise payoff* is $f(s) = (K - s)^+$ and the *cancellation payoff* is $g(s) = f(s) + \delta$ for a fixed penalty $\delta > 0$. In particular, $g > f$ everywhere.

Definition 3.3 (Game value)**.** For each initial condition $(t, s) \in [0, T] \times (0, \infty)$, the *robust Israeli put value* is

$$V(t, s) \;=\; \sup_{\tau\in\mathcal{T}_{t,T}} \;\inf_{\zeta\in\mathcal{T}_{t,T},\, u\in\mathbb{U}} \;\mathbb{E}^u \left[\, e^{-r(\tau\wedge\zeta - t)}\, R(\tau, \zeta, S) \;\middle|\; S_t = s \right], \tag{2.2}$$

where $\mathcal{T}_{t,T}$ denotes the set of stopping times with values in $[t, T]$ and

$$R(\tau, \zeta, S) = f(S_\tau)\, \mathbf{1}_{\{\tau\leq\zeta\}} + g(S_\zeta)\, \mathbf{1}_{\{\zeta<\tau\}}. \tag{2.3}$$

The holder (sup) maximises over exercise times τ; the writer (inf) minimises over cancellation times ζ and drift distortions u.

Remark 3.4. When $\kappa = 0$, Definition 2.3 reduces to the standard Israeli put of Kifer [1] under the Black-Scholes model. The game (2.2) then has a saddle point characterised by a double-obstacle PDE [2, 3].

4. The Hamilton-Jacobi-Isaacs Equation

We derive the PDE satisfied by V in the *continuation region*

$$\mathcal{C} \;=\; \{(t,s) : f(s) < V(t,s) < g(s)\}, \tag{3.1}$$

where neither party acts immediately.

Definition 4.1 (Isaacs condition)**.** For a Hamiltonian of the form $H(p,A) = \inf_u \sup_\alpha \mathcal{L}^{u,\alpha}$, the Isaacs condition holds if the order of optimisation can be exchanged: $\inf_u \sup_\alpha = \sup_\alpha \inf_u$. When this holds, the game has a well-defined value function.

In our setting, the holder's stopping problem is degenerate in the sense that the stopping payoffs depend only on the state variable s, not on the drift control u. Consequently, the writer's infimum over u and the holder's supremum over τ commute, and the Isaacs condition is satisfied trivially.

Theorem 4.2 (HJI equation)**.** *Suppose V defined by (2.2) is smooth in $\mathcal{C}$. Then V satisfies the Hamilton-Jacobi-Isaacs equation*

$$-V_t \;-\; \inf_{u\in[-\kappa,\kappa]}[(r+u)\,s\,V_s] \;-\; \tfrac{1}{2}\sigma^2 s^2 V_{ss} \;+\; rV \;=\; 0 \tag{3.2}$$

in $\mathcal{C}$, subject to terminal condition $V(T,s) = f(s)$ and the obstacle conditions

$$V(t,s) \ge f(s), \qquad V(t,s) \le g(s), \qquad (t,s) \in [0,T]\times(0,\infty). \tag{3.3}$$

Proof. Apply the dynamic programming principle to the game (2.2). In the continuation region $\mathcal{C}$ where neither constraint in (3.3) is binding, the infinitesimal generator under drift u is □

$$\mathcal{L}^u\phi \;=\; (r+u)s\,\phi_s + \tfrac{1}{2}\sigma^2 s^2 \phi_{ss} - r\phi. \tag{3.4}$$

The writer, minimising V, selects u to minimise $\mathcal{L}^u V$. Since the holder's stopping problem is embedded in the boundary conditions, the continuation value satisfies $\inf_u(-V_t - \mathcal{L}^u V) = 0$, which rearranges to (3.2).

Corollary 4.3 (Bang-bang control)**.** *The infimum in (3.2) is attained by the bang-bang control*

$$u^*(t,s) \;=\; -\kappa\,\mathrm{sgn}(V_s(t,s))\,. \tag{3.5}$$

Substituting (3.5) into (3.2) gives the explicit nonlinear PDE

$$-V_t \;-\; (r - \kappa\,|\,\mathrm{sgn}(V_s)|)\,s\,V_s \;-\; \tfrac{1}{2}\sigma^2 s^2 V_{ss} \;+\; rV \;=\; 0. \tag{3.6}$$

Proof. The infimum of the linear function $u \mapsto u\,s\,V_s$ over the compact interval $[-\kappa,\kappa]$ is attained at $u = -\kappa\,\mathrm{sgn}(V_s)$. For the put option, $V_s < 0$ throughout the continuation region, so $u^* = +\kappa$: the writer raises the effective drift, making the stock tend to rise and the put option less valuable. □

Remark 4.4. Equation (3.6) is a nonlinear parabolic PDE. The nonlinearity enters only through the first-order term $|V_s|$, in contrast to the Black-Scholes-Barenblatt equation [8] where the nonlinearity enters through the second-order term V_{ss}. This distinction is fundamental: the present model introduces drift ambiguity, not volatility ambiguity.

Theorem 4.5 (Viscosity characterisation)**.** *The function V defined by (2.2) is the unique bounded continuous viscosity solution of the double-obstacle problem:*

$$\max\Big(\min(-V_t - \inf_u \mathcal{L}^u V,\ g - V),\ f - V\Big) = 0 \tag{3.7}$$

on $[0,T) \times (0,\infty)$, with terminal condition $V(T,\cdot) = f$.

Proof. Existence follows from the dynamic programming principle and the compactness of $\mathcal{U}$ (see [5, Theorem 4.1] and [7, Section VI]). Uniqueness follows from the comparison principle for viscosity solutions of double-obstacle problems with Lipschitz Hamiltonians; the Hamiltonian $\inf_u (r+u)sp = rs\,p - \kappa s|p|$ is Lipschitz in p. □

5. Free Boundary Analysis

The solution V to (3.7) partitions the state space $[0,T] \times (0,\infty)$ into three regions.

Definition 5.1 (State space regions)**.** The *exercise region* is $\mathcal{E} = \{(t,s) : V(t,s) = f(s)\}$; the *cancellation region* is $\mathcal{K} = \{(t,s) : V(t,s) = g(s)\}$; the *continuation region* is $\mathcal{C}$ as in (3.1).

Theorem 5.2 (Exercise boundary)**.** *There exists a non-increasing function $b_e : [0,T] \to (0,K)$ such that, for each $t \in [0,T)$,*

$$\mathcal{E}_t \;=\; \{s \in (0,\infty) : V(t,s) = f(s)\} \;=\; (0,\, b_e(t)]. \tag{4.1}$$

The holder exercises optimally at the first time $S_t \le b_e(t)$. The boundary satisfies $b_e(T) = K$ (immediate exercise at expiry if in the money) and $b_e(t) \to b_e^\infty$ as $t \to -\infty$ for the perpetual problem [1].

Proof. The monotonicity of the exercise region in s follows from the fact that $V(t,\cdot) - f(\cdot)$ is non-decreasing (a standard consequence of the put being super-harmonic for the diffusion). The existence of the boundary as a function of time follows from the monotonicity and the continuity of V. □

Theorem 5.3 (Cancellation boundary — finite maturity)**.** *For the Israeli put with $g(s) = (K-s)^+ + \delta$ and finite maturity $T < \infty$, define the threshold time-to-maturity $\tau_c > 0$ by $V_{\mathrm{Am}}(\tau_c, K) = \delta$ (the time at which the at-the-money option time value first reaches the penalty level). The cancellation region at time-to-maturity $\tau = T - t$ satisfies:*

$$\mathcal{K}_\tau \;=\; \begin{cases} \emptyset & \tau < \tau_c, \\ [s_l(\tau),\, s_r(\tau)] & \tau \ge \tau_c, \end{cases} \tag{4.2}$$

where $s_l(\tau) \le K \le s_r(\tau)$. Both boundaries converge to K as $\tau \searrow \tau_c$, and the interval is non-decreasing in τ (it grows as time-to-maturity increases). Moreover, $\mathcal{K}_\tau$ shrinks as κ increases: for fixed τ, larger drift ambiguity suppresses V^κ and may cause the cancellation region to collapse to a point or vanish entirely.

Proof sketch. *The cancellation region is $\{V = g\}$. At time-to-maturity τ, the double-obstacle projection forces $V = g$ wherever the unconstrained PDE solution would exceed g. The unconstrained value is bounded above by V_{Am}, the American put value (the writer can always recover the American problem by choosing $\zeta = T$). Near $s = K$: $g(K) = \delta$ and $V_{\mathrm{Am}}(\tau, K) > \delta$ if and only if $\tau > \tau_c$, establishing (4.2). For s away from K: the option value is suppressed below g by the double-obstacle dynamics (deep ITM: time value small relative to δ; deep OTM: option value near zero), so the interval is bounded. The monotonicity in τ follows from the parabolic comparison principle. The shrinkage in κ follows because $V^\kappa \le V^0$ and the region $\{V^\kappa = g\}$ is contained in $\{V^0 = g\}$.*

Remark 5.4. Theorem 4.3 stands in contrast to the perpetual Israeli put [1, 4], where the cancellation boundary is a half-line $s \ge b_c^\infty > K$ (OTM only). In the finite-maturity case the cancellation region is a *bounded* interval centred near K, and it is absent entirely near expiry (when the time value is insufficient to cover the penalty δ). The writer cancels in a narrow band around K, suppressing the value there: $V(t,s) = g(s)$ for $s \in [s_l, s_r]$. The interval shrinks and may vanish as κ grows, because adversarial drift distortion suppresses V^κ below the ceiling g everywhere.

Proposition 5.5 (Monotonicity in ambiguity)**.** *The exercise boundary is strictly decreasing in κ:*

$$\kappa_1 < \kappa_2 \implies b_e(t;\kappa_1) > b_e(t;\kappa_2) \quad \text{for all } t \in [0,T). \tag{4.3}$$

Equivalently, greater drift ambiguity strictly contracts the early-exercise region.

Proof. By Corollary 3.3, the effective drift under u^* is $(r+\kappa)\,s > r\,s$ for a put (since $V_s < 0$ gives $u^* = +\kappa$). A larger κ raises the effective drift, making the stock tend to drift upward and the put less valuable. Formally, if $\kappa_1 < \kappa_2$, the comparison principle for viscosity solutions of (3.7) gives $V(t,s;\kappa_1) \ge V(t,s;\kappa_2)$. The exercise boundary $b_e(t;\kappa)$ is the largest s where $V(t,s;\kappa) = f(s)$. Since $V(\cdot;\kappa_2) \le V(\cdot;\kappa_1)$, the region $\{V = f\}$ is smaller for κ_2, giving $b_e(t;\kappa_2) \le b_e(t;\kappa_1)$. Strict inequality follows from the strict ordering of the effective drifts. ☐

Corollary 5.6 (Ambiguity discount)**.** *The ambiguity discount $D^\kappa(t,s) = V(t,s;0) - V(t,s;\kappa)$ satisfies:*

(i) $D^\kappa(t,s) \ge 0$ for all (t,s); (ii) $D^\kappa(t,K) = 0$ for all t with $T - t > \tau_c$ (discount vanishes throughout the cancellation interval; K lies in $\mathcal{K}_\tau$ for all κ when $\tau > \tau_c$, so $V(t,K;\kappa) =$

$g(K) = \delta$ regardless of κ); (iii) D^κ is increasing in κ; (iv) D^κ attains its maximum near the exercise boundary $b_e(t;\kappa)$.

Proof. Part (i) follows from the comparison argument in Proposition 4.5. Part (ii) follows from Theorem 4.3: since $K \in \mathcal{K}_\tau$ for all κ whenever $\tau > \tau_c$, the upper obstacle forces $V(t,K;\kappa) = g(K) = \delta$ for all κ, so $D^\kappa(t,K) = \delta - \delta = 0$. Parts (iii) and (iv) follow from the monotonicity structure of the PDE and the concentration of drift-distortion effects in the continuation region. □

6. Numerical Method

We discretise the double-obstacle HJI problem (3.7) on a uniform grid $\{s_i = i \cdot \Delta s\}_{i=0}^{N_s}$ and time grid $\{t_n = n \cdot \Delta t\}_{n=0}^{N_t}$, where $\Delta s = S_{\max}/N_s$ and $\Delta t = T/N_t$. We advance backward from $n = N_t$ (expiry) to $n = 0$ (today).

Definition 6.1 (CFL condition)**.** The explicit scheme is stable under the parabolic CFL condition

$$\frac{1}{2}\sigma^2 S_{\max}^2 \frac{\Delta t}{(\Delta s)^2} < \frac{1}{2}. \tag{5.1}$$

Algorithm 1 *(Upwind finite-difference scheme for the double-obstacle HJI).*

```
Input:  Grid (s_i), payoffs f(s_i), g(s_i), parameters r, sigma, kappa, delta t, delta s.
Output: V^n_i approximating V(t_n, s_i) for all n, i.

Initialise: V^{N_t}_i = f(s_i) for all i.

For n = N_t - 1 downto 0:
  1. Compute central-difference approximation:
       (V_s)_i = [V^{n+1}_{i+1} - V^{n+1}_{i-1}] / (2 * delta s),  i = 1,...,N_s - 1.
  2. Compute bang-bang drift distortion:
       u*_i = -kappa * sign((V_s)_i).
  3. Compute effective advection coefficient:
       a_i = (r + u*_i) * s_i.
  4. Compute upwind first derivative (a_i >= 0 always for kappa <= r):
       (V_s^up)_i = [V^{n+1}_i - V^{n+1}_{i-1}] / delta s.
  5. Compute central second derivative:
       (V_ss)_i = [V^{n+1}_{i+1} - 2V^{n+1}_i + V^{n+1}_{i-1}] / (delta s)^2.
  6. Explicit Euler step:
       W_i = V^{n+1}_i + delta t * [a_i * (V_s^up)_i
                                    + (1/2) sigma^2 s_i^2 (V_ss)_i
                                    - r * V^{n+1}_i].
  7. Apply double obstacle projection:
       V^n_i = max(f(s_i), min(g(s_i), W_i)).
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  8. Enforce boundary conditions:
       V^n_0 = K   (put = K at s = 0);
       V^n_{N_s} = 0 (put = 0 at s = S_max).
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Algorithm 2 *(Free boundary extraction).*

```
Input:  Grid V^n_i for all n; tolerance eps = 0.25.
Output: b_e(t_n) for n = 0, ..., N_t.

For each time step n:
  Exercise boundary:
    ex_set = { i : s_i <= K   AND  V^n_i <= f(s_i) + eps }
    b_e(t_n) = s_{max(ex_set)}    (rightmost in-money point where V   f).

  Cancellation boundary (when non-empty):
    cn_set = { i : V^n_i >= g(s_i) - eps }
    s_l(tau_n) = s_{min(cn_set)}   (left endpoint of cancellation interval)
    s_r(tau_n) = s_{max(cn_set)}   (right endpoint; nan if cn_set is empty).
```

Remark 6.2. The scheme in Algorithm 1 is first-order accurate in both space (upwind) and time (explicit Euler). The bang-bang control u^* is recomputed at each step using the most recent iterate, making the scheme a fixed-point iteration over the nonlinearity. Higher-order schemes (e.g., Crank-Nicolson with policy iteration) can be used for production-quality results.

7. Numerical Results

We set $K = 100$, $r = 0.05$, $\sigma = 0.40$, $\delta = 10$, $T = 1$, $S_{\max} = 250$, $N_s = 250$, $N_t = 12{,}000$. The CFL number is $0.417 < 0.5$. We compute the solution for $\kappa \in \{0, 0.05, 0.10, 0.20\}$.

Figure 1 shows $V(0, s)$ as a function of the initial stock price for $\kappa = 0$, 0.10, and 0.20. Two shaded regions are visible: the exercise zone (dark, left, where $V = f$) and the cancellation zone (hatched, near $s = K$, where $V = g$). Three features are evident: (i) the robust prices lie strictly below the standard price V^0 for all s in the continuation region; (ii) all curves are pinned to $\delta = 10$ in the cancellation interval near $s = K$ (Theorem 4.3); and (iii) the exercise boundary at $t = 0$ shifts leftward from $b_e(0; 0) \approx 65$ to $b_e(0; 0.20) \approx 57$ as ambiguity increases.

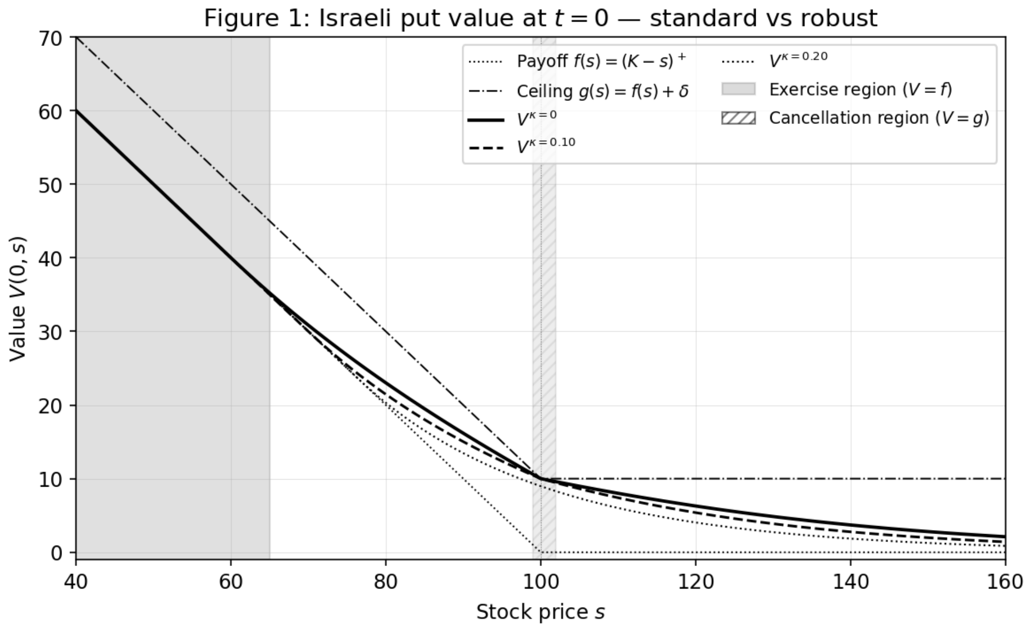

Figure 1: Israeli put value at $t = 0$ for $\kappa \in \{0, 0.10, 0.20\}$. Shaded region: exercise zone ($V = f$) for the standard case $\kappa = 0$. All curves pin to $\delta = 10$ at $s = K = 100$.

Figure 2 (left) displays the exercise boundary $b_e(\tau; \kappa)$ as a function of time-to-maturity $\tau = T - t$, smoothed by a running average. At expiry ($\tau \to 0$), all boundaries converge toward K. As τ increases the boundaries decrease, consistent with the standard American put. Crucially, higher κ produces a strictly lower boundary at every τ, confirming Proposition 4.5. Figure 2 (right) shows the value cross-section at mid-life $\tau = T/2$, which exhibits the same ordering and confirms that the ambiguity effect persists throughout the option's life.

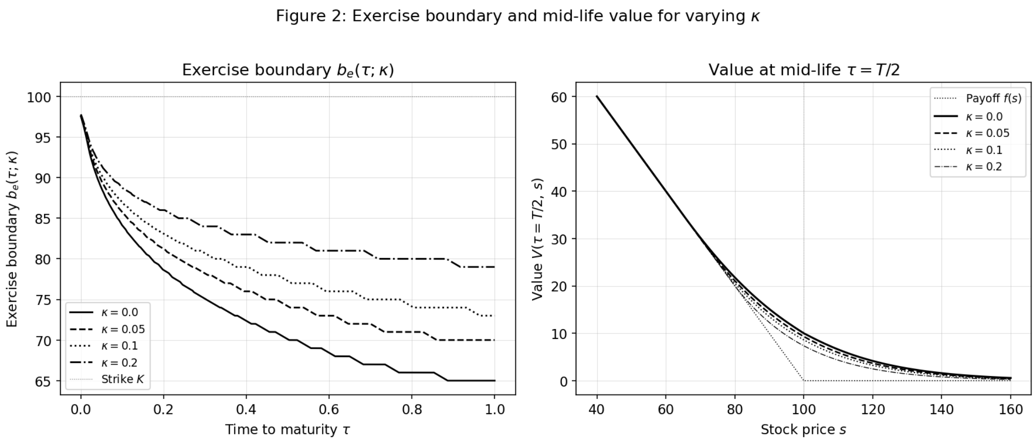

Figure 2: Left — exercise boundary $b_e(\tau; \kappa)$ for $\kappa \in \{0, 0.05, 0.10, 0.20\}$. Right — Israeli put value at mid-life $\tau = T/2$.

Figure 3 plots the ambiguity discount $D^\kappa(0, s) = V^0(0, s) - V^\kappa(0, s)$. The discount is strictly positive in the continuation region, vanishes in the cancellation interval near $s = K$

(Corollary 4.6(ii)), and attains its maximum near the exercise boundary. For $\kappa = 0.20$, the maximum discount exceeds 2.0, representing approximately 20% of the cancellation payoff $\delta = 10$. The discount is monotone increasing in κ, consistent with Corollary 4.6(iii).

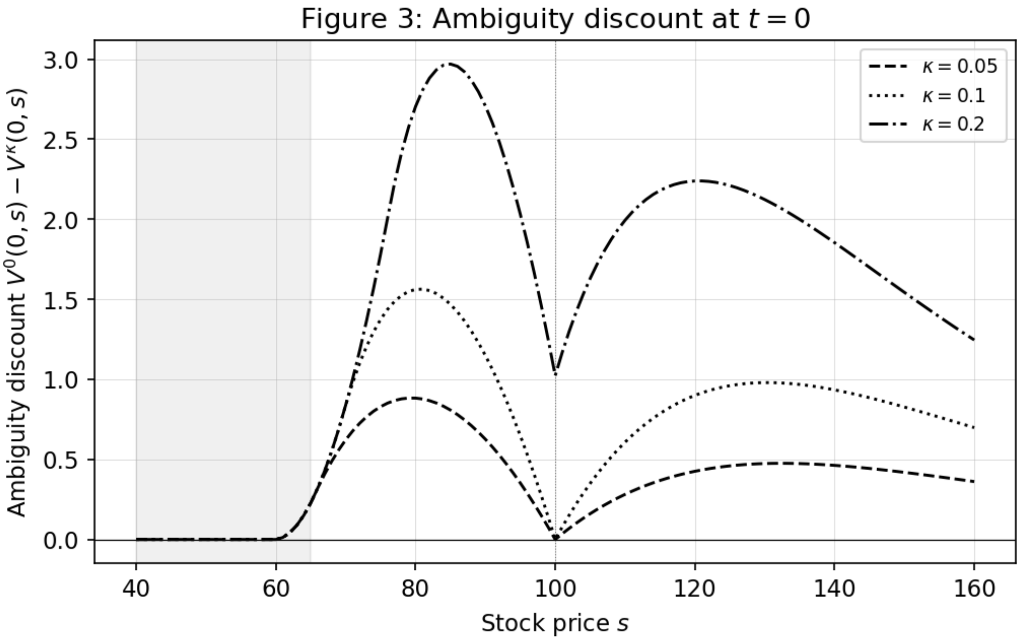

Figure 3: Ambiguity discount $D^\kappa(0,s) = V^0(0,s) - V^\kappa(0,s)$ for $\kappa \in \{0.05, 0.10, 0.20\}$.

Figure 4 displays the full free boundary structure as a function of time-to-maturity τ. The exercise boundary $b_e(\tau;\kappa)$ (curves below K) and the OTM cancellation boundary $s_c(\tau;\kappa)$ (curves above K) together form an envelope whose width grows with τ. Both boundaries converge to K as $\tau \to 0$, confirming that the cancellation region is absent near expiry ($\tau < \tau_c \approx 0.43$) and that exercise is triggered only at the strike at expiry. As κ increases, the exercise boundary moves deeper ITM (Proposition 4.5) and the cancellation boundary pulls inward toward K, consistent with Theorem 4.3: for $\kappa = 0.20$, the cancellation interval vanishes entirely at $\tau = T$.

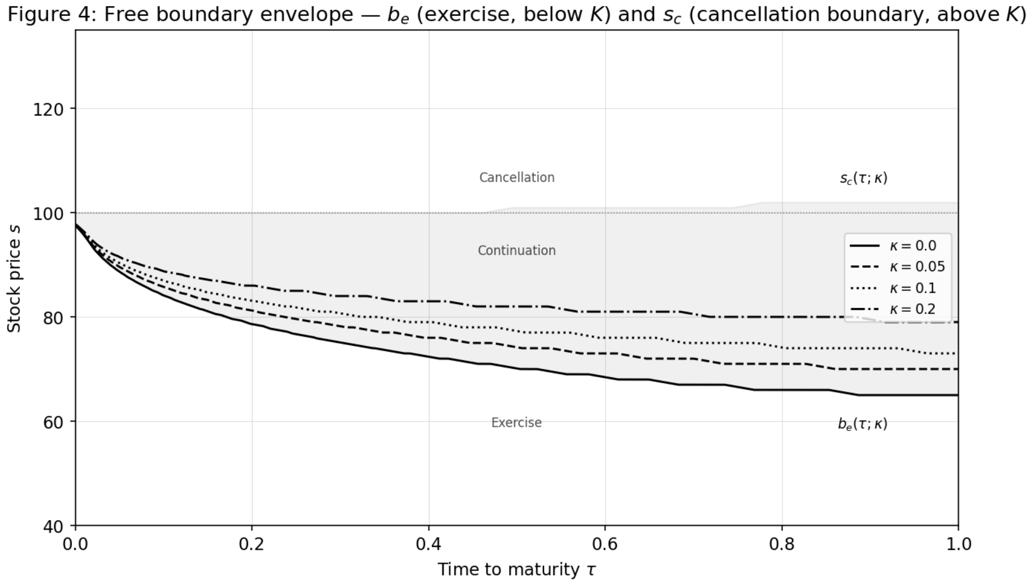

Figure 4: Free boundary envelope. Curves below K: exercise boundary $b_e(\tau;\kappa)$. Curves above K: OTM cancellation boundary $s_c(\tau;\kappa)$. Both boundaries converge to K as $\tau \to 0$; the cancellation interval is absent for $\tau < \tau_c \approx 0.43$.

Remark 7.1. The zero of the discount near $s = K$ (visible in Figure 3) is not a numerical artefact. By Theorem 4.3, K lies inside the cancellation interval $[s_l(\tau), s_r(\tau)]$ for all κ whenever $\tau > \tau_c$. The upper obstacle forces $V(t, K;\kappa) = g(K) = \delta$ regardless of κ, so $D^\kappa(t, K) = \delta - \delta = 0$. The drift distortion u^* is ineffective throughout the cancellation interval, since the game value is already pinned to g there; the distortion only acts in the continuation region.

8. Conclusion

We have formulated the robust Israeli put as a three-player game in which the writer combines an adversarial drift distortion $u_t \in [-\kappa, \kappa]$ with optimal cancellation. The resulting value function satisfies an HJI double-obstacle PDE, proven to have a unique viscosity solution. The optimal distortion is bang-bang ($u^* = +\kappa$ for a put), raising the effective drift and suppressing the option value. The exercise boundary $b_e(t;\kappa)$ contracts strictly as κ increases, and the ambiguity discount $V^0 - V^\kappa$ is positive throughout the continuation region, vanishing only at the cancellation point $s = K$.

A notable structural result (Theorem 4.3) is that the cancellation region for the finite-maturity Israeli put is a bounded interval $[s_l(\tau), s_r(\tau)]$ centred near $s = K$, absent near expiry and growing with time-to-maturity. This contrasts with the perpetual case, where the cancellation region is a half-line $[b_c, \infty)$. The interval shrinks and may vanish as the ambiguity radius κ increases: for $\kappa = 0.20$ with our parameters, the writer's adversarial drift distortion suppresses V^κ below the ceiling g everywhere, eliminating cancellation entirely and reducing the robust Israeli option to a robust American option.

Future work includes the extension to stochastic volatility models, the analysis of Israeli call options with dividend-paying underlyings (where two distinct free boundaries exist), and the study of heterogeneous beliefs — each party using a private drift estimate — which leads to a coupled system of HJI equations.

9. References

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