Problem 1  (20 points)
Answer the following questions:

a. Suppose the variable X follows the generalized Wiener process with drift rate \( \mu_X \) and variance \( \sigma_X^2 \), and the variable Y follows the generalized Wiener process with drift rate \( \mu_Y \) and variance \( \sigma_Y^2 \). Initially the variable X has the value \( \alpha \) and the variable Y the value \( \beta \). What is the distribution of \( X+Y \) after time \( \Delta t \) if:

1. The changes in X and Y in any short time interval \( \Delta t \) are uncorrelated?

\[
X \sim N \left( \alpha + \mu_X \Delta t, \sigma_X \Delta t \right), \quad Y \sim N \left( \beta + \mu_Y \Delta t, \sigma_Y \Delta t \right)
\]

\[
X + Y \sim N \left( \alpha + \beta + (\mu_X + \mu_Y) \Delta t, \sqrt{\sigma_X^2 + \sigma_Y^2} \right)
\]

2. There is a correlation \( \rho \) between the changes in X and Y in any short time interval \( \Delta t \)?

\[
X + Y \sim N \left( \alpha + \beta + (\mu_X + \mu_Y) \Delta t, \sqrt{\sigma_X^2 + \sigma_Y^2 + 2 \rho \sigma_X \sigma_Y} \right)
\]

b. Consider a variable \( S \) that follows the process \( dS = \mu dt + \sigma dz \). For the first three years, \( \mu = 2 \) and \( \sigma = 3 \). For the next three years, \( \mu = 3 \) and \( \sigma = 4 \). If the initial value of the variable \( S \) is 5, what is the probability distribution of the variable at the end of year 6?

\[
\begin{align*}
S_0 & = 5 + 3(2) + 3(1) = 10 \\
S_3 & = 5 + 3(3) + 3(2) = 20 \\
S_6 & = 5 + 3(2) + 3(3) = 20 \\
\end{align*}
\]

\[
\begin{align*}
\text{Var}(S) & = \text{Var}(DS_1) + \cdots + \text{Var}(DS_6) = 3 \times 2^2 + 3 \times 3^2 = 75 \\
\text{Var}(S_6) & = \text{Var}(S_3) + \text{Var}(DS_3) + \text{Var}(DS_6) = 75 + 9 + 9 = 93 \\
\end{align*}
\]

\[
S_6 \sim N \left( 20, 93 \right)
\]
Problem 2  (20 points)  
Answer the following questions:

a. Let \( c = S^{-\frac{x}{\sigma^2}} \). Does \( c \) satisfy the Black-Scholes differential equation?

\[
\frac{\partial c}{\partial t} = -\frac{x}{\sigma^2} S - \frac{x^2}{2 \sigma^2} \quad \frac{\partial^2 c}{\partial (\sigma S)} = \left( \frac{2x}{\sigma^2} \right) \left( \frac{x^2}{\sigma^2} + 1 \right) S
\]

\[
\frac{\partial c}{\partial S} + r S \frac{\partial c}{\partial S} + \left( \frac{x^2}{2 \sigma^2} \right) \frac{\partial^2 c}{\partial S^2} = - \frac{x}{\sigma^2} = r c \quad \text{YES}.
\]

b. Suppose the volatility for a stock goes to zero, i.e. \( \sigma \to 0 \). It means the stock is riskless and must earn the risk-free interest rate. Therefore, at expiration time of a call option, \( S_T = S_0 e^{rT} \). What is the value of the call option at time zero (now)?

\[
c = e^{-rt} \max \left( S_0 e^{rt} - E, 0 \right)
\]

\[
\sigma \rightarrow c = \max \left( S_0 - \frac{E}{e^{rt}}, 0 \right)
\]

c. What is the result obtained by the Black-Scholes model for the situation in (b)?

\[
\text{Suppose } S_0 > \frac{E}{e^{rt}} \rightarrow \ln \frac{S_0}{E} > -rt \Rightarrow \ln \frac{S_0}{E} + rt > 0
\]

\[
d_1 = \ln \frac{S_0}{E} + \left( r + \frac{x^2}{2 \sigma^2} \right) t = \frac{S_0}{E} - \frac{x^2}{2 \sigma^2} \rightarrow d_1 = \infty \quad \Rightarrow \quad c = S_0 - \frac{E}{e^{rt}} \quad \text{BLACK-SCHOLES}
\]

\[
\text{Suppose } S_0 < \frac{E}{e^{rt}} \Rightarrow \ln \frac{S_0}{E} + rt < 0
\]

\[
d_1 = \frac{S_0}{E} = \infty \rightarrow d_1 = -\infty
\]

\[
\phi(d_1) = \phi(d_2) = 0 \quad \Rightarrow \quad c = 0 \quad \text{BLACK-SCHOLES}
\]

d. A straddle is an option trading strategy where the investor buys a put and a call with the same expiration date and exercise price.

1. Construct a table that shows the payoff of the put, the call, and the total. Please do not use numbers. Use \( E, S_T \), etc.

\[
\begin{array}{|c|c|c|c|}
\hline
\frac{S_T}{S} & \text{LONG CALL} & \text{LONG PUT} & \text{TOTAL} \\
\hline
S < E & 0 & E - S & \text{E - S} \\
\hline
S > E & S - E & 0 & \text{S - E} \\
\hline
\end{array}
\]

2. Draw the diagram that shows the profit of the put, the call, and the total. Again, no numbers!
Problem 2  (20 points)  \( \text{buy put with } E_1, \parallel \text{sell put with } E_2 \)

Part A:
Consider a bull spread when puts with exercise prices \( E_1 \) and \( E_2 \), with \( E_2 > E_1 \), are used.

a. Construct a table that shows the payoff of the puts and the total. Please do not use numbers. Use \( E, S_T \), etc.

<table>
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<tr>
<th>( S_T )</th>
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<th>Short put</th>
<th>Total</th>
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<td>0</td>
<td>( E_1 - E_1 )</td>
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b. Draw the diagram that shows the payoff of the puts and the total. Again, no numbers!

Part B:
A straddle is an option trading strategy where the investor buys a put and a call with the same expiration date and exercise price.

a. Construct a table that shows the payoff of the put, the call, and the total. Please do not use numbers. Use \( E, S_T \), etc.

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b. Draw the diagram that shows the profit of the put, the call, and the total. Again, no numbers!
Problem 3 (15 points)
Answer the following questions:

a. The price of a stock at time \( t = 0 \) is $40. Over each of the next two 3-month periods it is expected to increase by 10% or decrease by 10%. The risk-free continuous interest rate is 12% per year. What is the value of a 6-month European put option with exercise price of $42? Show all your work and place all the values on a 2-step binomial tree.

\[ \begin{align*}
U &= 1.1^1 = 1.1, \\
D &= 0.9, \\
\rho &= \frac{e^{0.12 \frac{1}{2}} - 0.9}{1.1 - 0.9} = 0.55227, \\
1 - \rho &= 0.44773.
\end{align*} \]

\[
\frac{0.8 + 2.4 (1-\rho)}{e^{0.12 \frac{1}{4}}} = 0.80988
\]

\[
\frac{2.4 \rho + 9.6 (1-\rho)}{e^{0.12 \frac{1}{4}}} = 4.75873
\]

Finally,

\[
P = \frac{0.80988 + 4.75873 (1-\rho)}{e^{0.12 \frac{1}{4}}} \Rightarrow P = 2.11850
\]

b. Suppose the return of the underlying stock of a European call is equal to the risk-free interest rate. Show that the probability that a European call option will be exercised at time \( T \) is equal to \( \Phi(d_2) \).

Assume lognormal property of stock prices. Also, time now is 0, therefore \( \Delta t = T \).

\[ \ln S_T \sim N \left( \ln S_0 + \left( r - \frac{\sigma^2}{2} \right) T, \sigma \sqrt{T} \right) \]

\[
P (S_T > E) = P \left( \ln S_T > \ln E \right) = P \left( \frac{\ln E - \ln S_0 - \left( r - \frac{\sigma^2}{2} \right) T}{\sigma \sqrt{T}} > \frac{\ln E - \ln S_0 - \left( r - \frac{\sigma^2}{2} \right) T}{\sigma \sqrt{T}} \right) = \Phi(d_1)
\]

\[
= P \left( Z > \frac{\ln \frac{E}{S_0} - \left( r - \frac{\sigma^2}{2} \right) T}{\sigma \sqrt{T}} \right) = P \left( \frac{Z \times \ln \frac{E}{S_0} + \left( r - \frac{\sigma^2}{2} \right) T}{\sigma \sqrt{T}} \right) = \Phi(d_2)
\]

c. Refer to part (b): Again, the underlying stock earns the risk-free interest rate. Give an expression of the value of the European call that pays off $100 if the price of the stock at time \( T \) is greater than \( E \).

Payoff at expiration is: 100 \( P \left( S_T > E \right) \) = 100 \( \Phi(d_2) \)

Since this is riskless, the P.V. will be the price of the call discounted using continuous risk-free interest rate.

\[
C = \frac{100 \Phi(d_2)}{e^{rT}}
\]
Problem 4  (20 points)
Answer the following questions:

a. Assume that the price $S$ of stock $A$ follows the lognormal distribution. Its current value is $50$, with expected return and volatility 12% and 30% respectively per year. What is the probability that the stock price will be larger than $80$ in two years?

\[
P(S_T > 80) = P\left(\ln S_T > \ln 80\right) = P\left(Z > \frac{\ln 80 - \ln 50 - (0.12 - \frac{0.3^2}{2}) \cdot 2}{0.3 \sqrt{2}}\right)
\]

\[
= P\left(Z > 0.75\right) = 1 - 0.7234 = 0.2266
\]

b. Refer to question (a). A European put is written on stock $A$ with expiration date 6 months from now and with exercise price $60$. What is the probability that this put option will not be exercised?

\[
P(S_T > 60) = P\left(\ln S_T > \ln 60\right) = P\left(Z > \frac{\ln 60 - \ln 50 - (0.06 - \frac{0.3^2}{2}) \cdot 0.5}{0.3 \sqrt{0.5}}\right)
\]

\[
= P\left(Z > 0.68\right) = 1 - 0.7487 = 0.2513
\]

c. Suppose a call option is currently prices at $110$. You want to estimate volatility by trial and error using the Black-Scholes formula for $c$. You start with an initial guess of $\sigma = 0.30$ that gives $c = 115$. What should be your next guess for $\sigma$? Explain!

\[
c = 110 \text{ with } \sigma = 0.30 \text{ we get } c_1 = 115
\]

\[
\Rightarrow \text{ our next guess should be } \sigma < 0.30
\]

d. Consider the binomial option pricing model for a European put, with exercise price $52$, current stock price $50$, $u = 1.2$, $d = 0.3$ for a 30-period binomial tree. Find the maximum number of up movements so that the put will be in the money at expiration.

\[
\frac{\left(\frac{u}{d}\right)^k}{S_0 d^{30-k}} < 52 \Rightarrow k < \frac{\log \left(\frac{52}{50 \cdot (0.3)^{20}}\right)}{\log \frac{1.2}{0.8}}
\]

\[
k \leq 16
\]
Problem 5 (25 points)
Answer the following questions:

a. A stock price is currently $30. During each 2-month period for the next 4 months the stock will increase by 8% or decrease by 10%. The risk-free continuous interest rate is 5% per year. Use a two-step binomial tree to calculate the value of an option that pays off at expiration amount equal to $\max[(30 - S_T), 0]^2$, where $S_T$ is the price of the stock in 4 months.

$$p = \frac{e^{rt} - d}{u - d} = \frac{e^{0.05 \cdot 2} - 0.9}{1.08 - 0.9} = 0.6020$$

Value of the option:

$$0.7056 \times 2 \times \phi(d_1) + 32.49 \times \phi(d_2)$$

$$\Rightarrow c = 5.394$$

b. Assume the Black-Scholes model applies. Consider an option on a non-dividend paying stock when the stock price is $30, the exercise price is $29, the continuously risk-free interest rate 5%, the volatility is 25% per year, and the time to expiration is 4 months.

1. What is the price of the option if it is a European call?

$$c = S_0 \phi(d_1) - e^{-rt} \phi(d_2) = 30 \phi(0.4225) - 29 \phi(0.2282)$$

$$c = 2.4478$$

2. What is the price of the option if it is an American call?

SAME

3. What is the price of the option if it is a European put?

$$P + S_0 = C + e^{-rt} P = 2.4478 + 29 \phi(0.2282) - 30$$

$$P = 0.9985$$

c. A stock price is observed weekly with $S_i$ being the $i$th observation. Define $u_i = \ln(S_i/S_{i-1})$. Suppose that there are 40 observations on $u_i$ and $\sum_{i=1}^{40} u_i = 0.18$ while $\sum_{i=1}^{40} u_i^2 = 0.06$. Estimate the stock price volatility per year.

$$\mu = \frac{1}{40} \left(0.06 - \frac{0.18}{40}\right) \approx 0.003896$$

$$\sigma_{\text{annual}} = 0.07896 \sqrt{40} \approx 0.2869$$
The standard normal distribution table. Note: $P(Z \leq 1.13) = 0.8708$.

**Table 2**

Cumulative Normal Distribution—Values of $P$ Corresponding to $z_p$ for the Normal Curve

$z$ is the standard normal variable. The value of $P$ for $-z_p$ equals 1 minus the value of $P$ for $+z_p$, for example, the $P$ for $-1.62$ equals $1 - 0.9474 = 0.0526$.

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