

SOLUTIONS 9. 3.5.2016

Q1 *Brownian covariance.*For $s \leq t$,

$$B_t = B_s + (B_t - B_s), \quad B_s B_t = B_s^2 + B_s(B_t - B_s).$$

Take expectations: on the left we get $\text{cov}(B_s, B_t)$. The first term on the right is, as $E[B_s] = 0$, $\text{var}(B_s) = s$. As BM has independent increments, $B_t - B_s$ is independent of B_s , so

$$E[B_s(B_t - B_s)] = E[B_s] \cdot E[B_t - B_s] = 0 \cdot 0 = 0.$$

Combining, $\text{cov}(B_s, B_t) = s$ for $s \leq t$. Similarly, for $t \leq s$ we get t . Combining, $\text{cov}(B_s, B_t) = \min(s, t)$.

Q2 *Brownian scaling.*With $B_c(t) := B(c^2 t)/c$,

$$\text{cov}(B_c(s), B_c(t)) = E[B(c^2 s)/c \cdot B(c^2 t)/c] = c^{-2} \min(c^2 s, c^2 t) = \min(s, t) = \text{cov}(B_s, B_t).$$

So B_c has the same mean 0 and covariance $\min(s, t)$ as BM. It is also (from its definition) continuous, Gaussian, stationary independent increments etc. So it has all the defining properties of BM. So it *is* BM.

So BM is a *fractal*: it reproduces itself if time and space are scaled together in this way. This is why if we "zoom in and blow up" a Brownian path, it still looks like a Brownian path – however often we do this. By contrast, if we zoom in and blow up a smooth function, it starts to look straight (because it has a tangent).

Specialising to the zero set Z of BM B , this too is a fractal because B is.

Q3 *Time-inversion.*

Like BM, X is continuous (where it is defined – away from 0) and Gaussian. Its covariance is

$$\begin{aligned} \text{cov}(X_s, X_t) &= \text{cov}(sB(1/s), tB(1/t)) = st\text{cov}(B(1/s), B(1/t)) \\ &= st \min(1/s, 1/t) = \min(t, s) = \min(s, t). \end{aligned}$$

So as X has the same covariance as BM, X is BM. But BM is continuous everywhere, not just away from 0. So X is continuous at 0 too, and has $X(0) = 0$ as BM does. So

$$X_t \rightarrow 0 \quad (t \rightarrow 0) : \quad tB(1/t) \rightarrow 0 \quad (t \rightarrow 0) : \quad B(t)/t \rightarrow 0 \quad (t \rightarrow \infty).$$

Q4. To calculate $\int B(u)dB(u)$.

We start by approximating the integrand by a sequence of simple functions.

$$X_n(u) = \begin{cases} B(0) = 0 & \text{if } 0 \leq u \leq t/n, \\ B(t/n) & \text{if } t/n < u \leq 2t/n, \\ \vdots & \vdots \\ B((n-1)t/n) & \text{if } (n-1)t/n < u \leq t. \end{cases}$$

By definition,

$$\int_0^t B(u)dB(u) = \lim_{n \rightarrow \infty} \sum_{k=0}^{n-1} B(kt/n)(B((k+1)t/n) - B(kt/n)).$$

Replacing $B(kt/n)$ by $\frac{1}{2}(B((k+1)t/n) + B(kt/n)) - \frac{1}{2}(B((k+1)t/n) - B(kt/n))$, the RHS is

$$\begin{aligned} & \sum \frac{1}{2}(B((k+1)t/n) + B(kt/n)) \cdot (B((k+1)t/n) - B(kt/n)) \\ & - \sum \frac{1}{2}(B((k+1)t/n) - B(kt/n)) \cdot (B((k+1)t/n) - B(kt/n)). \end{aligned}$$

The first sum is $\sum \frac{1}{2}(B((k+1)t/n)^2 - B(kt/n)^2)$, which telescopes (as a sum of differences) to $\frac{1}{2}B(t)^2$ ($B(0) = 0$). The second sum is $\frac{1}{2} \sum (B((k+1)t/n) - B(kt/n))^2$, an approximation to the quadratic variation of B on $[0, t]$, which tends to $\frac{1}{2}t$ by Lévy's theorem on the QV. Combining,

$$\int_0^t B(u)dB(u) = \frac{1}{2}B(t)^2 - \frac{1}{2}t.$$

Note the contrast with ordinary (Newton-Leibniz) calculus! Itô calculus requires the second term on the right – the Itô correction term – which arises from the quadratic variation of B .

NHB