

Randomization and the American Put

Peter Carr

Morgan Stanley

While American calls on non-dividend-paying stocks may be valued as European, there is no completely explicit exact solution for the values of American puts. We use a technique called randomization to value American puts and calls on dividend-paying stocks. This technique yields a new semiexplicit approximation for American option values in the Black-Scholes model. Numerical results indicate that the approximation is both accurate and computationally efficient.

Closed-form solutions for the value of European-style options have been known since the seminal articles of Black and Scholes (1973) and Merton (1973). Since American calls on non-dividend-paying stocks are not rationally exercised early, they can be valued in closed form. Unfortunately, the vast majority of listed options are American style and are subject to early exercise. Despite a profusion of research on the subject, no completely satisfactory analytic solution for the value of such options has been found.

The principal difficulty in obtaining an analytic solution arises from the absence of a simple expression for

I thank the participants of presentations at the 1996 AFA Conference, the 1996 Columbia University Conference on Applied Probability, the 1996 Risk Congress, the 1996 Stanford University/LAFE Conference on Computational Finance, and the 1996 University of Warwick Options Conference. I would also like to thank participants of finance workshops at Cambridge University, the NYU Courant Institute, ESSEC, and Université Pierre et Marie Curie. In particular, I am grateful to an unknown referee, the editors Kerry Back and Ravi Jagannathan, as well as Michael Brennan, Darrell Duffie, Bernard Dumas, Dimitri Faguet, Nick Firoozye, Robert Jarrow, Herb Johnson, Eduardo Schwartz, Richard Skora, and especially Dilip Madan for many excellent suggestions. I would also like to acknowledge superb research assistance from Cem Inal, Jesse Yan, Guang Yang, and especially Dmitrije Frolov. Any errors are mine alone. Comments are welcome. Address correspondence to Peter Carr, Morgan Stanley, 1585 Broadway, 6th floor, New York, NY 14853, or e-mail:carrp@ms.com.

The Review of Financial Studies Fall 1998 Vol. 11, No. 3, pp. 597–626
© 1998 The Society for Financial Studies

the optimal exercise boundary. An exercise boundary is a time path of critical stock prices at which early exercise occurs. The optimal exercise boundary of an American option is not known *ex ante*, and must be determined as part of the solution to the valuation problem. Furthermore, it is difficult to analytically approximate American option values using boundary approximations that are consistent with the known short- and long-time behavior of the exercise boundary.

The purpose of this article is to develop a new approach for determining American option values and exercise boundaries based on a technique called randomization. In general, randomization describes a three-step procedure that can be used to solve a host of problems. The first step is to randomize a parameter by assuming a plausible distribution for it. The second step is to somehow calculate the expected value of the dependent variable in this random parameter setting. This is the difficult step since one does not know the dependent variable in the fixed parameter setting. The final step is to let the variance of the distribution governing the parameter approach zero, holding the mean of the distribution constant at the fixed parameter value.

For standard options, one can randomize the initial stock price, the strike price, the initial time, or the maturity date. In this article, we randomize the maturity date of an American option and determine the exact solution for its value. The owner of this random maturity American option can exercise at any time up to and including some random maturity date. Thus a random maturity American put gives its owner the right to sell an underlying security for a fixed price at any time up to and including its random maturity, while the call gives the corresponding right to buy. In this article the maturity date is determined by the waiting time to a prespecified number of jumps of a standard Poisson process, which is assumed to be independent of the underlying stock price process. We note that the only role of the Poisson process is to determine maturity; the stock price process used is continuous.

A random maturity contract has a value which approximates the value of its fixed maturity counterpart. In order to distinguish between these values, we refer to the former values as randomized. In general, the formulas for randomized values are simpler than the formulas for fixed maturity contracts. The simplest expression arises when the randomized American option matures at the first jump time of a Poisson process, in which case the maturity date is exponentially distributed. This random horizon problem is equivalent to an infinite horizon problem with an adjusted discount rate, as shown in a portfolio optimization setting by Cass and Yaari (1967) and Merton (1971). In the option pricing context, American options with infinite horizons were valued long ago by McKean (1965) and Samuelson (1965).

So it is somewhat natural that randomizing the maturity will lead to simpler option valuation formulas.¹

For American options, the simplicity of the solution arising from randomization is mainly due to the taming of the behavior of the exercise boundary. When the option matures with the first jump, the memoryless property of the exponential distribution implies that as calendar time elapses, the option gets no closer to its random maturity, and thus its value suffers no time decay. As the exercise value is also time stationary, the exercise boundary becomes independent of time as well. Thus the usual search for a time-dependent boundary is reduced to the search for a single critical stock price. When the underlying security has either no dividends or a constant continuous dividend flow, we can solve explicitly for the critical stock price. In contrast, if the underlying pays continuous proportional dividends, then a fairly simple algebraic equation must be solved numerically. As a result, the general formulation leads to semiexplicit valuation formulas.

While the assumption of an exponentially distributed maturity leads to simple approximations for American options, the approximation has too much error to be used in practice. To improve the approximation, we instead assume that the time to maturity may be subdivided into n independent exponential subperiods. Thus the randomized American option matures at the n th jump time of a standard Poisson process. The maturity time is thereby Erlang distributed with a mean equal to the fixed maturity date of the true American option. In this case the exercise boundary takes the form of a staircase, with the levels being determined by optimizing within each subperiod. The resulting expression for the randomized option value is a triple sum, involving no special functions other than the natural log.

As the number of random subperiods becomes large, the variance of the random maturity approaches zero, so that the Erlang probability density function governing maturity approaches a Dirac delta function centered at the American option's fixed maturity. Thus increasing the number of periods increases the accuracy of the solution at the expense of greater computational cost. However, when Richardson extrapolation is used, our numerical results indicate that our randomized option value converges to the true American option value in a computationally efficient manner.

The randomization approach taken in this article is to exactly value a contract which approximates the nature of an American option. An alternative approach is to approximate the valuation operator rather than the contract. This is the approach taken when finite differences [see, e.g., Brennan and Schwartz (1977)] are used to numerically solve the partial differential equation (PDE) governing the value of an American option. As is well known, the standard finite difference approach replaces all of the

¹ I thank the referee for this insight.

partial derivatives in a PDE with finite differences. When only the time derivative is discretized, the approach is termed the (horizontal) method of lines or Rothe's method [see Rothe (1930) and Rektorys (1982)]. The application of the method of lines to free boundary problems has been promulgated in Meyer (1970, 1979) and in Meyer and van der Hoek (1994), who use it to numerically value American options. Goldenberg and Schmidt (1995) test this numerical scheme against other approaches and find that it is highly accurate, although slightly slower than some other approaches.² Carr and Faguet (1994) give a semieexplicit solution to the sequence of ordinary differential equations which arise when the method of lines is applied to the Black-Scholes PDE. In fact, the solution obtained via randomization in this article is mathematically equivalent to the solution in Carr and Faguet.

The structure of this article is as follows. Section 1 reviews standard results on the pricing of American puts in the Black-Scholes model. Section 2 presents the randomization technique in the context of valuing an American put on a non-dividend-paying stock with an exponential maturity. Section 3 discusses the more general case of an Erlang distributed maturity. Section 4 discusses the implementation of our formula and compares this implementation with extant approaches in terms of both speed and accuracy. Section 5 extends the analysis to dividends and American calls. Section 6 summarizes and suggests directions for future research. An appendix collects all the formulas needed to implement the randomization approach.

1. American Put Valuation in the Black-Scholes Model

In this section we focus on the valuation of American puts in the Black-Scholes model. We defer the corresponding development for American calls until dividends have been introduced. The Black-Scholes model assumes that over the option's life $[0, T]$, the economy is described by frictionless markets, no arbitrage, a constant riskless rate $r > 0$, no dividends from the underlying stock, and that the underlying spot price process $\{S_t, t \in (0, T)\}$ is a geometric Brownian motion with a constant volatility rate $\sigma > 0$. Let $P(t, S; T)$ denote the value of an American put as a function of the current time t , the current stock price S , and the maturity date T . The critical stock price $\underline{S}(t; T)$, $t \in [0, T]$ is defined as the largest price S at which the American put value $P(t, S; T)$ equals its exercise value $K - S$, where K is the strike price. As the maturity is shortened, the alive American put value falls, while the exercise value remains constant. A reduction in time to maturity therefore raises the critical stock price at which exercise occurs.

² However, given the speed of modern computers, they argue that its inherent accuracy makes it the method of choice among those tested.

When graphed against time, the critical stock price is a smoothly increasing function termed the *exercise boundary*.

For quite general stochastic processes, the American put's initial value is given by the solution to an optimal stopping problem,

$$P(0, S; T) = \sup_{\tau_s \in [0, T]} E_{0, S} \{ e^{-r\tau_s} [K - S_{\tau_s}]^+ \}, \quad (1)$$

where τ_s is a stopping time and the expectation is calculated under the risk-neutral probability measure. In the Black-Scholes model, this optimal stopping time is the earlier of maturity and the first passage time to the exercise boundary. Consequently, the alive American put may alternatively be valued as

$$P(0, S; T) = \sup_{B(t); t \in [0, T]} E_{0, S} \{ e^{-r(\tau_B \wedge T)} [K - S_{\tau_B \wedge T}]^+ \}, \quad S > \underline{S}(0; T), \quad (2)$$

where $a \wedge b \equiv \min(a, b)$ and τ_B is the first passage time from S to an exercise boundary $B(t)$, $t \in [0, T]$.³

McKean (1965) showed that an application of Itô's lemma to Equation (1) implies that the alive American put value and exercise boundary jointly solve a free boundary problem, consisting of the Black-Scholes PDE:

$$\begin{aligned} \frac{\sigma^2}{2} S^2 P_{ss}(t, S; T) + r S P_s(t, S; T) - r P(t, S; T) &= P_T(t, S; T), \\ S \in (\underline{S}(t; T), \infty), t \in (0, T), \end{aligned} \quad (3)$$

the following terminal conditions:

$$P(T, S; T) = (K - S)^+, \quad S \in (\underline{S}(T; T), \infty), \quad \text{and} \quad \underline{S}(T; T) = K, \quad (4)$$

and the following boundary conditions:

$$\begin{aligned} \lim_{S \uparrow \infty} P(t, S; T) &= 0, \\ \lim_{S \downarrow \underline{S}(t; T)} P(t, S; T) &= K - \underline{S}(t; T), \\ \lim_{S \downarrow \underline{S}(t; T)} P_s(t, S; T) &= -1, \quad t \in (0, T). \end{aligned} \quad (5)$$

Boundary value problems arising in option valuation usually require one terminal condition and two boundary conditions to determine a unique solution. The extra terminal condition in Equation (4) and the extra boundary condition in Equation (5) arise from the requirement that the exercise boundary must also be uniquely determined.

Unfortunately there is no known exact and completely explicit solution to either the optimal stopping problem of Equation (1) or to the free boundary

³ As usual, the first passage time is considered to be infinite if the boundary is never touched.

problem of Equation (3). The next section presents a new approach for obtaining approximate solutions to these problems.

2. Exponential Maturity Valuation

In order to obtain an approximate solution for the value of an American put and its exercise boundary, we now suppose that the maturity date is random. Let τ denote the random maturity time. In this section we assume that τ is exponentially distributed with scale parameter λ :

$$\Pr\{\tau \in dt\} = \lambda e^{-\lambda t} dt. \quad (6)$$

Since the mean of τ is the reciprocal of λ , we set $\lambda = \frac{1}{T}$, so that the mean maturity of the randomized American put is T , the maturity of the true American put. Let $P^{(1)}(S)$ denote the randomized value of an American put, which matures at the first jump time of a standard Poisson process with intensity $\lambda = \frac{1}{T}$. We assume that the Poisson process is independent of the stock price process. Furthermore, we assume that the Poisson process is also uncorrelated with any market factor. It follows that the risk associated with the randomness of maturity can be diversified away by holding a large portfolio of random maturity options on different stocks. Thus the randomized value can be calculated in a risk-neutral fashion.

The analog to Equation (2) for randomized American option values is

$$P^{(1)}(S) = \sup_B E_{0,S} \{e^{-r(\tau_B \wedge \tau)} [K - S_{\tau_B \wedge \tau}]^+\}, \quad S > \underline{S}_1, \quad (7)$$

where \underline{S}_1 is the unknown optimal exercise boundary. Note that the supremum is taken only over time-stationary boundaries B rather than functions of time $B(t)$. The memoryless property of the exponential distribution implies that the passage of time has no effect on either the randomized option value or its optimal exercise boundary. Thus the time-dependent exercise boundary of a true American put becomes flat when we randomize the maturity. When the Poisson process governing maturity jumps up, the randomized option value jumps down to intrinsic value $(K - S)^+$. Thus one can think of the pent up time decay of the option as being released at the jump time. This release causes the exercise boundary to jump up from \underline{S}_1 to K , crudely approximating the behavior of the true exercise boundary.

The expectation in Equation (7) can be evaluated in closed form and the result can be maximized over barriers analytically. Since the details are cumbersome, a perhaps simpler approach is to rewrite Equation (7) as an iterated expectation:

$$P^{(1)}(S) = \sup_B E_{0,S} \{E_{0,S} \{e^{-r(\tau_B \wedge t)} [K - S_{\tau_B \wedge t}]^+ \mid \tau = t\}\}, \quad S > \underline{S}_1, \quad (8)$$

The first expectation is taken only over the random maturity, while the second is taken only over the future stock price at a given realization of this random maturity. Since the random maturity is exponentially distributed, Equations (6) and (8) imply the following relationship between random and fixed maturity put values:⁴

$$P^{(1)}(S) = \sup_B \lambda \int_0^\infty e^{-\lambda t} D(0, S; t; B) dt, \quad (9)$$

where $D(0, S; t; B)$ is the initial value of a down-and-out put with fixed maturity t , out barrier B , and rebate $K - B$:

$$D(0, S; t; B) = E_{0,S} \{e^{-r(\tau_B \wedge t)} [K - S_{\tau_B \wedge t}]^+\}, \quad S > B.$$

One can immediately observe from Equation (9) that the randomized American put value is simply the Laplace-Carson transform of a fixed maturity barrier put, maximized over barriers.⁵ Since down-and-out put values satisfy the Black-Scholes PDE [Equation (3)], one can take the Laplace-Carson transform of both sides of this PDE to obtain the following simpler ordinary differential equation (ODE):

$$\frac{\sigma^2}{2} S^2 P_{ss}^{(1)}(S) + r S P_s^{(1)}(S) - r P^{(1)}(S) = \lambda [P^{(1)}(S) - (K - S)^+], \quad S > \underline{S}_1, \quad (10)$$

subject to the following boundary conditions:

$$\lim_{S \uparrow \infty} P^{(1)}(S) = 0, \quad \lim_{S \downarrow \underline{S}_1} P^{(1)}(S) = K - \underline{S}_1, \quad \lim_{S \downarrow \underline{S}_1} P_s^{(1)}(S) = -1. \quad (11)$$

Using standard techniques for solving ODE's, the randomized value of an American put can be decomposed as

$$P^{(1)}(S) = \begin{cases} p^{(1)}(S) + b^{(1)}(S) & \text{if } S > \underline{S}_0 \equiv K \\ K R - S + c^{(1)}(S) + b^{(1)}(S) & \text{if } S \in (\underline{S}_1, \underline{S}_0) \\ K - S & \text{if } S \leq \underline{S}_1, \end{cases} \quad (12)$$

where $p^{(1)}(S)$ is the randomized value of a European put paying $(K - S)^+$

⁴ Note that the randomized value obtained in this article is strictly smaller than the value of an exponentially weighted portfolio of true American puts, that is, $P^{(1)}(S) < \lambda \int_0^\infty e^{-\lambda t} P(0, S; t) dt$. The reason is that the optimization over boundaries for our contract must be done with a random maturity. In contrast, the given integral simply averages American values over maturities, where each American value $P(0, S; t)$ is calculated by optimizing over a fixed maturity t . I thank the editor, Kerry Back, for correcting a mistake on this point in an earlier draft.

⁵ The Laplace-Carson transform differs from the standard Laplace transform only by the introduction of a constant λ in the kernel. See Rubinstein and Rubinstein (1993, pp. 512–517) for the properties of this transform.

at the first jump time,

$$p^{(1)}(S) = \left(\frac{S}{K}\right)^{\gamma-\epsilon} (qKR - \hat{q}K), \quad S > K, \quad (13)$$

with $\gamma \equiv \frac{1}{2} - \frac{r}{\sigma^2}$, $R \equiv \frac{1}{1+rT}$, $\epsilon \equiv \sqrt{\gamma^2 + \frac{2}{R\sigma^2T}}$, and

$$p \equiv \frac{\epsilon - \gamma}{2\epsilon}, q \equiv 1 - p, \hat{p} \equiv \frac{\epsilon - \gamma + 1}{2\epsilon}, \text{ and } \hat{q} \equiv 1 - \hat{p}, \quad (14)$$

$b^{(1)}(S)$ is the present value of interest received below the critical stock price \underline{S}_1 until the first jump time,

$$b^{(1)}(S) = \left(\frac{S}{\underline{S}_1}\right)^{\gamma-\epsilon} qKRrT, \quad (15)$$

and finally, $c^{(1)}(S)$ is the randomized value of a European call paying $(S - K)^+$ at the first jump time,

$$c^{(1)}(S) = \left(\frac{S}{K}\right)^{\gamma+\epsilon} (\hat{p}K - pKR), \quad S < K. \quad (16)$$

The first line of our formula [Equation (12)] represents the randomized version of a decomposition of the American put value into the European put value and the early exercise premium. This decomposition also holds in the fixed maturity setting, as shown previously in Kim (1990), Jacka (1991), and Carr, Jarrow, and Myneni (1992). Note that the formula [Equation (13)] for the randomized value of the European put is simpler than the Black-Scholes formula in that it does not use any special functions such as the normal distribution function. On the other hand, Equation (13) holds only for out-of-the-money values ($S > K$). In contrast to the Black-Scholes put formula which holds for all positive stock prices, Equation (13), which values the put when $S > K$, does not correctly value the put when $S < K$. The lack of smoothness in the payoff function implies that put call parity must be used to generate in-the-money values for European puts with random maturity.⁶ The second line of Equation (12) reflects this restriction. The third line of Equation (12) sets the randomized put value to exercise value below the critical stock price \underline{S}_1 . Figure 1 graphs the value of an exponential maturity American put against the stock price. The function is twice differentiable at the strike price, but only once differentiable at the exercise boundary, as is the case for a true American put.

Imposing value-matching in Equation (12) at the critical stock price \underline{S}_1

⁶ Put call parity holds so long as the options and a forward contract mature at the same jump time.

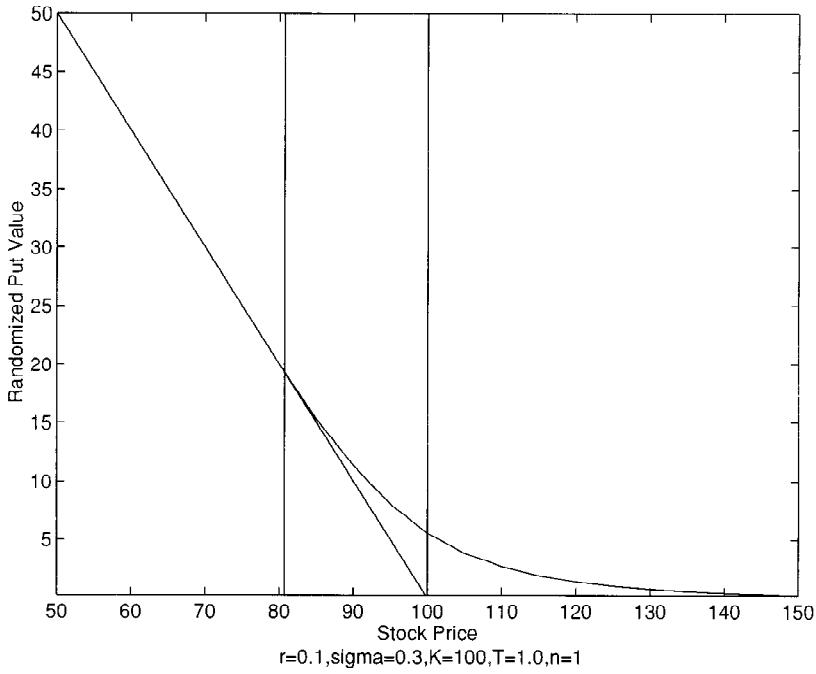


Figure 1
Value of exponential maturity put

yields the following balance equation:

$$c^{(1)}(S_1) = pK RrT. \quad (17)$$

The left-hand side is clearly the randomized value of a European call when the stock price is at the critical stock price. The right-hand side represents the randomized value of a claim paying interest on the strike price at all stock prices above the current stock price level. The critical stock price is chosen so that the call value just matches the present value of the interest flow received above the boundary. Stationarity in the values involved implies that the exercise boundary remains flat at this level until the jump time.

The simple expression of Equation (16) for the European call value implies that the balance equation [Equation (17)] can be explicitly solved for our first approximation to the exercise boundary, \underline{S}_1 :

$$\underline{S}_1 = K \left(\frac{p Rr T}{\hat{p} - R p} \right)^{\frac{1}{\gamma + \epsilon}}. \quad (18)$$

It is worth pointing out that explicit expressions for the critical stock price

are rare. Indeed, we will lose this explicitness once constant proportional dividends are introduced.⁷

For future use, note that substituting Equation (18) into Equation (16) implies that the randomized value of a European call is given by a formula similar to that of the randomized early exercise premium in Equation (15):

$$c^{(1)}(S) = \left(\frac{S}{\underline{S}_1} \right)^{\gamma+\epsilon} p K R r T \equiv A^{(1)}(S).$$

Equations (12) and (18) represent the randomized versions of the American put value and critical stock price, respectively. While these first approximations are simple and explicit, numerical implementation indicates substantial undervaluation of the put. Intuitively, the reason the randomized value is substantially smaller than the true value is that the owner of a random maturity put must optimize over boundaries without the benefit of knowing when the option will mature.

Clearly the valuation error can be reduced by lowering the variance of the distribution governing maturity. Unfortunately, if a random variable with an exponential distribution has mean T , then its variance is T^2 . The next section uses a two-parameter distribution for maturity, which permits keeping the mean maturity constant at T , while reducing the variance as much as desired. As the variance approaches zero, the result is a de facto inversion of the Laplace-Carson transform of Equation (12), yielding an accurate approximation of the American put value.

3. Erlang Maturity Valuation

Consider an investor who is faced with the problem of allocating his investable wealth among n different securities. If the security returns are independently and identically distributed (i.i.d.), the variance minimizing allocation is to invest an equal proportion in each security. By the same token, a simple and efficient way to reduce the variance of our option's random maturity is to split it into n i.i.d subperiods. If we also assume that each of the n periods is exponentially distributed with parameter λ , then the maturity date τ is Erlang distributed:

$$\Pr\{\tau \in dt\} = \frac{\lambda^n}{(n-1)!} t^{n-1} e^{-\lambda t} dt.$$

In order that the mean maturity be T , each subperiod must have mean

⁷ However, we retain the explicitness of the exercise boundary if the dividend flow is constant in dollar terms. For short-term options on stock indices, a constant dividend flow is more consistent with casual empirical observation than constant proportional dividends.

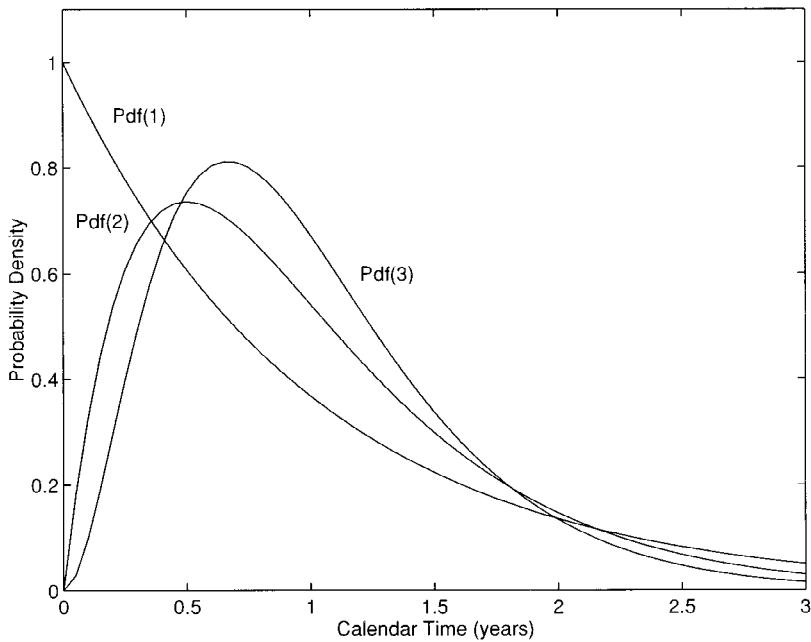


Figure 2
Convergence of gamma density functions

$\Delta \equiv T/n$, which implies $\lambda = 1/\Delta$. By assuming that the maturity is Erlang distributed instead of exponentially distributed, the variance is reduced by a factor of $\frac{1}{n}$ to only T^2/n . Figure 2 shows three Erlang density functions, with each corresponding to a maturity of mean $T = 1$ year, and with variances of 1, $1/2$, and $1/3$, respectively. The densities are converging to a Dirac delta function centered at $T = 1$ year.

Let $P^{(n)}(S)$ denote the randomized value of an American put option which can be exercised for $(K - S)^+$ at any time up to and including the n th jump time of a standard Poisson process (with intensity $\lambda = 1/\Delta$). To value this put, we use dynamic programming. Accordingly, suppose that $n - 1$ jumps have occurred and that the investor is holding a put maturing at the next jump time of the Poisson process. This valuation problem was solved in the previous section, with the solution $P^{(1)}(S)$ given by Equation (9), except that T must be everywhere replaced by $\Delta \equiv T/n$.

We now back up a random time period and think of $P^{(1)}(S)$ as the random payoff occurring at the end of this random period, provided that no exercise has occurred beforehand. Since exercising yields a payoff of $(K - S)^+$ as

usual, the randomized value of the American put with two jumps to maturity is

$$P^{(2)}(S) = \sup_{B>0} E_S\{e^{-r\tau_B} [K - B]^+ 1(\tau_B < \tau_2) + e^{-r\tau_2} P^{(1)}(S_{\tau_2}) 1(\tau_B \geq \tau_2)\}, \quad S > \underline{S}_2, \quad (19)$$

where τ_2 denotes the length of the second random period prior to maturity and \underline{S}_2 denotes the unknown optimal exercise boundary over this period. Once again, the stationarity of the barrier B over the period implies that the expectation in Equation (19) can be evaluated in closed form and the result can be maximized over barriers analytically.

As in the previous section, a perhaps simpler approach is to work with Laplace-Carson transforms. Proceeding by analogy with the previous section, let $D(S; T - t, B)$ denote the time t value of a down-and-out put with fixed maturity T , out barrier B , and which pays a rebate of $K - B$ at the first passage time to B , if this occurs before T , and which pays $P^{(1)}(S_T)$ at T otherwise. Then, $D(S; T - t, B)$ satisfies the Black-Scholes PDE,

$$\frac{\sigma^2}{2} S^2 D_{ss}(S; T - t, B) + r S D_s(S; T - t, B) - r D(S; T - t, B) = D_T(S; T - t, B), \quad S \in (B, \infty), t \in (0, T), \quad (20)$$

subject to the terminal condition $D(S; 0, B) = P^{(1)}(S)$ and the boundary conditions

$$\lim_{S \uparrow \infty} D(S; T - t, B) = 0, \quad \lim_{S \downarrow B} D(S; T - t, B) = K - B, \quad t \in (0, T).$$

The randomized value of the American put maturing after two more jumps of the Poisson process is related to this fixed maturity claim by

$$P^{(2)}(S) = \sup_B \lambda \int_0^\infty e^{-\lambda t} D(S; t, B) dt. \quad (21)$$

Taking Laplace-Carson transforms of both sides of the PDE, Equation (20) implies that

$$\frac{\sigma^2}{2} S^2 P_{ss}^{(2)}(S) + r S P_s^{(1)}(S) - r P^{(2)}(S) = \lambda [P^{(2)}(S) - P^{(1)}(S)], \quad S > \underline{S}_2, \quad (22)$$

subject to the following boundary conditions:

$$\lim_{S \uparrow \infty} P^{(2)}(S) = 0, \quad \lim_{S \downarrow \underline{S}_2} P^{(2)}(S) = K - \underline{S}_2, \quad \lim_{S \downarrow \underline{S}_2} P_s^{(2)}(S) = -1. \quad (23)$$

This simpler free boundary problem can be solved analytically for both the randomized put value $P^{(2)}(S)$ and the critical stock price \underline{S}_2 . The graph of the American put value is similar to Figure 1, but with slightly higher

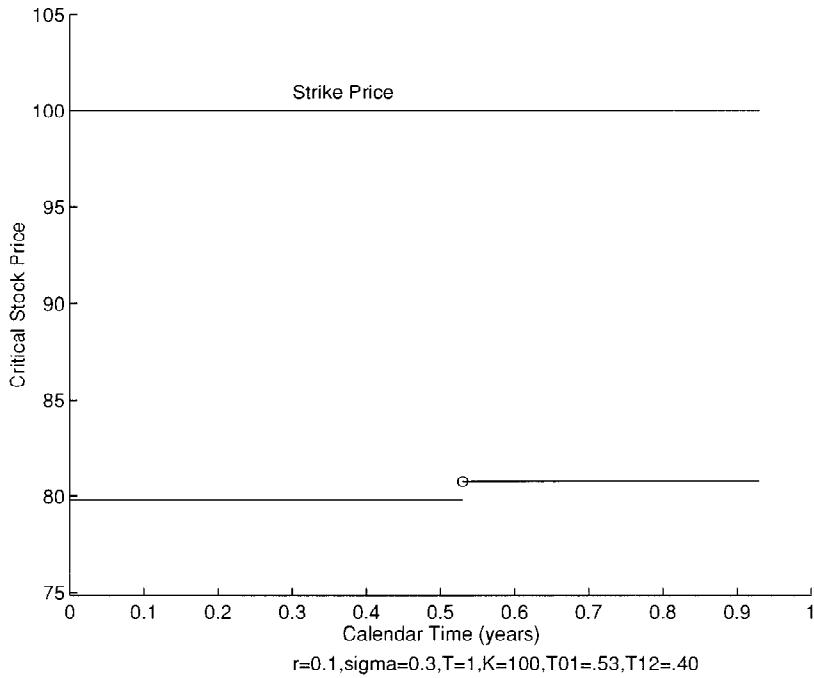


Figure 3
Exercise boundary of Erlang maturity put

value due to the lower variance in maturity. Figure 3 shows the exercise boundary for a realization in which the first jump happened to occur 0.53 years after issuance, while the put matured with the second jump 0.93 years after issuance. The critical stock price over the earlier of the two periods is below the critical stock price of the later period because the end-of-period payoff is greater (i.e., $P^{(1)}(S) \geq K - S$).

More generally, let $P^{(m)}(S)$ and \underline{S}_m denote the randomized put value and exercise boundary stair levels, respectively, with m random periods to maturity, $m = 0, 1, \dots, n$, with $P^{(0)}(S) \equiv (K - S)^+$ and $\underline{S}_0 \equiv K$. Then $P^{(m)}(S)$ and \underline{S}_m jointly solve the following sequence of free boundary problems:

$$\begin{aligned} \frac{\sigma^2}{2} S^2 P_{ss}^{(m)}(S) + r S P_s^{(m)}(S) - r P^{(m)}(S) \\ = \lambda [P^{(m)}(S) - P^{(m-1)}(S)], \text{ for } S \in (\underline{S}_m, \infty), \end{aligned} \quad (24)$$

subject to the boundary conditions

$$\begin{aligned}\lim_{S \uparrow \infty} P^{(m)}(S) &= 0, \\ \lim_{S \downarrow \underline{S}_m} P^{(m)}(S) &= K - \underline{S}_m, \\ \lim_{S \downarrow \underline{S}_m} P_s^{(m)}(S) &= -1, \text{ for } m = 1, \dots, n.\end{aligned}\tag{25}$$

Substituting $\lambda \equiv \frac{1}{\Delta}$ on the right-hand side of Equation (24) and comparing with the Black-Scholes PDE of Equation (3) indicates an alternative interpretation of the approximation induced by our randomization procedure. Our randomized put value $P^{(m)}(S)$ is also the approximation for $P(T - m\Delta, S; T)$ which arises when time is discretized and the maturity derivative $P_T(t, S; T) \equiv \frac{\partial P}{\partial T}(t, S; T)$ in Equation (3) is replaced with the finite difference $\frac{P^{(m)}(S) - P^{(m-1)}(S)}{\Delta} = \frac{\Delta P^{(m)}(S)}{\Delta}$. Note however that the spatial derivatives are not replaced with their finite differences, in contrast to standard finite difference schemes or the binomial model.⁸ As mentioned in the introduction, the notion of discretizing one variable while leaving the other continuous is known in the numerical methods literature as semi-discretization or the method of lines.

The accuracy of our approach may be anticipated a priori by noting that as the maturity date T approaches infinity holding the number of periods n fixed, then $\lambda \downarrow 0$ and thus Equation (24), describing the randomized put value, approaches that of the perpetual put. As a result, the randomized put solution with any number of jumps remaining will converge to the correct perpetual solution. Conversely, as n gets arbitrarily large with T held fixed, then the finite difference $\frac{\Delta P^{(m)}(S)}{\Delta}$ on the right-hand side of Equation (24) converges to the maturity derivative $P_T(t, S; T)$ in Equation (3). As a result, we conjecture that the solution $(P^{(n)}(S), \underline{S}_n)$ to our randomized option problem converges to the unknown solution $(P(0, S; T), \underline{S}(0; T))$ of the American problem in Equation (1) or (3).⁹

Recall from Section 2 that our formulas for random maturity option values depended on whether the option was in or out of the money. Similarly, our formula for the randomized put value, $P^{(n)}(S)$, depends on which

⁸ The binomial model uses a forward finite difference for the maturity derivative leading to an explicit scheme. The appearance of a backward difference for the maturity derivative indicates that our randomization procedure may be considered as the limiting case of a fully implicit scheme, where the size of each space step is infinitesimally small. Surprisingly, this implicit scheme has a semieexplicit solution for an American option and a fully explicit solution for a European or barrier option.

⁹ While numerical implementation of our solution will prove to be consistent with this conjectured convergence, a formal proof of convergence remains an open question.

interval $(\underline{S}_i, \underline{S}_{i-1})$ contains the current spot price S :¹⁰

$$P^{(n)}(S) = \begin{cases} p_0^{(n)}(S) + b_1^{(n)}(S) & \text{if } S > \underline{S}_0 \equiv K \\ v_i^{(n)}(S) + b_i^{(n)}(S) + A_i^{(n)}(S; 1) & \text{if } S \in (\underline{S}_i, \underline{S}_{i-1}], \\ K - S & \text{if } S \leq \underline{S}_n, \end{cases} \quad (26)$$

where $p_0^{(n)}(S)$ is the out-of-the-money value of a European put maturing in n (random-length) periods:¹¹

$$p_0^{(n)}(S) = \left(\frac{S}{K}\right)^{\gamma-\epsilon} \sum_{k=0}^{n-1} \frac{(2\epsilon \ln(\frac{S}{K}))^k}{k!} \sum_{l=0}^{n-k-1} \binom{n-1+l}{n-1} \times [KR^n q^n p^{l+k} - K\hat{q}^n \hat{p}^{l+k}], \quad S > K, \quad (27)$$

with $\Delta \equiv T/n$, $\gamma \equiv \frac{1}{2} - \frac{r}{\sigma^2}$,

$$R \equiv \frac{1}{1+r\Delta}, \quad \epsilon \equiv \sqrt{\gamma^2 + \frac{2}{R\sigma^2\Delta}}, \quad (28)$$

p, q, \hat{p}, \hat{q} given in Equation (14), and for $i = 1, \dots, n$, $v_i^{(n)}(S)$ is the randomized value of a short forward position maturing in $n-i+1$ periods:

$$v_i^{(n)}(S) = KR^{n-i+1} - S,$$

$b_i^{(n)}(S)$ is the present value of interest received below the boundary for the first $n-i+1$ periods:

$$b_i^{(n)}(S) = \sum_{j=1}^{n-i+1} \left(\frac{S}{\underline{S}_{n-j+1}}\right)^{\gamma-\epsilon} \sum_{k=0}^{j-1} \frac{(2\epsilon \ln(\frac{S}{\underline{S}_{n-j+1}}))^k}{k!} \times \sum_{l=0}^{j-k-1} \binom{j-1+l}{j-1} q^j p^{k+l} R^j Kr\Delta, \quad (29)$$

and finally, $A_i^{(n)}(S; 1)$ is the randomized value of an out-of-the-money European call less interest paid above the boundary over the complementary

¹⁰ Note that Equation (26) is closely related to the value of a fixed maturity American option when the variance rate is gamma distributed. See Madan and Chang (1997) for a closed form solution for European options.

¹¹ See Equations (54) and (53) in the Appendix for the randomized values of European calls and in-the-money European puts, respectively.

period:¹²

$$A_i^{(n)}(S; h) \equiv \sum_{j=h}^{n-i+1} \left(\frac{S}{S_{n-j+1}} \right)^{\gamma+\epsilon} \sum_{k=0}^{j-1} \frac{\left(2\epsilon \ln \left(\frac{S_{n-j+1}}{S} \right) \right)^k}{k!} \\ \times \sum_{l=0}^{j-k-1} \binom{j-1+l}{j-1} p^j q^{k+l} R^j Kr \Delta. \quad (30)$$

The formula in the first line of Equation (26) again reflects the randomized version of the well-known decomposition of the American put value into the value of the corresponding European put and the early exercise premium. The formula in the second line is the randomized version of a new decomposition of the American put value into the value if forced to sell at a given date prior to expiration, and the premia which arise because exercise can occur before or after this date. The final line of Equation (26) indicates that the put should be exercised immediately if the stock price S is at or below our approximation for the critical stock price \underline{S}_n .

The staircase levels comprising the exercise boundary can be determined by recursive solution of an explicit formula. Continuity at the strike price in each period $m = 1, \dots, n$ implies $c_1^{(m)}(K) = A_1^{(m)}(K; 1)$, which in turn implies the following explicit solution for each critical stock price \underline{S}_m :

$$\underline{S}_m = K \left(\frac{p R Kr \Delta}{c_1^{(m)}(K) - A_1^{(m)}(K; 2)} \right)^{\frac{1}{\gamma+\epsilon}}, \quad m = 1, \dots, n, \quad (31)$$

where from Equation (54) in the Appendix, the at-the-money call value with m periods to maturity simplifies to

$$c_1^{(m)}(K) = \sum_{l=0}^{m-1} \binom{m-1+l}{m-1} [K \hat{p}^m \hat{q}^l - K R^m p^m q^l], \quad m = 1, \dots, n. \quad (32)$$

Since $A^{(m)}$ in Equation (31) depends on \underline{S}_{m-1} to \underline{S}_1 , the critical stock prices must be solved recursively, with $\underline{S}_1 = K \left(\frac{p R Kr \Delta}{\hat{p} - R p} \right)^{\frac{1}{\gamma+\epsilon}}$.

4. Implementation

Our Equation (26) for the randomized put value $P^{(n)}(S)$ is a triple sum. Clearly we need the number of periods n to be small in order to achieve computational efficiency. This section describes how Richardson extrapolation can be used to provide accurate answers using just a few periods. Richard-

¹² This value also accounts for the smoothness at the exercise boundary in every period.

son extrapolation has been used previously to accelerate valuation schemes for American options. Geske and Johnson (1984) first used Richardson extrapolation in a financial context to speed up and simplify their compound option valuation model. In general, it is not a good idea to extrapolate on the number of time steps in the binomial model [see Cox, Ross, and Rubinstein (1979) and Rendleman and Bartter (1979)] due to the oscillatory nature of the convergence. However, Broadie and Detemple (1996) successfully use Richardson extrapolation to accelerate a hybrid of the binomial and Black-Scholes models. Furthermore, Liesen (1997) shows that randomizing the length of the time steps in the binomial model permits the successful use of extrapolation. Finally, Huang, Subrahmanyam, and Yu (1996) and Ju (1998) use the approach to accelerate the integral representation of the early exercise premium.

Denote our approximation [Equation (26)] by a function $\hat{P}(\Delta)$ of the mean period length Δ . Richardson extrapolation can be used when the approximation can be adequately described by the first N terms in a Taylor series expansion about the origin:

$$\hat{P}(\Delta) = \sum_{n=0}^{N-1} \frac{\partial^n \hat{P}(0)}{\partial \Delta^n} \frac{\Delta^n}{n!} + O(\Delta^N). \quad (33)$$

The explicit nature of our equation (26) can be used to show that our approximation has the requisite smoothness for any N . If we ignore the terms of $O(\Delta^N)$ in Equation (33), then the N coefficients $\frac{\partial^n \hat{P}(0)}{\partial \Delta^n}$, $n = 0, 1, \dots, N-1$ can be determined by using any N values of Δ for which $\hat{P}(\Delta)$ is known. The N -point Richardson extrapolation is then the first coefficient $\hat{P}(0)$. From Equation (33), this extrapolation has error of order $O(\Delta^N)$.

For example, a three-point Richardson extrapolation can be obtained by assuming that our approximation is approximately quadratic in the mean period length:

$$\hat{P}(\Delta) \approx \hat{P}(0) + \hat{P}'(0)\Delta + \frac{1}{2}\hat{P}''(0)\Delta^2.$$

Substituting in $\Delta = T$, $\Delta = T/2$, and $\Delta = T/3$ leads to three equations in the three unknowns $\hat{P}(0)$, $\hat{P}'(0)$, and $\hat{P}''(0)$. Inverting the system implies that the three point extrapolation is given by

$$\hat{P}^{1:3}(0) \equiv \frac{1}{2}\hat{P}(T) - 4\hat{P}(T/2) + \frac{9}{2}\hat{P}(T/3). \quad (34)$$

Figures 4 and 5 illustrate the idea behind a three-point extrapolation. From Marchuk and Shaidurov (1983, p. 24), an N -point Richardson extrapolation

Table 1
Convergence of randomized put value to American without and with Richardson extrapolation

Number of steps n or points N	Unextrapolated put value $P^{(n)}$	Extrapolated put value $P^{1:N}$
1	7.0405	7.0405
2	7.6175	8.1946
3	7.8353	8.3089
4	7.9505	8.3257
5	8.0220	8.3311
6	8.0709	8.3333
7	8.1065	8.3345
8	8.1335	8.3353
9	8.1548	8.3358
10	8.1720	8.3362
11	8.1862	8.3365
12	8.1981	8.3367
13	8.2082	8.3369
14	8.2169	8.3370
15	8.2246	8.3371

$S = 100, K = 100, T = 1, r = 0.1, \delta = 0, \sigma = 0.3$

is the following weighted average of N randomized put values:¹³

$$\hat{P}^{1:N}(0) \equiv \sum_{n=1}^N \frac{(-1)^{N-n} n^N}{n!(N-n)!} \hat{P}(T/n). \quad (35)$$

An accurate approximation for the critical stock price at the initial time can be obtained by imposing either of the smooth pasting conditions in Equation (25) or by Richardson extrapolation:¹⁴

$$\underline{S}^{1:N}(0) \equiv \sum_{n=1}^N \frac{(-1)^{N-n} n^N}{n!(N-n)!} \underline{S}(T/n), \quad (36)$$

where $\underline{S}(\Delta)$ is the function relating the initial critical stock price \underline{S}_n determined by Equation (31) to the mean period length.

The effectiveness of Richardson extrapolation is illustrated by a typical test case: $S = 100, K = 100, T = 1, r = .1$, and $\sigma = .3$. The true value based on the binomial method with 2000 time steps appears to be 8.3378. Table 1 shows that for this test case the unextrapolated values approach the true value very slowly from below. In contrast, the extrapolated put values converge rapidly to this true value, with penny accuracy obtained in only 5 points. Table 2 elaborates on the calculation of the first two unextrapolated values in Table 1. Besides indicating typical values of some of the variables, it should aid in the reproduction of the results of Table 1.

¹³ The weights always sum to unity and alternate in sign. In general, higher order approximations involve weights with greater absolute value. As a result, implementing higher order extrapolations on a computer requires double precision to control roundoff error.

¹⁴ We prefer the former method when accuracy is important and the latter method when speed matters.

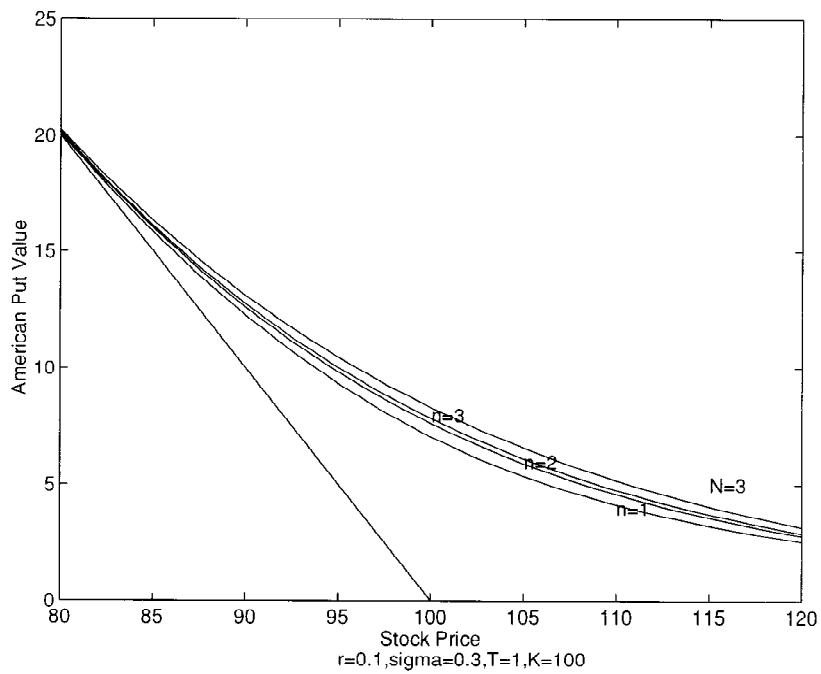


Figure 4
Three-point Richardson extrapolation

Table 2
Intermediate put values

Variable	$n = 1$	$n = 2$
Δ	1.0000	0.5000
γ	-0.6111	-0.6111
R	0.9091	0.9524
ϵ	4.9818	6.8586
p	0.5613	0.5446
q	0.4387	0.4554
\hat{p}	0.6617	0.6175
\hat{q}	0.3383	0.3825
S_1	77.9724	80.7216
S_2	N/A	77.2941
$v_1^{(n)}(S)$	-9.0909	-9.2971
$b_1^{(n)}(S)$	0.9917	1.0176
$A_1^{(n)}(S; 1)$	15.1397	15.8970
$P^{(n)}(S)$	7.0405	7.6175

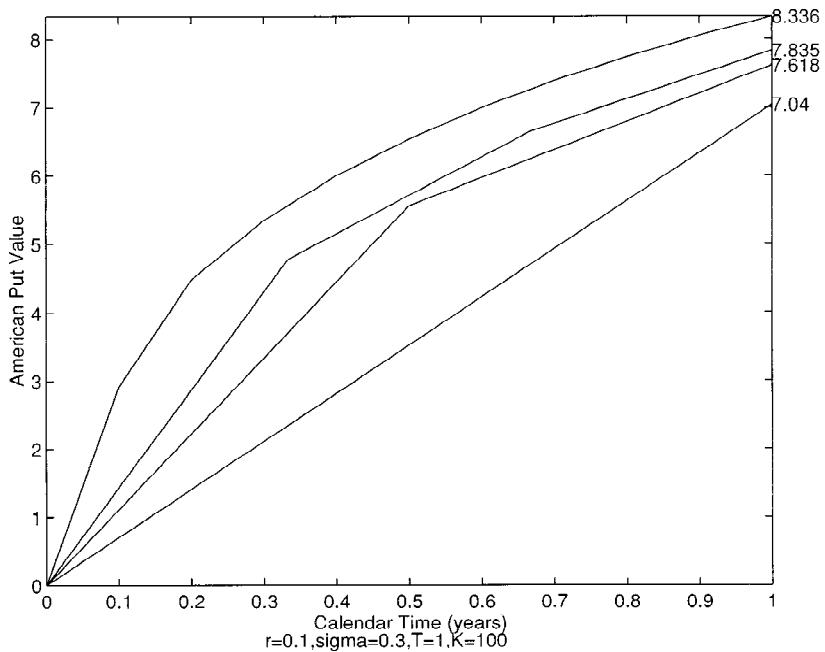


Figure 5
Three-step Richardson extrapolation

Broadie and Detemple (1996) and Ju (1998) conduct extensive numerical simulations of a wide array of methods for valuing American options. Both articles conclude that three approaches dominate other methods in terms of speed and accuracy. These three methods are the lower and upper bound approximation (LUBA) in Broadie and Detemple (1996), the piecewise exponential boundary approximation in Ju (1998), and the randomization approach discussed in this article. Of these three methods, LUBA has the singular advantage of providing bounds as well as an accurate approximation. The randomization approach is unique in that the exercise boundary is given by a recursion rather than root finding, when dividends are constant or zero. Finally, Ju's piecewise exponential boundary approach appears to deliver the best combination of speed and accuracy, although speed comparisons at each accuracy level were not conducted.

5. Extension to Positive Dividends and American Calls

It is reasonable to assume that the dividend stream from the underlying asset is continuous over time if the asset underlying the option is an index or a basket with a large number of stocks. Merton (1973) generalized the Black-

Scholes analysis to continuously paid dividends which are either constant or proportional to the price of the underlying. He did not permit a dividend rate which is linear in the spot price, presumably due to the difficulty in generating analytic solutions under this assumption. While we are also unable to deal with a linear dividend rate, this section develops formulas for randomized American option values when the dividend payout rate has both a fixed and a proportional component. We also show that our approximation to the put's critical stock price is still given by an explicit formula when dividends are constant, but must be determined numerically when there is a proportional component to the dividend flow. Finally, we show how to find the randomized values of American calls on dividend paying stocks.

We assume that the underlying stock pays dividends continuously until the fixed maturity T . To obtain a truly fixed component ϕ of this dividend flow, we follow Roll (1977) in assuming that this component has been escrowed out of the stock price. In other words, the time t stock price S_t decomposes into

$$S_t = \frac{\phi}{r}[1 - e^{-r(T-t)}] + s_t, \quad t \in [0, T], \quad (37)$$

where the first term is the present value at t of the constant flow ϕ until T , and the residual s_t is the stripped price, reflecting the stripping off of the fixed component of the dividend flow from the stock price. We assume that the risk-neutralized process for the stripped price $\{s_t, t \in [0, T]\}$ is the following geometric Brownian motion:

$$s_t = s \exp \left[\left(r - \delta - \frac{\sigma^2}{2} \right) t + \sigma W_t \right], \quad t \in [0, T], \quad (38)$$

where $\{W_t, t \in [0, T]\}$ is a standard Brownian motion, and from Equation (37), the initial value is

$$s = S - \frac{\phi}{r}[1 - e^{-rT}]. \quad (39)$$

Thus the dollar dividend rate d_t has both a fixed and a proportional component:

$$d_t = \phi + \delta s_t, \quad t \in [0, T]. \quad (40)$$

The parameter ϕ captures the stickiness of dividends in the short run, while δ captures the tendency for dividends to increase with stock prices in the long run. If $\delta = 0$, then ϕ is the constant dividend rate, while if $\phi = 0$, then δ is the constant dividend yield, since $s_t = S_t$ from Equation (37).

5.1 Positive dividends and American puts

We generalize the previous analysis by letting $P(t, s; T)$ denote the value of an American put as a function of the current time t , the current stripped price s , and the maturity date T . We also define the critical stripped price $\underline{s}(t)$ as the largest stripped price s at which the American put value $P(t, s; T)$ equals its exercise value $K - s - \frac{\phi}{r}[1 - e^{-r(T-t)}]$, for $t \in [0, T]$. From Equation (37), the critical stock price $\underline{S}(t)$ is now defined by

$$\underline{S}(t) \equiv \frac{\phi}{r}[1 - e^{-r(T-t)}] + \underline{s}(t), \quad t \in [0, T]. \quad (41)$$

In the random maturity setting, the underlying stock pays dividends continuously until the option matures. Recalling that $R \equiv \frac{1}{1+r\Delta}$ is the discount factor over a single period of random length, the random maturity analog of Equation (39) is

$$s = S - \phi\Delta(R + R^2 + \dots + R^n) = S - \frac{\phi}{r}R(1 - R^n). \quad (42)$$

We define $P^{(m)}(s)$ as our approximation for the American put value when m random periods remain, $m = 1, \dots, n$. Our approximation for the critical stripped price, \underline{s}_m , is the largest s satisfying $P^{(m)}(s) = K - s - \frac{\phi}{r}R(1 - R^m)$, $m = 1, \dots, n$.

The values of European options maturing in n random-length periods are

$$p^{(n)}(s) = \begin{cases} \left(\frac{s}{K}\right)^{\gamma-\epsilon} \sum_{k=0}^{n-1} \frac{(2\epsilon \ln(\frac{s}{K}))^k}{k!} \sum_{l=0}^{n-k-1} \binom{n-1+l}{n-1} \\ [KR^n q^n p^{k+l} - KD^n \hat{q}^n \hat{p}^{k+l}] & \text{if } s > K \\ KR^n - sD^n + c^{(n)}(S) & \text{if } s \leq K \end{cases} \quad (43)$$

$$c^{(n)}(s) = \begin{cases} sD^n - KR^n + p^{(n)}(s) & \text{if } s > K \\ \left(\frac{s}{K}\right)^{\gamma+\epsilon} \sum_{k=0}^{n-1} \frac{(2\epsilon \ln(\frac{s}{K}))^k}{k!} \sum_{l=0}^{n-k-1} \binom{n-1+l}{n-1} \\ [KD^n \hat{p}^n \hat{q}^{k+l} - KR^n p^n q^{k+l}] & \text{if } s \leq K, \end{cases} \quad (44)$$

where now $\gamma \equiv \frac{1}{2} - \frac{r-\delta}{\sigma^2}$, $R, \epsilon, p, q, \hat{p}, \hat{q}$, are again given by Equations (28) and (14), while

$$D \equiv \frac{1}{1 + \delta\Delta}. \quad (45)$$

For $\delta = 0$ and $\phi \geq rK$, American puts are not rationally exercised early. Consequently, the randomized put value $P^{(n)}(s)$ is given by Equation (43) in this case. For $\delta > 0$ or $\phi < rK$, the randomized put value decomposes

as

$$P^{(n)}(s) = \begin{cases} p_0^{(n)}(s) + b_1^{(n)}(s) & \text{if } s > \underline{s}_0 \equiv K \\ v_i^{(n)}(s) + b_i^{(n)}(s) + A_i^{(n)}(s; 1) & \text{if } s \in (\underline{s}_i, \underline{s}_{i-1}], i = 1, \dots, n \\ K - S & \text{if } s \leq \underline{s}_n, \end{cases} \quad (46)$$

where for $i = 1, \dots, n$, $v_i^{(n)}(s)$ is the randomized value of a short forward position maturing in $n - i + 1$ periods:

$$v_i^{(n)}(s) = KR^{n-i+1} - sD^{n-i+1} - \phi R \frac{R^{n-i+1} - R^n}{1 - R}, \quad (47)$$

$b_i^{(n)}(s)$ is the present value of the interest less dividends (net interest) received when below the boundary for the first $n - i + 1$ periods:

$$\begin{aligned} b_i^{(n)}(s) = & \sum_{j=1}^{n-i+1} \left(\frac{s}{\underline{s}_{n-j+1}} \right)^{\gamma-\epsilon} \sum_{k=0}^{j-1} \frac{\left(2\epsilon \ln \left(\frac{s}{\underline{s}_{n-j+1}} \right) \right)^k}{k!} \sum_{l=0}^{j-k-1} \binom{j-1+l}{j-1} \\ & \times [q^j p^{k+l} R^j (Kr - \phi) - \hat{q}^j \hat{p}^{k+l} D^j \underline{s}_{n-j+1} \delta] \Delta, \end{aligned} \quad (48)$$

while $A_i^{(n)}(s; 1)$ represents the randomized value of a European call less the net interest paid above the boundary over the complementary period, after accounting for the smoothness at the exercise boundary in every period:

$$\begin{aligned} A_i^{(n)}(s; h) = & \sum_{j=h}^{n-i+1} \left(\frac{s}{\underline{s}_{n-j+1}} \right)^{\gamma+\epsilon} \sum_{k=0}^{j-1} \frac{\left(2\epsilon \ln \left(\frac{\underline{s}_{n-j+1}}{s} \right) \right)^k}{k!} \sum_{l=0}^{j-k-1} \binom{j-1+l}{j-1} \\ & \times [p^j q^{k+l} R^j (Kr - \phi) - \hat{p}^j \hat{q}^{k+l} D^j \underline{s}_{n-j+1} \delta] \Delta. \end{aligned}$$

Continuity in s at the strike price in each period $m = 1, \dots, n$ again implies $c_1^{(m)}(K) = A_1^{(m)}(K; 1)$, which in turn implies that each critical stripped price \underline{s}_m implicitly solves

$$\begin{aligned} c_1^{(m)}(K) - A_1^{(m)}(K; 2) = & \left(\frac{K}{\underline{s}_m} \right)^{\gamma+\epsilon} [p R (Kr - \phi) - \hat{p} D \underline{s}_m \delta] \Delta, \\ m = 1, \dots, n, \end{aligned} \quad (49)$$

where from Equation (44), the at-the-money call value on the left-hand side of Equation (49) simplifies to

$$c_1^{(m)}(K) = \sum_{l=0}^{m-1} \binom{m-1+l}{m-1} [KD^m \hat{p}^m \hat{q}^l - KR^m p^m q^l] \quad m = 1, \dots, n. \quad (50)$$

It is straightforward to recursively solve Equation (49) numerically for each critical stripped price \underline{s}_m , since \underline{s}_m does not appear on the left-hand side. Setting $\delta = 0$ in Equation (49) implies the following explicit solution for the critical stripped prices when the dividend rate is constant at ϕ :

$$\underline{s}_m = K \left(\frac{pR(Kr - \phi)\Delta}{c_1^{(m)}(K) - A_1^{(m)}(K; 2)} \right)^{\frac{1}{\gamma+\epsilon}}, \quad m = 1, \dots, n, \quad (51)$$

where the call value $c_1^{(m)}(K)$ is now given by Equation (32). This solution is a good initial guess when numerically solving Equation (49). From Equation (42), each critical stock price \underline{S}_m is determined by

$$\underline{S}_m = \frac{\phi}{r} R(1 - R^m) + \underline{s}_m, \quad m = 1, \dots, n, \quad (52)$$

where \underline{s}_m is given by Equation (51) when $\delta = 0$ and solves Equation (49) otherwise. Letting $\underline{S}(\Delta)$ denote the initial critical stock price as a function of the mean period length Δ , one can use Richardson extrapolation [Equation (36)] to approximate the initial critical stock price for an American put on a dividend-paying stock.

5.2 Positive dividends and American calls

When there is no fixed component to the dividend (i.e., $\phi = 0$), an American put call symmetry result can be used to easily value American calls on stocks with a constant dividend yield, δ . Let $P(S, K; \delta, r)$ and $C(S, K; \delta, r)$ denote the respective values of American puts and calls with fixed maturity T . Working in the binomial model, McDonald and Schroder (1990) show that

$$C(S, K; \delta, r) = P(K, S; r, \delta).$$

In other words, the call value can be obtained from the put valuation formula by switching the stock price and strike price, and also by switching the riskfree rate and dividend yield. This result is proved in the Black-Scholes model by Carr and Chesney (1997) and Schroeder (1997), who also prove the corresponding result for critical stock prices:

$$\bar{S}(\delta, r) = \frac{K^2}{\underline{S}(r, \delta)}.$$

In words, the critical stock price for an American call can be obtained from that of an American put by switching the riskfree rate and dividend yield, and then obtaining the geometric reflection in the strike.

It can be shown that these symmetry results also hold for randomized option values and critical stock prices. Furthermore, randomized American calls can be valued directly when there is also a fixed component to the

dividend flow. The Appendix presents the formulas for the call value and critical stock price in this case.

6. Summary and Future Research

We implemented a new approach to valuing American options that is fast, accurate, and flexible. The approach is to value options which mature by definition at the n th jump time of a standard Poisson process. Between jump times, the memoryless property of the exponential distribution implies that the option value and exercise boundary are time stationary. In contrast, at jump times, the option value jumps down and the exercise boundary jumps nearer to the strike price. The local time stationarity yields semieexplicit solutions for the option value and critical stock price, while the jump behavior roughly captures the global behavior of these values. As we let the number of jump times approach infinity, keeping the mean maturity fixed, our numerical results indicate that the randomized option value appears to converge smoothly from below to the true American option value. This convergence is dramatically enhanced through the use of Richardson extrapolation.

Although randomization can be used to value fixed maturity or barrier options, its main advantage over traditional methods is in the application to free boundary problems. Such problems also arise when valuing American exotic options and passport options, that is, European options written on the profit or loss from a market timing strategy specified by the option's owner [see Andersen, Andreasen, and Brotherton-Ratcliffe (1997), Hyer, Lipton-Lifschitz, and Pugachevsky (1997), Jamshidian (1998), and Shreve and Večeř (1998)]. It is also possible to significantly generalize the analysis of this article to level dependent volatility. In the interests of brevity, these extensions are best left for future research.

Appendix

This appendix collects all the formulas needed to calculate random maturity values of European and American puts and calls when the underlying has a continuous payout with a fixed component ϕ and a proportional component δ . Letting $s = S - \frac{\phi}{r}[1 - e^{-rT}]$, the N -point Richardson extrapolation of the randomized European put formula is

$$p^{1:N}(s) \equiv \sum_{n=1}^N \frac{(-1)^{N-n} n^N}{n!(N-n)!} p^{(n)}(s),$$

where

$$p^{(n)}(s) = \begin{cases} \left(\frac{s}{K}\right)^{\gamma-\epsilon} \sum_{k=0}^{n-1} \frac{(2\epsilon \ln(\frac{s}{K}))^k}{k!} \sum_{l=0}^{n-k-1} \binom{n-1+l}{n-1} \\ [KR^n q^n p^{k+l} - KD^n \hat{q}^n \hat{p}^{k+l}] & \text{if } s > K \\ KR^n - sD^n + c^{(n)}(s) & \text{if } s \leq K, \end{cases} \quad (53)$$

and where

$$\begin{aligned} \gamma &\equiv \frac{1}{2} - \frac{r - \delta}{\sigma^2}, \quad \Delta \equiv \frac{T}{n}, \quad R \equiv \frac{1}{1 + r\Delta}, \\ D &\equiv \frac{1}{1 + \delta\Delta}, \quad \epsilon \equiv \sqrt{\gamma^2 + \frac{2}{R\sigma^2\Delta}}, \quad p \equiv \frac{\epsilon - \gamma}{2\epsilon}, \\ q &\equiv 1 - p, \quad \hat{p} \equiv \frac{\epsilon - \gamma + 1}{2\epsilon}, \quad \text{and } \hat{q} \equiv 1 - \hat{p}. \end{aligned}$$

The N -point Richardson extrapolation of the randomized put formula is

$$P^{1:N}(s) \equiv \sum_{n=1}^N \frac{(-1)^{N-n} n^N}{n!(N-n)!} P^{(n)}(s),$$

where

$$P^{(n)}(s) = \begin{cases} p_0^{(n)}(s) + b_1^{(n)}(s) & \text{if } s > \underline{s}_0 \equiv K \\ v_i^{(n)}(s) + b_i^{(n)}(s) + A_i^{(n)}(s; 1) & \text{if } s \in (\underline{s}_i, \underline{s}_{i-1}], i = 1, \dots, n \\ K - S & \text{if } s \leq \underline{s}_n, \end{cases}$$

where for $i = 1, \dots, n$,

$$\begin{aligned} v_i^{(n)}(s) &= KR^{n-i+1} - sD^{n-i+1} - \frac{\phi}{r} R(R^{n-i+1} - R^n), \\ b_i^{(n)}(s) &= \sum_{j=1}^{n-i+1} \left(\frac{s}{\underline{s}_{n-j+1}}\right)^{\gamma-\epsilon} \sum_{k=0}^{j-1} \frac{\left(2\epsilon \ln\left(\frac{s}{\underline{s}_{n-j+1}}\right)\right)^k}{k!} \sum_{l=0}^{j-k-1} \binom{j-1+l}{j-1} \\ &\quad \times [q^j p^{k+l} R^j (Kr - \phi) - \hat{q}^j \hat{p}^{k+l} D^j \underline{s}_{n-j+1} \delta] \Delta, \\ A_i^{(n)}(s; h) &= \sum_{j=h}^{n-i+1} \left(\frac{s}{\underline{s}_{n-j+1}}\right)^{\gamma+\epsilon} \sum_{k=0}^{j-1} \frac{\left(2\epsilon \ln\left(\frac{\underline{s}_{n-j+1}}{s}\right)\right)^k}{k!} \sum_{l=0}^{j-k-1} \binom{j-1+l}{j-1} \\ &\quad \times [p^j q^{k+l} R^j (Kr - \phi) - \hat{p}^j \hat{q}^{k+l} D^j \underline{s}_{n-j+1} \delta] \Delta. \end{aligned}$$

If $\delta = 0$, the critical stripped prices are given by

$$\underline{s}_m = K \left(\frac{pR(Kr - \phi)\Delta}{c_1^{(m)}(K) - A_1^{(m)}(K; 2)} \right)^{\frac{1}{\gamma+\epsilon}}, \quad m = 1, \dots, n.$$

If $\delta > 0$, the critical stripped prices solve

$$\begin{aligned} \sum_{l=0}^{m-1} \binom{m-1+l}{m-1} [KD^m \hat{p}^m \hat{q}^l - KR^m p^m q^l] - A_1^{(m)}(K; 2) \\ = \left(\frac{K}{\underline{s}_m} \right)^{\gamma+\epsilon} [pR(Kr - \phi) - \hat{p}D\underline{s}_m \delta] \Delta, \quad m = 1, \dots, n. \end{aligned}$$

Letting $\underline{s}(T/n) \equiv \underline{s}_n$ denote the solution obtained by recursing on \bar{s}_m , the N -point Richardson extrapolation of the put's initial critical stock price is $\underline{S}^{1:N} \equiv \frac{\phi}{r}[1 - e^{-rT}] + \sum_{n=1}^N \frac{(-1)^{N-n} n^N}{n!(N-n)!} \underline{s}(T/n)$.

Similarly, letting $s = S - \frac{\phi}{r}[1 - e^{-rT}]$, the N -point Richardson extrapolation of the randomized European call formula is

$$c^{1:N}(s) \equiv \sum_{n=1}^N \frac{(-1)^{N-n} n^N}{n!(N-n)!} c^{(n)}(s),$$

where

$$c^{(n)}(s) = \begin{cases} sD^n - KR^n + p^{(n)}(s) & \text{if } s > K \\ \left(\frac{s}{K}\right)^{\gamma+\epsilon} \sum_{k=0}^{n-1} \frac{(2\epsilon \ln(\frac{K}{s}))^k}{k!} \sum_{l=0}^{n-k-1} \binom{n-1+l}{n-1} \\ [KD^n \hat{p}^n \hat{q}^{k+l} - KR^n p^n q^{k+l}] & \text{if } s \leq K, \end{cases} \quad (54)$$

and where again

$$\begin{aligned} \gamma &\equiv \frac{1}{2} - \frac{r - \delta}{\sigma^2}, \quad \Delta \equiv \frac{T}{n}, \quad R \equiv \frac{1}{1 + r\Delta}, \\ D &\equiv \frac{1}{1 + \delta\Delta}, \quad \epsilon \equiv \sqrt{\gamma^2 + \frac{2}{R\sigma^2\Delta}}, \quad p \equiv \frac{\epsilon - \gamma}{2\epsilon}, \\ q &\equiv 1 - p, \quad \hat{p} \equiv \frac{\epsilon - \gamma + 1}{2\epsilon}, \quad \text{and } \hat{q} \equiv 1 - \hat{p}. \end{aligned}$$

For $\delta = 0$ and $\phi \leq rK$, early exercise is not optimal, so the randomized call value is given by Equation (54). For $\delta > 0$ or $\phi > rK$, the N -point Richardson extrapolation of the randomized call value is $C^{1:N}(s) \equiv$

$\sum_{n=1}^N \frac{(-1)^{N-n} n^N}{n!(N-n)!} C^{(n)}(s)$, where

$$C^{(n)}(s) = \begin{cases} S - K & \text{if } s \geq \bar{s}_n \\ -v_i^{(n)}(s) + \alpha_i^{(n)}(s) + B_i^{(n)}(s; 1) & \text{if } s \in [\bar{s}_{i-1}, \bar{s}_i), \\ c_0^{(n)}(s) + \alpha_1^{(n)}(s) & \text{if } s < \bar{s}_0 \equiv K \end{cases} \quad i = 1, \dots, n$$

where for $i = 1, \dots, n$, $-v_i^{(n)}(s) = s D^{n-i+1} + \frac{\phi}{r} R (R^{n-i+1} - R^n) - K R^{n-i+1}$ is the initial value of a long forward position maturing in $n-i+1$ periods,

$$\begin{aligned} \alpha_i^{(n)}(s) = & \sum_{j=1}^{n-i+1} \left(\frac{s}{\bar{s}_{n-j+1}} \right)^{\gamma+\epsilon} \sum_{k=0}^{j-1} \frac{\left(2\epsilon \ln \left(\frac{\bar{s}_{n-j+1}}{s} \right) \right)^k}{k!} \sum_{l=0}^{j-k-1} \binom{j-1+l}{j-1} \\ & \times [\hat{p}^j \hat{q}^{k+l} D^j \bar{s}_{n-j+1} \delta - p^j q^{k+l} R^j (K r - \phi)] \Delta, \end{aligned}$$

is the initial value of dividends less interest received above the boundary for the first $n-i+1$ periods, while

$$\begin{aligned} B_i^{(n)}(s; h) = & \sum_{j=h}^{n-i+1} \left(\frac{s}{\bar{s}_{n-j+1}} \right)^{\gamma-\epsilon} \sum_{k=0}^{j-1} \frac{\left(2\epsilon \ln \left(\frac{s}{\bar{s}_{n-j+1}} \right) \right)^k}{k!} \sum_{l=0}^{j-k-1} \binom{j-1+l}{j-1} \\ & \times [\hat{q}^j \hat{p}^{k+l} D^j \bar{s}_{n-j+1} \delta - q^j p^{k+l} R^j (K r - \phi)] \Delta. \end{aligned}$$

$B_i^{(n)}(s; h)$ is the initial value of a European put less the excess of dividends over interest received below the boundary over the complementary period, after accounting for the smoothness of the exercise boundary in every period. Continuity in s at K in each period implies that \bar{s}_m solves

$$\begin{aligned} p_0^{(m)}(K) - B_1^{(m)}(K; 2) = & \left(\frac{K}{\bar{s}_m} \right)^{\gamma-\epsilon} [\hat{q} D \bar{s}_m \delta - q R (K r - \phi)] \Delta, \\ m = 1, \dots, n, \end{aligned} \tag{55}$$

where from Equation (53),

$$p_0^{(m)}(K) = \sum_{l=0}^{m-1} \binom{m-1+l}{m-1} [K R^m q^m p^l - K D^m \hat{q}^m \hat{p}^l].$$

If $\phi = r K$, Equation (55) can be solved, and $\bar{s}_m = K \left(\frac{K \hat{q} D \delta \Delta}{p_0^{(m)}(K) - B_1^{(m)}(K; 2)} \right)^{\frac{1}{\gamma-\epsilon-1}}$, $m = 1, \dots, n$. This solution is a good initial guess when solving Equa-

tion (55) numerically. Recursively solving for each \bar{s}_m results in $\bar{s}(T/n) \equiv \bar{s}_n$. The N -point Richardson extrapolation of the call's critical stock price is $\bar{S}^{1:N}(T) \equiv \frac{\phi}{r}[1 - e^{-rT}] + \sum_{n=1}^N \frac{(-1)^{N-n} n^N}{n!(N-n)!} \bar{s}(T/n)$.

References

Andersen, L., J. Andreasen, and R. Brotherton-Ratcliffe, 1998, "The Passport Option," *Journal of Computational Finance*, 1, 15–36.

Black, F., and M. Scholes, 1973, "The Pricing of Options and Corporate Liabilities," *Journal of Political Economy*, 81, 637–659.

Brennan, M., and E. Schwartz, 1977, "The Valuation of American Put Options," *Journal of Finance*, 32, 449–462.

Broadie, M., and J. Detemple, 1996, "American Option Valuation: New Bounds, Approximations, and a Comparison of Existing Methods," *Review of Financial Studies*, 9, 1211–1250.

Carr, P., and M. Chesney, 1997, "American Put Call Symmetry," forthcoming in *Journal of Financial Engineering*.

Carr, P., and D. Faguet, 1994, "Fast Accurate Valuation of American Options," working paper, Cornell University.

Carr, P., R. Jarrow, and R. Myneni, 1992, "Alternative Characterizations of American Put Options," *Mathematical Finance*, 2, 87–106.

Cass, D., and M. Yaari, 1967, "Individual Savings, Aggregate Capital Accumulation, and Efficient Growth," in K. Shell (ed.), *Essays on the Theory of Optimal Economic Growth*, MIT Press, Cambridge, Mass.

Cox, J., S. Ross, and M. Rubinstein, 1979, "Option Pricing: A Simplified Approach," *Journal of Financial Economics*, 7, 229–263.

Geske, R., and H. Johnson, 1984, "The American Put Option Valued Analytically," *Journal of Finance*, 39, 1511–1524.

Goldenberg, D., and R. Schmidt, 1995, "Estimating the Early Exercise Boundary and Pricing American Options," working paper, Rensselaer Polytechnic Institute.

Huang, J., M. Subrahmanyam, and G. Yu, 1996, "Pricing and Hedging American Options: A Recursive Integration Method," *Review of Financial Studies*, 9, 1, 277–300.

Hyer, T., A. Lipton-Lifschitz, and D. Pugachevsky, 1997, "Passport to Success," *Risk*, September, 127–131.

Jacka, S. D., 1991, "Optimal Stopping and the American Put," *Mathematical Finance*, 1, 1–14.

Jamshidian, F., 1998, "A Note on the Passport Option," working paper, Sakura Global Capital.

Ju, N., 1998, "Pricing an American Option by Approximating its Early Exercise Boundary as a Multipiece Exponential Function," *Review of Financial Studies*, 11, 627–646.

Kim, I. J., 1990, "The Analytic Valuation of American Puts," *Review of Financial Studies*, 3, 547–572.

Leisen, D., 1997, "The Random-Time Binomial Model," working paper, University of Bonn.

McKean, H. P., Jr., 1965, "Appendix: A Free Boundary Problem for the Heat Equation Arising from a Problem in Mathematical Economics," *Industrial Management Review*, 6, 32–39.

Madan, D., and E. Chang, 1997, "The Variance Gamma Process and Option Pricing," working paper, University of Maryland.

Marchuk, G., and V. Shaidurov, 1983, *Difference Methods and Their Extrapolations*, Springer Verlag, New York.

McDonald, R., and M. Schroder, 1990, "A Parity Result for American Options," working paper, Northwestern University.

Merton, R. C., 1971, "Optimum Consumption and Portfolio Rules in a Continuous Time Economy," *Journal of Economic Theory*, 3, 373–413.

Merton, R. C., 1973, "Theory of Rational Option Pricing," *Bell Journal of Economics and Management Science*, 4, 141–183.

Meyer, G. H., 1970, "On a Free Boundary Problem for Linear Ordinary Differential Equations and the One-Phase Stefan Problem," *Numerical Mathematics*, 16, 248–67.

Meyer, G. H., 1979, "One-Dimensional Free Boundary Problems," *SIAM Review*, 19, 17–34.

Meyer, G. H., and J. van der Hoek, 1994, "The Evaluation of American Options with the Method of Lines," working paper, Georgia Institute of Technology.

Rektorys, K., 1982, *The Method of Discretization in Time and Partial Differential Equations*, D. Reidel Publishing, Boston, Mass.

Rendleman R., and B. Bartter, 1979, "Two-State Option Pricing," *Journal of Finance*, 34, 1093–1110.

Roll, R., 1977, "An Analytic Valuation Formula for Unprotected American Call Options on Stocks with Known Dividends," *Journal of Financial Economics*, 5, 251–258.

Rothe, E., 1930, "Zweidimensionale parabolische Randwertaufgaben als Grenzfall eindimensionaler Randwerttaufgaben," *Math. Ann.* 102.

Rubinstein, I., and L. Rubinstein, 1993, *Partial Differential Equations in Classical Mathematical Physics*, Cambridge University Press, Cambridge.

Samuelson, P. A., 1965, "Rational Theory of Warrant Pricing," *Industrial Management Review*, 6, 13–31.

Schroeder, M., 1997, "Results on Futures, Forwards, and Options Obtained Using a Change of Numeraire," working paper, State University of New York, Buffalo.

Shreve, S., and J. Večeř, 1998, "Passport Option: Probabilistic Approach for Solving the Symmetric Case," working paper, Carnegie Mellon University.