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SECTIONALLY CONTINUOUS BARRIERS**

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Let $C_w \equiv C[0, T]$ denote the Wiener space on $[0, T]$. The Wiener integrals of various functionals $F[x]$ over the space C_w are well-known. In this paper we establish formulas for the Wiener integrals of $F[x]$ over the subsets of C_w bounded by sectionally continuous functions.

1. Introduction. Let $C_w \equiv C[0, T]$ be the Wiener space on $[0, T]$, i.e., the space of all real-valued continuous functions on $[0, T]$ vanishing at the origin. The standard Wiener process $\{X(t) \equiv X(t, \cdot); 0 \leq t \leq T\}$ and C_w are related by $X(t, x) = x(t)$ for each x in C_w . Evaluation formulas for the Wiener integral

$$\int_{C_w} F[x] d_w x \equiv E\{F[x]\}$$

of various functionals $F[x]$ are of course well-known (for example see [7] for some of these formulas). Now, consider sets of the type

$$\begin{aligned} \Gamma_f &\equiv \left\{ \sup_{0 \leq t \leq T} X(t) - f(t) < 0 \right\} \\ &= \left\{ x \in C_w : \sup_{0 \leq t \leq T} x(t) - f(t) < 0 \right\} \end{aligned}$$

where $f(t)$ is sectionally continuous on $[0, T]$ and $f(0) \geq 0$. It is well-known that for $b \geq 0$

$$P[\Gamma_b] = 2\Phi(bT^{-1/2}) - 1$$

and

$$P[\Gamma_{at+b}] = \Phi[(aT + b)T^{-1/2}] - e^{-2ab} \Phi[(aT - b)T^{-1/2}]$$

where Φ is the standard normal distribution function. In [3], [5], and [6] more general functions $f(t)$ are considered and formulas given for the probabilities of the sets Γ_f .

The main purpose of this paper is to derive formulas for Wiener integrals over the sets Γ_f . In §2 we state and prove the main results, while in §3 we discuss some applications and examples.

2. Integration formulas. Our first theorem is preliminary; it plays a key role in the proof of Theorem 2.

THEOREM 1. *Let $0 = t_0 < t_1 < \cdots < t_n = T$ be a partition of $[0, T]$. For $j = 1, 2, \cdots, n$ let $f_j(t)$ be continuous on $[t_{j-1}, t_j]$. Then the conditional probability*

$$\begin{aligned} & P \left[\sup_{t_{j-1} \leq t \leq t_j} X(t) - f_j(t) < 0, 1 \leq j \leq n \mid X(t_j) = u_j, 1 \leq j \leq n \right] \\ &= \prod_{j=1}^n P \left[\sup_{0 \leq t \leq \Delta t_j} X(t) - \{f_j(t + t_{j-1}) - u_{j-1}\} < 0 \mid X(\Delta t_j) = \Delta u_j \right] \\ &= \prod_{j=1}^n P \left(\sup_{0 \leq t < \infty} X(t) - \left\{ \frac{t + t \Delta t_j}{\Delta t_j} \left[f_j \left(\frac{\Delta t_j}{1 + t \Delta t_j} + t_{j-1} \right) - u_{j-1} \right] - \frac{\Delta u_j}{\Delta t_j} \right\} < 0 \right) \end{aligned}$$

where $\Delta t_j = t_j - t_{j-1}$ and $\Delta u_j = u_j - u_{j-1}$ with $u_0 = 0$.

Proof. First we note that

$$\begin{aligned} & P \left[\sup_{t_{j-1} \leq t \leq t_j} X(t) - f_j(t) < 0, 1 \leq j \leq n \mid X(t_j) = u_j, 1 \leq j \leq n \right] \\ &= P \left\{ \sup_{t_{j-1} \leq t \leq t_j} X(t) - X(t_{j-1}) - [f_j(t) - u_{j-1}] < 0, \right. \\ &\quad \left. 1 \leq j \leq n \mid X(t_j) - X(t_{j-1}) = \Delta u_j, 1 \leq j \leq n \right\}. \end{aligned}$$

Now since the Wiener process has independent increments, the above expression equals

$$\prod_{j=1}^n P \left\{ \sup_{t_{j-1} \leq t \leq t_j} X(t) - X(t_{j-1}) - [f_j(t) - u_{j-1}] < 0 \mid X(t_j) - X(t_{j-1}) = \Delta u_j \right\}.$$

Hence the first equality in the theorem follows from the fact that stationarity implies that $X(t) - X(t_{j-1})$ is the same process as $X(t - t_{j-1})$. To prove the second equality in the theorem, we note that $X(t)$ and $tX(1/t)$ are identical Wiener processes for $t > 0$ by checking the covariance function. Thus

$$\begin{aligned} & P \left\{ \sup_{0 \leq t \leq \Delta t_j} X(t) - [f_j(t + t_{j-1}) - u_{j-1}] < 0 \mid X(\Delta t_j) = \Delta u_j \right\} \\ &= P \left\{ \sup_{0 < t \leq \Delta t_j} X \left(\frac{1}{t} \right) - \frac{1}{t} [f_j(t + t_{j-1}) - u_{j-1}] < 0 \mid X \left(\frac{1}{\Delta t_j} \right) = \frac{\Delta u_j}{\Delta t_j} \right\} \\ &= P \left\{ \sup_{0 < t \leq \Delta t_j} X \left(\frac{1}{t} \right) - X \left(\frac{1}{\Delta t_j} \right) - \frac{1}{t} [f_j(t + t_{j-1}) - u_{j-1}] + \frac{\Delta u_j}{\Delta t_j} < 0 \right\}. \end{aligned}$$

The result now follows by the transformation

$$t^{-1} - (\Delta t_j)^{-1} \rightarrow t.$$

THEOREM 2. *Let $0 = t_0 < t_1 < \dots < t_n = T$ be a partition of $[0, T]$. Let $g(u_1, \dots, u_n)$ be a Lebesgue measurable function on R^n and for $x \in C_w$ let $G[x] = g(x(t_1), \dots, x(t_n))$. For $j = 1, 2, \dots, n$ let $f_j(t)$ be a continuous function on $[t_{j-1}, t_j]$. Then the Wiener integral of $G[x]$ over the set*

$$\Gamma_f \equiv \left\{ x \in C_w : \sup_{t_{j-1} \leq t \leq t_j} x(t) - f_j(t) < 0, j = 1, 2, \dots, n \right\}$$

is given by

$$\int_{\Gamma_f} G[x] d_w x = \int_{-\infty}^{\lambda_1} \dots \int_{-\infty}^{\lambda_n} g(u_1, \dots, u_n) H(u_1, \dots, u_n) du_n \dots du_1$$

in the sense the existence of either side implies that of their equality, where

$$\lambda_j = \begin{cases} \min \{f_j(t), f_{j+1}(t)\}, & j = 1, 2, \dots, n - 1 \\ f_n(T), & j = n \end{cases}$$

$$f(t) = \begin{cases} f_j(t), & t_{j-1} < t < t_j, \quad j = 1, 2, \dots, n \\ f_1(0), & t = 0 \\ \lambda_j, & t = t_j, \quad j = 1, 2, \dots, n \end{cases},$$

and

$$H(u_1, \dots, u_n) = \prod_{j=1}^n (2\pi \Delta t_j)^{-1/2} \exp \{ -(\Delta u_j)^2 / (2\Delta t_j) \}$$

$$P \left[\sup_{0 \leq t \leq \Delta t_j} X(t) - \{f_j(t + t_{j-1}) - u_{j-1}\} < 0 \mid X(\Delta t_j) = \Delta u_j \right].$$

Proof. First consider the case where $G[x]$ is the characteristic function of a Wiener interval I . That is to say I has the form

$$I = \{x \in C_w \mid [x(t_1), \dots, x(t_n)] \in E\}$$

for some Lebesgue measurable set E in R^n . Then $G[x] = \chi_I(x) = \chi_E[x(t_1), \dots, x(t_n)]$ and so in this case

$$\begin{aligned} \int_{\Gamma_f} G[x] d_w x &= \int_{\Gamma_f} \chi_I(x) d_w x = P[\Gamma_f \cap I] \\ &= \int_{-\infty}^{\lambda_1} \cdot (n) \cdot \int_{-\infty}^{\lambda_n} P \left\{ \sup_{t_{j-1} \leq t \leq t_j} X(t) - f_j(t) < 0, 1 \leq j \leq n, \right. \\ &\quad \left. [x(t_1), \dots, x(t_n)] \in E \mid x(t_j) = u_j, 1 \leq j \leq n \right\} K(\vec{t}, \vec{u}) du_n \cdots du_1 \end{aligned}$$

where

$$K(\vec{t}, \vec{u}) \equiv \prod_{j=1}^n (2\pi \Delta t_j)^{-1/2} \exp \{ -(\Delta u_j)^2 / (2\Delta t_j) \}.$$

Next we observe that

$$\begin{aligned} P \left\{ \sup_{t_{j-1} \leq t \leq t_j} X(t) - f_j(t) < 0, 1 \leq j \leq n, [x(t_1), \dots, x(t_n)] \in E \mid \right. \\ \left. x(t_j) = u_j, 1 \leq j \leq n \right\} &= \chi_E(u_1, \dots, u_n) P \left[\sup_{t_{j-1} \leq t \leq t_j} X(t) - f_j(t) < 0, \right. \\ &\quad \left. 1 \leq j \leq n \mid x(t_j) = u_j, 1 \leq j \leq n \right]. \end{aligned}$$

Next, applying Theorem 1 to the last conditional probability above gives the desired result for this case. The general case follows by the usual arguments in integration theory.

THEOREM 3. *Let $f(t)$ be sectionally continuous on $[0, T]$ with $f(0) \geq 0$. Let $g(u_1, \dots, u_n)$ be a Lebesgue measurable function on R^n , and let $\alpha(t) \in BV[0, T]$. Then*

$$\begin{aligned} \int_{\Gamma_f} g[x(t_1), \dots, x(t_n)] e^{\int_0^T \alpha(t) dx(t)} d_w x \\ = e^{1/2 \int_0^T \alpha^2(t) dt} \int_{\Gamma_{f(\alpha) - \int_0^t \alpha(s) ds}} g \left[x(t_1) + \int_0^{t_1} \alpha(s) ds, \dots, x(t_n) \right. \\ \left. + \int_0^{t_n} \alpha(s) ds \right] d_w x \end{aligned}$$

in the sense the existence of either side implies that of the other and their equality.

COROLLARY. *If f and α satisfy the conditions in Theorem 3, then*

$$\int_{\Gamma_f} e^{\int_0^T \alpha(t) dx(t)} d_w x = e^{1/2 \int_0^T \alpha^2(t) dt} P \left\{ \sup_{0 \leq t \leq T} X(t) - \left[f(t) - \int_0^t \alpha(s) ds \right] < 0 \right\}.$$

Proof (of Theorem 3). Using the Cameron–Martin translation theorem (see [1] or [7]) with the translation

$$x(t) \rightarrow x(t) + \int_0^t \alpha(u) du$$

we obtain

$$\begin{aligned} & \int_{\Gamma_t} g[x(t_1), \dots, x(t_n)] e^{\int_0^t \alpha(u) dx(u)} d_w x \\ &= e^{-1/2 \int_0^t \alpha^2(u) du} \int_{\Gamma(t) - \int_0^t \alpha(s) ds} g \left[x(t_1) + \int_0^{t_1} \alpha(u) du, \dots, x(t_n) + \int_0^{t_n} \alpha(u) du \right] \\ & \cdot e^{\int_0^t \alpha(u) d[x(t) + \int_0^t \alpha(u) du]} e^{-\int_0^t \alpha(u) dx(u)} d_w x. \end{aligned}$$

The result now follows by simplifying the last expression.

THEOREM 4. Assume that $g(z) = \sum_0^\infty a_n z^n$ is an entire function such that for some M, N and $\gamma \in (0, 2)$, $|g(z)| \leq M \exp(N|z|^\gamma)$ for all complex numbers z . For some $r \in (2, \infty]$ and $b > 0$ assume that $\theta(t, u) \in L_r([0, T] \times (-\infty, b])$, i.e., $\int_{-\infty}^b |\theta(t, u)| du \in L_r[0, T]$. Then for any $\psi(u) \in L_1(-\infty, b] \cup L_\infty(-\infty, b]$,

$$(1) \quad \int_{\Gamma_b} g \left[\int_0^T \theta(t, x(t)) dt \right] \psi(x(T)) d_w x = \sum_0^\infty a_n J_n(T) n!$$

where for $n = 0, 1, 2, \dots$

$$\begin{aligned} (2) \quad J_n(T) &\equiv \int_0^{t_{n+1}} \cdot (n) \cdot \int_0^{t_2} \int_{-\infty}^b \cdot (n+1) \cdot \int_{-\infty}^b \psi(u_{n+1}) \prod_{j=1}^n \theta(t_j, u_j) \\ & \prod_{j=1}^{n+1} (2\pi \Delta t_j)^{-1/2} \exp\{- (\Delta u_j)^2 / (2\Delta u_j)\} \\ & \cdot [1 - \exp\{-2(b - u_{j-1})(b - u_j) / \Delta t_j\}] \\ & \cdot du_{n+1} \cdots du_1 dt_1 \cdots dt_n \end{aligned}$$

and where $u_0 \equiv 0$, and $0 = t_0 < t_1 < \dots < t_{n+1} = T$.

Proof. Proceeding formally we obtain

$$\begin{aligned} & \int_{\Gamma_b} g \left[\int_0^T \theta(t, x(t)) dt \right] \psi(x(T)) d_w x \\ &= \sum_0^\infty a_n \int_{\Gamma_b} \left[\int_0^T \theta(t, x(t)) dt \right]^n \psi(x(T)) d_w x. \end{aligned}$$

But for $n = 1, 2, \dots$

$$\begin{aligned} & \int_{\Gamma_b} \left[\int_0^T \theta(t, x(t)) dt \right]^n \psi(x(T)) d_w x \\ &= \int_{\Gamma_b} \left[\int_0^T \cdot (n) \cdot \int_0^T \prod_{j=1}^n \theta(t_j, x(t_j)) dt_1 \cdots dt_n \right] \psi(x(T)) d_w x \\ &= n! \int_0^{t_{n+1}} \cdot (n) \cdot \int_0^{t_2} \left[\int_{\Gamma_b} \psi(x(t_{n+1})) \prod_{j=1}^n \theta(t_j, x(t_j)) d_w x \right] dt_1 \cdots dt_n \\ &= n! \int_0^{t_{n+1}} \cdot (n) \cdot \int_0^{t_2} \int_{-\infty}^b \cdot (n+1) \cdot \int_{-\infty}^b \psi(u_{n+1}) \prod_{j=1}^n \theta(t_j, u_j) \prod_{j=1}^{n+1} \{(2\pi \Delta t_j)^{-1/2} \\ & \quad \cdot \exp[-(\Delta u_j)^2 / (2\Delta t_j)] [1 - \exp(-2(b - u_{j-1})(b - u_j) / \Delta t_j)]\} \\ & \quad \cdot du_{n+1} \cdots du_1 dt_1 \cdots dt_n \end{aligned}$$

where the last equality above is obtained using Theorem 2, Theorem 1, and the fact that

$$\begin{aligned} P \left(\sup_{0 \leq t < \infty} X(t) - \{(b_j - u_{j-1})t + (b_j - u_j) / \Delta t_j\} < 0 \right) \\ = 1 - \exp[-2(b - u_{j-1})(b - u_j) / \Delta t_j]. \end{aligned}$$

Thus proceeding formally we have obtained equation (1). The Theorem follows readily once the absolute convergence of the series

$$\sum_0^\infty n! a_n J_n(T)$$

is established.

Recall that $r \in (2, \infty]$. We will establish the absolute convergence when $2 < r < \infty$ and $\psi \in L_1(-\infty, b]$; then other cases are similar, but easier. Let p satisfy $1/r + 1/p = 1$. Then $1 < p < 2$ and by Hölder's inequality we obtain

$$\begin{aligned} |J_n(T)| &\leq \|\psi\|_1 \int_0^{t_{n+1}} \cdot (n) \cdot \int_0^{t_2} \prod_{j=1}^n \|\theta(t_j, \cdot)\|_1 \prod_{j=1}^{n+1} (2\pi \Delta t_j)^{-1/2} dt_1 \cdots dt_n \\ &\leq \|\psi\|_1 \left\{ \int_0^{t_{n+1}} \cdot (n) \cdot \int_0^{t_2} [t_1(t_2 - t_1) \cdots (t_{n+1} - t_n)]^{-p/2} dt_1 \cdots dt_n \right\}^{1/p} \\ & \quad \cdot \left\{ \int_0^{t_{n+1}} \cdot (n) \cdot \int_0^{t_2} \prod_{j=1}^n \|\theta(t_j, \cdot)\|_1 dt_1 \cdots dt_n \right\}^{1/r} (2\pi)^{-(n+1)/2}. \end{aligned}$$

But

$$\begin{aligned} & \left\{ \int_0^{t_{n+1}} \cdot (n) \cdot \int_0^{t_2} \prod_{j=1}^n \|\theta(t_j, \cdot)\|_i^2 dt_1 \cdots dt_n \right\}^{1/r} \\ &= \left\{ \frac{1}{n!} \int_0^T \cdot (n) \cdot \int_0^T \prod_{j=1}^n \|\theta(t_j, \cdot)\|_i^2 dt_1 \cdots dt_n \right\}^{1/r} \\ &= \left(\frac{1}{n!}\right)^{1/r} \left(\int_0^T \|\theta(t, \cdot)\|_i^2 dt\right)^{n/r} \\ &= \left(\frac{1}{n!}\right)^{1/r} \|\theta\|_{1,r}^n. \end{aligned}$$

In addition

$$\begin{aligned} & \int_0^{t_{n+1}} \cdot (n) \cdot \int_0^{t_2} [t_1(t_2 - t_1) \cdots (t_{n+1} - t_n)]^{-p/2} dt_1 \cdots dt_n \\ &= \frac{T^{n(2-p)/2} \{\Gamma(1 - p/2)\}^{n+1}}{T^{p/2} \Gamma[(n + 1)(1 - p/2)]} \end{aligned}$$

where $\Gamma(z)$ denotes the Gamma function.

Thus the series $\sum_0^\infty |a_n J_n(T)| n!$ is dominated by the series

$$\begin{aligned} (3) \quad & \sum_0^\infty \frac{n! |a_n| (n!)^{-1/r} \|\theta\|_{1,r}^n T^{n(2-p)/2p} \{\Gamma(1 - p/2)\}^{(n+1)/p}}{T^{1/2} \{\Gamma[(n + 1)(1 - p/2)]\}^{1/p}} \\ &= \sum_0^\infty \frac{|a_n| \|\theta\|_{1,r}^n T^{n(2-p)/2p} \{\Gamma(1 - p/2)\}^{(n+1)/p}}{T^{1/2}} \left\{ \frac{n!}{\Gamma[(n + 1)(1 - p/2)]} \right\}^{1/p}. \end{aligned}$$

But since $g(z)$ is an entire function of order at most γ we know that

$$\limsup_{n \rightarrow \infty} \left(\frac{n \ln n}{-\ln |a_n|} \right) \leq \gamma < \frac{\gamma + 2}{2}$$

and so for n sufficiently large we obtain that

$$|a_n| < n^{-2n/(\gamma+2)}.$$

But $\Gamma(z) = z^{z-1/2} e^{-z} (2\pi)^{1/2} (1 + O(1))$ and hence for positive z sufficiently large

$$\frac{1}{\Gamma(z)} < \frac{2e^z z^{1/2}}{(2\pi)^{1/2} z^z}.$$

Also by Stirling's formula

$$n! \leq (n/e)^n (2\pi n)^{1/2} \exp\left(\frac{1}{12n}\right).$$

Thus for n sufficiently large we obtain

$$\begin{aligned} & |a_n| \left\{ \frac{n!}{\Gamma[(n+1)(1-p/2)]} \right\}^{1/p} \\ (4) \quad & \leq 2^{1/p} \exp\left(\frac{12n+1}{12np}\right) n^{1/2} e^{-(n+1)/2} \left(\frac{2}{2-p}\right) \\ & \times [(n+1)(2-p) - 1] / 2p n^{-n(2-\gamma)/2(\gamma+2)}. \end{aligned}$$

Now using inequality (4) the convergence of the series (3) follows by the root test.

COROLLARY 1. *Let $\theta(t, u)$ be as in Theorem 4. Then*

$$\int_{\Gamma_b} \exp\left[\int_0^T \theta(s, x(s)) ds\right] d_w x = \sum_0^\infty J_n(T)$$

where $J_n(T)$ is given by (2) with $\psi \equiv 1$.

COROLLARY 2. *Let $\alpha(t)$ be of bounded variations on $[0, T]$. Then for any $b > 0$,*

$$\int_{\Gamma_b} e^{\int_0^T \alpha(t) dx(t)} d_w x = \sum_0^\infty (-1)^n K_n(T)$$

where

$$\begin{aligned} (5) \quad K_n(T) & \equiv \int_0^{t_{n+1}} \cdot (n) \cdot \int_0^{t_2} \int_{-\infty}^b \cdot (n+1) \cdot \int_{-\infty}^b e^{\alpha(T)u_{n+1}} \prod_{j=1}^n u_j \prod_{j=1}^{n+1} (2\pi \Delta t_j)^{-1/2} \\ & \cdot \exp[-(\Delta u_j)^2 / (2\Delta t_j)] \{1 - \exp[-2(b - u_{j-1})(b - u_j) / \Delta t_j]\} \\ & \cdot du_{n+1} \cdots du_1 d\alpha(t_1) \cdots d\alpha(t_n). \end{aligned}$$

Proof (of Corollary 2). The Corollary follows quite readily once the absolute convergence of the series $\sum_0^\infty (-1)^n K_n(T)$ is established. Now proceeding formally we see that

$$\begin{aligned} \int_{\Gamma_b} e^{\int_0^T \alpha(t) dx(t)} d_w x & = \int_{\Gamma_b} e^{\alpha(T)x(T) - \int_0^T x(t) d\alpha(t)} d_w x \\ & = \int_{\Gamma_b} \sum_{n=0}^\infty \frac{(-1)^n}{n!} e^{\alpha(T)x(T)} \left[\int_0^T x(t) d\alpha(t) \right]^n d_w x \end{aligned}$$

and so

$$|K_n(T)| = \left| \frac{1}{n!} \int_{\Gamma_b} e^{\alpha(T)x(T)} \left[\int_0^T x(t) d\alpha(t) \right]^n d_w x \right| \\ \cong \frac{1}{n!} \int_{C_w} e^{\alpha(T)x(T)} \left| \int_0^T x(t) d\alpha(t) \right|^n d_w x.$$

Thus

$$\sum_0^\infty |K_n(T)| \cong \sum_0^\infty \frac{1}{n!} \int_{C_w} e^{\alpha(T)x(T)} \left| \int_0^T x(t) d\alpha(t) \right|^n d_w x \\ = \int_{C_w} e^{\alpha(T)x(T)} e^{|\int_0^T x(t) d\alpha(t)|} d_w x \\ \cong \int_{C_w} e^{2|\alpha(T)x(T)|} e^{|\int_0^T \alpha(t) dx(t)|} d_w x \\ \cong \left[\int_{C_w} e^{4|\alpha(T)x(T)|} d_w x \right]^{1/2} \left[\int_{C_w} e^{2|\int_0^T \alpha(t) dx(t)|} d_w x \right]^{1/2} \\ < \infty \quad \text{since } \alpha(t) \in L^2[0, T].$$

3. Applications and examples.

A. *Application 1.* For our first application we obtain a formula for the probability that a Wiener path always stays below the broken line segments $f_j(t) = a_j t + b_j$, $t_{j-1} \leq t \leq t_j$, $1 \leq j \leq n$, where $b_1 > 0$. Using Theorems 1 and 2 we obtain

$$P \left[\sup_{t_{j-1} \leq t \leq t_j} X(t) - (a_j t + b_j) < 0, 1 \leq j \leq n \right] \\ = \int_{-\infty}^{\lambda_1} \cdot (n) \cdot \int_{-\infty}^{\lambda_n} \prod_{j=1}^n P \left(\sup_{0 \leq t < \infty} X(t) - \left\{ \frac{1+t\Delta t_j}{\Delta t_j} \left[a_j \left(\frac{\Delta t_j}{1+t\Delta t_j} + t_{j-1} \right) \right. \right. \right. \\ \left. \left. \left. + b_j - u_{j-1} \right] - \frac{\Delta u_j}{\Delta t_j} \right\} < 0 \right) K(\vec{t}, \vec{u}) du_n \cdots du_1$$

where

$$\lambda_j = \begin{cases} \min \{ a_j t_j + b_j, a_{j+1} t_j + b_{j+1} \}, & 1 \leq j < n \\ a_n T + b_n, & j = n \end{cases}$$

and

$$K(\vec{t}, \vec{u}) = \prod_{j=1}^n (2\pi \Delta t_j)^{-1/2} \exp\{-(\Delta u_j)^2/(2\Delta t_j)\}.$$

But the probability in the integrand simplifies into

$$P\left(\sup_{0 \leq t < \infty} X(t) - \{(a_j t_{j-1} + b_j - u_{j-1})t + (a_j t_j + b_j - u_j)/\Delta t_j\} < 0\right)$$

which, using Doob [2, p. 397], equals the expression

$$[1 - \exp\{-2(a_j t_{j-1} + b_j - u_{j-1})(a_j t_j + b_j - u_j)/\Delta t_j\}].$$

Thus, we finally obtain the formula

$$\begin{aligned} & P\left[\sup_{t_{j-1} \leq t \leq t_j} X(t) - (a_j t + b_j) < 0, 1 \leq j \leq n\right] \\ &= \int_{-\infty}^{\lambda_1} \cdot (n) \cdot \int_{-\infty}^{\lambda_n} \prod_{j=1}^n [1 - \exp\{-2(a_j t_{j-1} + b_j - u_{j-1})(a_j t_j + b_j - u_j)/\Delta t_j\}] \\ &\quad \cdot [2\pi \Delta t_j]^{-1/2} \exp\{-(\Delta u_j)^2/(2\Delta t_j)\} du_n \cdots du_1. \end{aligned}$$

B. Example 1. For $j = 1, 2, \dots, n$ let the a_j and b_j be as above. Let

$$E \equiv \left\{x \in C_w \mid \sup_{t_{j-1} \leq t \leq t_j} X(t) - (a_j t + b_j) < 0, 1 \leq j \leq n\right\}.$$

Let $g(u_1, \dots, u_n)$ be Lebesgue measurable on R^n . Then

$$\begin{aligned} & \int_E g(x(t_1), \dots, x(t_n)) d_w x \\ &= \int_{-\infty}^{\lambda_1} \cdot (n) \cdot \int_{-\infty}^{\lambda_n} g(u_1, \dots, u_n) \prod_{j=1}^n [2\pi \Delta t_j]^{-1/2} \exp\{-(\Delta u_j)^2/(2\Delta t_j)\} \\ &\quad \cdot \prod_{j=1}^n [1 - \exp\{-2(a_j t_{j-1} + b_j - u_{j-1})(a_j t_j + b_j - u_j)/\Delta t_j\}] du_n \cdots du_1 \end{aligned}$$

in the sense the existence of either side implies that of the other and their equality.

C. Application 2. Assume $\alpha(t)$ is of bounded variation on $[0, T]$ and let $f(t) \equiv \int_0^t \alpha(s) ds$. For $b > 0$ we want to find the probability of the set

$$\Gamma_{f(\cdot)+b} = \left\{ \sup_{0 \leq t \leq T} X(t) - f(t) < b \right\}.$$

First, using the Corollary to Theorem 3, we have that

$$P[\Gamma_{f(\cdot)+b}] = e^{-1/2 \int_0^T \alpha^2(t) dt} \int_{\Gamma_b} e^{-\int_0^T \alpha(t) dx(t)} d_w x.$$

Next, using Corollary 2 of Theorem 4, we obtain

$$P[\Gamma_{f(\cdot)+b}] = e^{-1/2 \int_0^T \alpha^2(t) dt} \sum_{n=0}^{\infty} K_n(T)$$

where $K_n(T)$ is given by equation (5). This expression is an entirely different series expansion of the probability than the ones given by Park and Paranjape in [5].

D. Application 3. The Corollary to Theorem 3 is also useful to evaluate integrals of the type

$$\int_{\Gamma_f} e^{\int_0^T \alpha(t) dx(t)} d_w x$$

numerically for given $\alpha(t)$, $f(t)$, and T . By the Corollary, the above integral is equal to

$$e^{1/2 \int_0^T \alpha^2(t) dt} P \left\{ \sup_{0 \leq t \leq T} X(t) - \left[f(t) - \int_0^t \alpha(s) ds \right] < 0 \right\},$$

and the last probability can be evaluated numerically using the Park-Schuermann method [6].

The following table was computed by an IBM/168 with the unit interval divided into 2^9 equal subintervals.

Estimates of $\int_{\Gamma_f} e^{\int_0^T \alpha(t) dx(t)} d_w x$				
$\alpha(t)$	$\sin t$	e^t	t	\sqrt{t}
$f(t)$	$t + 1$	$t^2 + t + 1$	$\cos t$	$\ln(t + 1) + 1$
The integral	.976414	3.729278	.467819	.939285

REFERENCES

1. R. H. Cameron and W. T. Martin, *On transformation of Wiener integrals under translations*, Ann. Math., **45** (1944), 386–396.
2. J. L. Doob, *Heuristic approach to the Kolmogorov–Smirnov theorems*, Ann. Math. Stat., **20** (1949), 393–403.
3. J. Durbin, *Boundary-crossing probabilities for the Brownian motion and Poisson processes and techniques for computing the power of the Kolmogorov–Smirnov test*, J. Appl. Probability, **8** (1971), 431–453.
4. G. W. Johnson and D. L. Skoug, *The Cameron–Storvick function space integral: the L_1 theory*, J. Math. Anal. Appl., **50** (1975), 647–667.
5. C. Park and S. R. Paranjape, *Probabilities of Wiener paths crossing differentiable curves*, Pacific J. Math., **53** (1974), 579–583.
6. C. Park and F. J. Schuurmann, *Evaluation of barrier crossing probabilities of Wiener paths*, J. Appl. Probability, **13** (1976), 267–275.
7. J. Yeh, *Stochastic Processes and the Wiener Integral*, Marcel Dekker, Inc., N. Y. (1973).

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