Ch 1. Wiener Process (Brownian Motion)

I. Introduction of Wiener Process

II. Itô's Lemma

III. Stochastic Integral

IV. Solve Stochastic Differential Equations with Stochastic Integral

• This chapter introduces the stochastic process (especially the Wiener process), Itô's Lemma, and the stochastic intergral. The knowledge of the stochastic process is the foundation of derivative pricing and thus indispensable in the field of financial engineering.

• This course, however, is not a mathematic course. The goal of this chapter is to help students to build enough knowledge about the stochastic process and thus to be able to understand academic papers associated with derivative pricing.

I. Introduction of Wiener Process

• The Wiener process, also called Brownian motion, is a kind of Markov stochastic process.

⊙ Stochastic process: whose value changes over time in an uncertain way, and thus we only know the distribution of the possible values of the process at any time point. (In contrast to the stochastic process, a deterministic process is with an exact value at any time point.)

⊙ Markov process: the likelihood of the state at any future time point depends only on its present state but not on any past states.

⊙ In a word, the Markov stochastic process is a particular type of stochastic process where only the current value of a variable is relevant for predicting the future movement.

⊙ The Wiener process $Z(t)$ is in essence a series of normally distributed random variables, and for later time points, the variances of these normally distributed random variables increase to reflect that it is more uncertain (thus more difficult) to predict the value of the process after a longer period of time. See Figure 1-1 for illustration.

Figure 1-1
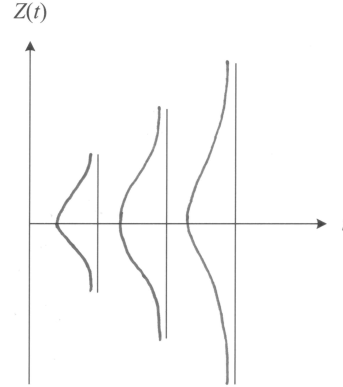
- Instead of assuming $Z(t) \sim N(0, t)$, which cannot support algebraic calculations, the Wiener process dZ is introduced.

- $\triangle Z \equiv \varepsilon \sqrt{\triangle t}$ (change in a time interval $\triangle t$)

  $\varepsilon \sim N(0,1) \Rightarrow \triangle Z$ follows a normal distribution

  $\Rightarrow \begin{cases} E[\triangle Z] & = & 0 \\ \text{var}(\triangle Z) & = & \triangle t \Rightarrow \text{std}(\triangle Z) = \sqrt{\triangle t} \end{cases}$

- $Z(T) - Z(0) = \sum\limits_{i=1}^{n} \varepsilon_i \sqrt{\triangle t} = \sum\limits_{i=1}^{n} \triangle Z_i$, where $n = \frac{T}{\triangle t}$

  $\Rightarrow Z(T) - Z(0)$ also follows a normal distribution

  $\Rightarrow \begin{cases} E[Z(T) - Z(0)] & = & 0 \\ \text{var}(Z(T) - Z(0)) & = & n \cdot \triangle t = T \Rightarrow \text{std}(\triangle Z) = \sqrt{T} \end{cases}$

  $\uparrow$

  variance is additive because any pair of $\triangle Z_t$ and $\triangle Z_s$ are assumed to be independent

- As $n \to \infty$, $\triangle t$ converges to 0 and is denoted as dt, which means an infinitesimal time interval. Correspondingly, $\triangle Z$ is redenoted as dZ.

- In conclusion, dZ is noting more than a notation. It is invented to simplify the representation of a series of normal distributions, i.e., a Wiener process.

- The properties of the Wiener process $\{Z(t)\}$ for $t \geq 0$:

  (i) (Normal increments) $Z(t) - Z(s) \sim N(0, t-s)$.

  (ii) (Independence of increments) $Z(t) - Z(s)$ and $Z(u)$ are independent, for $u \leq s < t$.

  (iii) (Continuity of the path) $Z(t)$ is a continuous function of t.

  Other properties:

  - $\odot$ Jagged path: not monotone in any interval, no matter how small a interval is.

  - $\odot$ None-differentiable everywhere: $Z(t)$ is continuous but with infinitely many edges.

  - $\odot$ Infinite variation on any interval: $V_Z([a,b]) = \infty$
    variation of a real-valued function g on $[a,b]$:
    $$V_g([a,b]) = \sup_{\mathbf{P}} \sum_{i=1}^{n} |g(t_i) - g(t_{i-1})|, \ a = t_1 < t_2 < \cdots < t_n = b,$$
    where $\mathbf{P}$ is the set of all possible partitions (even $n \to \infty$ being allowed)

  - $\odot$ Quadratic variation on $[0, t]$ is t

    $$[Z, Z](t) = [Z, Z]([0, t]) = \lim_{n \to \infty} \sum_{i=1}^{n} |Z(t_i) - Z(t_{i-1})|^2$$

  - $\odot$ $\text{cov}(Z(t), Z(s)) = E[Z(t)Z(s)] - E[Z(t)]E[Z(s)] = E[Z(t)Z(s)]$

    (If $s < t, Z(t) = Z(s) + Z(t) - Z(s)$.)

    $= E[Z^2(s)] + E[Z(s)(Z(t) - Z(s))] = E[Z^2(s)] = \text{var}(Z(s)) = s = \min(t, s)$

    (The covariance is the length of the overlapping time period (or the sharing path) between $Z(t)$ and $Z(s)$.)

- Generalized Wiener process

  $dX = adt + bdZ$

  $\Rightarrow \begin{cases} E[dX] &= adt \\ \text{var}(dX) &= b^2 dt \Rightarrow \text{std}(dX) = b\sqrt{dt} \end{cases}$

  $\Rightarrow dX \sim N(adt, b^2 dt)$

  $\Rightarrow X(T) - X(0) = \sum_{i=1}^{n} \Delta X_i \sim N(aT, b^2 T)$

- Itô process (also called diffusion process) (Kiyoshi Itô, a Japanese mathematician, deceased in 2008 at the age of 93.)

$dX = a(X, t)dt + b(X, t)dZ$

     ↘ ↙

  drift and volatility are not constants, so it is no more simple to derive $E[dX]$ and

  $\text{var}(dX)$

(Both generalized Wiener processes and Itô process are called stochastic differential equation (SDE).)

- For the stock price, it is commonly assumed to follow an Itô process

$dS = \mu S dt + \sigma S dZ$

$\Rightarrow \frac{dS}{S} = \mu dt + \sigma dZ$ (also known as the geometric Brownian motion, GBM)

$\Rightarrow \frac{dS}{S} \sim N(\mu dt, \sigma^2 dt)$

  $\left\|\begin{array}{l}\frac{d \ln S}{dS} = \frac{1}{S} \Rightarrow d \ln S = \frac{dS}{S}\end{array}\right.$ (WRONG!) (Note that this differential result is true only when S is a real-number variable. This kind of differentiation CANNOT be applied to stochastic processes. The stochastic calculus is not exactly the same as the calculus for real-number variables.)

  In fact, the stock price follows the lognormal distribution based on the assumption of the geometric Brownian motion, but it does not mean $d \ln S \sim N(\mu dt, \sigma^2 dt)$.

- (Advanced content) Stochastic volatility (SV) process for the stock price (Heston(1993)):

$$dS = \mu S dt + \sqrt{V} S dZ_S,$$
$$dV = \kappa(\theta - V)dt + \sigma_V \sqrt{V} dZ_V,$$

and $\text{corr}(dZ_S, dZ_V) = \rho_{SV}$.

- (Advanced content) Jump-diffusion process for the stock price (Merton(1976)):

$$dS = (\mu - \lambda E[Y_S - 1])S dt + \sigma S dZ + (Y_S - 1)S dq,$$

where dq is a Poisson (counting) process with the jump intensity λ, i.e., the probability of an event occuring during a time interval of length Δt is

$$\begin{cases} \text{Prob \{the event does not occur in } (t, t + \Delta t], \text{ i.e., } dq = 0\} &=& 1 - \lambda \Delta t - \lambda^2 (\Delta t)^2 - \dots \\ \text{Prob \{the event occurs once in } (t, t + \Delta t], \text{ i.e., } dq = 1\} &=& \lambda \Delta t \\ \text{Prob \{the event occurs twice in } (t, t + \Delta t], \text{ i.e., } dq = 2\} &=& \lambda^2 (\Delta t)^2 \to 0 \\ \qquad\qquad\qquad\qquad\vdots \end{cases},$$

and the random variable $(Y_S - 1)$ is the random percentage change in the stock price if the Poisson event occurs. Merton (1976) considers $\ln Y_S \sim N(\mu_J, \sigma_J^2)$. Note that dZ, Y_S, and dq are mutually independent. The introduction of the term $(\lambda E[Y_S - 1])$ in the drift is to maintain the growth rate of S to be μ. This is because $E[(Y_S - 1)dq] = E[Y_S - 1] \cdot E[dq] = E[Y_S - 1] \cdot \lambda dt$.

$\Vert$ If Y_S follows the lognormal distribution, $E[Y_S - 1] = E[Y_S] - 1 = e^{E[\ln Y_S] + \frac{1}{2}\text{var}(\ln Y_S)}$
$\Vert$ $-1 = e^{\mu_J + \frac{1}{2}\sigma_J^2} - 1$.

II. Itô's Lemma

- Itô's Lemma is in essence the Taylor series.

  Taylor series: $f(x, y) = f(x_0, y_0) + \frac{\partial f}{\partial x}(x - x_0) + \frac{\partial f}{\partial y}(y - y_0)$

  $$+ \frac{1}{2!}\left[\frac{\partial^2 f}{\partial x^2}(x - x_0)^2 + 2\frac{\partial^2 f}{\partial x \partial y}(x - x_0)(y - y_0) + \frac{\partial^2 f}{\partial y^2}(y - y_0)^2\right] + \cdots$$

  Using Itô's Lemma to derive a stochastic differential equation:

  Given $dX = a(X, t)dt + b(X, t)dZ$, and $f(X, t)$ as a function of X and t, the stochastic differential equation for f can be derived as follows.

  $$df = (\frac{\partial f}{\partial t} + \frac{\partial f}{\partial X}a + \frac{1}{2}\frac{\partial^2 f}{\partial X^2}b^2)dt + (\frac{\partial f}{\partial X}b)dZ,$$

  where a and b are the abbreviations of $a(X, t)$ and $b(X, t)$.

  $\Vert$ The Itô's Lemma holds under the following approximations:
  $\Vert$ (i)
  $\Vert$ $(dt)^1 \to dt$
  $\Vert$ $(dt)^{1.5} \to 0$
  $\Vert$ $(dt)^2 \to 0$
  $\Vert$ $\vdots$
  $\Vert$
  $\Vert$ (ii)
  $\Vert$ $dZ \cdot dZ = ?$
  $\Vert$ By definition, $dZ \cdot dZ = \varepsilon^2 \cdot dt$.
  $\Vert$ $\because \varepsilon \sim N(0, 1)$
  $\Vert$ $\therefore \text{var}(\varepsilon) = 1 \Rightarrow E[\varepsilon^2] - (E[\varepsilon])^2 = 1 \Rightarrow E[\varepsilon^2] = 1 \Rightarrow E[(dZ)^2] = dt$
  $\Vert$ In addition, $\text{var}((dZ)^2) = \text{var}(\varepsilon^2 dt) = (dt)^2\text{var}(\varepsilon^2) \to 0$ (because $(dt)^2 \to 0$)
  $\Vert$ $\Rightarrow dZ \cdot dZ \overset{a.s.}{=} dt$ ("a.s." means "almost surely")

Itô's Lemma vs. differentiation of a deterministic function of time.

∗ For a deterministic function of time $f(t)$, if $\frac{df}{dt} = g(t)$, we can interpret that with an infinitesimal change of dt, the change in f is $g(t)dt$, which is deterministic.

∗ The interpretation of the Itô's Lemma: with a infinitesimal change of dt, the change in f is $(\frac{\partial f}{\partial t} + \frac{\partial f}{\partial X}a + \frac{1}{2}\frac{\partial^2 f}{\partial X^2}b^2)dt + (\frac{\partial f}{\partial X}b)dZ$. Note that the first term plays a similar role as $g(t)dt$, but the second term tells us that the change in f is random.

∗ To apply the Itô's Lemma is similar to taking the differentiation for stochastic processes.

- Based on the result of $dZ{\cdot}dZ = (dZ)^2 = dt$, it is straightforward to infer that the quadratic variation of the Wiener process over $[0, t]$, i.e., $[Z, Z](t) = [Z, Z]([0, t]) = \lim\limits_{n \to \infty} \sum\limits_{i=1}^{n} |Z(t_i) - Z(t_{i-1})|^2$, equals t.

Similar to the derivation of the Itô's Lemma that $E[(dZ)^2] = dt$ and $\text{var}((dZ)^2) \to 0$ when $n \to \infty$ ($dt \to 0$), $(Z(t_i) - Z(t_{i-1}))^2$ converges to $t_i - t_{i-1}$ almost surely if $(t_i - t_{i-1})$ is very small. This is because $E[(Z(t_i) - Z(t_{i-1}))^2] = E[\varepsilon^2(t_i - t_{t-1})] = t_i - t_{t-1}$, and $\text{var}((Z(t_i) - Z(t_{i-1}))^2) = \text{var}(\varepsilon^2(t_i - t_{t-1})) = (t_i - t_{t-1})^2\text{var}(\varepsilon^2) \to 0$.

So, we can conclude that when $n \to \infty$ ($t_i - t_{t-1} \to 0$), $\lim\limits_{n \to \infty} \sum\limits_{i=1}^{n}(Z(t_i) - Z(t_{i-1}))^2 = t$.

- Example 1 of applying the Itô's Lemma: $f = \ln S$, $dS = \mu S dt + \sigma S dZ$

$\Rightarrow d\ln S = (0 + \frac{1}{S}\cdot\mu S - \frac{1}{2}\frac{1}{S^2}\cdot\sigma^2 S^2)dt + \frac{1}{S}\sigma S dZ$

$\qquad = (\mu - \frac{\sigma^2}{2})dt + \sigma dZ$

⊙ $\Delta \ln S = (\mu - \frac{\sigma^2}{2})\Delta t + \sigma \Delta Z$

$\Rightarrow \ln S_{t+\Delta t} - \ln S_t = (\mu - \frac{\sigma^2}{2})\Delta t + \sigma\Delta Z \sim N((\mu - \frac{\sigma^2}{2})\Delta t, \sigma^2 \Delta t)$

$\Rightarrow \ln S_{t+\Delta t} \sim N(\ln S_t + (\mu - \frac{\sigma^2}{2})\Delta t, \sigma^2 \Delta t)$

⊙ Consider $\frac{T-t}{n} = \Delta t$,

$$\begin{cases} \ln S_{t+\Delta t} - \ln S_t & \sim \quad N((\mu - \frac{\sigma^2}{2})\Delta t, \sigma^2 \Delta t) \\ \ln S_{t+2\Delta t} - \ln S_{t+\Delta t} & \sim \quad N((\mu - \frac{\sigma^2}{2})\Delta t, \sigma^2 \Delta t) \\ \qquad\qquad \vdots & \\ \ln S_T - \ln S_{T-\Delta t} & \sim \quad N((\mu - \frac{\sigma^2}{2})\Delta t, \sigma^2 \Delta t) \end{cases}$$

$\Rightarrow \ln S_T - \ln S_t \sim N((\mu - \frac{\sigma^2}{2})n\Delta t, \sigma^2 n\Delta t)$

$\Rightarrow \ln S_T - \ln S_t \sim N((\mu - \frac{\sigma^2}{2})(T-t), \sigma^2(T-t))$

$\Rightarrow \ln S_T \sim N(\ln S_t + (\mu - \frac{\sigma^2}{2})(T-t), \sigma^2(T-t))$

$\Rightarrow$ The stock price is lognormal distributed.

> Another derivation: apply the stochastic integral on the both side of the equation
> $\int_t^T d\ln S_\tau = \int_t^T (\mu - \frac{\sigma^2}{2})d\tau + \int_t^T \sigma dZ(\tau)$
> $\qquad\qquad\qquad \downarrow$
>
> Since the integrand is a constant and the variable τ is a real-number variable, it is simply the integral for a real-number variable.
> $\Rightarrow \ln S_\tau|_t^T = (\mu - \frac{\sigma^2}{2})(T-t) + \sigma(\underline{Z(\tau)|_t^T})$
> $\qquad\qquad\qquad\qquad\qquad\qquad \downarrow$
> $\qquad\qquad\qquad Z(T) - Z(t) \equiv \triangle Z_{T-t} \sim N(0, T-t)$
> $\Rightarrow \ln S_T - \ln S_t \sim N((\mu - \frac{\sigma^2}{2})(T-t), \sigma^2(T-t))$

- Example 2: $f = S - Ke^{-r(T-t)}$ (f is the value of a forward agreement)

  $df = (\mu S - rKe^{-r(T-t)})dt + \sigma S dZ$

- Example 3: $F = Se^{r(T-t)}$ (F is the forward price of a stock)

  $dF = (\mu - r)Fdt + \sigma F dZ$

- Itô's Lemma for multiple variates

  $\frac{dS}{S} = \mu_S dt + \sigma_S dZ_S$ (foreign stock price)

  $\frac{dX}{X} = \mu_X dt + \sigma_X dZ_X$ (exchange rate: 1 foreign dollar $= X$ domestic dollars)

  Define $f = S \cdot X$ (the value of a foreign stock share in units of domestic dollars)

  $df = [\frac{\partial f}{\partial t} + \frac{\partial f}{\partial S} \cdot \mu_S S + \frac{\partial f}{\partial X} \cdot \mu_X X + \frac{1}{2} \cdot \frac{\partial^2 f}{\partial S^2} \cdot \sigma_S^2 S^2 + \frac{1}{2} \cdot \frac{\partial^2 f}{\partial X^2} \cdot \sigma_X^2 X^2 +$

  $\qquad \frac{\partial^2 f}{\partial S \partial X} \cdot \rho_{XS} \cdot \sigma_S \cdot \sigma_X \cdot S \cdot X]dt + \frac{\partial f}{\partial S}\sigma_S S dZ_S + \frac{\partial f}{\partial X}\sigma_X X dZ_X$

  $df = [\mu_S XS + \mu_X XS + \rho_{XS}\sigma_S\sigma_X SX]dt + \sigma_S XS dZ_S + \sigma_X XS dZ_X$

  $\frac{df}{f} = (\mu_S + \mu_X + \rho_{XS}\sigma_S\sigma_X)dt + \sigma_S dZ_S + \sigma_X dZ_X$ (because $f = SX$)

  > $dZ_S \cdot dZ_X = \varepsilon_S\sqrt{dt} \cdot \varepsilon_X\sqrt{dt} = \varepsilon_S\varepsilon_X dt$
  > $E[dZ_S \cdot dZ_X] = E[\varepsilon_S\varepsilon_X]dt = \rho_{XS}dt$
  > $\text{var}(dZ_S \cdot dZ_X) = (dt)^2\text{var}(\varepsilon_S\varepsilon_X) \to 0$
  > $\Rightarrow dZ_S \cdot dZ_X \overset{a.s.}{=} \rho_{XS}dt$

- (Advanced content) Given $dS = (\mu - \lambda K_Y)Sdt + \sigma SdZ + (Y_S - 1)Sdq$, where $K_Y = E[Y_S - 1]$ and $f(S,t)$ as a function of S and t, the Itô's Lemma implies

$$df = \{\frac{\partial f}{\partial t} + \frac{\partial f}{\partial S}(\mu - \lambda K_Y)S + \frac{1}{2}\frac{\partial^2 f}{\partial S^2}\sigma^2 S^2 + \lambda E[f(SY_S,t) - f(S,t)]\}dt$$
$$+ \frac{\partial f}{\partial S}\sigma SdZ + (Y_f - 1)fdq,$$

where $\lambda dt E[f(SY_S,t) - f(S,t)]$ is the expected jump effect on f, and $(Y_f - 1)dq$ is introduced to capture the unexpected (zero-mean) jump effect on f, where $(Y_f - 1)$ is the random percentage change in f if the Poisson event occurs. Note that $\lambda dt E[f(SY_S,t) - f(S,t)] + (Y_f - 1)fdq$ represents the total effect on f if the Poisson event occurs.

⊙ Suppose $f = \ln S$, the Itô's Lemma implies

$$d\ln S = (\mu - \lambda K_Y - \frac{1}{2}\sigma^2)dt + \sigma dZ + J_{\ln S},$$

where $J_{\ln S}$ represents the total effect on $\ln S$ due to the random jump in S.

|| If the jump occurs in S at t, we can obtain
$$\frac{S(t^+) - S(t)}{S(t)} = (Y_S - 1),$$
|| since $(Y_S - 1)$ is the precentage change if the jump occurs. Rewriting the above
|| eguation leads to
|| $S(t^+) - S(t) = (Y_S - 1)S(t) = Y_S S(t) - S(t) \Rightarrow S(t^+) = Y_S S(t).$

|| The random jump in $\ln S$ at t, if the Poisson event occurs, is
|| $\ln S(t^+) - \ln S(t) = \ln Y_S + \ln S(t) - \ln S(t) = \ln Y_S.$

According to the above inference, we can express the total jump effect by

$$J_{\ln S} = \ln Y_S dq,$$

and thus

$$d\ln S = (\mu - \frac{1}{2}\sigma^2 - \lambda K_Y)dt + \sigma dZ + \ln Y_S dq.$$

III. Stochastic Integral

- Stochastic integral (or called Itô intergral or Itô calculus): allows one to integrate one stochastic process (the integrand) over another stochastic process (the integrator). Usually, the integrator is a Wiener process.

- Integral over a stochastic process: $\int_a^b X(\tau)dZ(\tau)$, where $X(\tau)$ can be a deterministic function or a stochastic process, and $dZ(\tau)$ is a Wiener process. (vs. integral over a real-number variable: $\int_a^b f(y)dy$, where $f(y)$ is a deterministic function of the real-number variable y)

- Three cases of $X(\tau)$ are discussed: simple deterministic processes, simple predictable processes, and general predictable processes (or Itô's processes).

- Stochastic integral for "simple deterministic" processes

  If $X(\tau)$ is a deterministic process, given any value of t, the value of $X(\tau)$ can be known exactly. Therefore, in an infinitesimal time interval, $(t_{i-1}, t_i]$, the value of $X(\tau)$ can be approximated by a constant C_i. The term "simple" means to approximate the process by a step function. (In contrast, if $X(\tau)$ is a stochastic process, given any value of τ, we only konw the distribution of possible values for $X(\tau)$.)

Figure 1-2
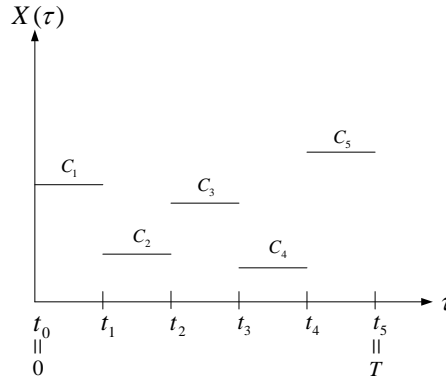
For simple deterministic processes, we can define the stochastic integral as follows. (This definition is similar to the rectangle method to define the integral over a real-number variable.)

$$\int_0^T X(\tau)dZ(\tau) = \sum_{i=1}^n C_i(Z(t_i) - Z(t_{i-1})) \sim N(0, \sum_{i=1}^n C_i^2(t_i - t_{i-1}))$$

∗ There should be a term $\lim_{n \to \infty}$ in front of each $\sum_{i=1}^n$. It is omitted for simplicility.

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∗ In the above equation, the reason for the final normal distribution:

1. The sum of normally distributed random variables is still a normally distributed random variable.

2. The mean for the resulting random variable is the sum of the mean of all normally distributed random variables.

3. The variance for the resulting random variable is the sum of the variances of all normally distributed random variables because all normally distributed random variables are independent.

∗ Note that the result of a stochastic intergral is a distribution, and we are interested in the mean and variance of this distribution.

(i) According to the above definition, if $X(t) = 1$, the result of the stochastic integral is consistent with the definition of the Wiener process.

$$\int_0^T X(\tau)dZ(\tau) = \int_0^T dZ(\tau) = Z(\tau)|_0^T = Z(T) - Z(0) \sim N(0, T)$$
$$= \sum_{i=1}^n (Z(t_i) - Z(t_{i-1})) \sim N(0, \sum_{i=1}^n (t_i - t_{i-1})) = N(0, T)$$

(ii) Alternative way to calculate the variance of the result of the stochastic integral.

$$\text{var}(\int X dZ) = E[(\int X dZ)^2] - (E[\int X dZ])^2 = E[(\int X dZ)^2] = E[(\sum_{i=1}^n C_i(Z(t_i) - Z(t_{i-1})))^2]$$
$$= \sum_{i=1}^n \sum_{j=1}^n C_i C_j E[(Z(t_i) - Z(t_{i-1}))(Z(t_j) - Z(t_{j-1}))]$$

↑

calculate the squared term in the expectation, and then apply the distributive property of the expectation over the addition and scaler multiplication

$$= \sum_{i=1}^n C_i^2 (t_i - t_{i-1})$$

↑

because $\text{cov}(Z(t_i) - Z(t_{i-1}), Z(t_j) - Z(t_{j-1})) = 0$, and $\text{var}(Z(t_i) - Z(t_{i-1})) = t_i - t_{i-1}$

- "Simple predictable" process: in the time interval $(t_{i-1}, t_i]$, the constant C_i is replaced by a "random variable" ξ_i, which depends on the values of $Z(t)$ for $t \le t_{i-1}$, but not on values of $Z(t)$ for $t > t_{i-1}$. Therefore, $X(t)$ is defined as follows.

$$X(t) = \xi I_{\{t|t=0\}} + \sum_{i=1}^n \xi_i I_{\{t|t_{i-1}<t\le t_i\}},$$

where I is a indicator function and ξ is a constant. The corresponding stochastic intergral is defined as follows.

$$\int_0^T X(\tau)dZ(\tau) \equiv \sum_{i=1}^n \xi_i(Z(t_i) - Z(t_{i-1})).$$

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- The reason for the name "predictable":

  1. The value of $X(t)$ for $(t_{i-1}, t_i]$, ξ_i, is determined based on the information set formed by $\{Z(t)\}$ until t_{i-1}, denoted by $\mathcal{F}_{t_{i-1}}$. It is also called that ξ_i is $\mathcal{F}_{t_{i-1}}$-measurable. (See Figure 1-3)

  2. In contrast, the value of $Z(t_i) - Z(t_{i-1})$ will not realize until the time point t_i, i.e., this value will be known based on the information set $\mathcal{F}_{t_i}$. In other words, $Z(t_i)$ is $\mathcal{F}_{t_i}$-measurable. (See Figure 1-3)

  3. Therefore, we say that $X(t)$ is "predictable" since we know its realized value just before the time point at which $Z(t)$ is realized.

  4. In the continuous-time model, $Z(t)$ is $\mathcal{F}_t$-measurable (the realized value is known at t). For any process that we can know its realized value just before t, we call this process to be $\mathcal{F}_{t-}$-measurable and thus "predictable".

Figure 1-3
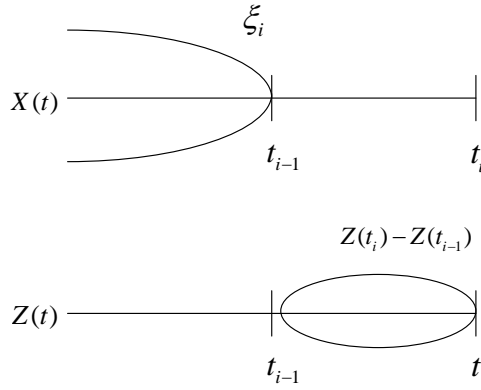
- Stochastic integral of "general predictable" processes

  Let $X^n(t)$ be a sequence of simple predictable processes (which can be approximated by a step function with a series of predictable random variables) convergent in probability to the process $X(t)$, which is "general predictable" (i.e., $X(t)$ is predictable and $\int_0^T X^2(\tau)d\tau < \infty$). The sequence of their integrals $\int_0^T X^n(\tau)dZ(\tau)$ also converges to $\int_0^T X(\tau)dZ(\tau)$ in probability, i.e.,

  $$\lim_{n \to \infty} \int_0^T X^n(\tau)dZ(\tau) = \int_0^T X(\tau)dZ(\tau).$$

 (In practice, the general predictable process is also known as the predictable process for short.)

- Any "adapted" and "left continuous" process is a "predictable" process.

  A process is an adapted process iff it is $\mathcal{F}_t$ measurable. For example, the Wiener process $Z(t)$ is an adapted process.

  A left-continuous function is a function which is continuous at all points when approached from the left. In addition, a function is continuous if and only if it is both right-continuous and left-continuous. Since $Z(t)$ is a continuous function of t, it must be left-continuous.

  Thus, we can conclude that Wiener process $Z(t)$ is a predictable process, so $Z(t)$ itself (or even all Itô processes) can be the integrand in a stochastic intrgral. This is also the reason for the name of the Itô integral.

Figure 1-4
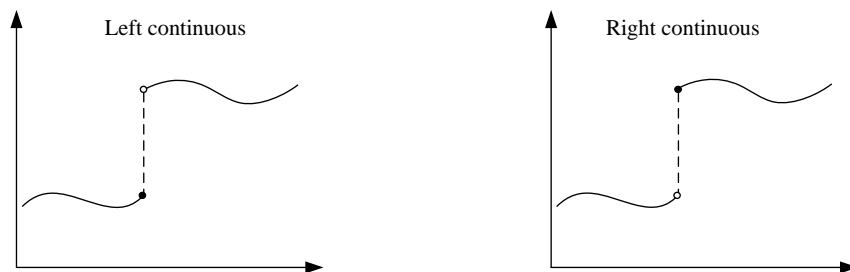
- Solve $\int_0^T Z(\tau)dZ(\tau)$, given $Z(0) = 0$.

  Define $X^n(t) = \sum_{i=1}^{n} Z(t_{i-1})I_{\{t|t_{i-1}<t\leq t_i\}}$ ($\lim_{n\to\infty} X^n(t)$ converges to $Z(t)$ in probability)

$$\int_0^T X^n(\tau)dZ(\tau) = \sum_{i=1}^{n} Z(t_{i-1})(Z(t_i) - Z(t_{i-1}))$$

$$= \tfrac{1}{2}\sum_{i=1}^{n}[(Z(t_i))^2 - (Z(t_{i-1}))^2 - (Z(t_i) - Z(t_{i-1}))^2]$$

$$= \tfrac{1}{2}(Z(T))^2 - \tfrac{1}{2}(Z(0))^2 - \tfrac{1}{2}\sum_{i=1}^{n}(Z(t_i) - Z(t_{i-1}))^2$$

$$\Rightarrow \int_0^T Z(\tau)dZ(\tau) = \lim_{n\to\infty}\int_0^T X^n(\tau)dZ(\tau) = \tfrac{1}{2}(Z(T))^2 - \tfrac{1}{2}T$$

- Properties of Itô Integral:

(i) $\int_0^T (\alpha X(\tau) + \beta Y(\tau)) dZ(\tau) = \alpha \int_0^T X(\tau) dZ(\tau) + \beta \int_0^T Y(\tau) dZ(\tau)$ (distributive property)

(ii) $\int_0^T I_{[a,b]}(\tau) dZ(\tau) = Z(b) - Z(a)$, $0 < a < b < T$

(iii) $E[\int_0^T X(\tau) dZ(\tau)] = 0$

(iv) $\text{var}(\int_0^T X(\tau) dZ(\tau)) = E[(\int_0^T X(\tau) dZ(\tau))^2] = \int_0^T E[X(\tau)^2] d\tau$ (Itô Isometry)

- Find $E[\int_0^T Z(\tau) dZ(\tau)]$ and $\text{var}(\int_0^T Z(\tau) dZ(\tau))$.

(i) $\because E[(Z(T))^2] = \text{var}(Z(T)) + E[Z(T)]^2 = T$

$\therefore E[\int_0^T Z(\tau) dZ(\tau)] = E[\frac{1}{2}(Z(T))^2 - \frac{1}{2}T] = 0$

(Property (iii) can be applied to obtaining the identical result directly.)

(ii) $\text{var}(\int_0^T Z(\tau) dZ(\tau)) = \frac{1}{4}\text{var}((Z(T))^2)$

$$= \frac{1}{4}\{E[(Z(T))^4] - E[(Z(T))^2]^2\} = \frac{1}{4}\{3T^2 - T^2\} = \frac{T^2}{2}$$

$\Big\|$ If $x \sim N(\mu, \sigma^2)$, then $E[x^4] = \mu^4 + 6\mu^2\sigma^2 + 3\sigma^4$.
Since $Z(T) \sim N(0, T)$, we can derive $E[(Z(T))^4] = 3T^2$.

Apply Property (iv) to finding $\text{var}(\int_0^T Z(\tau) dZ(\tau))$ as follows:

$\text{var}(\int_0^T Z(\tau) dZ(\tau)) = \int_0^T E[(Z(\tau))^2] d\tau = \int_0^T \tau d\tau = \frac{1}{2}\tau^2|_0^T = \frac{T^2}{2}$

IV. Solve Stochastic Differential Equations with Stochastic Integral

- How to solve $X(t)$ systematically through the stochastic integral is the major application of the stochastic integral.

- Given $\underbrace{dX(t) = -\alpha X(t)dt + \sigma dZ(t)}$, solve $X(t)$.

    Ornstein-Uhlenbeck process
    $$\begin{cases} -\alpha X(t) \to \mu(X,t) \\ \sigma \to \sigma(X,t) \end{cases}$$
    According to the stochastic integral, $X(t)$ should satisfy
    $$X(t) = X(0) + \int_0^t \mu(X,\tau)d\tau + \int_0^t \sigma(X,\tau)dZ(\tau)$$

    $\|$ However, $\mu(X,t)$ is a function of $X(t)$, so $\mu(X,t)$ is a stochastic process as well.
    $\|$ Moreover, since the value of $\mu(X,t)$ is unknown due to the unsolved $X(t)$. Thus,
    $\|$ we cannot derive $X(t)$ by applying the stochastic integral directly.

    Define $Y(t) = X(t)e^{\alpha t} \Rightarrow dY(t) = e^{\alpha t}dX(t) + \alpha e^{\alpha t}X(t)dt$ (through the Itô's Lemma)
    $$= e^{\alpha t}[-\alpha X(t)dt + \sigma dZ(t)] + \alpha e^{\alpha t}X(t)dt$$
    $$= \sigma e^{\alpha t}dZ(t)$$

    $$\Rightarrow Y(t) = Y(0) + \int_0^t \sigma e^{\alpha \tau}dZ(\tau)$$
    $$\downarrow$$
    a simple deterministic process

    $$\Rightarrow X(t) = e^{-\alpha t}(Y(0) + \int_0^t \sigma e^{\alpha \tau}dZ(\tau)), \text{ where } Y(0) = X(0)$$

    * Without the stochastic integral, as shown in the above example, different techniques should be employed to solve $X(t)$.

    * Later a systematical way to apply the stochastic integral to solving linear stochastic differential equations is introduced. It is worth noting that in the field of financial engineering, there is at least 95% of probability to consider linear stochastic differential equations.

- Solution of a linear stochastic differential equation:

  Given $dX(t) = (\alpha(t) + \beta(t)X(t))dt + (\gamma(t) + \delta(t)X(t))dZ(t)$, solve $X(t)$.

(i) Like solving a differential equation (it needs to solve the corresponding homogeneous differential equation first), we solve this SDE in the case of $\alpha(t) = \gamma(t) = 0$ first.

$$dU(t) = \beta(t)U(t)dt + \delta(t)U(t)dZ(t)$$

$$\Rightarrow \frac{dU(t)}{U(t)} = \beta(t)dt + \delta(t)dZ(t)$$

(The $U(t)$ is similar to $S(t)$, so we can apply the result on p.1-6 to solve $U(t)$.)

$$\Rightarrow U(t) = \underbrace{U(0) \cdot \exp(\int_0^t (\beta(\tau) - \frac{1}{2}\delta^2(\tau))d\tau + \int_0^t \delta(\tau)dZ(\tau))}_{(1)}$$

(ii) Consider $X(t) = U(t) \cdot V(t)$, and $U(0) = 1$ and $V(0) = X(0)$,

  where $dU(t) = \beta(t)U(t)dt + \delta(t)U(t)dZ(t)$,

  $\quad\quad dV(t) = a(t)dt + b(t)dZ(t)$.

  ⊙ The integration by parts for stochastic processes:

  $\quad\quad U(t)V(t) - U(0)V(0) = \int_0^t V(\tau)dU(\tau) + \int_0^t U(\tau)dV(\tau) + [U,V](t),$

  where $[U,V](t) = \lim\limits_{n\to\infty} \sum\limits_{i=1}^n (U(t_i) - U(t_{i-1}))(V(t_i) - V(t_{i-1}))$ (quadratic covariation).

  In addition, $d[U,V](t) = dU(t) \cdot dV(t) = \sigma_U \cdot \sigma_V \cdot dt$.

  (there is no product of drift terms because they are all with $(dt)^2$ or $(dt)^{1.5}$, which is too small relative to dt.)

  ⊙ Stochastic product rule:

  $$dX(t) = dU(t) \cdot V(t) + U(t) \cdot dV(t) + d[U,V](t),$$

  where $d[U,V](t) = dU(t) \cdot dV(t) = \delta(t)U(t)b(t)dt$

  ⊙ Substitute $dU(t)$ and $dV(t)$ into the above equation, and compare with $dX(t)$.

  $\Rightarrow b(t) \cdot U(t) = \gamma(t)$, $a(t) \cdot U(t) = \alpha(t) - \delta(t) \cdot \gamma(t)$

  $\Rightarrow b(t) = \frac{\gamma(t)}{U(t)}, \quad a(t) = \frac{\alpha(t) - \delta(t)\gamma(t)}{U(t)}$

  $$\Rightarrow V(t) = \underbrace{V(0) + \int_0^t \frac{\alpha(\tau) - \delta(\tau)\gamma(\tau)}{U(\tau)}d\tau + \int_0^t \frac{\gamma(\tau)}{U(\tau)}dZ(\tau)}_{(2)\quad\text{where } V(0) = X(0)},$$

  $\Rightarrow X(t) = U(t) \cdot V(t) = (1) \times (2)$

- Brownian bridge (pinned Brownian motion):

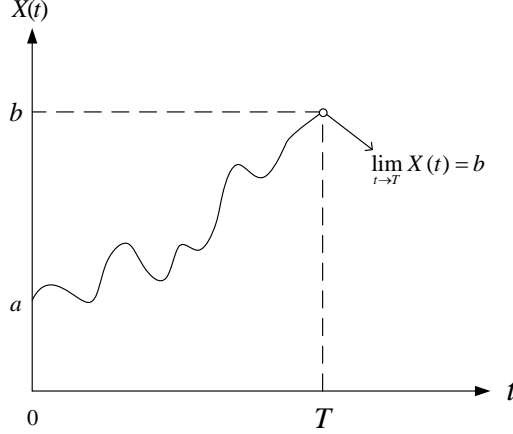$dX(t) = \frac{b-X(t)}{T-t}dt + dZ(t)$, $0 \le t \le T$, $X(0) = a$

$\Rightarrow \alpha(t) = \frac{b}{T-t}$, $\beta(t) = \frac{-1}{T-t}$, $\gamma(t) = 1$, $\delta(t) = 0$

$$\left\| \begin{aligned}
&U(t) = U(0)\exp(\int_0^t (\beta(\tau) - \tfrac{1}{2}\delta^2(\tau))d\tau + \int_0^t \delta(\tau)dZ(\tau)) \\
&\qquad = \exp(\int_0^t \tfrac{-1}{T-\tau}d\tau) = \exp(\ln(T-\tau)|_0^t) \\
&\qquad = \exp(\ln \tfrac{T-t}{T}) = \tfrac{T-t}{T} \\
&b(t) = \tfrac{T}{T-t} \\
&a(t) = \tfrac{\frac{b}{T-t} - 0 \cdot 1}{\frac{T-t}{T}} = \tfrac{bT}{(T-t)^2} \\
&V(t) = \underbrace{V(0)}_{X(0)=a} + \underbrace{\int_0^t \frac{bT}{(T-\tau)^2}d\tau}_{\frac{bT}{T-t} - b} + \int_0^t \tfrac{T}{T-\tau}dZ(\tau) \\
&X(t) = U(t) \cdot V(t) = \tfrac{T-t}{T}[a + \tfrac{bT}{T-t} - b + T\int_0^t \tfrac{1}{T-\tau}dZ(\tau)]
\end{aligned} \right.$$

$X(t) = a(1 - \frac{t}{T}) + b\frac{t}{T} + (T-t)\int_0^t \frac{1}{T-\tau}dZ(\tau)$, $0 \le t < T$, $\lim_{t \to T} X(t) = b$

Figure 1-5

$$\left\| \begin{aligned}
&E[X(t)] = a(1 - \tfrac{t}{T}) + b\tfrac{t}{T} \\
&\text{var}(X(t)) = t - \tfrac{t^2}{T} = \tfrac{Tt-t^2}{T} = \tfrac{t(T-t)}{T} \\
&\text{cov}(X(t), X(s)) = \min(s, t) - st/T
\end{aligned} \right.$$

- The Brownian bridge is suited to formulate the process of the zero-coupon bond price because the bond price today is known and the bond value is equal to its face value on the maturity date. The disadvantage of fomulating the bond price to follow the Brownian bridge is that the zero-coupon bond price could be negative due to the normal distribution of $dZ(t)$ in $dX(t)$.

- Given $X(t) = a(1 - \frac{t}{T}) + b\frac{t}{T} + (T - t)\int_0^t \frac{1}{T-\tau}dZ(\tau)$,

  prove (i) $\text{var}(X(t)) = \frac{t(T-t)}{T}$.

       (ii) $\text{cov}(X(t), X(s)) = s - \frac{st}{T}$ (if $t > s$).

  (i) According to the fourth property of Itô integral, that is,

     $\text{var}(\int_0^T X(\tau)dZ(\tau)) = \int_0^T E[X(\tau)^2]d\tau$, we can derive

$$\begin{aligned} \text{var}(X(t)) &= (T-t)^2 \int_0^t \left(\frac{1}{T-\tau}\right)^2 d\tau = (T-t)^2 \left((T-\tau)^{-1}\big|_0^t\right) \\ &= (T-t)^2\left(\frac{1}{T-t} - \frac{1}{T}\right) = \frac{t(T-t)}{T} \end{aligned}$$

(ii) $\text{cov}(X(t), X(s))$

  $= \text{cov}(X(s) + X(t) - X(s), X(s))$ (assume $s < t$)

  $= \text{var}(X(s)) + \text{cov}(X(t) - X(s), X(s))$

  $= \frac{s(T-s)}{T} + \text{cov}((T-t)\int_0^t \frac{1}{T-\tau}dZ(\tau) - (T-s)\int_0^s \frac{1}{T-\tau}dZ(\tau), (T-s)\int_0^s \frac{1}{T-\tau}dZ(\tau))$

$\Big\| \quad (T-t)\int_0^t \frac{1}{T-\tau}dZ(\tau) - (T-s)\int_0^s \frac{1}{T-\tau}dZ(\tau)$

$\Big\| \quad \overset{T-s=T-t+t-s}{\Longrightarrow} (T-t)\int_s^t \frac{1}{T-\tau}dZ(\tau) - (t-s)\int_0^s \frac{1}{T-\tau}dZ(\tau)$

  $= \frac{s(T-s)}{T} - (t-s)(T-s)\text{var}(\int_0^s \frac{1}{T-\tau}dZ(\tau))$

  $= \frac{s(T-s)}{T} - (t-s)(T-s)(\int_0^s (\frac{1}{T-\tau})^2 d\tau)$

  $= \frac{s(T-s)}{T} - (t-s)(T-s)(\frac{1}{(T-s)} - \frac{1}{T})$

  $= \frac{sT-s^2}{T} - (t-s)(T-s)(\frac{s}{T(T-s)})$

  $= \frac{sT-s^2-st+s^2}{T} = s - \frac{st}{T}$

- "Introduction to Stochastic Calculus with Applications," Klebaner, 2005