Exam 2018/2019

January 9, 2019, from 09:00 to 12:00

Documents allowed, Internet not allowed
Do what you can, and do not worry

\((\Omega, \mathcal{F}, (\mathcal{F}_t)_{t \geq 0}, \mathbb{P})\) is a filtered probability space, with complete and right continuous filtration.

\(B = (B_t)_{t \geq 0}\) is a \(d\)-dimensional Brownian motion issued from the origin, \(d \geq 1\).

If \(Z\) is a semi-martingale, we denote by \(\langle Z \rangle\) the increasing process of its local martingale part.

If \(Z = Z_0 + M + V\), do not confuse \(\langle Z \rangle = \langle M \rangle\) with the finite variation part \(V\) of \(Z\).

**Exercise 1** (Nature of an integral). Set \(d = 1\). Let us consider the following integral, for \(t \geq 0\),

\[ I_t = \int_0^t B_s ds. \]

2. Show that \(d(tB_t) = B_t dt + tdB_t\).
3. Deduce from the preceding question that \(I_t = \int_0^t (t-s)dB_s\) for all \(t \geq 0\).
4. Deduce from the preceding question that \(I_t \sim \mathcal{N}(0, \frac{1}{3}t^3)\) for all \(t \geq 0\).
5. For all \(t \geq 0, n \geq 1, 0 \leq k \leq n\), let us define \(t_k = \frac{k}{n} t\). Show that

\[ \sum_{k=0}^{n-1} B_{t_k}(t_{k+1} - t_k) = \frac{t}{n} \sum_{j=0}^{n-2} (n - j - 1)(B_{t_{j+1}} - B_{t_j}). \]

6. Deduce from the preceding question another proof that \(I_t \sim \mathcal{N}(0, \frac{1}{3}t^3)\) for all \(t \geq 0\).
7. Is the process \((I_t)_{t \geq 0}\) a martingale?

**Exercise 2** (Study of a special process). Set \(d = 2\). For all \(t \geq 0\), we write \(B_t = (X_t, Y_t)\) and

\[ A_t = \int_0^t X_s dY_s - \int_0^t Y_s dX_s. \]

1. Show that \(\langle A \rangle = \int_0^t (X_s^2 + Y_s^2) ds\) and that the process \(A\) is a square integrable martingale.
2. From now on let \(\lambda > 0\). Show that for all \(t \geq 0\),

\[ \mathbb{E}e^{\lambda A_t} = \mathbb{E}(\lambda A_t). \]

3. From now on, let \(f : \mathbb{R} \to \mathbb{R}\) be \(\mathcal{C}^2\), and let us define the continuous semi-martingales

\((Z_t)_{t \geq 0} = (\cos(\lambda A_t))_{t \geq 0}\) and \((W_t)_{t \geq 0} = \left(-\frac{f'(t)}{2}(X_t^2 + Y_t^2) + f(t)\right)_{t \geq 0}\).

Show that for all \(t \geq 0\),

\[ Z_t = 1 - \lambda \int_0^t \sin(\lambda A_s) dA_s - \frac{\lambda^2}{2} \int_0^t (X_s^2 + Y_s^2) Z_s ds. \]

and

\[ W_t = f(0) - \int_0^t f'(s) X_s dX_s - \int_0^t f'(s) Y_s dY_s - \frac{1}{2} \int_0^t f''(s)(X_s^2 + Y_s^2) ds, \]

and deduce that

\[ \langle Z, W \rangle = 0. \]
4. Show that if \( f \) solves \( f'' = f'^2 - \lambda^2 \) then \( Ze^W \) is a continuous local martingale and

\[
Ze^W = e^{f(0) - \lambda t} \int_0^t \sin(\lambda A_s) e^W dA_s - \int_0^t f'(s)Z_s e^W X_s dX_s - \int_0^t f'(s)Z_s e^W Y_s dY_s.
\]

5. Let \( r > 0 \). By using \( f(t) = -\log(\cosh(\lambda (r - t)) \) deduce from the previous question that

\[
\mathbb{E} e^{\lambda A_t} = \frac{1}{\cosh(\lambda r)}.
\]

**Exercise 3** (Criterion for a stochastic differential equation). Set \( d = 1 \). Let \( \sigma, b \) be two functions \( \mathbb{R} \rightarrow \mathbb{R} \) such that for some finite constant \( C < \infty \) and for all \( x, y \in \mathbb{R} \),

\[
|\sigma(x) - \sigma(y)| \leq C\sqrt{x - y} \quad \text{and} \quad |b(x) - b(y)| \leq C|x - y|
\]

The goal of this exercise is to prove pathwise uniqueness for the stochastic differential equation

\[
dx_t = \sigma(X_t) dB_t + b(X_t) dt.
\]

A solution \( X \) is a continuous semi-martingale with canonical decomposition \( X = X_0 + M + V \) with \( X_0 \in L^2 \), local martingale part \( M = \int_0^t \sigma(X_s) dB_s \), and finite variation part \( V = \int_0^t b(X_s) ds \). Note that the continuity of \( \sigma, X, b \) gives that almost surely, for all \( t \geq 0, s \rightarrow \sigma(X_s) + b(X_s) \) is locally bounded.

1. Let \( Z \) be a continuous semi-martingale such that \( \langle Z \rangle = \int_0^t \varphi_s ds \) for a progressive process \( \varphi \) such that \( 0 \leq \varphi \leq C|Z| \) for some constant \( C < \infty \). Prove that for all \( t \geq 0 \) and all \( a > 0 \),

\[
\mathbb{E} \int_0^t \frac{1_{0<|Z_s|\leq a}}{|Z_s|} d\langle Z \rangle_s \leq Ct.
\]

2. Deduce from the preceding question that for all \( t \geq 0 \),

\[
\lim_{n \to \infty} n \mathbb{E} \int_0^t \frac{1_{0<|Z_s|\leq \frac{1}{n}}}{|Z_s|} d\langle Z \rangle_s = 0.
\]

3. For all \( n \geq 1, x \in \mathbb{R} \), let us define \( g_n(x) = 2n(1 + nx)1_{x \in [-\frac{1}{n}, 0]} + 2n1_{x=0} + 2n(1 - nx)1_{x \in (0, \frac{1}{n})} \).

Let \( f_n : \mathbb{R} \rightarrow \mathbb{R} \) be the twice differentiable function such that \( f_n'' = g_n \) and \( f_n(0) = f_n'(0) = 0 \). Show that for all \( x \in \mathbb{R} \), the following properties hold true:

   (a) \( f_n'(x) \in [-1, 1] \) and \( \lim_{n \to \infty} f_n'(x) = \text{sign}(x) = 1_{x>0} - 1_{x<0} \)

   (b) \( |f_n(x)| \leq |x| \) and \( \lim_{n \to \infty} f_n(x) = |x| \).

4. By using Itô formula, prove that for all continuous semi-martingale \( Z = (Z_t)_{t \geq 0} \), all \( t \geq 0 \),

\[
\int_0^t 1_{Z_s = 0} d\langle Z \rangle_s = 0.
\]

5. From now on, let \( X \) and \( X' \) be two solutions of (SDE) on \((\Omega, \mathcal{F}, (\mathcal{F}_t)_{t \geq 0}, \mathbb{P})\) and with respect to the Brownian motion \( B \). Show that for all \( t \geq 0 \),

\[
\langle X - X' \rangle_t = \int_0^t (\sigma(X_s) - \sigma(X'_s))^2 ds.
\]

6. By using the assumption on \( \sigma \), deduce from the preceding questions that for all \( t \geq 0 \),

\[
\lim_{n \to \infty} \mathbb{E} \int_0^t g_n(X_s - X'_s) d\langle X - X' \rangle_s = 0.
\]
7. Set $Z = X - X'$. From now on, let $T$ be a stopping time such that the semi-martingale $(Z_{t∧T})_{t≥0}$ is bounded. By using notably the assumption on $σ$, prove that for all $t ≥ 0, n ≥ 1$,

$$E(f_n(Z_{t∧T})) = E(f_n(Z_0)) + E\int_0^{t∧T} f'_n(Z_s)(b(X_s) - b(X'_s))ds + \frac{1}{2} E\int_0^{t∧T} f''_n(Z_s)d\langle Z \rangle_s.$$  

8. Deduce from the preceding questions and the assumption on $b$ that for all $t ≥ 0$,

$$E(|X_{t∧T} - X'_{t∧T}|) = E(|X_0 - X'_0|) + E\int_0^{t∧T} (b(X_s) - b(X'_s))\text{sign}(X_s - X'_s)ds.$$  

9. By using the Grönwall lemma, deduce that if $X_0 = X'_0$ then $X_t = X'_t$ for all $t ≥ 0$. 
