PDE for Finance Notes – Section 4

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Reminders: No lecture March 10 [I'm out of town], March 17 [spring break], and March 31 [Passover].

Stochastic differential equations. You know, by now, that it's important to understand something about stochastic differential equations and the Ito calculus. We'll fill in the basics this week. Source material: Neftci does a good job of covering the main ideas, though he gives very few real proofs. (Chapter 8 of Neftci, concerning the relevance of diffusion processes to finance, covers important material rarely discussed in texts at this level.) Baxter & Rennie is much briefer, and more organized around martingales, but well worth reading. Arnold's book goes deeper, giving a fully rigorous yet very readable treatment. (By sticking to the continuous-time setting he keeps the proofs quite elementary; alas, his book is out of print. No doubt there are comparable treatments in print; please tell me if you know of one.)

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Brownian motion. In passing from deterministic control to stochastic control, we inserted "noise" on the right hand side of our state equation in a very specific way. We focus here on explaining what we've done; see Neftci Chapter 8 (or Merton, whose work Neftci is explaining) for discussion of why this type of noise is natural and what it ignores. (Briefly: it ignores the possibility of sudden large changes in the market due to rare but randomly occurring events.)

The basic building block is the *Brownian motion* process. A one-dimensional Brownian motion $w(t)$ is a stochastic process with the following properties:

- For $s < t$ the increment $w(t) - w(s)$ is Gaussian with mean zero and variance $E[(w(t) - w(s))^2] = t - s$. Moreover the increments associated with disjoint intervals are independent.
- Its sample paths are continuous, i.e. the function $t \mapsto w(t)$ is (almost surely) continuous.
- It starts at 0, in other words $w(0) = 0$.

This process is unique (up to a suitable notion of equivalence). One "construction" of Brownian motion obtains it as the limit of discrete-time random walks; students of finance who have considered the continuous-time limit of a binomial lattice have seen something very similar.

The sample paths of Brownian motion, though continuous, are non-differentiable. Here is an argument that proves a little less but captures the main point. Given any interval

(a, b), divide it into subintervals by $a = t_1 < t_2 \ldots < t_N = b$. Clearly

$$\sum_{i=1}^{N-1} |w(t_{i+1}) - w(t_i)|^2 \leq \max_i |w(t_{i+1}) - w(t_i)| \cdot \sum_{i=1}^{N-1} |w(t_{i+1}) - w(t_i)|.$$

As $N \to \infty$, the left hand side has expected value $b - a$ (independent of N). The term in brackets on the right tends to zero (almost surely) by continuity. So the second term on the right must tend to infinity (almost surely). Thus the sample paths of w have unbounded total variation on any interval. One can show, in fact, that $|w(t) - w(s)|$ is of order $\sqrt{|t-s| \log\log 1/|t-s|}$ as $|t - s| \to 0$.

It's easy to construct, for any constant $\sigma > 0$, a process whose increments are mean-value-zero, independent, and variance $\sigma^2|t - s|$: just use $\sigma w(t)$. The vector-valued version of this construction is more interesting. We say $w(t) = (w_1, \ldots, w_n)$ is an R^n-valued Brownian motion if its components are *independent* scalar Brownian motions. Thus $E[(w(t) - w(s))_i(w(t) - w(s))_j]$ equals 0 if $i \neq j$ and $|t - s|$ if $i = j$. Given such w, we can obtain a process with correlated increments by taking linear combinations, i.e. by considering $z(t) = Aw(t)$ where A is a (constant, deterministic) matrix. Its covariance is $E[(z(t) - z(s))_i(z(t) - z(s))_j] = (AA^T)_{ij}$. If the desired variance σ is a function of time (deterministic, or random but nonanticipating) – or if the desired covariance matrix A is a function of time (deterministic, or random but nonanticipating) – the construction requires solving a stochastic integral (to be discussed below).

Filtrations and conditional expectations. It was natural, in discussing stochastic control, to insist that the control be "non-anticipating." Let's discuss informally what this means. This discussion is also essential for understanding the term "martingale."

The meaningful *statements* about a Brownian motion (or any stochastic process, for that matter) are statements about its values at various times. Here is an example of a statement: "$-3 < w(.5) < -2$ and $w(1.4) > 3$". Here is another: "$\max_{0 \leq t \leq 1} |w(t)| < 3$". A statement is either true or false for a given sample path; it has a certain probability of being true. We denote by $\mathcal{F}_t$ the set of all statements about w that involve only the values of w up to time t. Obviously $\mathcal{F}_s \subset \mathcal{F}_t$ if $s < t$. These $\mathcal{F}_t$'s are called the *filtration* associated with w. A non-anticipating control $\alpha(t)$ is one whose value at time t is determined by time-t information, i.e. by statements in $\mathcal{F}_t$.

We can also consider *functions* of a Brownian path. When we take the expected value of some expression involving Brownian motion we are doing this. Here are some examples of functions: $f[w] = w(.5) - w(1)^2$; $g[w] = \max_{0 \leq t \leq 1} |w(t)|$. Notice that both these examples are determined entirely by time-1 information (jargon: f and g are $\mathcal{F}_1$-measureable). It's often important to discuss the expected value of some uncertain quantity given the information available at time t. For example, we may wish to know the expected value of $\max_{0 \leq t \leq 1} |w(t)|$ given knowledge of w only up to time .5. This is a *conditional expectation*, sometimes written $E_t[g] = E[g|\mathcal{F}_t]$ (in this case t would be .5). We shall define it in a moment via orthogonal projection. This definition is easy but not so intuitive. After giving it, we'll explain why the definition captures the desired intuition.

Let V be the vector space of all functions $g[w]$, endowed with the inner product $\langle f, g\rangle = E[fg]$. It has subspaces

$$V_t = \text{space of functions whose values are determined by time-t information.}$$

The conditional expectation is defined by orthogonal projection:

$$E_t[g] = \text{orthogonal projection of } g \text{ onto } V_t.$$

In other words: $E_t[g]$ is the unique function in V_t such that

$$E[E_t[g]f] = E[gf] \text{ for all } f \in V_t.$$

All the key properties of conditional expectation follow easily from this definition. Example: "tower property"

$$s < t \Longrightarrow E_s[E_t[f]] = E_s[f]$$

since projecting first to V_t then to $V_s \subset V_t$ is the same as projecting directly to V_s. Another fact: E_0 is the ordinary expectation operator E. Indeed, V_0 is one-dimensional (its elements are functions of a single point $w(0) = 0$, i.e. it consists of those functions that aren't random at all). From the definition of orthogonal projection we have

$$E_0[g] \in V_0 \text{ and } E[E_0[g]f] = E[gf] \text{ for all } f \in V_0.$$

But when f is in V_0 it is deterministic, so $E[gf] = fE[g]$. Similarly $E[E_0[g]f] = fE_0[g]$. Thus $E_0[g] = E[g]$.

To see that this matches our intuition, i.e. that E_t is properly interpreted as "the expected value based on future randomness, given all information available at time t", let's consider the simplest possible discrete-time analogue. Consider a 2-stage coin-flipping process which obtains at each stage heads (probability p) or tails (probability $q = 1 - p$). We visualize it using a nonrecombining binomial) tree, numbering the states as shown.

The space V_2 is 4-dimensional; its functions are determined by the full history, i.e. they can be viewed as functions of the time-2 nodes (numbered 3,4,5,6 in the figure). The space V_1 is two-dimensional; its functions are determined by just the first flip. Its elements can be viewed as functions of the time-1 nodes (numbered 1,2 in the figure); or, equivalently, they are elements of V_2 such that $f(3) = f(4)$ and $f(5) = f(6)$. The "expected value of f given time-1 information" intuitively has values

$$\tilde{E}_1[f](1) = pf(4) + qf(3), \quad \tilde{E}_1[f](2) = pf(6) + qf(5).$$

To check that this agrees with our prior definition, we must verify that when $g(5) = g(6)$ and $g(3) = g(4)$,

$$\langle \tilde{E}_1[f], g\rangle = \langle f, g\rangle,$$

which amounts to

$$[pf(6)+qf(5)]g(2)+[pf(4)+qf(3)]g(1) = p^2 f(6)g(6)+pqf(5)g(5)+pqf(4)g(4)+q^2 f(3)g(3)$$

with the convention $g(2) = g(5) = g(6)$, $g(1) = g(3) = g(4)$. It's true.

A stochastic process $x(t)$ is "adapted" to $\mathcal{F}_t$ if its values up to and including time t are determined by the statements in $\mathcal{F}_t$. (The stochastic processes obtained from Brownian motion by solving stochastic differential equations automatically have this property.) Such a stochastic process is called a *martingale* if $E_s[x(t)] = x(s)$ for $s < t$. An equivalent statement: $E_s[x(t) - x(s)] = 0$ for $s < t$. Intuitively: given current information, there's no point betting on the future of the process; it's equally likely to go up or down.

Stochastic integrals. We have been writing stochastic differential equations of the type

$$dy = f(y, \alpha)ds + g(y, \alpha)dw, \quad y(t) = x.$$

where $\alpha(s)$ is some control. This is really shorthand for the associated integral equation

$$y(b) = x + \int_t^b f(y(s), \alpha(s))ds + \int_t^b g(y(s), \alpha(s))dw. \tag{1}$$

To understand what this means we must understand the two integrals on the right.

The first one is relatively easy. If y and α are continuous in s then

$$\int_t^b f(y(s), \alpha(s))ds$$

makes perfect sense as a Riemann integral. (All the processes we'll consider do have y continuous in s, so this hypothesis is OK. The condition that α be continuous in s is less natural – but it holds for feedback controls, i.e. controls in which $\alpha(s)$ is specified as a deterministic function of $y(s)$ and s, provided that the feedback law is continuous. For more general non-anticipating $\alpha(s)$ the definition of this integral is more subtle – the successful treatment is similar to the one of $\int g dw$ explained below.)

The second "stochastic" integral is more subtle. The proper interpretation is this: for any random but nonanticipating integrand $g(s)$,

$$\int_a^b g dw = \lim_{\Delta t \to 0} \sum_{i=1}^{N-1} g(t_i)[w(t_{i+1}) - w(t_i)] \tag{2}$$

with the notation $a = t_1 < t_2 < \ldots < t_N = b$ and $\Delta t = \max_i |t_{i+1} - t_i|$. (We may, but we don't have to, choose the t_i's equally spaced.) The important point is that we evaluate g at the beginning of the increment. We'll show presently that making the opposite choice

$$\sum_{i=1}^{N-1} g(t_{i+1})[w(t_{i+1}) - w(t_i)]$$

would give a *different* answer. Thus the stochastic integral is not a Riemann integral, but something different.

A key property of the stochastic integral is immediately clear: since g is nonanticipating,

$$E_a \int_a^b g dw = 0 \tag{3}$$

because each term in the sum has

$$E_{t_i}\left[g(t_i)\left(w(t_{i+1}) - w(t_i)\right)\right] = 0$$

(since $w(t_{i+1}) - w(t_i)$ is independent of all time-t_i information, hence independent of $g(t_i)$). Therefore by the tower property $E_a\left[g(t_i)[w(t_{i+1}) - w(t_i)]\right] = 0$, and summing gives (3). We used this property repeatedly in our stochastic control discussion. Remembering the definition of a martingale, (3) says the solution of a stochastic differential equation of the form $dy = gdw$ (with no dt term on the right) is a martingale.

What kind of limit do we mean in (3)? The mean-square kind. If a sequence of functions $\phi_n(x)$ is defined for $x \in (0,1)$, one says $\phi = \lim_{n\to\infty} \phi_n$ in the mean-square sense if $\int_0^1 |\phi_n(x) - \phi(x)|^2\, dx \to 0$. The situation for the stochastic integral is similar, except the integral is replaced by expectation:

$$E\left[\left(\int_a^b g dw - \sum_{i=1}^{N-1} g(t_i)[w(t_{i+1}) - w(t_i)]\right)^2\right] \to 0.$$

We won't prove the existence of this limit in any generality (you'll find this in Arnold). Instead let's do a simple example – which actually displays many of the essential ideas of the general case. Specifically: let's show that

$$\int_a^b w\, dw = \tfrac{1}{2}w^2(b) - \tfrac{1}{2}w^2(a) - (b-a)/2.$$

Notice that this is *different* from the formula you might have expected based on elementary calculus ($wdw \neq \frac{1}{2}w^2$). The calculus rule is based on Chain Rule, whereas in the stochastic setting we must use Ito's formula – as we'll explain presently. If I skip too many details, you'll find a slower treatment in Neftci pp. 179-184.

According to the definition, $\int_a^b w\, dw$ is the limit of

$$\sum_{i=1}^{N-1} w(t_i)(w(t_{i+1}) - w(t_i)).$$

A bit of manipulation shows that this is exactly equal to

$$\tfrac{1}{2}w^2(b) - \tfrac{1}{2}w^2(a) - \tfrac{1}{2}\sum_{i=1}^{N-1}(w(t_{i+1}) - w(t_i))^2,$$

so our assertion is equivalent to the statement

$$\lim_{\Delta t \to 0} \sum_{i=1}^{N-1}(w(t_{i+1}) - w(t_i))^2 = b - a. \tag{4}$$

In the Ito calculus we sometimes write "$dw \times dw = dt$;" when we do, it's basically shorthand for (4). Notice that each term $(w(t_{i+1}) - w(t_i))^2$ is random (the square of a Gaussian random variable with mean 0 and variance $t_{i+1} - t_i$). But in the limit the sum is deterministic, by a sort of law of large numbers. If you believe it's deterministic then the value is clear, since $S_N = \sum_{i=1}^{N-1}(w(t_{i+1}) - w(t_i))^2$ has expected value $b - a$ for any N.

To prove (4) in the mean-square sense, we must show that

$$E\left[(S_N - (b-a))^2\right] \to 0$$

as $N \to \infty$. Expanding the square, this is equivalent to

$$E\left[S_N^2 - (b-a)^2\right] \to 0.$$

Now,

$$\begin{aligned} E\left[S_N^2\right] &= E\left[\sum_{i=1}^{N-1}(w(t_{i+1}) - w(t_i))^2 \sum_{j=1}^{N-1}(w(t_{j+1}) - w(t_j))^2\right] \\ &= E\left[\sum_{i,j=1}^{N-1}(w(t_{i+1}) - w(t_i))^2(w(t_{j+1} - w(t_j))^2\right]. \end{aligned}$$

The last term is easy to evaluate, using the properties of Brownian motion:

$$E\left[(w(t_{i+1}) - w(t_i))^2(w(t_{j+1}) - w(t_j))^2\right] = (t_{i+1} - t_i)(t_{j+1} - t_j)$$

when $i \neq j$, and

$$E\left[(w(t_{i+1}) - w(t_i))^4\right] = 3(t_{i+1} - t_i)^2.$$

(The latter follows from the fact that $w(t_{i+1}) - w(t_i)$ is Gaussian with mean 0 and variance $t_{i+1} - t_i$.) We deduce after some manipulation that

$$\begin{aligned} E\left[S_N^2 - (b-a)^2\right] &= 2\sum_{i=1}^{N-1}(t_{i+1} - t_i)^2 \\ &\leq 2(\max_i |t_{i+1} - t_i|)(b-a) \end{aligned}$$

which does indeed tend to 0 as $\max_i |t_{i+1} - t_i| \to 0$.

We now confirm a statement made earlier, that the stochastic integral just defined is different from

$$\lim_{\Delta t\to 0}\sum_{i=1}^{N-1} w(t_{i+1})[w(t_{i+1})-w(t_i)]. \tag{5}$$

Indeed, we have

$$\sum_{i=1}^{N-1} w(t_{i+1})[w(t_{i+1})-w(t_i)] - \sum_{i=1}^{N-1} w(t_i)[w(t_{i+1})-w(t_i)] = \sum_{i=1}^{N-1}[w(t_{i+1})-w(t_i)]^2$$

which tends in the limit (we proved above) to $b-a$. Thus the alternative (wrong) definition (5) equals $\frac{1}{2}w^2(b)-\frac{1}{2}w^2(a)+\frac{1}{2}(b-a)$. If we had used this definition, the stochastic integral would not have been a martingale.

Stochastic differential equations. We didn't prove the existence of solutions to ordinary differential equations early in the course, and we won't prove the existence of solutions to stochastic ones now. But it's important to say that solutions do exist, under reasonable conditions on the form of the equation. Moreover the resulting stochastic process $y(s)$ has continuous sample paths (y is a continuous function of s).

The Ito calculus. If $y(s)$ solves a stochastic differential equation, it's natural to seek a stochastic differential equation for $\phi(s, y(s))$ where ϕ is any smooth function. If y solved an ordinary differential equation we would obtain the answer using chain rule. When y solves a stochastic differential equation we must use the Ito calculus instead. It replaces the chain rule.

Let's first review the situation for ordinary differential equations. Suppose $dy/dt = f(y,t)$ with initial condition $y(0) = x$. It is a convenient mnemonic to write the equation in the form

$$dy = f(y,t)dt.$$

This reminds us that the solution is well approximated by its finite difference approximation $y(t_{i+1}) - y(t_i) = f(y(t_i), t_i)(t_{i+1} - t_i)$. Let us write

$$\Delta y = f(y,t)\Delta t$$

as an abbreviation for the finite difference approximation. (In this section Δ is always an increment, never the Laplacian.) The ODE satisfied by $z(t) = \phi(y(t))$ is, by chain rule, $dz/dt = \phi'(y(t))dy/dt$. The mnemonic for this is

$$d\phi = \phi' dy.$$

It reminds us of the proof, which boils down to the fact that (by Taylor expansion)

$$\Delta\phi = \phi'(y)\Delta y + \text{error of order } |\Delta y|^2.$$

In the limit as the time step tends to 0 we can ignore the error term, because $|\Delta y|^2 \le C|\Delta t|^2$ and the sum of these terms is of order $\max_i |t_{i+1} - t_i|$.

OK, now the stochastic case. Suppose y solves

$$dy = f(y,t)dt + g(y,t)dw$$

where f and g are possibly random but non-anticipating (for example there might be a choice of control hiding inside). Ito's lemma, in its simplest form, says that if ϕ is smooth then $z = \phi(y)$ satisfies the stochastic differential equation

$$dz = \phi'(y)dy + \tfrac{1}{2}\phi''(y)g^2 dt = \phi'(y)g dw + \left[\phi'(y)f + \tfrac{1}{2}\phi''(y)g^2\right] dt.$$

Here is a heuristic justification: carrying the Taylor expansion of $\phi(y)$ to second order gives

$$\begin{aligned} \Delta\phi &= \phi(y(t_{i+1})) - \phi(y(t_i)) \\ &= \phi'(y(t_i))[y(t_{i+1}) - y(t_i)] + \tfrac{1}{2}\phi''(y(t_i))[y(t_{i+1}) - y(t_i)]^2 + \text{error of order } |\Delta y|^3. \end{aligned}$$

So far we haven't cheated. It's tempting to write the last expression as

$$\phi'(y)(g\Delta w + f\Delta t) + \tfrac{1}{2}\phi''(y)g^2(\Delta w)^2 + \text{errors of order } |\Delta y|^3 + |\Delta w||\Delta t| + |\Delta t|^2$$

where $\phi'(y) = \phi'(y(t_i))$, $g = g(y(t_i), t_i)$, $\Delta w = w(t_{i+1}) - w(t_i)$, etc. (In other words: it's tempting to substitute $\Delta y = f\Delta t + g\Delta w$.) That's not quite right: in truth $\Delta y = y(t_{i+1}) - y(t_i)$ is given by a stochastic integral from t_i to t_{i+1}, and our cheat pretends that the integrand is constant over this time interval. But fixing this cheat is a technicality – much as it is in the deterministic setting – so let's proceed as if the last formula were accurate. I claim that the error terms are negligible in the limit $\Delta t \to 0$. This is easy to see for the $|\Delta t|^2$ terms, since

$$\sum_i (t_{i+1} - t_i)^2 \le \max_i |t_{i+1} - t_i| \sum_i |t_{i+1} - t_i|$$

A similar argument works for the $|\Delta t||\Delta w|$ terms. The $|\Delta y|^3$ term is a bit more subtle; we'll return to it presently. Accepting this, we have

$$\Delta\phi \approx \phi'(y)(g\Delta w + f\Delta t) + \tfrac{1}{2}\phi''(y)g^2(\Delta w)^2.$$

Now comes the essence of the matter: we can replace $(\Delta w)^2$ by Δt. A more careful statement of this assertion: if $a = t_1 < t_2 < \ldots < t_N = b$ then

$$\lim_{\Delta t \to 0} \sum_{i=1}^{N-1} h(t_i)[w(t_{i+1}) - w(t_i)]^2 = \int_a^b h(t)dt \tag{6}$$

if h is non-anticipating. Notice: we don't claim that $h(\Delta w)^2$ is literally equal to $h\Delta t$ for any single time interval, no matter how small. Rather, we claim that once the contributions of *many* time intervals are combined, the fluctuations of w cancel out and the result is an integral dt. We proved (6) in the case $h = 1$; the general case is more technical, of course, but the ideas are similar.

We skipped over why the $|\Delta y|^3$ error terms can be ignored. The reason is that they're controlled by

$$\max_i |y(t_{i+1}) - y(t_i)| \sum_i |y(t_{i+1}) - y(t_i)|^2.$$

The argument above shows that the sum is finite. Since $y(t)$ is continuous, $\max_i |y(t_{i+1}) - y(t_i)|$ tends to zero. So this term is negligible.

The same logic applies more generally, when w is a vector-valued Brownian motion, y is vector-valued, and ϕ is a function of time as well as y. The only new element (aside from some matrix algebra) is that the quadratic terms in Δw are now of the form

$$\Delta w_j \Delta w_k = [w_j(t_{i+1}) - w_j(t_i)][w_k(t_{i+1}) - w_k(t_i)].$$

An argument very much like the proof of (4) shows that

$$\lim_{\Delta t \to 0} \sum_{i=1}^{N-1} [w_j(t_{i+1}) - w_j(t_i)][w_k(t_{i+1}) - w_k(t_i)] = \begin{cases} 0 & \text{if } j \neq k \\ b-a & \text{if } j = k, \end{cases}$$

which justifies (at the same heuristic level as our scalar treatment) the rule that $\Delta w_j \Delta w_k$ should be replaced by dt when $j = k$, and 0 when $j \neq k$.

Knowing these proofs is less important than having some facility with actually applying Ito's lemma. We've seen good examples of that in our treatment of stochastic control. You'll find many more examples in textbook treatments of financial models. The next homework set will mainly involve applications of Ito's lemma.