Simulating and Manipulating Stochastic Differential Equations

In this lecture. . .

I

- Using Itô's lemma to manipulate stochastic differential equations

* extension of kolmogorov eq$^{\underline{n}}$'s

II

- Continuous-time stochastic differential equations as discrete-time processes

- Simple ways of generating random numbers in Excel

- Correlated random walks

By the end of this lecture you will be able to

- manipulate stochastic differential equations : Further Itô

- find transition probability density functions for arbitrary stochastic differential equations trans^{n} pdf via more complex Kolmogorov eq^{n}s

- simulate stochastic differential equations
  as discrete time eq^{n}s

Introduction

In order to become comfortable with the kind of models commonly used in quantitative finance you must be able to manipulate stochastic differential equations and generate random walks numerically.

dS cts. time

δS discrete time

$\phi \sim N(0,1)$ $dX \sim \phi\sqrt{dt}$

Manipulating stochastic differential equations

An equation of the form $\{G_t : t \in \mathbb{R}^+\}$ uncertainty known

across a time step $t \longrightarrow t+dt$

$$dG = a\,(G,t)\,dt + b\,(G,t)\,dX$$

$X_{t+1} - X_t$

$G_{t+1} - G_t$

is called a Stochastic Differential Equation (SDE) for G (or random walk for dG) and consists of two components:

1. $a\,(G,t)\,dt$ is deterministic – coefficient of dt is known as the **drift** or **growth**

probability terms

2. $b\,(G,t)\,dX$ is random – coefficient of dX is known as the **diffusion** or **volatility**

$dG^2 = b^2(G,t)\,dt$

and we say G evolves according to (or follows) this process.

So if for example we have a random walk

$$dS = \mu S dt + \sigma S dX \tag{1}$$

then the drift is $a(S,t) = \mu S$ and the diffusion is $b(S,t) = \sigma S$.

The process (1) is also called **Geometric Brownian Motion** (GMB) or ~~**Exponential Brownian motion** (EMB)~~ and is a popular model for a wide class of asset prices.

We have previously considered Itô's lemma to obtain the change in a function $f(X)$ when $X \to X + dX$, where X is a standard Brownian motion.

This jump $df = f(X + dX) - f(X)$ is given by

X_t

$\mathbb{E}\left[dX_t^2\right] = dt$

$F(X_t)$ Itô I

$$df = \frac{df}{dX}dX + \frac{1}{2}\frac{d^2 f}{dX^2}dt \qquad \boxed{dX_t^2 = dt} \qquad (2)$$

$F(t, X_t)$ Itô II

using the result

$$df = \left(\frac{\partial f}{\partial t} + \frac{1}{2}\frac{\partial^2 f}{\partial X^2}\right)dt + \frac{\partial f}{\partial X}dX$$

$\mathbb{E}\left[dX^2\right] = dt$

$$\boxed{\lim_{dt \to 0} dX^2 = dt.}$$

Suppose we now wish to extend the result (2) to consider the change in an ~~option price~~ $V(S)$ where the underlying variable S follows a geometric Brownian motion.

[function] Contract

(Of course, you are not supposed to know anything about options yet. Just think of manipulating functions.)

Itô multiplication Table

$\times$	dt	dX_t
dt	0 (dt^2)	0 $(dt^{3/2})$
dX_t	0 $(dt^{3/2})$	dt (dX^2)

$V(\text{stock})$

$V(S)$

$\downarrow$

$$\frac{dS}{S} = \mu\,dt + \sigma\,dX$$

If we rewrite (1) as

$$dS^2 = \mu^2 S^2 \underbrace{dt^2}_{=0} + 2\mu\sigma S^2 \overbrace{dX\,dt}^{=0} + \sigma^2 S^2 \underbrace{dX^2}_{=dt}$$

$$\frac{dS}{S} = \mu\, dt + \sigma\, dX$$

$$\boxed{dS^2 = \sigma^2 S^2 dt}$$

then dS represents the change in asset price S in a small time interval dt.

This expression is the return on the asset.

μ is the average growth rate of the asset and σ the associated volatility (standard deviation) of the returns.

dX is an increment of a Brownian Motion, known as a Wiener process and is a Normally distributed random variable such that $dX \sim N(0, dt)$.

An obvious question we may ask is, what is the jump in $V(S + dS)$ when $S \to S + dS$?

$V(S+dS)$?

We begin (again) by using a Taylor series as in (2), but for $V(S + dS)$ to get

1D TSE : $V(S+dS) = V(S) + \frac{dV}{dS} dS + \frac{1}{2} \frac{d^2V}{dS^2} dS^2$

$$dV = \frac{dV}{dS} dS + \tfrac{1}{2} \frac{d^2V}{dS^2} dS^2.$$

$dV = V(S+dS) - V(S) = \frac{dV}{dS}\left(\mu S\, dt + \sigma S\, dX\right) + \frac{1}{2}\sigma^2 S^2 \frac{d^2V}{dS^2} dt$

$V = V(S)$

We can proceed further now as we have an expression for dS (and hence dS^2). As dt is very small, any terms in $dt^{\frac{3}{2}}$ or dt^2 are insignificant in comparison and can be ignored. So working to $O\left(dt\right)$

$$\boxed{dS^2 = \sigma^2 S^2 dt.}$$

If we substitute this into the previous expression for dV we get Itô's lemma as applied to $V(S)$:

SDE for V or
random walk for dV

Itô III

$$dV = \underbrace{\left(\mu S \frac{dV}{dS} + \frac{1}{2}\,\sigma^2 S^2 \frac{d^2V}{dS^2}\right)}_{\text{drift}} dt + \overbrace{\left(\sigma S \frac{dV}{dS}\right)}^{\text{diffusion}} dX. \qquad (3)$$

Note that this is another stochastic differential equation!

It contains a predictable part and a random part.

Now consider $V = V(S, t)$

$t \to t + dt \qquad S \to S + dS$

2D TSE

dV

$$V(t+dt, S+dS) = V(t, S) + \frac{\partial V}{\partial t} dt + \frac{\partial V}{\partial S} dS + \frac{1}{2} \frac{\partial^2 V}{\partial S^2} dS^2$$

$$dV = \frac{\partial V}{\partial t} dt + \frac{\partial V}{\partial S} \left(\mu S\, dt + \sigma S\, dX \right) + \frac{1}{2} \sigma^2 S^2 \frac{\partial^2 V}{\partial S^2} dt$$

$$dV = \underbrace{\left(\frac{\partial V}{\partial t} + \mu S \frac{\partial V}{\partial S} + \frac{1}{2} \sigma^2 S^2 \frac{\partial^2 V}{\partial S^2} \right)}_{\text{drift}} dt + \underbrace{\sigma S \frac{\partial V}{\partial S}}_{\text{diffusion}} dX$$

Itô IV

Very, Very Important Example

Suppose that we had a formula for $V(S)$. Let's take a very special case, let's consider

Itô III on log(S)

$dS = \mu S\, dt + \sigma S\, dX$

$\mu, \sigma \in \mathbb{R}$

$\boxed{S>0}$

$$V(S) = \log S.$$

Differentiating this once gives

$$(*) \quad \frac{dV}{dS} = \frac{1}{S}.$$

Differentiating this again gives

$$(**) \quad \frac{d^2V}{dS^2} = -\frac{1}{S^2}.$$

Subst. in (3)

i.e Itô III

$$dV = d(\log S) = \left[\mu \cancel{S} \times \frac{1}{\cancel{S}} + \frac{1}{2}\sigma^2 \cancel{S^2}\left(-\frac{1}{\cancel{S^2}}\right)\right]dt + \sigma \cancel{S}\left(\frac{1}{\cancel{S}}\right) dX$$

Now from (3) we have

d(something)

we want this term

$$d\,(\log S) = \left(\mu - \tfrac{1}{2}\sigma^2\right) dt + \sigma dX.$$

now ← → some time in the future

Integrating both sides between 0 and t

$$\int_0^t d\,(\log S) = \int_0^t \left(\mu - \frac{1}{2}\sigma^2\right) d\tau + \int_0^t \sigma\, dX \qquad (t > 0)$$

$$= \left(\mu - \tfrac{1}{2}\sigma^2\right) t + \sigma\,(X\,(t) - X\,(0))\,.$$

$\int dX$

$X(0) \to 0$

$\log S\big|_0^t = \log S_t - \log S_0 = \log \frac{S_t}{S_0}$

Therefore

$$\log\left(\frac{S(t)}{S(0)}\right) = \left(\mu - \tfrac{1}{2}\sigma^2\right)t + \sigma\left(X(t) - X(0)\right)$$

Take exp of both sides

Assuming $X(0) = 0$ and $\boxed{S(0) = S_0,}$ the exact solution becomes

Stock at $t=0$

Take $S(0)$ across

$$S(t) = S_0 \exp\left(\left(\mu - \tfrac{1}{2}\sigma^2\right)t + \sigma X(t)\right). \tag{4}$$

Closed form sol^n

$\int_0^t$: $S_t = S_0 \exp\left\{\left(\mu - \frac{1}{2}\sigma^2\right)t + \sigma\phi\sqrt{t}\right\}$

$\int_t^T$: $S_T = S_t \exp\left\{\left(\mu - \frac{1}{2}\sigma^2\right)(T-t) + \sigma\phi\sqrt{T-t}\right\}$

$\int_t^{t+dt}$: $S_{t+dt} = S_t \exp\left\{\left(\mu - \frac{1}{2}\sigma^2\right)dt + \sigma\phi\sqrt{dt}\right\}$

$\eta, \gamma, \sigma \in \mathbb{R}$

Another example: $dr = (\eta - \gamma r)\,dt + \sigma\,dX$

Let's take a look at the Vasicek interest rate model for short-term interest rates, and try manipulating that.

γ – speed (of reversion)

σ – vol.

$\bar{r} = \dfrac{\eta}{\gamma}$ – mean rate

$\eta = \bar{r}\gamma$

$$dr = \gamma\,(\bar{r} - r)\,dt + \sigma dX.$$

$dr = -\gamma(r - \bar{r})\,dt + \sigma\,dX$

γ refers to the **reversion rate** and $\bar{r}$ denotes the **mean rate**.

$\exists$ a closed form sol$\underline{\text{n}}$

by using a subst$\underline{\text{n}}$ $dr = -\gamma(\underbrace{r - \bar{r}}_{u})\,dt + \sigma\,dX$

Let $u = r - \bar{r} \implies du = dr - d(\bar{r}) = dr$

By setting $u = r - \overline{r}$, u is a solution of

Ornstein - Uhlenbeck process →

$$du = -\gamma u \, dt + \sigma dX.$$

→ closed form sol$^{\text{n}}$

An analytic solution for this equation exists. To see, this write the equation as

$\int_0^t \frac{\partial F}{\partial X} dX_s$ →

$$d\left(ue^{\gamma t}\right) = \sigma e^{\gamma t} dX.$$

$e^{\gamma(s-t)}$

by parts or use stoch. integration formula

Integrating over from zero to t gives

$$(*) \quad \boxed{u(t) = u(0)e^{-\gamma t} + \sigma \int_0^t e^{\gamma(s-t)} dX_s.} \quad (*)$$

This can be **integrated by parts** to give Ito

Extra

$$\boxed{u(t) = u(0)e^{-\gamma t} + \sigma \left(X(t) - \gamma \int_0^t X(s) e^{\gamma(s-t)} \, ds \right)}$$

Extra working for p.15

$$du = -\gamma u\,dt + \sigma\,dX \qquad u(0) = x \quad \text{I.C.}$$

$$du + \gamma u\,dt = \sigma\,dX$$

We want to do "something" to the l.h.s $\longrightarrow$ exact differential. Recall the linear eq^n. We multiplied by an I.F (integrating factor) to create an exact derivative. So multiply both sides by I.F. $e^{\gamma t}$.

$$e^{\gamma t}(\gamma u\,dt + du) = \sigma e^{\gamma t}\,dX$$

$$d\left(e^{\gamma t}u\right) = \sigma e^{\gamma t}\,dX$$

Now integrate between 0 and t $\therefore \int_0^t d(e^{\gamma s}u_s) = \sigma\int_0^t e^{\gamma s}\,dX_s$

$$e^{\gamma t}u(t) - u_0 = \sigma\int_0^t e^{\gamma s}\,dX_s$$

take u_0 to RHS & $\div$ thro' by $e^{\gamma t}$

$$d(ue^{\gamma t}) = e^{\gamma t}du + u\,d(e^{\gamma t})$$
$$= e^{\gamma t}du + \gamma e^{\gamma t}u\,dt$$

Now $\frac{d}{dt}(e^{\gamma t}) = \gamma e^{\gamma t}$

$$d(e^{\gamma t}) = \gamma e^{\gamma t}\,dt$$

Derivation to follow.

Transition probability density functions again

Let's look at the equations governing the probability distribution for an arbitrary random walk: stoch. process

$$\boxed{y_t}$$

$$dy = A(y,t)\,dt + B(y,t)\,dX$$

for the variable y.

Remember the **transition probability density function** $p(y,t;y',t')$ defined by

$$\text{Prob}(a < y' < b \text{ at time } t' | y \text{ at time } t) = \int_a^b p(y,t;y',t')\,dy'.$$

In words this is 'the probability that the random variable y lies between a and b at time t' in the future, given that it started out with value y at time t.'

Think of y and t as being current values with y' and t' being future values.

The transition probability density function can be used to answer questions such as

"What is the probability of the variable y being in a certain range at time t' given that it started out with value y at time t?"

The transition probability density function $p(y, t; y', t')$ satisfies two equations.

One involves derivatives with respect to the future state and time (y' and t') and is called the **forward equation.**

The other involves derivatives with respect to the current state and time (y and t) and is called the **backward equation.**

$A(G, t) \qquad B(G, t)$

These can be derived by the same trinomial idea we used before (but the details are a lot messier for the general stochastic differential equation). $dG = A\,dt + B\,dX$

$\mathbb{E}[dG] = \mathbb{E}[A\,dt] + \mathbb{E}[B\,dX] = A\,dt\,\mathbb{E}[1] + B\,\mathbb{E}(dX) = A\,dt$

$\mathbb{V}[dG] = \mathbb{V}(A\,dt) + \mathbb{V}(B\,dX) = B^2\,\mathbb{V}(dX) = B^2\,dt$

The forward equation

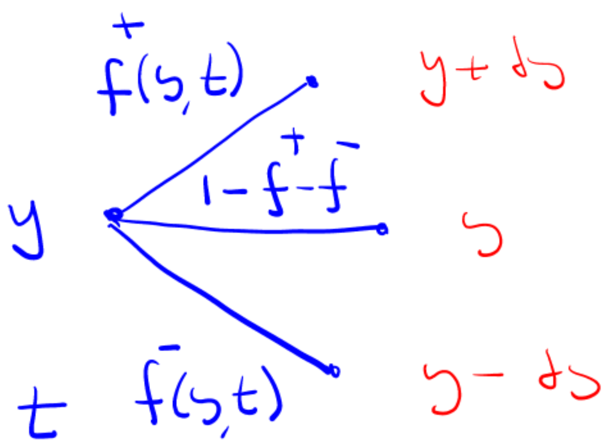
Cutting to the chase, the transition probability density function satisfies the partial differential equation

$A(y,t) \rightarrow A(y',t')$

$\sigma y \qquad \mu y$

$$\frac{\partial p}{\partial t'} = \frac{1}{2}\frac{\partial^2}{\partial y'^2}\left(B(y',t')^2 p\right) - \frac{\partial}{\partial y'}\left(A(y',t')p\right)$$

This is the **Fokker–Planck** or **forward Kolmogorov equation**.



$\underline{f^+} \qquad \underline{f^-}$

mean of trinomial RW = mean of S.D.E

var of trinomial RW = var. of S.D.E.

Example: The most important example to us is that of the distribution of equity prices in the future. If we have the random walk

$$dS = \overbrace{\mu S}^{A}\, dt + \overbrace{\sigma S}^{B}\, dX$$

(*) Transform to a 1D heat eq$^{\underline{n}}$

then the forward equation becomes

(*) Use sim reduction

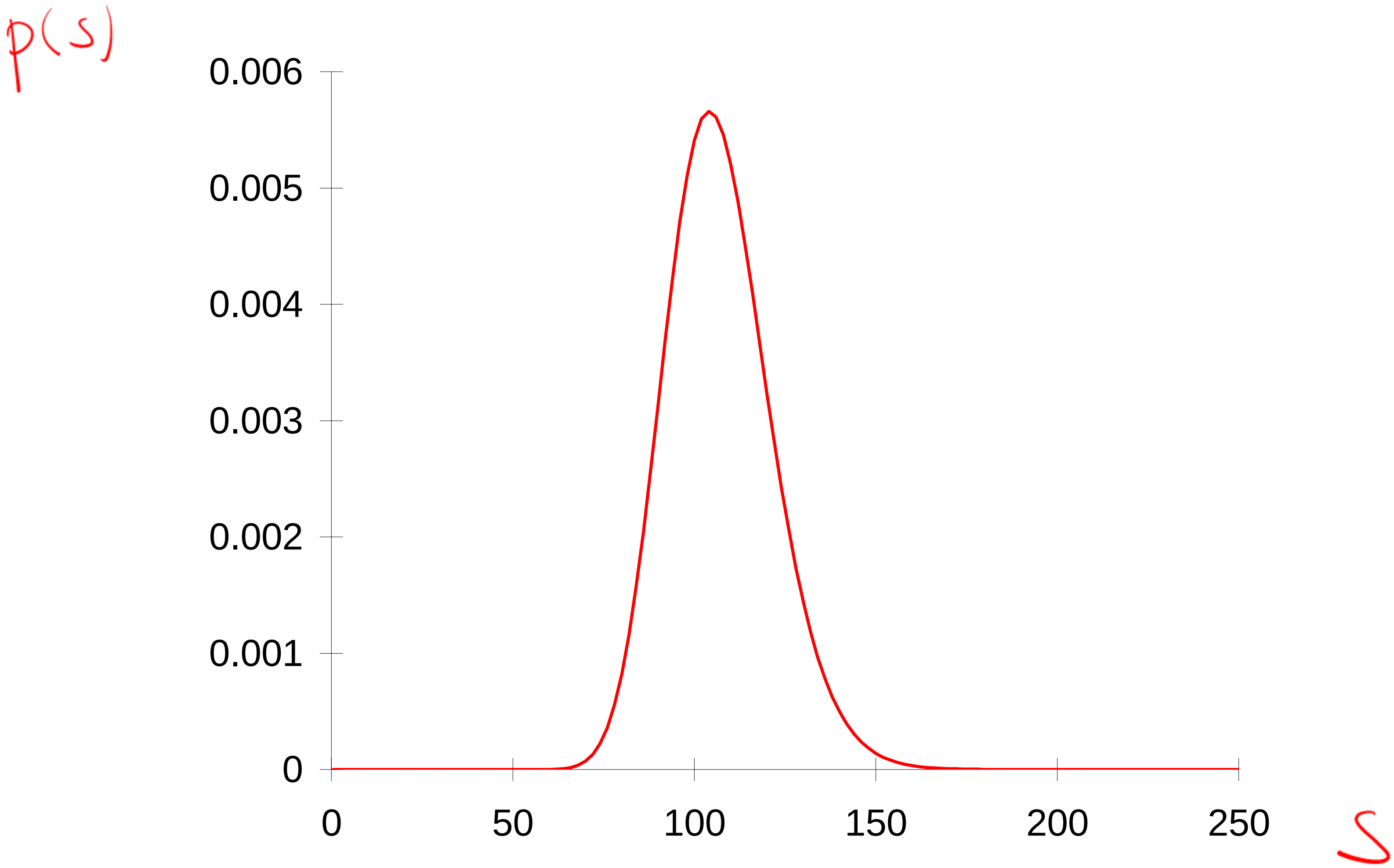
(*) unwind the steps

Mod 3 I will solve a more complicated version.

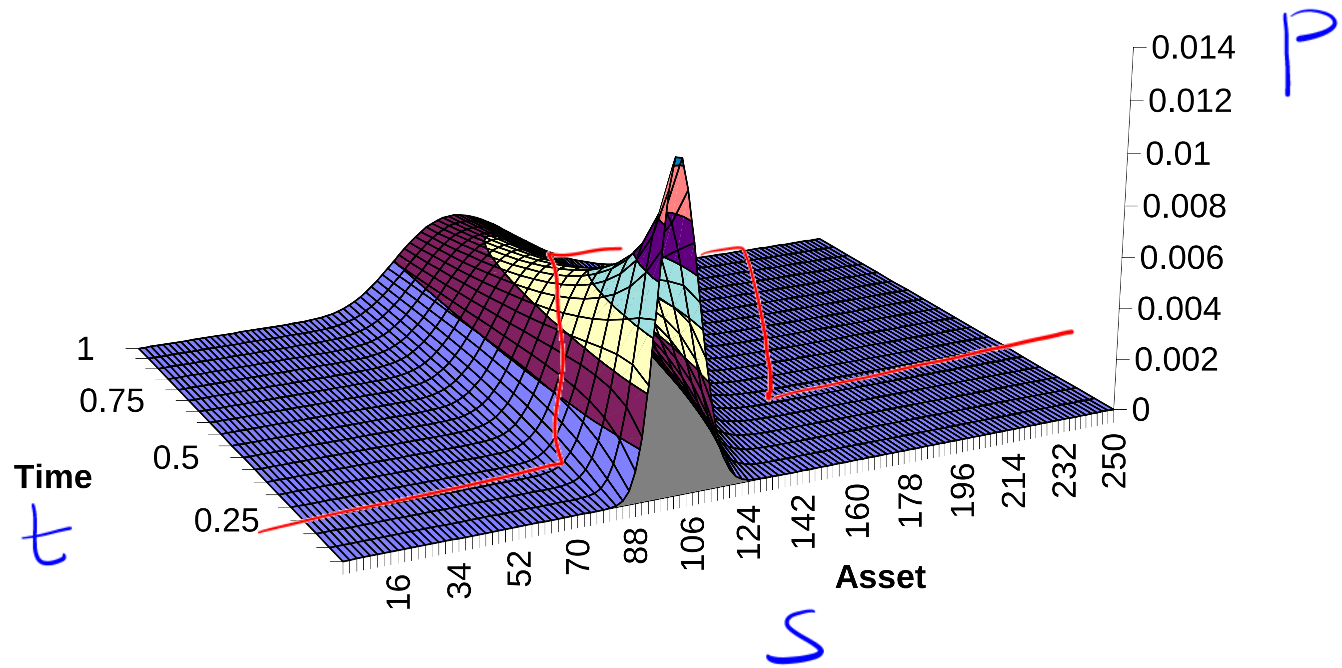
$$\boxed{\frac{\partial p}{\partial t'} = \frac{1}{2}\frac{\partial^2}{\partial S'^2}\left(\sigma^2 S'^2 p\right) - \frac{\partial}{\partial S'}\left(\mu S' p\right)}$$

The solution of this representing a stock price starting at $S' = S$ at $t' = t$ is

$$p(S,t;S',t') = \frac{1}{\sigma S' \sqrt{2\pi(t'-t)}} e^{-\left(\boxed{\log(S/S')} + (\mu - \frac{1}{2}\sigma^2)(t'-t)\right)^2 / 2\sigma^2(t'-t)}$$



The probability density function for the lognormal random walk, after a certain time.



The probability density function for the lognormal random walk evolving through time.

time-indep.

The steady-state distribution

$t' \to \infty$

Some random walks have a [steady-state distribution.]

That is, in the long run as $t' \to \infty$ the distribution $p(y, t; y', t')$ as a function of y' settles down to be independent of the starting state y and time t. Possible examples are stochastic differential equation models for interest rates, inflation, volatility.

r, σ

Some random walks have no such steady state even though they have a time-independent equation. For example the lognormal random walk either grows without bound or decays to zero.

$p(y', t')$ $\qquad$ $p(y')$

$\frac{\partial p}{\partial t'} \to 0$ $\qquad$ $\partial \to d$

If there is a steady-state distribution $p_\infty(y')$ then it satisfies the *ordinary* differential equation

steady state eq$^{\underline{n}}$ O.D.E

$$\frac{1}{2}\frac{d^2}{dy'^2}\left(B^2 p_\infty\right) - \frac{d}{dy'}\left(A p_\infty\right) = 0.$$

Example: The Vasicek model

$$dr = \gamma\left(\overset{A}{\overline{r}} - r\right)dt + \overset{B}{\sigma}\, dX.$$

The steady-state distribution $p_\infty(r')$ satisfies

$$\frac{1}{2}\sigma^2\frac{d^2 p_\infty}{dr'^2} - \gamma\frac{d}{dr'}\left((\overline{r} - r')p_\infty\right) = 0.$$

$\frac{1}{2}\sigma^2$

$$\frac{1}{2}\sigma^2\frac{d^2p}{dr^2} - \gamma\frac{d}{dr}(\bar{r}-r)p = 0$$

$$\frac{1}{2}\sigma^2\frac{d^2p}{dr^2} = -\gamma\frac{d}{dr}(r-\bar{r})p$$ Now integrate

$$\frac{1}{2}\sigma^2\frac{dp}{dr} = -\gamma(r-\bar{r})p + \text{Const.}$$ $r \to \infty \left\{ \begin{array}{l} p \to 0 \\ \frac{dp}{dr} \to 0 \end{array} \right. \Rightarrow \text{const} = 0$

$$\frac{1}{2}\sigma^2\frac{dp}{dr} = -\gamma(r-\bar{r})p$$

$$\frac{dp}{p} = -\frac{2\gamma}{\sigma^2}(r-\bar{r})dr$$ Now integrate $\int\frac{dp}{p} = -\frac{2\gamma}{\sigma^2}\int(r-\bar{r})dr$

$$\log p = -\frac{2\gamma}{\sigma^2}\int\frac{1}{2}\frac{d(r-\bar{r})^2}{dr}dr = -\frac{\gamma}{\sigma^2}(r-\bar{r})^2 + \text{Const.}$$

Take exp $\quad p(r) = Ae^{-\frac{\gamma}{\sigma^2}(r-\bar{r})^2}$ $\quad A$ is normalising $\therefore$

$$\int_{\mathbb{R}} p(r)\,dr = 1$$

$$A\int_{-\infty}^{\infty} e^{-\frac{\gamma}{\sigma^2}(r-\bar{r})^2} dr = 1$$ Integ. by subst^n $\quad x = \frac{\sqrt{\gamma}}{\sigma}(r-\bar{r}) \quad \frac{\sigma}{\sqrt{\gamma}}dx = dr$

$$\frac{\sigma}{\sqrt{\gamma}}A\int_{-\infty}^{\infty}e^{-x^2}dx = 1 \quad \therefore \quad \sigma\sqrt{\frac{\pi}{\gamma}}A = 1 \quad \therefore \quad A = \frac{1}{\sigma}\sqrt{\frac{\gamma}{\pi}}$$

Finally $\quad p_\infty(r') = \frac{1}{\sigma}\sqrt{\frac{\gamma}{\pi}}\exp\left[-\frac{\gamma}{\sigma^2}(r-\bar{r})^2\right]$

The solution is

$p_\infty(r')$ pdf at large times

in the long run

$$p_\infty = \frac{1}{\sigma}\sqrt{\frac{\gamma}{\pi}}\ e^{-\frac{\gamma(\bar{r}-r')^2}{\sigma^2}}.$$

In other words, the interest rate r is Normally distributed with mean $\bar{r}$ and standard deviation $\sigma/\sqrt{2\gamma}$.

$$-\frac{\gamma}{\sigma^2}(r'-\bar{r})^2 = -\frac{1}{2}\times\frac{2\gamma}{\sigma^2}(r-\bar{r})^2$$

$$= -\frac{1}{2}\,\frac{(r-\bar{r})^2}{\sigma^2/2\gamma}$$

mean

Variance

$$r' \sim N\left(\bar{r}, \frac{\sigma^2}{2\gamma}\right)$$

The backward equation

Now we come to the backward equation. This will be useful if we want to calculate probabilities of reaching a specified final state from various initial states.

The transition probability density function satisfies the **backward Kolmogorov equation**

$$\frac{\partial p}{\partial t} + \tfrac{1}{2} B(y,t)^2 \frac{\partial^2 p}{\partial y^2} + A(y,t) \frac{\partial p}{\partial y} = 0.$$

Simulating SDE

Simulating the lognormal random walk

The lognormal random walk model for assets can be written in continuous time as

$$dS = \mu S\,dt + \sigma S\,dX. \qquad \text{continuous time}$$

$$\delta S = \mu S\,\delta t + \sigma S\,\phi\sqrt{\delta t} \qquad \text{discrete time}$$

In discrete time this is

$$S_{i+1} - S_i = \mu S_i\,\delta t + \sigma S_i\,\phi\sqrt{\delta t}$$

$$\boxed{S_{i+1} - S_i = S_i\left(\mu\,\delta t + \sigma\phi\,\delta t^{1/2}\right).}$$

To generate representative simulations of possible asset paths we must obviously work in discrete time.

The random walk on a spreadsheet

The random walk can be written as a 'recipe' for generating S_{i+1} from S_i:

$$S_{i+1} = S_i \left(1 + \mu\, \delta t + \sigma \phi\, \delta t^{1/2} \right).$$

difference eq

next time step. known

We can easily simulate the model using a spreadsheet.

The method is called the **Euler** Maruyama **method**.

I.C S_0 = something

Start with an initial stock price, say, 100.

And a couple of parameters, $\mu = 0.1$ and $\sigma = 0.2$, say, that best represent the asset in question.

Decide on a (small) time step, $\delta t = 0.01$, say.

Now start picking random numbers! ϕ

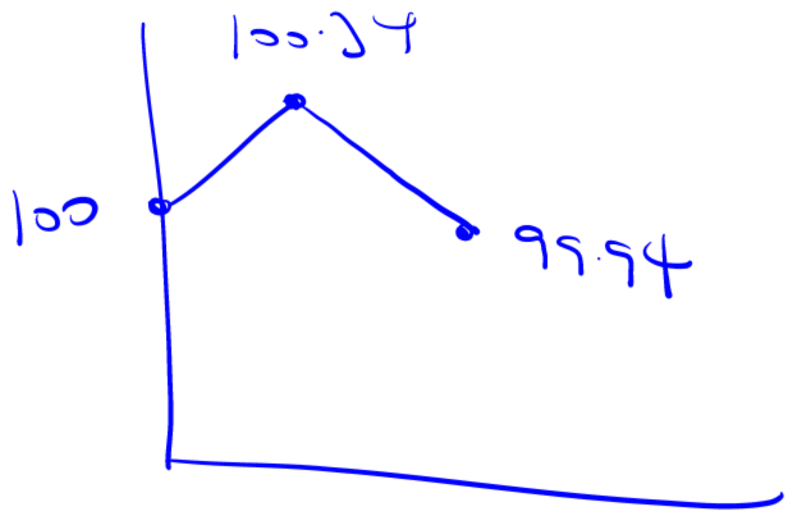
First time step: The random number is. . . 0.12. So

$$S_1 = S_{i+1} = \underset{S_0}{100}\,(1 + 0.1 \times 0.01 + 0.2 \times 0.1 \times 0.12) = 100.34.$$

Second time step: The random number is. . . -0.25. So

$$S_2 = S_{i+1} = \underset{S_1}{100.34}\,(1 + 0.1 \times 0.01 + 0.2 \times 0.1 \times (-0.25)) = 99.94.$$

And so on.



= NORMSINV(probability)

In this simulation there are several input parameters, which remain constant:

- a starting value for the asset
- a time step δt
- the drift rate μ
- the volatility σ
- the total number of time steps

Then, at each time step, we must choose a random number ϕ from a Normal distribution.

This can be done easily in Excel in several ways, we will see a couple now.

Slow but accurate

RAND() is $U \sim U(0,1)$

The Excel spreadsheet function `RAND()` gives a uniformly-distributed random variable. $\mathbb{E}[\text{RAND()}] = \frac{1}{2}$ $\mathbb{V}[\text{RAND()}] = \frac{1}{12}$

This can be used, together with the inverse cumulative distribution function `NORMSINV` to give a genuinely Normally distributed number:

$\phi \sim N(0,1)$

F(x) is a probability → $U(0,1)$

- $\left[\texttt{NORMSINV(RAND()).}\right]$

F^{-1} is inverse CDF

In Excel ⟶ $N(0,1)$

Why does this work?

Inverse Transform Method

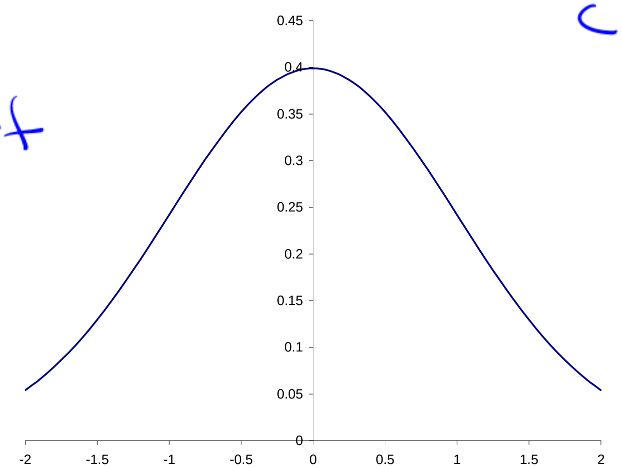
CDF: $F(x) = \int_{-\infty}^{\boxed{x}} p(x)\,dx$ $N(0,1)$

$= p(X < x)$

$U = F(x) \qquad x = F^{-1}(U)$

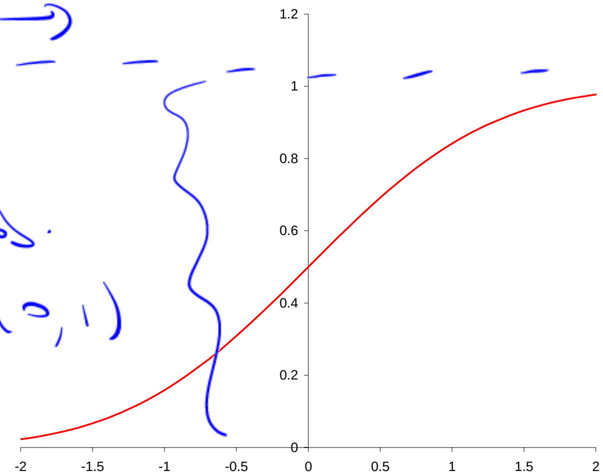
The pdf and cdf for the Normal distribution

pdf



CDF →

prob. U(0,1)



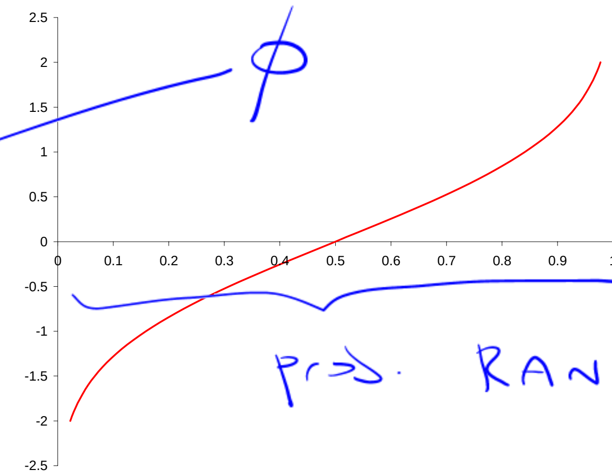
$\phi \sim N(0,1)$

The inverse cumulative distribution function

Inverse CDF

$N^{-1}(\text{RAND}())$

ϕ



prob. RAND()

$$p(x) = \begin{cases} 1 & 0 < x < 1 \\ 0 & \text{otherwise} \end{cases} \qquad \mathbb{E}(X) = \int_0^1 x\,dx = \frac{1}{2}$$

Fast but inaccurate

$$\mathbb{V}[X] = \int_0^1 x^2\,dx - \left(\frac{1}{2}\right)^2 = \frac{1}{12}$$

An approximation to a Normal variable that is fast in a spreadsheet, and quite accurate, is simply to add up twelve random variables drawn from a uniform distribution over zero to one, and subtract six:

1) Sum n lots of RAND() $\sum_{i=1}^{n} \text{RAND}()$

2) Examine the mean $\mathbb{E}\left[\sum_{i=1}^{n} \text{RAND}()\right]$

- $$\left(\sum_{i=1}^{12} \texttt{RAND()}\right) - 6.$$

$\sum_{i=1}^{n} \mathbb{E}[\text{RAND}()] = \sum_{i=1}^{n} \frac{1}{2} = \frac{n}{2} \neq 0 \quad \therefore$ subtract off $\frac{n}{2}$: $\sum_{i=1}^{n} \text{RAND}() - \frac{n}{2}$

3) Examine variance $\mathbb{V}\left(\sum_{i=1}^{n} \text{RAND}() - \frac{n}{2}\right) = \sum_{i=1}^{n} \mathbb{V}(\text{RAND}()) = \sum_{i=1}^{n} \frac{1}{12} = \frac{n}{12} \neq 1$

4) Consider a normalising const. $\mathbb{V}\left[\alpha\left(\sum_{i=1}^{n} \text{RAND}() - \frac{n}{2}\right)\right] = \alpha^2 \underbrace{\mathbb{V}[\ldots\ldots]}_{n/12} = 1$

5) $\alpha^2 \frac{n}{12} = 1 \Rightarrow \alpha = \sqrt{\frac{12}{n}}$ $\qquad \sqrt{\frac{12}{n}}\left[\sum_{i=1}^{n} \text{RAND}() - \frac{n}{2}\right]$

Why 12?

Any 'large' number will do. The larger the number, the closer the end result will be to being normal, but the slower it is.

Why subtract off 6?

The random number must have a mean of zero.

And the standard deviation?

Must be 1. $\sqrt{\frac{12}{n}}\left[\sum_{i=1}^{n} \mathrm{RAND}() - \frac{n}{2}\right] = \lim_{n\to\infty} \frac{\sum_{i=1}^{n} \mathrm{RAND}() - n \times \overset{\mu}{\frac{1}{2}}}{\underbrace{\sqrt{\frac{1}{12}}}_{\sigma}\sqrt{n}}$

Y_i iid R.V.

$Y_i \sim D$

(*) $\lim_{n\to\infty} \frac{\sum Y_i - n\mu}{\sigma\sqrt{n}}$ (*)

	A	B	C	D	E	F	G
1	**Asset**	**100**		**Time**	**Asset**		
2	**Drift**	**0.15**		0	100		
3	**Volatility**	**0.25**		0.01	96.10692		
4	**Timestep**	**0.01**		0.02	96.99647		
5				0.03	94.76352		
6				0.04	91.46698		
7				0.05	88.83325		
8				0.06	88.42727		
9				0.07	90.62882		
10				0.08	88.80545		
11							
12							
13				0.11	84.93865		

=D4+$B$4

=E7*(1+$B$2*$B$4+$B$3*SQRT($B$4)*(RAND()+RAND()+RAND()+RAND()
+RAND()+RAND()+RAND()+RAND()+RAND()+RAND()+RAND()+RAND()-6))


Starting point of
Monte Carlo
180
160
140
120
100
80
60
40
20
0
0
0.2
0.4
0.6
0.8
1
1.2

Simulating other random walks

This method is not restricted to the lognormal random walk.

Later in the course we will be modeling interest rates as stochastic differential equations.

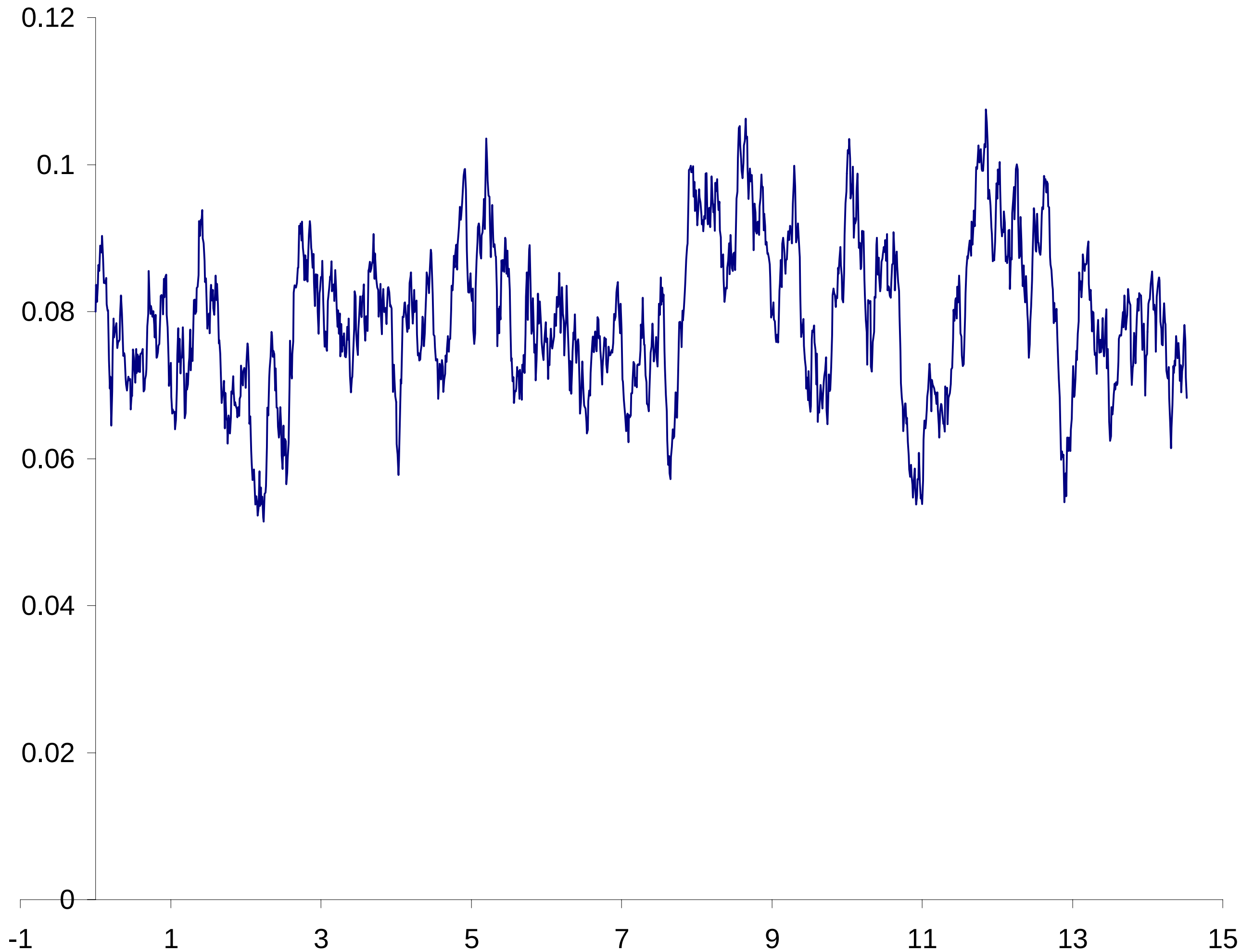
The following is a stochastic differential equation model for an interest rate, that goes by the name of an **Ornstein-Uhlenbeck process** (an example of a mean-reverting random walk), or when used in an interest rate context the **Vasicek model**:

$$dr = \gamma\,(\overline{r} - r)\,dt + \sigma dX.$$

$r_{i+1} - r_i = -\gamma(r - \overline{r})\,\delta t + \sigma\,\phi\,\sqrt{\delta t}$

In discrete time we can approximate this by

$$r_{i+1} = r_i + \gamma\,(\overline{r} - r_i)\,dt + \sigma\phi\,\delta t^{1/2}.$$


0.12
0.1
0.08
0.06
0.04
0.02
0
-1
1
3
5
7
9
11
13
15

Producing correlated random numbers

We will often want to simulate paths of correlated random walks.

We may want to examine the statistical properties of a portfolio of stocks, or value a convertible bond under the assumption of random asset price and random interest rates.

$V(t, S_1, S_2)$

$dS_i = \mu_i S_i \, dt + \sigma_i S_i \, dX_i \qquad i = 1, 2$

$t \to t + dt, \quad S_i \to S_i + dS_i$

Now 2D TSE

$V(t+dt, S_1 + dS_1, S_2 + dS_2) = V(t, S_1, S_2) + \frac{\partial V}{\partial t} dt + \frac{\partial V}{\partial S_1} dS_1 + \frac{\partial V}{\partial S_2} dS_2 + \frac{1}{2} \frac{\partial^2 V}{\partial S_1^2} dS_1^2 + \frac{1}{2} \frac{\partial^2 V}{\partial S_2^2} dS_2^2 + \frac{\partial^2 V}{\partial S_1 \partial S_2} dS_1 dS_2$

$\mathbb{E}[\phi_1 \phi_2] = \rho$

$\therefore \mathbb{E}(dX_1 dX_2) = \mathbb{E}[\phi_1 \sqrt{dt} \, \phi_2 \sqrt{dt}]$

$= dt \, \mathbb{E}[\phi_1 \phi_2]$

$= \rho \, dt$

$dS_i^2 = \sigma_i^2 S_i^2 \, dt$

$dS_1 dS_2 = \rho \sigma_1 \sigma_2 S_1 S_2 \, dt$

Itô V

Rearranging & subst. in dS_i, dS_i^2, $dS_1 dS_2$ and grouping

$$dV = \left(\frac{\partial V}{\partial t} + \mu_1 S_1 \frac{\partial V}{\partial S_1} + \mu_2 S_2 \frac{\partial V}{\partial S_2} + \frac{1}{2}\sigma_1^2 S_1^2 \frac{\partial^2 V}{\partial S_1^2} + \frac{1}{2}\sigma_2^2 S_2^2 \frac{\partial^2 V}{\partial S_2^2} + \rho \sigma_1 \sigma_2 S_1 S_2 \frac{\partial^2 V}{\partial S_1 \partial S_2} \right) dt$$

$$+ \sigma_1 S_1 \frac{\partial V}{\partial S_1} dX_1 + \sigma_2 S_2 \frac{\partial V}{\partial S_2} dX_2$$

Example:

Assets S_1 and S_2 both follow lognormal random walks with correlation ρ.

In continuous time we write

$$dS_1 = \mu_1 S_1 \, dt + \sigma_1 S_1 \, dX_1,$$

$$dS_2 = \mu_2 S_2 \, dt + \sigma_2 S_2 \, dX_2,$$

with

$$E[dX_1 \, dX_2] = \rho \, dt.$$

In discrete time these become

$$S_{1_{i+1}} - S_{1_i} = S_{1_i} \left(\mu_1 \, \delta t + \sigma_1 \phi_1 \, \delta t^{1/2} \right)$$

$\to \varepsilon_1$

and

$$S_{2_{i+1}} - S_{2_i} = S_{2_i} \left(\mu_2 \, \delta t + \sigma_2 \phi_2 \, \delta t^{1/2} \right)$$

$\to \rho \varepsilon_1 + \sqrt{1-\rho^2}\, \varepsilon_2$

with

$$E[\phi_1 \, \phi_2] = \rho.$$

Cholesky decomp. for multiple stocks.

Q: How can we choose a ϕ_1 and a ϕ_2 which are both Normally distributed, both have mean zero and standard deviation of one, and with a correlation of ρ between them?

A: This can be done in two steps, first pick two *uncorrelated* Normally distributed random variables, and then combine them.

Uncorrelated pair: $\varepsilon_1, \varepsilon_2 \sim N(0,1)$ with $\mathbb{E}[\varepsilon_1 \varepsilon_2] = 0$

$i = 1, 2$ $\quad \mathbb{E}[\varepsilon_i] = 0 \quad \mathbb{E}(\varepsilon_i^2) = 1$

Produce $\phi_i \sim N(0,1)$ s.t. $\mathbb{E}[\phi_i] = 0$; $\mathbb{E}[\phi_i^2] = 1$

$\mathbb{E}[\phi_1 \phi_2] = \rho$

Step 1: Choose uncorrelated ϵ_1 and ϵ_2, both Normally distributed with zero means and standard deviations of one.

Step 2: Convert these independent Normal numbers into correlated Normals by taking a linear combination.

Proposition:

$$\boxed{\phi_1 = \epsilon_1}$$

$$\boxed{\phi_2 = \rho\,\epsilon_1 + \sqrt{1-\rho^2}\,\epsilon_2.}$$

Check:

$$E[\phi_1^2] = 1,$$

$$E\left[\phi_2^2\right] = E\left[\rho^2\epsilon_1^2 + 2\rho\sqrt{1-\rho^2}\epsilon_1\epsilon_2 + (1-\rho^2)\epsilon_2^2\right]$$

$$= \rho^2 + 0 + (1-\rho^2) = 1,$$

and

$$E\left[\phi_1\phi_2\right] = E\left[\rho\epsilon_1^2 + \sqrt{1-\rho^2}\epsilon_1\epsilon_2\right] = \rho.$$

And Normality?

Let $\phi_1 = \varepsilon_1$; $\phi_2 = \alpha\varepsilon_1 + \beta\varepsilon_2$ for some pair of constants $\alpha, \beta \in \mathbb{R}$ to be determined. So we have formed a linear comb^n of $\varepsilon_1, \varepsilon_2$

① $\mathbb{E}[\phi_1\phi_2] = \rho = \mathbb{E}[\varepsilon_1(\alpha\varepsilon_1 + \beta\varepsilon_2)]$

$= \alpha\mathbb{E}[\underbrace{\varepsilon_1^2}_{=1}] + \beta\mathbb{E}[\underbrace{\varepsilon_1\varepsilon_2}_{=0}] = \alpha$ i.e. $\alpha = \rho$

② $\mathbb{E}[\phi_2^2] = 1 = \mathbb{E}[(\alpha\varepsilon_1 + \beta\varepsilon_2)^2] = \mathbb{E}[\alpha^2\varepsilon_1^2 + 2\alpha\beta\varepsilon_1\varepsilon_2 + \beta^2\varepsilon_2^2]$

$= \underbrace{\alpha^2}_{=\rho^2}\mathbb{E}[\underbrace{\varepsilon_1^2}_{=1}] + 2\alpha\beta\mathbb{E}[\underbrace{\varepsilon_1\varepsilon_2}_{=0}] + \beta^2\mathbb{E}[\underbrace{\varepsilon_2^2}_{=1}] = 1$

$\therefore \rho^2 + \beta^2 = 1 \longrightarrow \beta = \sqrt{1-\rho^2}$

$\phi_1 = \varepsilon_1 \qquad \phi_2 = \rho\varepsilon_1 + \sqrt{1-\rho^2}\,\varepsilon_2$

Weighted sums of Normally distributed numbers are themselves Normally distributed!

If $X_i \sim N(\mu_i, \sigma_i^2)$ for $i = 1, \ldots, n$ then

generalisation of Itô $\underline{\text{IV}}$

Itô $\underline{\text{VI}}$

$$\sum_{i=1}^{n} \underline{\underline{w_i}} X_i \sim N\left(\sum_{i=1}^{n} w_i \mu_i, \sum_{i=1}^{n} w_i^2 \sigma_i^2\right).$$

new mean

Variance.

Consider a general SDE

$dG = A(G,t)\,dt + B(G,t)\,dX$

Consider $F = F(t, G)$. Then the SDE for F or differential

$$dF = \left(\frac{\partial F}{\partial t} + A(G,t)\frac{\partial F}{\partial G} + \frac{1}{2}B^2(G,t)\frac{\partial^2 F}{\partial G^2}\right)dt + B(G,t)\frac{\partial F}{\partial G}\,dX$$

Vasicek

$dr = -\gamma(r-\bar{r})dt + \sigma dX$

$du = -\gamma u \, dt + \sigma dX$

Summary

Please take away the following important ideas

- With the right tool (Itô's lemma) you can examine functions of stochastic variables
- Partial differential equations can be used for finding probability density functions for arbitrary random walks
- Simulating random walks can be very easy indeed