

Stochastic Differential Equations: Final Project

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NOTE: Still need to complete Problems 2, 7, 8

Problem 1.

We know that the probability density of the sum of two independent random variables can be computed by the convolutions of f_X and f_Y . Thus, the probability density of $X + Y$, denoted by f_Z , is

$$f_Z(z) = (f_Y * f_X) = \int_{-\infty}^{\infty} f_Y(z - x) f_X(x) dx \quad (1)$$

We know that the normal density function is given by,

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

Plugging this density function into equation (1) and letting $\sigma_Z = \sqrt{\sigma_X^2 + \sigma_Y^2}$ yields,

$$\begin{aligned}
f_Z(z) &= \int_{-\infty}^{\infty} \left[\frac{1}{\sigma_Y \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{z-x-\mu_Y}{\sigma_Y} \right)^2} \frac{1}{\sigma_X \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{x-\mu_X}{\sigma_X} \right)^2} \right] dx \\
&= \int_{-\infty}^{\infty} \left[\frac{1}{\sigma_Y \sigma_X (2\pi)} e^{-\frac{1}{2} \left[\left(\frac{z-x-\mu_Y}{\sigma_Y} \right)^2 + \left(\frac{x-\mu_X}{\sigma_X} \right)^2 \right]} \right] dx \\
&= \int_{-\infty}^{\infty} \left[\frac{1}{\sigma_Y \sigma_X (2\pi)} e^{-\frac{\sigma_X^2 (z-x-\mu_Y)^2 + \sigma_Y^2 (x-\mu_X)^2}{2\sigma_Y^2 \sigma_X^2}} \right] dx \\
&= \int_{-\infty}^{\infty} \left[\frac{1}{(2\pi) \sigma_X \sigma_Y} e^{-\frac{x^2 (\sigma_X^2 + \sigma_Y^2) - 2x (\sigma_X^2 (z-\mu_Y) + \sigma_Y^2 \mu_X) + \sigma_X^2 (z^2 + \mu_Y^2 - 2z\mu_Y) + \sigma_Y^2 \mu_X^2}{2\sigma_Y^2 \sigma_X^2}} \right] dx \\
&= \int_{-\infty}^{\infty} \left[\frac{1}{\sqrt{2\pi} \sigma_Z} e^{-\frac{\sigma_Z^2 (\sigma_X^2 (z-\mu_Y)^2 + \sigma_Y^2 \mu_X^2) - (\sigma_X^2 (z-\mu_Y) + \sigma_Y^2 \mu_X)^2}{2\sigma_Z^2 (\sigma_X \sigma_Y)^2}} \frac{1}{\sqrt{2\pi} \frac{\sigma_X \sigma_Y}{\sigma_Z}} e^{-\frac{\left(x - \frac{\sigma_X^2 (z-\mu_Y) + \sigma_Y^2 \mu_X}{\sigma_Z^2} \right)^2}{2 \left(\frac{\sigma_X \sigma_Y}{\sigma_Z} \right)^2}} \right] dx \\
&= \frac{1}{\sqrt{2\pi} \sigma_Z} e^{-\frac{(z-(\mu_X+\mu_Y))^2}{2\sigma_Z^2}} \int_{-\infty}^{\infty} \left[\frac{1}{\sqrt{2\pi} \frac{\sigma_X \sigma_Y}{\sigma_Z}} e^{-\frac{\left(x - \frac{\sigma_X^2 (z-\mu_Y) + \sigma_Y^2 \mu_X}{\sigma_Z^2} \right)^2}{2 \left(\frac{\sigma_X \sigma_Y}{\sigma_Z} \right)^2}} \right] dx
\end{aligned}$$

The equation inside the integral symbol represents a valid normal density function for x , so we know it integrates to 1. Thus, the probability density function for $X + Y$ is given by

$$f_Z(z) = \frac{1}{\sqrt{2\pi} \sigma_Z} e^{-\frac{(z-(\mu_X+\mu_Y))^2}{2\sigma_Z^2}}$$

This is precisely a normal density function with mean $\mu_X + \mu_Y$ and variance $\sigma_Z^2 = (\sqrt{\sigma_X^2 + \sigma_Y^2})^2 = \sigma_X^2 + \sigma_Y^2$.

Hence, we have shown that, given $X \sim N(\mu_X, \sigma_X^2)$ and $Y \sim N(\mu_Y, \sigma_Y^2)$, $X + Y$ is distributed as $N(\mu_X + \mu_Y, \sigma_X^2 + \sigma_Y^2)$.

Problem 2.

Let $Z = Y + 1$. We'll begin by finding the probability density function for Z . Since Y is a standard uniform random variable, we know that

$$f(y) = \begin{cases} 1 & 0 \leq y \leq 1 \\ 0 & \text{elsewhere} \end{cases}$$

Thus, the distribution function approach yields,

$$\begin{aligned}
 F_Z(z) &= P(Z \leq z) = P(Y + 1 \leq z) = P(Y \leq z - 1) \\
 &= \int_{-\infty}^{z-1} f(y) dy \\
 &= \int_0^{z-1} 1 dy \\
 &= z - 1
 \end{aligned}$$

So, since as Y ranges from 0 to 1, Z ranges from 1 to 2, we have

$$F_Z(z) = \begin{cases} 0 & z < 1 \\ z - 1 & 1 \leq z \leq 2 \\ 1 & \text{elsewhere} \end{cases}$$

And the density function for Z is

$$f_Z(z) = \frac{dF_Z(z)}{dz} = \begin{cases} 1 & 1 \leq z \leq 2 \\ 0 & \text{elsewhere} \end{cases}$$

Now we can simplify the original function to be $U = X/Z$, where we now know the probability density function for both random variables ($X \sim \text{Unif}(0, 1)$ and $Z \sim \text{Unif}(1, 2)$).

So the distribution function is given by,

$$\begin{aligned}
 F_U(u) &= P(U \leq u) = P(X/Z \leq u) = P(X \leq uZ) \\
 &= \int_{-\infty}^{uz} f(x) dx \\
 &= \int_0^{uz} 1 dx \\
 &= uz
 \end{aligned}$$

FINISH THIS LATER.

Problem 3.

Let Y be a standard normal variable. Then the moment-generating function of Y is given by,

$$\begin{aligned}
 m(t) &= E(e^{tY}) \\
 &= \int_{-\infty}^{\infty} e^{ty} f(y) dy
 \end{aligned}$$

Since Y is a standard normal variable, we know that $\mu = 0$ and $\sigma = 1$. Thus, we have

$$f(y) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}y^2}$$

Plugging this into the above equation yields,

$$\begin{aligned}
m(t) &= \int_{-\infty}^{\infty} e^{ty} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}y^2} dy \\
&= \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{y^2}{2} + ty} dy \\
&= \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(y-t)^2} e^{\frac{1}{2}t^2} dy \\
&= e^{\frac{1}{2}t^2} \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(y-t)^2} dy
\end{aligned}$$

We can see that the integral is precisely the integral for a normal random variable with $\mu = y - t$ and $\sigma = 1$. Thus, it integrates to 1, yielding,

$$m(t) = e^{\frac{1}{2}t^2}$$

Problem 4.

Suppose $g(x)$ is a monotone increasing function and X is a random variable with the probability density function f_X .

Let $U = g(X)$ where X has the above density function. Since $g(x)$ is an increasing function of x , then $g^{-1}(u)$ is an increasing function of u . Thus,

$$\begin{aligned}
P(U \leq u) &= P[g(X) \leq u] \\
&= P\{g^{-1}[g(X)] \leq g^{-1}(u)\} \\
&= P[X \leq g^{-1}(u)]
\end{aligned}$$

The above sequence of equalities implies that,

$$F_U(u) = F_X[g^{-1}(u)]$$

When we differentiate with respect to u , we get,

$$f_U(u) = \frac{dF_X[g^{-1}(u)]}{du} = f_X(g^{-1}(u)) \frac{d[g^{-1}(u)]}{du}$$

Problem 5.

We know that the moment-generating function of X is $\phi(t)$. Thus,

$$\begin{aligned}
\phi(t) &= E(e^{tX}) \\
&= \int_{-\infty}^{\infty} e^{tx} f(x) dx \\
&= \int_{-\infty}^{\infty} \left(1 + tx + \frac{t^2 x^2}{2!} + \frac{t^3 x^3}{3!} + \cdots\right) f(x) dx \\
&= \int_{-\infty}^{\infty} f(x) dx + t \int_{-\infty}^{\infty} x f(x) dx + \frac{t^2}{2!} \int_{-\infty}^{\infty} x^2 f(x) dx + \cdots
\end{aligned}$$

Now plugging in $aX + b$ to the above equation yields,

$$\begin{aligned} E(e^{t(aX+b)}) &= E(e^{taX+tb}) \\ &= E[e^{taX}(e^{tb})] \end{aligned}$$

Since expected value is a linear operator and e^{tb} is a constant, we can pull it out of the expectation operator,

$$\begin{aligned} E[e^{taX}(e^{tb})] &= e^{tb} E(e^{taX}) \\ &= e^{tb} \int_{-\infty}^{\infty} e^{tax} f(ax) dx \end{aligned}$$

We can see from the above equation that this is equal to $e^{tb}\phi(ta)$.

Thus, the moment-generating function for $aX + b$ with constants $a \neq 0$ and b is $e^{tb}\phi(ta)$.

Problem 6.

We know by Theorem 2.11.1 that the distribution of the sum of two random variables X and Y is given by the convolution of their densities, f_X and f_Y .

Thus, with $Z = X + Y$, we have,

$$f_Z(z) = (f * g)(z) = \int_{-\infty}^{\infty} f_X(z - y)f_Y(y)dy$$

The mean of this distribution is,

$$E(Z) = \int_{-\infty}^{\infty} z f_Z(z - y)f_Y(y)dy$$

where $z = x + y$. Thus, we have,

$$\begin{aligned} E(Z) &= \int_{-\infty}^{\infty} z f_Z(z)dz \\ &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [(x + y)f_X((x + y) - y)f_Y(y)] dx dy \\ &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [(x + y)f_X(x)f_Y(y)] dx dy \\ &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [(xf_X(x) + yf_X(x))f_Y(y)] dx dy \\ &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [xf_X(x)f_Y(y) + yf_X(x)f_Y(y)] dx dy \\ &= \int_{-\infty}^{\infty} [\mu_X f_Y(y) + yf_Y(y)] dy \\ &= \mu_X + \mu_Y \end{aligned}$$

In the above equations, we are using the properties that, for any random variable X with density function $f(x)$ and mean μ , we have that $\int_{-\infty}^{\infty} f(x) = 1$ and $\int_{-\infty}^{\infty} xf(x) = \mu$.

Now for the variance, we know that for a given random variable X , $\text{Var}(X) = E[X^2] - E[X]^2$. Plugging in Z to this formula yields,

$$\begin{aligned}
\text{Var}(Z) &= \sigma_Z^2 = E[Z^2] - E[Z]^2 \\
&= \int_{-\infty}^{\infty} z^2 f_Z(z) dz + (\mu_X + \mu_Y)^2 \\
&= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [(x+y)^2 f_X((x+y)-y) f_Y(y)] dx dy - (\mu_X + \mu_Y)^2 \\
&= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [(x+y)^2 f_X(x) f_Y(y)] dx dy - (\mu_X + \mu_Y)^2 \\
&= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [x^2 + 2xy + y^2] f_X(x) f_Y(y) dx dy - (\mu_X + \mu_Y)^2 \\
&= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [x^2 f_X(x) f_Y(y) + 2xy f_X(x) f_Y(y) + y^2 f_X(x) f_Y(y)] dx dy - (\mu_X + \mu_Y)^2 \\
&= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} x^2 f_X(x) f_Y(y) dx dy - \mu_X + \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} 2xy f_X(x) f_Y(y) dx dy + \\
&\quad \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} y^2 f_X(x) f_Y(y) dx dy - \mu_Y \\
&= \left[\int_{-\infty}^{\infty} x^2 f_X(x) dx - \mu_X \right] + 2\mu_X \mu_Y + \left[\int_{-\infty}^{\infty} y^2 f_Y(y) dy - \mu_Y \right] \\
&= \sigma_X^2 + 2\mu_X \mu_Y + \sigma_Y^2
\end{aligned}$$

Thus, we have $\text{Var}(Z) = \sigma_X^2 + 2\mu_X \mu_Y + \sigma_Y^2$.

Problem 7.

The definition of the Central Limit Theorem is as follows:

Let Y_1, Y_2, \dots, Y_n be independent and identically distributed random variables with $E(Y_i) = \mu$ and $V(Y_i) = \sigma^2 < \infty$. Define

$$U_n = \frac{\sum_{i=1}^n Y_i - n\mu}{\sigma\sqrt{n}} = \frac{\bar{Y} - \mu}{\sigma/\sqrt{n}}$$

where $\bar{Y} = \frac{1}{n} \sum_{i=1}^n Y_i$.

Then the distribution function of U_n converges to the standard normal distribution function as $n \rightarrow \infty$. That is,

$$\lim_{n \rightarrow \infty} P(U_n \leq u) = \int_{-\infty}^u \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt$$

for all u .

Let $f_n(x)$ be the probability mass function for a binomial random variable with n trials and success probability p .

FINISH THIS LATER.

Problem 8.

Let X and Y be two independent, continuous random variables described by probability density functions f_X and f_Y . Also let $Z = XY$. We'll begin by finding the cumulative distribution function for Z . This yields,

$$\begin{aligned}
 F_Z(z) &= P(Z \leq z) \\
 &= P(XY \leq z) \\
 &= P(XY \leq z, X \geq 0) + P(XY \leq z, X \leq 0) \\
 &= P(Y \leq z/X, X \geq 0) + P(Y \geq z/X, X \leq 0) \\
 &= \int_0^\infty f_X(x) \int_{-\infty}^{z/x} f_Y(y) dy dx + \int_{-\infty}^0 f_X(x) \int_{z/X}^\infty f_Y(y) dy dx
 \end{aligned}$$

Now in order to find the probability density function for Z , we need to differentiate with respect to z on both sides of the above equation.

$$\begin{aligned}
 f_Z(z) &= \frac{d}{dz} F_Z(z) \\
 &= \frac{d}{dz} \left[\int_0^\infty f_X(x) \int_{-\infty}^{z/x} f_Y(y) dy dx + \int_{-\infty}^0 f_X(x) \int_{z/X}^\infty f_Y(y) dy dx \right] \\
 &= \int_0^\infty f_X(x) \left[f_Y(z/x) \left(\frac{1}{x} \right) - f(-\infty) \right] dx + \int_{-\infty}^0 f_X(x) \left[f_Y(\infty) - f_Y(z/x) \left(\frac{1}{x} \right) \right] dx
 \end{aligned}$$

We obtained the above equation using the fundamental theorem of calculus and the chain rule. Now, we will use the fact that if $f(x)$ is a distribution function, as $x \rightarrow \infty$, $f(x) \rightarrow 0$. The same holds true as $x \rightarrow -\infty$. This yields,

$$\begin{aligned}
 f_Z(z) &= \int_0^\infty f_X(x) \left[f_Y(z/x) \left(\frac{1}{x} \right) - f(-\infty) \right] dx + \int_{-\infty}^0 f_X(x) \left[f_Y(\infty) - f_Y(z/x) \left(\frac{1}{x} \right) \right] dx \\
 &= \int_0^\infty f_X(x) f_Y(z/x) \frac{1}{x} dx + \int_{-\infty}^0 f_X(x) (-f_Y(z/x)) \frac{1}{x} dx \\
 &= \int_0^\infty f_X(x) f_Y(z/x) \frac{1}{x} dx - \int_{-\infty}^0 f_X(x) f_Y(z/x) \frac{1}{x} dx \\
 &= \int_0^\infty f_X(x) f_Y(z/x) \frac{1}{|x|} dx + \int_{-\infty}^0 f_X(x) f_Y(z/x) \frac{1}{|x|} dx \\
 &= \int_{-\infty}^\infty f_X(x) f_Y(z/x) \frac{1}{|x|} dx
 \end{aligned}$$

Now we need to find the mean of Z where $Z = XY$,

$$\begin{aligned}
E[Z] &= \int_{-\infty}^{\infty} z f_Z(z) dz \\
&= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} (xy) f_X(x) f_Y(y) \frac{1}{|x|} dx dy \\
&= \mu_Y \int_{-\infty}^{\infty} \frac{x}{|x|} f_X(x) dx \\
&= \mu_Y \left[\int_{-\infty}^0 -f_X(x) dx + \int_0^{\infty} f_X(x) dx \right] \\
&= \mu_Y \left[- \int_{-\infty}^0 f_X(x) dx + \int_0^{\infty} f_X(x) dx \right]
\end{aligned}$$

FINISH THIS LATER.

Problem 9.

We have that,

$$\begin{aligned}
t_j - t_{j-1} &= (j/N)(b-a) + a - [(j-1/N)(b-a) + a] \\
&= (jb - ja)/N + a - (jb - ja - b + a)/N - a \\
&= (jb - ja - jb + ja + b - a)/N \\
&= (b-a)/N
\end{aligned}$$

In addition, since the function f is bounded on $[a, b]$, we know that $\exists M \in \mathbb{N}$ such that $M \geq |f|$. These two facts yield the following,

$$\begin{aligned}
\lim_{N \rightarrow \infty} \sum_{j=1}^N f(t_{j-1})(t_j - t_{j-1})^p &= \lim_{N \rightarrow \infty} \sum_{j=1}^N f(t_{j-1})((b-a)/N)^p \\
&\leq \lim_{N \rightarrow \infty} \sum_{j=1}^N M((b-a)/N)^p \\
&= \lim_{N \rightarrow \infty} MN((b-a)/N)^p \\
&= M \lim_{N \rightarrow \infty} N((b-a)/N)^p \\
&= M(b-a)^p \lim_{N \rightarrow \infty} N/N^p \\
&= M(b-a)^p \lim_{N \rightarrow \infty} N^{1-p}
\end{aligned}$$

Since $1-p < 0$, we have that $\lim_{N \rightarrow \infty} N^{1-p} = 0$. Thus, this gives us,

$$\begin{aligned}
\lim_{N \rightarrow \infty} \sum_{j=1}^N f(t_{j-1})(t_j - t_{j-1})^p &\leq M(b-a)^p \lim_{N \rightarrow \infty} N^{1-p} \\
&= [M(b-a)]0 = 0
\end{aligned}$$

Now, if we use $-M$ for the lower bound, we get,

$$\begin{aligned}
\lim_{N \rightarrow \infty} \sum_{j=1}^N f(t_{j-1})(t_j - t_{j-1})^p &\geq -M(b-a)^p \lim_{N \rightarrow \infty} N^{1-p} \\
&= [-M(b-a)]0 = 0
\end{aligned}$$

Since we have shown that

$$0 \leq \lim_{N \rightarrow \infty} \sum_{j=1}^N f(t_{j-1})(t_j - t_{j-1})^p \leq 0$$

we have that $\lim_{N \rightarrow \infty} \sum_{j=1}^N f(t_{j-1})(t_j - t_{j-1})^p = 0$.

Problem 10.