Derivatives Pricing in Continuous Time

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Price Processes

Let's start considering a non-dividend paying stock S over the time interval $[0, T]$. Of course, a stock that does not pay dividends forever is a bubble but we will focus on a finite period of time in which the stock does not pay dividends. The stock price process follows a geometric Brownian of the form

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

and there is a money-market account β that grows at the risk-free rate r such that

$$\frac{d\beta}{\beta} = r dt.$$

Since our objective is to price derivatives written on S with payoffs given by some function of the stock price at time T, we can write the discount factor as

$$\frac{d\Lambda}{\Lambda} = -r dt - \lambda dB.$$

The stochastic part of the discount factor that matters for this application is the one that is perfectly correlated with the stock price process. For the moment, we assume that μ, r, σ and λ are all adapted process to the filtration on which all Brownian motions are adapted.

The pricing equation implies that λ should be the instantaneous Sharpe ratio of the stock price. Indeed,

$$(\mu - r) dt = -\frac{d\Lambda}{\Lambda}\frac{dS}{S} = \lambda \sigma dt,$$

so that

$$\lambda = \frac{\mu - r}{\sigma}.$$

The Risk-Neutral Measure

Girsanov's theorem allows us to create Brownian motions under a different measure by using strictly positive martingales. The risk-neutral measure is a particular measure created by using the process $\mathcal{E} = \Lambda\beta$. The pricing equation implies that $\mathcal{E}$ is a strictly positive local martingale. If $\mathcal{E}$ is actually a martingale, we can create a new measure P^* such that

$$\frac{d\,\mathrm{P}^*}{d\,\mathrm{P}} = \mathcal{E}_T.$$

There are many models in which $\mathcal{E}$ is a proper martingale. For example, if r is constant, then it is not hard to show that $\mathcal{E}$ is a martingale. In the following, we assume that $\mathcal{E}$ is a strictly positive martingale.

Girsanov's theorem then implies that

$$B_t^* = B_t - \int_0^t \frac{d\mathcal{E}_s}{\mathcal{E}_s} dB_s$$

is a P^*-Brownian motion. In this particular case, we have that

$$\frac{d\mathcal{E}}{\mathcal{E}} dB = \left(\frac{d\Lambda}{\Lambda} + \frac{d\beta}{\beta}\right) dB = -\lambda dt.$$

Thus,

$$dB^* = dB + \lambda dt.$$

The dynamics of S under P^* are then given by

$$\begin{aligned} \frac{dS}{S} &= \mu dt + \sigma(dB^* - \lambda dt) \\ &= (\mu - \lambda\sigma)dt + \sigma dB^*. \end{aligned} \tag{1}$$

Thus, we have that

$$\frac{dS}{S} = r dt + \sigma dB^*.$$

The previous expression implies that the drift of the stock is just the risk-free rate under P^*.

Consider now another asset V exposed to the same Brownian motion B,

$$\frac{dV}{V} = \mu_V dt + \sigma_V dB. \tag{2}$$

Hence, it must also be the case that

$$\lambda = \frac{\mu - r}{\sigma} = \frac{\mu_V - r}{\sigma_V},$$

and

$$\frac{dV}{V} = r dt + \sigma dB^*. \tag{3}$$

Thus, all assets under P^* earn the same rate of return equal to the risk-free rate. This is why we call the measure P^* the **risk-neutral measure**. In a risk-neutral world, all investors are happy discounting all cash flows at the risk-free rate.

If ΛV is a martingale it must be the case that

$$\Lambda_0 V_0 = \mathsf{E}(\Lambda_T V_T).$$

Thus,

$$V_0 = \mathsf{E}\left(\frac{\Lambda_T \beta_T}{\Lambda_0 \beta_0} \frac{\beta_0}{\beta_T} V_T\right) = \mathsf{E}^*\left(e^{-\int_0^T r_s ds} V_T\right).$$

More generally, we must have

$$V_t = \mathsf{E}_t^*\left(e^{-\int_t^T r_s ds} V_T\right). \tag{4}$$

Therefore, we can value any asset by discounting expected cash flows at the risk-free rate of return.

Example 1. The price of a zero-coupon bond paying 1 unit of consumption at time T is just

$$Z(T) = \mathsf{E}\left(\frac{\Lambda_T}{\Lambda_0} 1\right) = \mathsf{E}\left(\frac{\Lambda_T \beta_T}{\Lambda_0 \beta_0} \frac{\beta_0}{\beta_T}\right) = \mathsf{E}^*\left(e^{-\int_0^T r_s ds}\right).$$

Therefore, $e^{-\int_0^T r_s ds}$ acts like a discount factor under the risk-neutral measure. More generally,

$$Z_t(T) = \mathsf{E}_t^*\left(e^{-\int_t^T r_s ds}\right),$$

denotes the time-t price of a zero-coupon bond paying 1 unit of consumption at time T. $\square$

Example 2. A futures contract is an obligation to purchase or sell an asset S for a pre-specified price namely the futures price at a specific date T in the future. The key feature of futures contracts is that the gains or losses are realized daily. Also, to buy or sell a futures there is no cash outflow. Even though in real markets investors need to deposit a small margin, for the purpose of pricing the futures we can assume that the margin amount is negligible.

Therefore, if we denote by dF the futures gains or losses in a long position from t to $t + dt$, it must be the case that

$$\mathsf{E}_t(\Lambda_t dF) = 0,$$

since no cash is required to obtain a potential gain or loss of dF during the period. We can then re-write the previous expression as

$$0 = \mathsf{E}_t\left(\frac{\Lambda_t \beta_t}{\Lambda_0 \beta_0} dF\right) = \mathsf{E}_t^* \, dF.$$

Thus, under the risk-neutral measure the futures price process must be a local martingale. For many models, we can actually write that the futures price is a martingale under the risk-neutral measure, implying

$$F_t(T) = \mathsf{E}_t^* \, S_T.$$

Even though sometimes it might be hard to show that the futures is a P^*-martingale, we can always compute $\mathsf{E}_t^* \, S_T$ and verify that the futures satisfy the local martingale property. $\square$

Example 3. The forward price $\varphi(T)$ is the delivery price in a forward contract expiring at time T such that the value of the contract is zero, i.e.,

$$\mathsf{E}^* \, e^{-\int_0^T r_s ds}(S_T - \varphi(T)) = 0.$$

Therefore,

$$\varphi(T) = \frac{\mathsf{E}^*\left(e^{-\int_0^T r_s ds} S_T\right)}{\mathsf{E}^*\left(e^{-\int_0^T r_s ds}\right)} = \frac{\mathsf{Cov}^*\left(e^{-\int_0^T r_s ds}, S_T\right)}{Z(T)} + F(T).$$

Therefore, the forward price is equal to the futures price plus the risk-neutral covariance between the risk-neutral discount factor and the underlying asset. Thus, the forward price is equal to the futures price only when this covariance is zero. □

The Black-Scholes Model

The Black-Scholes formula to price options is one of the most important accomplishments in finance. A European call option gives its buyer the right but not the obligation to purchase an asset for a pre-determined price K at a future date T. Thus, the buyer of the call option pays K to receive a stock worth S_T only when $S_T > K$.

In their original model, Black and Scholes (1973) assumes that all parameters are constant. This implies that

$$\beta_T = \beta_0 e^{rT},$$

and

$$V_t = e^{-rT}\,\mathrm{E}_t^*\,S_T.$$

In the Black-Scholes model, the stock price process under the risk-neutral measure is

$$\frac{dS}{S} = r dt + \sigma dB^*.$$

We can solve for S_t to find

$$S_t = S_0 e^{(r-\frac{1}{2}\sigma^2)t+\sigma B_t^*}.$$

Thus, under the risk-neutral measure $\ln(S_t)$ is normally distributed with mean

$$\mathrm{E}\ln(S_t) = \ln(S_0) + \left(r - \frac{1}{2}\sigma^2\right)t,$$

and variance

$$\mathrm{V}\ln(S_t) = \sigma^2 t.$$

Example 4. The risk-neutral probability that the stock price S_T is greater than K at time T is

$$\begin{aligned}
\mathsf{P}^*(S_T > K) &= \mathsf{P}^*(\ln(S_T) > \ln(K)) \\
&= \mathsf{P}^*\left(Z > \frac{\ln(K) - \ln(S_0) - \left(r - \frac{1}{2}\sigma^2\right)T}{\sigma\sqrt{T}}\right) \\
&= \mathsf{P}^*\left(Z < \frac{\ln(S/K) + \left(r - \frac{1}{2}\sigma^2\right)T}{\sigma\sqrt{T}}\right),
\end{aligned}$$

where Z denotes a standard normally distributed random variable. In the Black-Scholes model, we typically write

$$d_2 = \frac{\ln(S/K) + \left(r - \frac{1}{2}\sigma^2\right)T}{\sigma\sqrt{T}},$$

and $N(d) = \mathsf{P}^*(Z < d)$, so that $\mathsf{P}^*(S_T > K) = N(d_2)$. □

For a given event $A \in \mathcal{F}$, the indicator function $\mathbb{1}_{\{A\}}(\omega)$ is equal to 1 if $\omega \in A$ and 0 otherwise. Thus, $\mathbb{1}_{\{S_T > K\}}$ is equal to 1 whenever $S_T > K$ and zero otherwise. The payoff of a call option can then be defined as

$$\text{Call Payoff} = (S_T - K)\mathbb{1}_{\{S_T > K\}} = S_T\mathbb{1}_{\{S_T > K\}} - K\mathbb{1}_{\{S_T > K\}}.$$

The price of a call must then be given by

$$C_0 = \mathsf{E}\,\frac{\Lambda_T}{\Lambda_0}(S_T - K)\mathbb{1}_{\{S_T > K\}} = \mathsf{E}\,\frac{\Lambda_T}{\Lambda_0}S_T\mathbb{1}_{\{S_T > K\}} - K\,\mathsf{E}\,\frac{\Lambda_T}{\Lambda_0}\mathbb{1}_{\{S_T > K\}}. \quad (5)$$

To compute the first expectation in (5), a nice trick is to realize that $\mathcal{E}^S = \Lambda S$ is a strictly positive martingale defining a new measure P^S such that

$$\frac{d\,\mathsf{P}^S}{d\,\mathsf{P}} = \mathcal{E}_T^S.$$

Thus,

$$\mathsf{E}\,\frac{\Lambda_T}{\Lambda_0}S_T\mathbb{1}_{\{S_T > K\}} = S_0\,\mathsf{E}\,\frac{\Lambda_T S_T}{\Lambda_0 S_0}\mathbb{1}_{\{S_T > K\}} = S_0\,\mathsf{E}^S\,\mathbb{1}_{\{S_T > K\}} = S_0\,\mathsf{P}^S(S_T > K).$$

To compute the second expectation in (5) we can just use the risk-neutral measure

$$\mathsf{E}\,\frac{\Lambda_T}{\Lambda_0}\mathbb{1}_{\{S_T>K\}} = \frac{\beta_0}{\beta_T}\,\mathsf{E}\,\frac{\Lambda_T\beta_T}{\Lambda_0\beta_0}\mathbb{1}_{\{S_T>K\}} = e^{-rT}\,\mathsf{E}^*\,\mathbb{1}_{\{S_T>K\}} = e^{-rT}\,\mathsf{P}^*(S_T>K).$$

The price of the call can then be written as

$$C_0 = S_0\,\mathsf{P}^S(S_T>K) - Ke^{-rT}\,\mathsf{P}^*(S_T>K).$$

To compute $\mathsf{P}^S(S_T>K)$, we know that

$$B_t^S = B_t - \int_0^t \frac{d\mathcal{E}^S}{\mathcal{E}^S}dB = B_t + (\lambda-\sigma)t$$

is a Brownian motion under P^S. Thus,

$$\frac{dS}{S} = (r+\sigma^2)dt + \sigma dB^S.$$

We can follow the steps in Example 4 to conclude that

$$\mathsf{P}^S(S_T>K) = N(d_1),$$

where

$$d_1 = \frac{\ln(S/K) + \left(r+\frac{1}{2}\sigma^2\right)T}{\sigma\sqrt{T}}.$$

To price a European put option we can proceed in a similar way. Remember that a European put option gives it’s buyer the right but not the obligation to sell an asset for a pre-determined price K at a future date T. Therefore, the payoff of the European put at maturity is

$$\text{Put Payoff} = K\mathbb{1}_{\{S_T<K\}} - S_T\mathbb{1}_{\{S_T<K\}}.$$

The price P_0 of the put today is then given by

$$P_0 = Ke^{-rT}\,\mathsf{P}^*(S_T<K) - S_0\,\mathsf{P}^S(S_T<K).$$

Thus, $\mathrm{P}^*(S_T < K) = 1 - N(d_2) = N(-d_2)$ and $\mathrm{P}^S(S_T < K) = 1 - N(d_1) = N(-d_1)$. We can summarize these results in the following property.

Property 1. *In the Black-Scholes model, the prices C and P of European call and put options, respectively, are given by*

$$C = SN(d_1) - Ke^{-rT}N(d_2),$$
$$P = Ke^{-rT}N(-d_2) - SN(-d_1),$$

where

$$d_1 = \frac{\ln(S/K) + \left(r + \frac{1}{2}\sigma^2\right)T}{\sigma\sqrt{T}},$$
$$d_2 = \frac{\ln(S/K) + \left(r - \frac{1}{2}\sigma^2\right)T}{\sigma\sqrt{T}},$$

and $N(d)$ denotes the cumulative probability than a standard normal random variable is less than d.

Partial Differential Equations in the Black-Scholes Model

The Black-Scholes formula was originally derived as the solution of a partial differential equation (PDE). It is indeed the case that any asset in the Black-Scholes model must satisfy the same PDE. Consider a derivative V that pays $f(S_T)$ at time T.

If V is a function of S and t[1], then Ito's lemma implies that

$$\begin{aligned} dV &= \frac{\partial V}{\partial S}dS + \frac{1}{2}\frac{\partial^2 V}{\partial S^2}(dS)^2 + \frac{\partial V}{\partial t}dt \\ &= \left(rS\frac{\partial V}{\partial S} + \frac{1}{2}\sigma^2 S^2 \frac{\partial^2 V}{\partial S^2} + \frac{\partial V}{\partial t}\right)dt + \sigma S \frac{\partial V}{\partial S}dB^*. \end{aligned}$$

Equation (3) then implies that any derivative written on S must satisfy the following partial differential equation

$$rS\frac{\partial V}{\partial S} + \frac{1}{2}\sigma^2 S^2 \frac{\partial^2 V}{\partial S^2} + \frac{\partial V}{\partial t} = rV.$$

[1] More specifically, we assume that $V_t = F(S_t, t)$.

To price a specific derivative, the PDE must be solved subject to a terminal condition $V(S,T) = f(S)$ and appropriate boundary conditions. For a European call option, the terminal condition and boundary conditions are

$$V(S,T) = (S-K)^+, \quad V(0,t) = 0, \quad V(S,t) \approx S - Ke^{-r(T-t)} \text{ as } S \to \infty.$$

For a European put option,

$$V(S,T) = (K-S)^+, \quad V(0,t) = Ke^{-r(T-t)}, \quad V(S,t) \to 0 \text{ as } S \to \infty.$$

The Greeks and the PDE

The sensitivities of an option price to its inputs are known as the *Greeks*. The most important ones are the delta, gamma, and theta:

$$\Delta = \frac{\partial V}{\partial S}, \qquad \Gamma = \frac{\partial^2 V}{\partial S^2}, \qquad \Theta = \frac{\partial V}{\partial t}.$$

In terms of the Greeks, the Black-Scholes PDE takes the form

$$\Theta + rS\Delta + \frac{1}{2}\sigma^2 S^2 \Gamma = rV,$$

or equivalently,

$$\Theta + \frac{1}{2}\sigma^2 S^2 \Gamma = r(V - S\Delta).$$

This has a clean financial interpretation. Consider a delta-hedged portfolio: long one unit of the derivative and short Δ shares of stock. Its value is $V - S\Delta$, and the right-hand side is the risk-free return on that portfolio. The left-hand side captures two sources of return: the time decay Θ (which is negative for long option positions) and the gamma P&L $\frac{1}{2}\sigma^2 S^2 \Gamma$. The PDE says that these must balance exactly so the portfolio earns the risk-free rate.

Solving the PDE

The Black-Scholes formula is the explicit solution to this PDE for European calls and puts. One can verify this directly by computing the Greeks of the call price $C = SN(d_1) - Ke^{-r(T-t)}N(d_2)$:

$$\Delta = N(d_1), \qquad \Gamma = \frac{n(d_1)}{S\sigma\sqrt{T-t}}, \qquad \Theta = -\frac{S\sigma n(d_1)}{2\sqrt{T-t}} - rKe^{-r(T-t)}N(d_2),$$

where $n(d) = N'(d)$ is the standard normal density, and checking that the PDE holds.

Alternatively, the PDE can be reduced to the classical heat equation. Making the substitution $\tau = T - t$, $x = \ln(S/K)$, and $V(S,t) = e^{\alpha x + \beta\tau}u(x,\tau)$ for appropriately chosen constants α and β, the Black-Scholes PDE simplifies to

$$\frac{\partial u}{\partial \tau} = \frac{\sigma^2}{2}\frac{\partial^2 u}{\partial x^2}.$$

The solution is given by the Gaussian convolution

$$u(x,\tau) = \frac{1}{\sqrt{2\pi\sigma^2\tau}}\int_{-\infty}^{\infty} u(y,0)\exp\left(-\frac{(x-y)^2}{2\sigma^2\tau}\right)dy,$$

and evaluating this integral for the call payoff recovers the Black-Scholes formula.

References

Black, Fischer, and Myron Scholes. 1973. "The Pricing of Options and Corporate Liabilities." *Journal of Political Economy* 81 (3): 637–54.