LOSE A DOLLAR
OR DOUBLE YOUR FORTUNE

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1. Summary and introduction

A gambler with initial fortune $x$ (a positive integer number of dollars) plays a sequence of identical games in which he loses one dollar with probability $\pi$, $0 < \pi < 1$, and doubles his fortune with probability $1 - \pi$. Playing continues until, if ever, the gambler is ruined (his fortune drops to zero). Let $q_x$ denote the probability that the gambler starting with initial fortune $x$ will eventually be ruined. Then, $q_x$ satisfies the difference equation

$$q_x = \pi q_{x-1} + (1 - \pi)q_{2x}, \quad x = 1, 2, \ldots,$$

with boundary conditions $q_0 = 1$ and $\lim_{x\to\infty} q_x = 0$. In Section 2, a solution to this difference equation subject to these boundary conditions is explicitly exhibited, and it is shown that there is only one such solution. In Section 3, the equation is extended to allow arbitrary noninteger values for the fortune, and again a solution is found. Section 4 contains several other extensions.

Equation (1.1) arises in connection with the following more general gambling problem described in [2]. A gambler is confronted with a sequence of games affording him even money bets at varying probabilities of success, $p_1, p_2, \ldots$, chosen independently from a distribution function $F$ known to the gambler. The probability of winning the $j$th game $p_j$ is told to the gambler after he plays game $j - 1$ and before he plays game $j$. The gambler must decide how much to bet in the $j$th game as a function of the past history, his present fortune, and the win probability $p_j$. He may bet any amount not exceeding his present fortune; however, he must bet at least one dollar on each game (called Model 2 in [2]). The problem of the gambler is to choose a betting system (a sequence of functions $b_1, b_2, \ldots$, where $b_j$ is the amount bet in game $j$) that minimizes the probability of eventual ruin. Theorems relating to the dynamic programming solution of this problem may be found in Truelove [4].

Let $q_x$ denote the infimum, over all betting systems, of the probability of ruin given the initial fortune $x$. It was shown in [2] that $q_x$ tends to zero exponentially as $x$ tends to infinity, and it was conjectured that, for some $0 < r < 1$ and $c > 0$,

$$q_x x^r \to c \quad \text{as} \quad x \to \infty.$$

(1.2)

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Under this conjecture, the asymptotic (for large $x$) form of the optimal betting system was found to be

\begin{equation}
(1.3) \quad b(p) = \max \left\{ 1, \frac{\log (1 - p) - \log p}{\log r^2} \right\},
\end{equation}

where $r$ is the unique root between zero and one of the equation

\begin{equation}
(1.4) \quad \int_0^1 \left[ pr^{b(p)} + (1 - p)r^{-b(p)} \right] dF(p) = 1.
\end{equation}

In [1], Breiman proved conjecture (1.2) to be valid under the condition that $F$ give no mass to some neighborhood of 1, that is, that there exists an $\varepsilon > 0$ such that $F(1 - \varepsilon) = 1.$

There remains the question of the validity of the conjecture (1.2), or more generally the validity of the asymptotic form of the optimal betting function (1.3), when $F$ gives mass to all neighborhoods of 1.

In this paper, the simplest such $F$ is considered, namely, the $F$ that gives mass $\pi$ to 0 and mass $1 - \pi$ to 1, where $0 < \pi < 1.$ Under this $F,$ the form of the optimal betting function for all $x$ is obvious: bet the minimum value 1 when the probability of win $p$ is 0 and bet the maximum value $x$ when $p$ is 1. If $p$ is 0, you lose a dollar; if $p$ is 1, you double your fortune.

This leads to the recurrence equation (1.1) for $q_x,$ with the boundary condition $q_0 = 1.$ As noted before, it is known that $q_x$ tends to zero exponentially. We add as a boundary condition the weaker assertion $\lim_{x \to 0} q_x = 0,$ that together with $q_0 = 1$ is sufficient to insure the unicity of the solution to (1.1), for integer values of $x.$ However, it is of interest, in connection with the gambling system problem from which equation (1.1) originally arose, to investigate (1.1) for noninteger values of $x.$ This investigation leads to a useful solution for rational $x.$ If the initial boundary conditions on $q_x$ for $0 \leq x < 1$ are continuous in $x,$ then approximations may be found for $q_x$ for $x$ irrational. Furthermore, it is observed that the conjecture (1.2) is not valid for the boundary condition $q_x = 1$ for $0 \leq x < 1.$

2. A solution of difference equation (1.1)

We present in Theorem 1, the unique solution to the difference equation (1.1) subject to the boundary conditions $q_0 = 1$ and $\lim_{x \to \infty} q_x = 0,$ as a series in $\pi^{2/3} j = 0, 1, 2, \ldots,$ with coefficients depending on $\pi.$

The systems of equations (1.1), even with $q_0$ fixed equal to one, is vastly underdetermined. In fact, the values of $q_x$ for $x$ odd, $x = 1, 3, 5, \ldots,$ may be chosen arbitrarily and the system (1.1) will serve only to determine the values of $q_x$ for $x$ even. However, the addition of the single boundary condition $\lim_{x \to \infty} q_x = 0$ determines all the $q_x$ uniquely as follows.
Theorem 1. Let $0 < \pi < 1$. There exists a unique solution to the difference equation $q_x = \pi q_{x-1} + (1 - \pi)q_{2x}$, $x = 1, 2, 3, \ldots$, subject to the boundary conditions

\begin{align*}
(2.1) & \quad q_0 = 1 \\
(2.2) & \quad \lim_{x \to \infty} q_x = 0.
\end{align*}

That solution is

\begin{equation}
q_x = \alpha \sum_{j=0}^{\infty} c_j \pi^{2jx}, \quad x = 0, 1, 2, 3, \ldots,
\end{equation}

where the $c_j$ are defined inductively by

\begin{align*}
(2.4) & \quad c_0 = 1, \quad c_j = \frac{1 - \pi}{1 - \pi^{1-2j}} c_{j-1}, \\
\text{and where} & \\
(2.5) & \quad \alpha = \left( \sum_{j=0}^{\infty} c_j \right)^{-1}.
\end{align*}

Proof. The following proof of unicity is taken from Theorem 1 of MacQueen and Redheffer [3].

If $q_x$ and $q'_x$ both satisfy (1.1), (2.1), and (2.2), then the difference $d_x = q_x - q'_x$ satisfies (1.1), $d_0 = 0$, and (2.2). Suppose that $q_x \neq q'_x$ for some $x$, and assume, without loss of generality, that $q_x > q'_x$ for some $x$. Let $x_0 \geq 1$ be the largest value of $x$ at which $d_x$ achieves its maximum value, assumed to be positive. Then $q_{x0-1} \leq q_{x0}$, and $q_{2x0} < q_{x0}$. This contradicts (1.1), thus proving unicity.

To see that (2.3) is a solution, note first from (2.4) that $|c_j| \leq |c_{j-1}|$ so that (2.3) converges absolutely for $0 < \pi < 1$. Thus, (2.2) is obviously satisfied and (2.1) is satisfied from (2.5). Using (2.3), we compute the right side of (1.1):

\begin{align*}
(2.6) & \quad \pi q_{x-1} + (1 - \pi)q_{2x} \\
& \quad = \pi \alpha \sum_{j=0}^{\infty} c_j \pi^{2j(x-1)} + (1 - \pi) \alpha \sum_{j=1}^{\infty} c_j \pi^{2jx} \\
& \quad = \alpha \sum_{j=0}^{\infty} c_j (\pi^{1-2j}) \pi^{2jx} + \alpha \sum_{j=1}^{\infty} c_{j-1} (1 - \pi) \pi^{2jx} \\
& \quad = \alpha c_0 \pi^x + \alpha \sum_{j=1}^{\infty} (c_j \pi^{1-2j} + c_{j-1} (1 - \pi)) \pi^{2jx}.
\end{align*}

From the recurrence relation (2.4), this is equal to $q_x$, thus showing that (1.1) is satisfied and completing the proof.
The solution (2.3) is quite suitable for computational purposes, provided \( \pi \) is not too close to one. Table I, for which I am greatly indebted to David Cantor, gives an indication of the behavior of \( q_x \) for moderate values of \( \pi \). As \( \pi \) tends to one, \( q_x/(1-\pi) \) tends to \( H(z) = x' \sum_{j=0}^{\infty} c_j \exp \{-2^j z\} \), where \( c_0' = 1 \), \( c_j' = \Pi \{ (1 - 2^j)^{-1} \) and \( x' = (\sum_{j=0}^{\infty} c_j')^{-1} \). In Section 4.5, it is seen that \( 1 - H(z) \) is the cumulative distribution function of \( Z = \sum_{j=0}^{\infty} 2^{-j} Y_j \), where \( Y_0, Y_1, Y_2, \cdots \) are independent identically distributed exponential variables.

A simple asymptotic approximation to \( q_x \) as \( \pi \) tends to zero is \( q_x \sim \pi^x (1 + \pi) \), \( x = 1, 2, \cdots \).

### Table 1

**TABLE OF \( q_x \)**

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### 3. Fractional fortunes

The problem of the preceding section may be extended to the case in which the initial fortune \( x \) may be any nonnegative number. The difference equation to be considered is thus

\[
q_x = \pi q_{x-1} + (1 - \pi) q_{2x}, \quad x \geq 1.
\]

If the gambler is declared ruined when his fortune falls below one, then the boundary condition (2.1) is replaced by \( q_x = 1 \) if \( 0 \leq x < 1 \). We consider in this section an arbitrary bounded \( q_x \) for \( 0 \leq x < 1 \).

We first note that if \( q_x \) satisfies (3.1) and (2.2), then \( q_x \) is bounded for \( x \geq 0 \). Since \( \lim_{x \to \infty} q_x = 0 \), there exists an integer \( N \) such that \( |q_x| < 1 \) if \( x \geq N \). From (3.1),

\[
|q_{x-1}| = \pi^{-1} |q_x - (1 - \pi) q_{2x}| \leq \pi^{-1} |q_x| + \pi^{-1} (1 - \pi) |q_{2x}|,
\]

so that \( |q_x| < \pi^{-1} (2 - \pi) \) for \( x \geq N - 1 \). By induction therefore, \( |q_x| < (\pi^{-1} (2 - \pi))^N \) for \( x \geq 0 \).
We next note that probabilistic considerations alone allow us to infer the existence of a solution to (3.1) and (2.2) subject to an arbitrary initial condition on \( q_x \) for \( 0 \leq x < 1 \), provided \( 0 \leq q(x) \leq 1 \). Then, since the product of a solution to (3.1) and (2.2) by a scalar, and the sum of two solutions to (3.1) and (2.2) are also solutions to (3.1) and (2.2), we may achieve any bounded initial condition on \( q_x \) for \( 0 \leq x < 1 \).

Finally, we note that an extension of the argument of the previous section allows us to conclude that there exists a unique solution to (3.1) and (2.2) subject to an arbitrary bounded initial condition on \( q_x \), for \( 0 \leq x < 1 \), provided \( 0 < q(x) < 1 \). Then, since the product of a solution to (3.1) and (2.2) by a scalar, and the sum of two solutions to (3.1) and (2.2) are also solutions to (3.1) and (2.2), we may achieve any bounded initial condition on \( q_x \) for \( 0 < x < 1 \).

**Theorem 2.** Let \( a(x) \) be a bounded periodic function of period one, and let, for \( 0 < \pi < 1 \),

\[
q(x) = \sum_{j=0}^{\infty} c_j a(2^j x) \pi^{2^j x}, \quad x \geq 0,
\]

where \( c_0 = 1 \) and \( c_j = (1 - \pi)(1 - \pi^{-2^j})^{-1} c_{j-1} \) for \( j = 1, 2, \ldots \). Then \( q_x \) satisfies (3.1) and (2.2).

The proof, being similar to the corresponding part of Theorem 1, is omitted. The hypothesis that \( a \) be bounded is equivalent to (2.2).

This theorem may be used to find \( q_x \) for all \( x \) with dyadic fractional part for an arbitrary boundary condition on \( q_x \) for \( 0 \leq x < 1 \). Such a solution depends only on \( q_x \), \( 0 \leq x < 1 \), through the dyadic rational values of \( x \). To accomplish this, it is sufficient to find \( a(\frac{1}{2}), a(\frac{1}{4}), a(\frac{1}{8}), \ldots \). As in Theorem 1, equation (3.3) with \( x = 0 \) enables us to find \( a(0) \). For \( x = \frac{1}{2} \), equation (3.3) becomes

\[
q_{1/2} = c_0 a(\frac{1}{2}) \pi^{1/2} + \sum_{j=1}^{\infty} c_j a(0) \pi^{2^{j-1}}
\]

from which \( a(\frac{1}{2}) \) may be found. For \( x = \frac{1}{4} \), equation (3.3) becomes

\[
q_{1/4} = c_0 a(\frac{1}{4}) \pi^{1/4} + c_1 a(\frac{1}{2}) \pi^{1/2} + \sum_{j=2}^{\infty} c_j a(0) \pi^{2^{j-2}},
\]

from which \( a(\frac{1}{4}) \) may be found. It is clear that \( a(x) \) may be found for all dyadic rational \( x \) by this method.
In addition, one can find \( \alpha(x) \), and thus \( q(x) \) for rational \( x \) directly. We illustrate for \( x = \frac{1}{3} \). Evaluating (3.3) at \( x = \frac{1}{3} \) and \( x = \frac{2}{3} \) yields

\[
\begin{align*}
q_{1/3} &= \alpha(\frac{1}{3}) \sum_{j \text{ even}} c_j \pi^{2j/3} + \alpha(\frac{2}{3}) \sum_{j \text{ odd}} c_j \pi^{2j/3} \\
q_{2/3} &= \alpha(\frac{1}{3}) \sum_{j \text{ odd}} c_j \pi^{2j/3} + \alpha(\frac{2}{3}) \sum_{j \text{ even}} c_j \pi^{2j/3}
\end{align*}
\]  

(3.6)

from which one can solve for \( \alpha(\frac{1}{3}) \) and \( \alpha(\frac{2}{3}) \) provided the determinant of this system of equations does not vanish. In this case, it is clear that the determinant is not zero, since in each row the summation over \( j \) odd is larger than the absolute value of the summation over \( j \) even.

The general problem of finding \( q_x \) for \( x \) irrational seems more difficult. If the boundary condition on \( qx \) for \( 0 \leq x < 1 \) specifies a bounded continuous function of \( x \), in particular, if it is assumed that \( qx = 1 \) for \( 0 \leq x < 1 \), then \( qx \) for \( x \geq 1 \) has discontinuities only at the dyadic rationals, and hence can be approximated as closely as desired by \( qx \) for \( x \) dyadic rational.

To see that if the boundary condition specifies a bounded continuous function of \( x \), then \( qx \) is continuous at all \( x \) for which \( x \) is not dyadic rational, we may argue as follows. Let \( qx \) be a solution to (3.1) and (2.2), suppose that \( qx \) is continuous for \( 0 < x < 1 \), and let

\[
\begin{align*}
q^+ &= \limsup_{x \to x^-} qx, \\
q^- &= \liminf_{x \to x^-} qx
\end{align*}
\]

for \( x > 0 \). Then, for \( x > 0 \),

\[
\begin{align*}
q^+ &\leq nq^- + (1 - \pi)q^+, \\
q^- &\geq nq^- + (1 - \pi)q^-
\end{align*}
\]

(3.7)

Hence, letting \( d_x = q^+ - q^- \), we see that

\[
\begin{align*}
0 &\leq d_x \leq n d_x - 1 + (1 - \pi) d_x, \\
d_x &= 0, \\
\lim_{x \to 0} d_x &= 0.
\end{align*}
\]

(3.8)  (3.9)  (3.10)

If we consider this equation on the set of all positive \( x \) not dyadic rational, then the argument used to prove the unicity of (3.1) may be used here again to show \( d_x = 0 \) for all \( x \) not dyadic rational even though there is an inequality in (3.8) (as in MacQueen and Redheffer [3]) instead of equality. Hence, \( qx \) is continuous at all \( x \) not dyadic rational.

Finally, we note that the conjecture (1.2) is false in the present case. In fact

\[
q_x = \alpha(x) + \sum_{j=1}^{\infty} \alpha(2^j x) c_j \pi^{2^j x - x}
\]

which is not constant in \( x \), but periodic of period one. However, the trivially optimal betting system is still of the (asymptotic) form (1.3).
4. Other extensions

The method of expanding $q_x$ as a series in $\pi^{2jx}$ appears to be quite useful. We mention several other related difference equations that can be solved by the use of such an expansion.

4.1. Given $\pi_{-1} > 0$, $\pi_i \geq 0$ for $i = 0, \cdots, n$, $\pi_{n+1} > 0$, and $\Sigma_{i=0}^{n} \pi_i = 1$, find $q_x$ to satisfy

$$ q_x = \sum_{i=-1}^{n} \pi_i q_{x+i} + \pi_{n+1} q_{2x}, \quad x = 1, 2, \cdots, $$

subject to

$$ q_0 = 1, \quad \lim_{x \to \infty} q_x = 0. $$

The unicity of the solution follows as before. We attempt a series for $q_x$ of the form

$$ q_x = \sum_{j=0}^{\infty} c_j \pi^{2jx}, \quad x = 0, 1, 2, \cdots. $$

Formal substitution of this series into (4.1) yields

$$ \sum_{j=0}^{\infty} c_j \pi^{2jx} = \sum_{j=0}^{\infty} c_j \left( \sum_{i=-1}^{n} \pi_i \pi^{2ji} \right) \pi^{2jx} + \pi_{n+1} \sum_{j=0}^{\infty} c_{j-1} \pi^{2jx}. $$

We equate the coefficients of $r^{2jx}$. For $j = 0$, we obtain

$$ c_0 = c_0 \sum_{i=-1}^{n} \pi_i r^i. $$

This equation in $r$ has a unique root between zero and one, since the right side is convex in $r$, tends to $+\infty$ as $r$ tends to zero, and to $c_0 \Sigma_{i=1}^{n} \pi_i < c_0$ as $r$ tends to one. For arbitrary $j \geq 1$, we obtain

$$ c_j = c_j \sum_{i=-1}^{n} \pi_i r^{2ji} + c_{j-1} \pi_{n+1}. $$

Thus, the solution of (4.1) subject to (4.2) is (4.3), where $r$ satisfies (4.5) and the $c_j$ are defined recursively by (4.6), and where $c_0$ is chosen to satisfy $q_0 = 1$.

4.2. The model called Model I in [2] leads in the present context to the equation

$$ q_x = \pi q_{x-1} + (1 - \pi)q_{2x-1}, \quad x = 1, 2, \cdots, $$

subject to $q_0 = 1$ and $\lim_{x \to \infty} q_x = 0$. Since no new ideas are involved, we omit the details.

4.3. Analogous methods can be used to treat difference equations involving more terms of the form $q_{x-n}$ and correspondingly more boundary conditions.
As an example, consider the equation $(\pi_1 > 0, \pi_2 > 0, \pi_1 + \pi_2 < 1)$

\begin{equation}
q_x = \pi_1 q_{x-1} + \pi_2 q_{x-2} + (1 - \pi_1 - \pi_2)q_{2x}, \quad x = 1, 2, \cdots,
\end{equation}

subject to specified values of $q_0$ and $q_{-1}$ and subject to $\lim_{x \to \infty} q_x = 0$. The unicity of the solution follows as before. Again we try a solution of the form (4.2). Formal substitution into (4.8) yields

\begin{equation}
\sum_{j=0}^{\infty} c_j r^{2/j} = \sum_{j=0}^{\infty} c_j (\pi_1 r^{-2/j} + \pi_2 r^{-2/j+1}) r^{2/j} + (1 - \pi_1 - \pi_2) \sum_{j=1}^{\infty} c_{j-1} r^{2/j}.
\end{equation}

Again, we equate coefficients of $r^{2/j}$. For $j = 0$, we obtain $1 = \pi_1 r^{-1} + \pi_2 r^{-2}$. There are two roots to this equation,

\begin{equation}
r_1 = \frac{1}{2} [\pi_1 + (\pi_1^2 + 4\pi_2)^{1/2}], \quad r_2 = \frac{1}{2} [\pi_1 - (\pi_1^2 + 4\pi_2)^{1/2}].
\end{equation}

For $j > 0$, we obtain for each $r$, a recursion formula for the $c_j$, denoted by $c_{j,i}$:

\begin{equation}
c_{j,i} = c_{j,i}(\pi_1 r^{-2/j} + \pi_2 r^{-2/j+1}) + c_{j-1,i} (1 - \pi_1 - \pi_2)
\end{equation}

for $j = 1, 2, \cdots$ and $i = 1, 2$. Hence, the general solution of (4.8) subject to $\lim_{x \to \infty} q_x = 0$ is

\begin{equation}
q_x = \sum_{j=0}^{\infty} c_{j,1} r_1^{2/j} + \sum_{j=0}^{\infty} c_{j,2} r_2^{2/j}.
\end{equation}

The values of $c_{0,1}$ and $c_{0,2}$ may be chosen to obtain specified values of $q_0$ and $q_{-1}$.

Finally, we note that in expanding $q_x$ in terms of $r^{2/j}$, the “2” appears because we are concerned with the doubling of the fortune. To solve an equation of the type $q_x = \pi q_{x-1} + (1 - \pi)q_{3x}$ an expansion as a series in $\pi^{3/j}$ works. The details involve no new ideas. However, it might be worthwhile to give an explicit solution to the equation

\begin{equation}
q_x = \pi_1 q_{x-1} + \pi_2 q_{2x} + \pi_3 q_{3x}, \quad x = 1, 2, \cdots,
\end{equation}

where $\pi_1 > 0$, $\pi_2 > 0$, $\pi_3 > 0$, and $\pi_1 + \pi_2 + \pi_3 = 1$ subject to the condition $\lim_{x \to \infty} q_x = 0$. This equation requires an expansion of the form

\begin{equation}
q_x = \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} c_{i,j} \pi_1^{2/j}.
\end{equation}
By substituting this expansion into (4.13) and equating coefficients of \( \pi_1^{2i/3j} \), we find the following recurrence relations for the \( c_{i,j} \),

\[
c_{i,j} = \frac{c_{i-1,j} \pi_2 + c_{i,j-1} \pi_3}{1 - \pi_1^{1-2i/3j}}, \quad i = 1, 2, \ldots, \\
c_{i,0} = \frac{c_{i-1,0} \pi_2}{1 - \pi_1^{1-2i}}, \quad i = 1, 2, \ldots, \\
c_{0,j} = \frac{c_{0,j-1} \pi_3}{1 - \pi_1^{1-3j}}, \quad j = 1, 2, \ldots.
\]

(4.15)

The value of \( c_{0,0} \) may be chosen to obtain a specified value of \( q_0 \).

4.5. Let \( Y_0, Y_1, Y_2, \ldots \) be independent identically distributed random variables with exponential densities

\[
f(y) = \begin{cases} e^{-y}, & y \geq 0, \\ 0, & y < 0. \end{cases}
\]

(4.16)

Let \( 0 < \beta < 1 \), and let \( Z = \sum_0^\infty \beta^j Y_j \). We find the distribution function of \( Z \), \( G(z) = P(Z \leq z) \), as follows. Note that \( Z \) may be written as \( Z = Y_0 + \beta Z_1 \), where \( Z_1 = Y_1 + \beta Y_2 + \cdots \) has the same distribution as \( Z \), and is independent of \( Y_0 \). Therefore, for \( z > 0 \),

\[
G(z) = \int_0^z e^{-y} G \left( \frac{z-y}{\beta} \right) dy
\]

(4.17)

\[
= \beta \int_0^{z/\beta} e^{-z' + \beta x} G(x) \, dx.
\]

Multiplying both sides by \( e^z \) and differentiating with respect to \( z \), yields

\[
G(z) + G'(z) = G \left( \frac{z}{\beta} \right).
\]

(4.18)

We solve this equation subject to the boundary conditions

\[
G(0) = 0, \quad \lim_{z \to \infty} G(z) = 1,
\]

(4.19)

and subject to the existence of one continuous derivative of \( G \). (In the present case \( G \), being the convolution of an infinite number of absolutely continuous random variables, must be \( C^\infty \).) The unicity of the solution to (4.18) subject to (4.19) and the continuity of \( G' \) follows as in the previous problems. It is then a straightforward matter to check that the expansion

\[
G(z) = 1 - \alpha \sum_{j=0}^\infty c_j \exp \{-\beta^{-1}z\},
\]

(4.20)
where

\[(4.21) \quad c_0 = 1, \quad c_j = \prod_{i=1}^{j} (1 - \beta^{-i})^{-1}, \quad \alpha = \left(\sum_{j=0}^{\infty} c_j\right)^{-1},\]

satisfies (4.18) and (4.19), and thus represents the distribution function of \( Z \).

\[\Diamond \quad \Diamond \quad \Diamond \quad \Diamond \quad \Diamond\]

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REFERENCES


