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FÖRELÄSNINGSATECKNINGAR

# Finansiella Derivat

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## 1. OPTIONS

**Motivating Discussion:**

Say a Swedish company has signed a contract to buy a machine from a US company for 100000USD to be paid at delivery 6 months from now.  $T = \frac{1}{2}$  years.

Current exchange rate is 11SEK/USD. The buyer is subject to currency risk. There are 3 possible strategies to implement:

1. Buy 100000USD today and deposit in the bank.

The risk is eliminated but money is tied up for a long time and the company may not have access to this money

2. Buy a *forward contract* from a bank, i.e the bank delivers the sum you need at  $T = \frac{1}{2} = t$ , in return, the company pays some constant  $K \cdot 100000USD$  at  $T = t$ , where  $K$  is chosen at  $t = 0$  such that no transfer of money is needed at  $t = 0$ . Here, the bank takes all of the risk, but if the exchange rate drops below  $K$  then we would have preferred to do nothing.
3. Buy a *European call option* on 100000USD, with strike price  $K$  and exercise date  $T$ . I.e, it gives the right but not the obligation to buy 100000USD at price  $K \cdot 100000USD$  at time  $T = t$ . If exchange rate at  $T$  is  $> K$ , then we use the option. If its below at  $t = T$  thne we do not use the option (right, not obligation)

The last one is a good choice, but not free. This leads to the 2 main problems in the course:

- How much is a fair price for an option?
- If you are the seller of an option, how to protect (hedge) from risk of exchange rate not going up?

**Motivating Example in discrete time**

At  $t = 0$ , we can trade in a market with 2 assets:

- *Bank account* (risk-free/non-risky asset)

At  $t = 0$  the value is 1 and at  $t = 1$  the value is 1

- *Stock* (risky asset)

At  $t = 0$ ,  $S_0 = 100$  then it either grows ( $S_1 = 120$ ) or declines ( $S_1 = 80$ ) with probability  $p = 0.6$  and  $p = 0.4$  respectively

**Definition 1.1 Call option**

A *call option* is a contract that gives its holder the right but not the obligation to buy one share of a stock at time  $T$  with predetermined price  $K$ . Thus, at time  $t = 1$ , the option is worth  $S_1 - K$  if  $S_1 > K$  and 0 else

What is a fair price of the option? The sensible thing to pay would be  $p(S_1 - K)$ . Assuming  $K = 110$  in the above example, then  $0.6(120 - 110) = 6$ . But this is not the best price!

The idea is to replicate the option by finding a trading strategy using both the risk-free (B) and the risky asset (S) such that the value of the stock at  $t = 1$  coincides with the value of hte option.

Is that possible? Yes. Let  $x$  = amount in the bank at  $t = 0$  and  $y$  be the number of shares of stock. We want to pick  $x, y$  such that regardless if stock goes up or down we have increase.

At  $t = 1$

$$\left. \begin{aligned} x + S_1 y &= S_1 - K \\ x + S_1 y &= 0 \end{aligned} \right\}$$

If  $K = 110$  and  $S_1 = \{120, 80\}$ , then  $x = -20$  and  $y = \frac{1}{4}$  since

$$\begin{cases} x + 120y = 10 \\ x + 80y = 0 \end{cases}$$

At  $t = 0$ . Our strategy is therefore to borrow 20 from the bank and buy  $\frac{1}{4}$  of a share. The cost is  $25 - 20 = 5$  which is less than 6.

At time  $t = 1$  our holdings are worth  $\frac{1}{4}S_1 - 20 = \begin{cases} 10 & \text{if } S_1 = 120 \\ 0 & \text{if } S_1 = 80 \end{cases}$  which is exactly the same as the option.

**Conclusion:**

By the APT (Arbitrage pricing theory), the price of the call must be equal to the cost of setting up this portfolio.

**Remark:**

The probabilities do not influence the option value. They were never used in the calculation of the price.

**Remark:**

Let us change  $p$  into  $q$  such that  $\mathbb{E}(S_1) = S_0 = 100$  in the example, which value of  $q$  satisfies this? It is symmetric in the example, so let  $p = q = \frac{1}{2}$

Then  $\mathbb{E}(\max\{S_1 - k, 0\}) = 10 \cdot \frac{1}{2} + 0 \cdot \frac{1}{5} = 5$

In general, the option price is  $\mathbb{E}^Q\left(\frac{B_0}{B_1} \max\{S_1 - k, 0\}\right)$  where  $Q$  is chosen such that  $\mathbb{E}^Q\left(\frac{B_0 S_1}{B_1}\right) = \frac{S_0}{B_0}$

**Notation:**

$a^+ = \max\{a, 0\}$ . In particular,

$$(s - K)^+ = \begin{cases} s - K & \text{if } s \geq K \\ 0 & \text{if } s < K \end{cases}$$

**Exercise:**

- In the above example, find a replicating strategy for a put option (right but not obligated to sell one share) at price  $K = 110$
- Find the value of the option at  $t = 0$

**Answer:**

$$\left. \begin{array}{l} x = 90 \\ y = \frac{-3}{4} \end{array} \right\} \text{ option value of 15}$$

## 2. CONTINUOUS TIME &amp; BROWNIAN MOTION

## 2.1. Simple Random Walk.

Let  $X_i$  be i.i.d.r.v with  $\mathbb{P}(X_k = 1) = \mathbb{P}(X_k = -1) = \frac{1}{2}$

Let  $S_n = \sum_{i=1}^n X_i$ , then this is a stochastic process, still in discrete time. Do note that the expectation is 0 for the r.v. and that:

$$\mathbb{E}(S_n) = \sum_{k=1}^n \mathbb{E}(X_i) = 0$$

$$\text{Var}(S_n) = \mathbb{E}(S_n^2) - \underbrace{(\mathbb{E}(S_n))^2}_{=0} = \sum_{k=1}^n \text{Var}(X_i) = \sum_{k=1}^n 1 = n$$

Note that this was discrete time, how do we proceed to make this continuous?

We do this by scaling to finer time. Frist, fix a time interval:

**Stage 1**

Let  $X_0^1 = 0$

At  $t = 0$ , toss a coin,  $X_T^1 = \begin{cases} \sqrt{T} & \text{heads} \\ -\sqrt{T} & \text{tails} \end{cases}$ .

Here  $\mathbb{E}(X_T^1) = 0$  and  $\text{Var}(X_T^1) = T = \text{elapsed time}$ .

**Stage 2**

Add another time step. Let  $X_0^2 = 0$ , toss a coin,  $X_{T/2}^2 = \begin{cases} \sqrt{\frac{T}{2}} & \text{heads} \\ -\sqrt{\frac{T}{2}} & \text{tails} \end{cases}$

Repeat at  $t = \frac{T}{2}$ , adding/subtracting  $\sqrt{\frac{T}{2}}$

**Stage n**

Let  $X_0^n = 0$ , at each time  $t_k = \frac{k}{n}T$ , toss a coin.

Define  $X_{t_{k+1}}^n = X_{t_k}^n + Y_k$  where  $Y_k = \pm \sqrt{\frac{T}{n}}$  with prob. 1/2. Simulating our coin tosses.

Here

$$\mathbb{E}(X_{t_k}^n) = \mathbb{E}\left(\sum_{i=1}^{k-1} Y_i\right) = \sum_{i=1}^{k-1} \mathbb{E}(Y_i) = 0$$

$$\text{Var}(X_{t_k}^n) = \text{Var}\left(\sum_{i=1}^n Y_i\right) \stackrel{\text{indep}}{=} \sum_{i=1}^k = \frac{T}{n}k = t_k$$

Now the question becomes, what happens when  $n \rightarrow \infty$ ? We obtain *Brownian Motion*, aka Wiener process.

**Definition 2.2 Brownian Motion**

*Brownian Motion* is a stochastic process  $W$  if:

- $W_0 = 0$
- Independent increments, i.e  $W_{t_4} - W_{t_3}$  and  $W_{t_2} - W_{t_1}$  are independent (as long as they are not overlapping)
- $W_t - W_s \sim N(0, t - s)$
- $t \mapsto W_t$  is continuous

This is a nice definition and all, but does there even exists something which satisfies our definition?

**Sats 2.1**

$t \mapsto W_t$  is of infinite variation and nowhere differentiable  
By infinite variation, it is meant

$$\lim_{n \rightarrow \infty} \sum_k |W_{t_{k+1}} - W_{t_k}| = \infty$$

A regular differentiable function has bounded variation. The next goal is to define the stochastic integral  $\int_0^t g_s dW_s$ , where  $g_t$  is a stochastic process determined by the Brownian motion  $W$

### Definition 2.3 Measurable w.r.t $\sigma$ -algebra

Let  $X_t$  be a stochastic process. An event  $A$  is  $\mathcal{F}_t^X$  measurable (denoted  $A \in \mathcal{F}_t^X$ ) if it is possible to determine whether  $A$  has happened or not based on observations of  $\{X_s : 0 \leq s \leq t\}$

**Example:**

$$A = \{X_s \leq 7 : \forall s \leq 9\} \in \mathcal{F}_9^X$$

### Definition 2.4

If a random variable  $Z$  can be determined by observations of  $\{X_s : 0 \leq s \leq t\}$ , then  $Z \in \mathcal{F}_t^X$

**Example:**

$$Z = \int_0^5 X_s ds \in \mathcal{F}_5^X$$

If you only know  $X_5$  up to 4, then you cannot determine  $Z$

### Definition 2.5

A stochastic process  $Y_t$  with  $Y_t \in \mathcal{F}_t^X \quad \forall t$  is *adapted to the filtration*  $\mathcal{F}_t^X$

**Example:**

$Y_t = \sup_{0 \leq s \leq t} W_s$  is adapted to  $\mathcal{F}_t^W$

### Definition 2.6

The process  $g_t \in \mathcal{L}^2$  if

- $g$  is adapted to  $\mathcal{F}_t^W$
- $\int_0^t \mathbb{E}(g_s^2) ds < \infty$

**Example:**

Brownian motion  $\in \mathcal{L}^2$ , its adapted to  $\mathcal{F}_t^W$  and  $\int_0^t \mathbb{E}(\overbrace{W_s^2}^{\sim N(0, \sqrt{s})}) ds = \int_0^t s ds = \frac{t^2}{2} < \infty$

## 2.2. Stochastic integration.

Assume  $g \in \mathcal{L}^2$ . If  $g$  is simple (i.e.  $g_s = g_{t_k}$  for  $s \in [t_k, t_{k+1}]$ ), then we define

$$\int_0^t g_s dW_s = \sum_{k=0}^{n-1} g_{t_k} (W_{t_{k+1}} - W_{t_k})$$

For egeneral  $g \in \mathcal{L}^2$ , we can approximate  $g$  using step functions which are simple such that

$$\int_0^t \mathbb{E}((g_s - g_s^n)^2) ds \rightarrow 0 \quad \text{as } n \rightarrow \infty$$

Then, one defines the stochastic integral as

$$\int_0^t g_s dW_s = \lim_{n \rightarrow \infty} \int_0^t g_s^n dW_s$$

### Remark

One can show that the limit indeed exists and does not depend on the sequence used for approximation.

### Remark:

Forward increments are used! The integrand is fixed at  $t_k$ , and we look at forward movements of the Brownian motion.

### Remark:

Steiltjes integration si not possible since paths are not of unbounded variation.

### Proposition:

Assume  $g \in \mathcal{L}^2$  and adapted to a filtration, then:

1.  $\mathbb{E} \left( \int_0^t g_s dW_s \right) = 0$
2.  $\mathbb{E} \left( \left( \int_0^t g_s dW_s \right)^2 \right) = 0 = \int_0^t \mathbb{E}(g_s^2) dW_s$  (Ito isometry)
3.  $X_t = \int_0^t g_s dW_s$ , then  $X_t$  is  $\mathcal{F}^W$ -adapted

### Bevis 2.1

Assume  $g$  is simple (if it was not, then approximate using step functions).

1.

$$\begin{aligned} \mathbb{E} \left( \int_0^t g_s dW_s \right) &= 0 = \mathbb{E} \left( \sum_{k=0}^{n-1} g_{t_k} (W_{t_{k+1}} - W_{t_k}) \right) = \sum_{k=0}^{n-1} \mathbb{E} \left( \underbrace{g_{t_k}}_{\text{indep.}} \underbrace{(W_{t_{k+1}} - W_{t_k})}_{\text{indep.}} \right) \\ &= \sum_{k=0}^{n-1} \mathbb{E}(g_{t_k}) \underbrace{\mathbb{E}(W_{t_{k+1}} - W_{t_k})}_{\sim N(0, \sigma^2)} = 0 \end{aligned}$$

2. This is the variance of a stochastic integral:

$$\begin{aligned} \mathbb{E} \left( \left( \sum_{k=0}^{n-1} g_{t_k} (W_{t_{k+1}} - W_{t_k}) \right)^2 \right) &= \mathbb{E} \left( \sum_{k=0}^{n-1} g_{t_k}^2 (W_{t_{k+1}} - W_{t_k})^2 \right) + 2 \sum_{j < k} \underbrace{g_{t_k} g_{t_j}}_{\in \mathcal{F}_{t_k}} \underbrace{(W_{t_{k+1}} - W_{t_k})}_{\text{indep. of } \mathcal{F}_{t_k}} \underbrace{(W_{t_{j+1}} - W_{t_j})}_{\in \mathcal{F}_{t_k}} \\ &= \sum_{k=0}^{n-1} \mathbb{E}(g_{t_k}^2 (W_{t_{k+1}} - W_{t_k})^2) + 2 \sum_{j < k} \mathbb{E}(g_{t_k} g_{t_j} (W_{t_{k+1}} - W_{t_k}) (W_{t_{j+1}} - W_{t_j})) \\ &= \sum_{k=0}^{n-1} \mathbb{E}(g_{t_k}^2) \underbrace{\mathbb{E}((W_{t_{k+1}} - W_{t_k})^2)}_{t_{k+1} - t_k} + 2 \sum_{j < k} \mathbb{E}(\dots) \underbrace{\mathbb{E}(W_{t_{k+1}} - W_{t_k})}_{=0} \\ &= \int_0^t \mathbb{E}(g_s^2) dW_s \end{aligned}$$



### 2.3. Properties of the stochastic integral.

#### Examples:

$\int_0^t 1 dW_s = W_t - W_0 = W_t$ , but that is  $\int_0^t W_s dW_s$ ?  $W_s$  is not piecewise constant, but we may approximate it by letting  $g_t^n = W_{t_k}$  for  $t \in [t_k, t_{k+1})$ . What happens here is essentially discretisation but for finer and finer time.

This yields the approximation

$$\begin{aligned} \int_0^t \mathbb{E}((g_s^n - W_s)^2) ds &= \sum_{k=0}^{n-1} \int_{t_k}^{t_{k+1}} \underbrace{\mathbb{E}((W_s - W_{t_k})^2)}_{s=t_k} \leftarrow \text{variance of increment of BM} \\ &= \sum_{k=0}^{n-1} \int_{t_k}^{t_{k+1}} (s - t_k) ds = \sum_{k=0}^{n-1} \frac{1}{2} (t_{k+1} - t_k)^2 = \sum_{k=0}^{n-1} \frac{1}{2} \Delta t \\ \Delta t &= \frac{t}{n} \Rightarrow \frac{1}{2} (\Delta t)^2 \frac{t}{\Delta t} = \frac{\Delta t}{2} t \rightarrow 0 \quad \text{as } n \rightarrow \infty \\ \Rightarrow \sum_{k=0}^{n-1} W_{t_k} (W_{t_{k+1}} - W_{t_k}) &= \frac{1}{2} \sum_{k=0}^{n-1} (W_{t_{k+1}}^2 - W_{t_k}^2) = \frac{1}{2} W_{t_n}^2 - \underbrace{\frac{1}{2} \sum_{k=0}^{n-1} (W_{t_{k+1}} - W_{t_k})^2}_{I_n} \end{aligned}$$

We claim  $I_n \rightarrow t$  as  $n \rightarrow \infty$ :

$$\mathbb{E}(I_n) = \underbrace{\mathbb{E} \left( \sum_{k=0}^{n-1} (W_{t_{k+1}} - W_{t_k})^2 \right)}_{\text{2nd moment}} = \sum_{k=0}^{n-1} (t_{k+1} - t_k) = t_n = t$$

Need to check  $\mathbb{E}((I_n - t)^2) = 0$ :

$$\begin{aligned} &\mathbb{E} \left( \left( \sum_{k=0}^{n-1} (W_{t_{k+1}} - W_{t_k})^2 - \overbrace{(t_{k+1} - t_k)}^{\Delta t} \right) \right)^2 \\ &= \sum_{k=0}^{n-1} \mathbb{E} \left( ((W_{t_{k+1}} - W_{t_k})^2 - \Delta t)^2 \right) + \sum_{j \neq k} \mathbb{E} \left( ((W_{t_{k+1}} - W_{t_k})^2 - \Delta t)((W_{t_{j+1}} - W_{t_j})^2 - \Delta t) \right) \\ &= \sum_{j \neq k} \mathbb{E} \left( (W_{t_{k+1}} W_{t_k})^4 \right) - (\Delta t)^2 = \sum_{k=0}^{n-1} 2(\Delta t)^2 \sim \Delta t \rightarrow 0 \end{aligned}$$

thus,  $I_n \rightarrow t$  as  $n \rightarrow \infty$ , so

$$\int_0^t W_s dW_s = \frac{1}{2} W_t^2 - \frac{t}{2}$$

#### Remark:

Lets prove if  $X \sim N(0, \sigma)$ , then  $\mathbb{E}(X^4) = 3\sigma^2$

$$\begin{aligned} \mathbb{E}(X^4) &= \int z^4 \frac{1}{\sqrt{2\pi}\sigma} \exp \left\{ -\frac{z^2}{2\sigma^2} \right\} dz \stackrel{\text{parts}}{=} - \left[ z^3 \frac{1}{\sqrt{2\pi}\sigma} \exp \left\{ -z^2/2\sigma^2 \right\} \right]_{-\infty}^{\infty} - \int 3z^2 \frac{\sigma^2}{\sqrt{2\pi}\sigma} \exp \left\{ -z^2/2\pi\sigma^3 \right\} dz \\ &= 3\sigma^2 \cdot \underbrace{\int z^2 \frac{1}{\sqrt{2\pi}\sigma} \exp \left\{ -z^2/2\sigma^2 \right\} dz}_{\sigma^2} = 3\sigma^4 \end{aligned}$$



## 3. MARTINGALES

Let  $\mathcal{F}_t$  be a filtration, "information generated by B; up to a time  $t$ ".

If  $Y$  is a random variable, then  $\mathbb{E}(Y \mid \mathcal{F}_t)$  is the conditional expectation given all information up to time  $t$

**Example:**

$$\mathbb{E}(W_s \mid \mathcal{F}_t) = W_t$$

**Definition 3.7 Martingale**

A process  $X$  is a martingale if  $X$  is  $\mathcal{F}_t$ -adapted.  $X_t$  integrable, i.e

- $\mathbb{E}(|X_t|) < \infty \quad \forall t$
- $\mathbb{E}(X_s \mid \mathcal{F}_t) = X_t$  for  $s > t$

**Example:**

$W_t$  is a martingale,  $W_t^2 - t$  is a martingale since

$$\begin{aligned} Y_t &:= W_t^2 - t & \mathbb{E}(Y_t \mid \mathcal{F}_s) &= \mathbb{E}(W_t^2 - t \mid \mathcal{F}_s) \\ &= \mathbb{E}((W_t - W_s)^2 + 2W_s W_t - W_s^2 \mid \mathcal{F}_s) - t \\ &= t - s + 2\mathbb{E}(W_s W_t \mid \mathcal{F}_s) - \mathbb{E}(W_s^2 \mid \mathcal{F}_s) - t = 2W_s \underbrace{\mathbb{E}(W_t \mid \mathcal{F}_s)}_{W_s} W_s^2 - s \\ &= W_s^2 - s = Y_s \end{aligned}$$

$Y_t = \int_0^t g_u dW_u$  is a martingale since:

$$\mathbb{E}(Y_t \mid \mathcal{F}_s) = \mathbb{E}\left(\int_0^s g_u dW_u \mid \mathcal{F}_s\right) + \mathbb{E}\left(\int_s^t g_u dW_u \mid \mathcal{F}_s\right) = \int_0^s g_u dW_u = Y_s$$

However,  $W_t^3$  is *not* a martingale:

$$\begin{aligned} \mathbb{E}(W_t^3 \mid \mathcal{F}_s) &= \mathbb{E}(W_s^3 + (W_t - W_s)^3 - 3W_t W_s^2 + 3W_t^2 W_s \mid \mathcal{F}_s) \\ &= W_s^3 + 0 - 3W_s^2 \underbrace{\mathbb{E}(W_t \mid \mathcal{F}_s)}_{W_s} + 3W_s \underbrace{\mathbb{E}(W_t^2 \mid \mathcal{F}_s)}_{t-s+W_s^2} \\ &= W_s^3 + 3(t-s)W_s \neq W_s^3 \end{aligned}$$

**Remark:** A martingale is a "fair game"

## 4. ITOS FORMULA

Assume

$$X_t = a + \int_0^t \mu_s ds + \int_0^t \sigma_s dW_s$$

for some adapted process  $\mu_t$  and  $\sigma_t$ . Short-hand notation  $\begin{cases} dX_t = \mu_t dt + \sigma_t dW_t \\ X_0 = a \end{cases}$

Let  $f(t, x)$  be a  $C^{1,2}$ -function and define  $Z_t = f(t, X_t)$ , what does  $dZ_t$  look like?

**Recall:**

$$\int_0^t W_s dW_s = \frac{W_t^2}{2} - \frac{t}{2}$$

so  $W_t^2 = t + 2 \int_0^t W_s dW_s$ , thus

$$d(W_t^2) = dt + 2W_t dW_t$$

Fix  $n$  and let  $t_k = \frac{k}{n}t$

Let  $\Delta W_{t_k} = W_{t_{k+1}} - W_{t_k}$  and consider

$$S_n = \sum_{k=0}^{n-1} (\Delta W_{t_k})^2$$

We have

$$\mathbb{E}(S_n) = \sum_{k=0}^{n-1} \mathbb{E}((\Delta W_{t_k})^2) = \sum_{k=0}^{n-1} \frac{t}{n} = t$$

and

$$\text{Var}(S_n) \stackrel{\text{indep.}}{=} \sum_{k=0}^{n-1} \text{Var}((\Delta W_{t_k})^2) = n \text{Var}((\Delta W_{t_0})^2) = n \cdot 2 \frac{t^2}{n^2} \rightarrow 0 \quad \text{as } n \rightarrow \infty$$

Thus  $S_n \rightarrow t$  as  $n \rightarrow \infty$  (in  $\mathcal{L}^2$ ). This motivates to write

$$\begin{aligned} \int_0^t (dW_s)^2 &= t \\ \Leftrightarrow dW_t^2 &= dt \end{aligned}$$

## 4.1. Taylor Expansion.

$$\begin{aligned} dZ_t &= \frac{\partial f}{\partial t} dt + \frac{\partial f}{\partial x} dX_t + \frac{1}{2} + \frac{\partial^2 f}{\partial x^2} (dX_t)^2 + \frac{\partial^2 f}{\partial t^2} (dt)^2 + \frac{\partial^2 f}{\partial t \partial x} dt dX_t + \text{higher order terms} \\ &= \left( \frac{\partial f}{\partial t} + \mu_t \frac{\partial f}{\partial x} + \frac{1}{2} \sigma_t^2 \frac{\partial^2 f}{\partial x^2} \right) dt + \sigma_t \frac{\partial f}{\partial x} dW_t + \text{higher order terms} \end{aligned}$$

**Sats 4.2: Itos formula**

If  $dX_t = \mu_t dt + \sigma_t dW_t$  and  $Z_t = f(t, X_t)$ , then

$$dZ_t = \left( \frac{\partial f}{\partial t} + \mu_t \frac{\partial f}{\partial x} + \frac{1}{2} \sigma_t^2 \frac{\partial^2 f}{\partial x^2} \right) dt + \sigma_t \frac{\partial f}{\partial x} dW_t$$

Here  $\frac{\partial f}{\partial t} = \frac{\partial f}{\partial t}(t, X_t)$  and similarly for other derivatives of  $f$

**Alternative formulation:**

$$dZ_t = \frac{\partial f}{\partial t} dt + \frac{\partial f}{\partial x} dX_t + \frac{1}{2} \frac{\partial^2 f}{\partial x^2} (dX_t)^2$$

Where  $(dX_t)^2$  is calculated using

- $(dt)^2 = 0$

- $dt dW_t = 0$
- $(dW_t)^2 = dt$

**Example:**

Compute  $\int_0^t W_s dW_s$ . Let  $Z_t = W_t^2$ , then by Itos formula

$$\begin{aligned} dZ_t &= 2W_t dW_t + \frac{1}{2} \cdot 2(dW_t)^2 \\ &= dt + 2W_t dW_t \end{aligned}$$

Thus  $W_t^2 = Z_t = t + 2 \int_0^t W_s dW_s$ , so  $\int_0^t W_s dW_s = \frac{W_t^2}{2} - \frac{t}{2}$

**Example:**

Compute  $\mathbb{E}(W_t^4)$

Let  $Z_t = W_t^4$ , then by Itos formula

$$\begin{aligned} dZ_t &= 4W_t^3 dW_t + \frac{1}{2} \cdot 12W_t^2 (dW_t)^2 \\ &= 6W_t^2 dt + 4W_t^3 dW_t \end{aligned}$$

Thus

$$W_t^4 = Z_t = 6 \int_0^t W_s^2 ds + 4 \int_0^t W_s^3 dW_s$$

Taking expectation yields

$$\begin{aligned} \mathbb{E}(W_t^4) &= 6 \int_0^t \underbrace{\mathbb{E}(W_s^2)}_s ds + 4 \underbrace{\mathbb{E} \left( \int_0^t W_s^3 dW_s \right)}_{=0} \\ &= 6 \int_0^t s ds = 3t^2 \end{aligned}$$

Alternatively, without using Itos formula

$$\begin{aligned} \mathbb{E}(W_t^4) &= \int_{\mathbb{R}} x^4 \frac{1}{\sqrt{2\pi t}} e^{-x^2/(2t)} dx \stackrel{\text{parts.}}{=} \left[ x^3 \frac{t}{\sqrt{2\pi t}} e^{-x^2/(2t)} \right]_{-\infty}^{\infty} + \int_{\mathbb{R}} 3x^2 \frac{t}{\sqrt{2\pi t}} e^{-x^2/(2t)} dx \\ &= 3t \text{Var}(W_t) = 3t^2 \end{aligned}$$

**Example:**

Compute  $\mathbb{E}(e^{\alpha W_t})$

Let  $Z_t = e^{\alpha W_t}$ . Itos formula yields

$$\begin{aligned} dZ_t &= \alpha e^{\alpha W_t} dW_t + \frac{1}{2} \alpha^2 e^{\alpha W_t} (dW_t)^2 \\ &= \frac{\alpha^2}{2} e^{\alpha W_t} dt + \alpha e^{\alpha W_t} dW_t \\ &= \frac{\alpha^2}{2} Z_t dt + \alpha Z_t dW_t \end{aligned}$$

Integration yields

$$Z_t = 1 + \frac{\alpha^2}{2} \int_0^t Z_s ds + \alpha \int_0^t Z_s dW_s$$

So

$$\begin{aligned} \mathbb{E}(Z_t) &= 1 + \mathbb{E} \left( \frac{\alpha^2}{2} \int_0^t Z_s ds \right) + \underbrace{\mathbb{E} \left( \alpha \int_0^t Z_s dW_s \right)}_{=0} \\ &= 1 + \frac{\alpha^2}{2} \int_0^t \mathbb{E}(Z_s) ds \end{aligned}$$

Let  $m(t) = \mathbb{E}(Z_t)$ , then

$$\begin{cases} \frac{dm}{dt} = \frac{\alpha^2}{2} m(t) \\ m(0) = 1 \end{cases}$$

Which has the solution  $m(t) = e^{\frac{\alpha^2}{2} t}$

#### 4.2. Multi-dimensional Ito formula.

Assume  $dX_t^i = \mu_t^i dt + \sum_{j=1}^d \sigma_t^{ij} dW_t^j$  where  $W^i$  are  $d$  independent Brownian motions.

On a matrix form:

$$\underbrace{dX_t}_{n \times 1} = \underbrace{\mu_t}_{n \times 1} dt + \underbrace{\sigma_t}_{n \times d} \underbrace{dW_t}_{d \times 1}$$

Let  $Z_t = f(t, X_t)$  where  $f : [0, \infty] \times \mathbb{R}^2 \rightarrow \mathbb{R}$  is  $C^{1,2}$

#### Sats 4.3: Itos multi-dimensional formula

$$dZ_t = \frac{\partial f}{\partial t} dt + \sum_{i=1}^n \frac{\partial f}{\partial x_i} dX_t^i + \frac{1}{2} \sum_{i,j=1}^n \frac{\partial^2 f}{\partial x_i \partial x_j} dX_t^i dX_t^j$$

Where

- $dW_t^i dW_t^j = 0$  if  $i \neq j$
- $(dW_t^i)^2 = dt$
- $(dt)^2 = dt dW_t = 0$

**Alternatively**

$$dZ_t = \left( \frac{\partial f}{\partial t} + \sum_{i=1}^n \mu_t^i \frac{\partial f}{\partial x_i} + \frac{1}{2} \sum_{i,j=1}^n C_t^{i,j} \frac{\partial^2 f}{\partial x_i \partial x_j} \right) dt + \sum_{i=1}^n \frac{\partial f}{\partial x_i} \sigma_t^i dW_t$$

Where  $C = \sigma \sigma^*$  and  $\sigma^i$  is the  $i$ :th row of  $\sigma$

Indeend,

$$\begin{aligned} dX_t^i dX_t^j &= \left( \sum_{k=1}^d \sigma^{ik} dW_t^k \right) \left( \sum_{l=1}^d \sigma^{jl} dW_t^l \right) \\ &= \left( \sum_{k=1}^d \sigma^{ik} \sigma^{jl} \right) dt \\ &= (\sigma \sigma^*)^{ij} dt \end{aligned}$$

**Example:**

If  $\begin{cases} dX_t = \alpha X_t dt + \sigma X_t dW_t \\ dY_t = \gamma Y_t dt + \delta Y_t dV_t \end{cases}$  and  $Z_t = X_t Y_t$ ; find  $dZ_t$

Itos formula yields

$$\begin{aligned} dZ_t &= Y_t dX_t + X_t dY_t + \frac{1}{2} \cdot 2 dX_t dY_t \\ &= (\alpha + \gamma) Z_t dt + Z_t (\sigma dW_t + \delta dV_t) \end{aligned}$$

Setting  $\bar{W}_t = \frac{1}{\sqrt{\sigma^2 + \delta^2}} (\sigma W_t + \delta V_t)$ , then  $\bar{W}$  is a Brownian Motion and

$$dZ_t = (\alpha + \gamma) Z_t dt + \sqrt{\sigma^2 + \delta^2} Z_t d\bar{W}_t$$

## 5. CORRELATED BROWNIAN MOTIONS

Let  $\bar{W} = \begin{bmatrix} \bar{W}^1 \\ \vdots \\ \bar{W}^d \end{bmatrix}$  where  $\bar{W}^1, \dots, \bar{W}^d$  are independent

Consider  $W = \delta \bar{W}$  where

$$\delta = \begin{bmatrix} \delta_{11} & \cdots & \delta_{1d} \\ \vdots & \vdots & \vdots \\ \delta_{d1} & \cdots & \delta_{dd} \end{bmatrix} = \underbrace{\begin{bmatrix} \delta_1 \\ \vdots \\ \delta_d \end{bmatrix}}_{\text{Row vectors with } \|\delta_i\| = 1}$$

Here  $\|\delta_i\| = \sqrt{\delta_{i1}^2 + \cdots + \delta_{id}^2}$ .  
So  $W^i$  is a Brownian motion.

Moreover,

$$\begin{aligned} dW_t^i dW_t^j &= \left( \sum_{k=1}^d \delta_{ik} d\bar{W}_t^k \right) \left( \sum_{l=1}^d \delta_{jl} d\bar{W}_t^l \right) \\ &= \sum_{k=1}^d \delta_{ik} \delta_{jk} dt = (\delta \delta^*)_{ij} dt \end{aligned}$$

**Definition 5.8 Correlated Wiener Process**

$W_t$  as constructed above is a  $d$ -dimensional *correlated Wiener process* with correlation matrix  $\rho = \delta \delta^*$

**Sats 5.4: Itos formula, correlated version**

If  $W_t$  is a correlated Wiener process as above, and

$$\underbrace{dX_t}_{n \times 1} = \underbrace{\mu_t}_{n \times 1} dt + \underbrace{\sigma_t}_{n \times d} \underbrace{dW_t}_{d \times 1}$$

satisfies

$$dZ_t = \frac{\partial f}{\partial t} dt + \sum_{i=1}^n \frac{\partial f}{\partial x_i} dX_t^i + \frac{1}{2} \sum_{i,j=1}^n \frac{\partial^2 f}{\partial x_i \partial x_j} dX_t^i dX_t^j$$

where

- $(dt)^2 = dt dW^i = 0$
- $dW^i dW^j = \rho_{ij} dt$

**Example:**

Given  $\bar{W} = \begin{bmatrix} \bar{W}^1 \\ \bar{W}^2 \end{bmatrix}$  (where  $\bar{W}^1, \bar{W}^2$  are independent), construct  $W = \begin{bmatrix} W^1 \\ W^2 \end{bmatrix}$  with correlation matrix

$$\rho = \begin{bmatrix} 1 & \rho_0 \\ \rho_0 & 1 \end{bmatrix}$$

Note that  $\delta = \begin{bmatrix} 1 & 0 \\ \rho_0 & \sqrt{1 - \rho_0^2} \end{bmatrix}$  satisfies  $\rho \rho^* = \begin{bmatrix} 1 & \rho_0 \\ \rho_0 & 1 \end{bmatrix} = \rho$

Thus  $W = \begin{bmatrix} \bar{W}^1 \\ \rho_0 \bar{W}^1 + \sqrt{1 - \rho_0^2} \bar{W}^2 \end{bmatrix}$  is a correlated Wiener process with correlated matrix  $\delta$

What other choices for  $\delta$  are possible?

## 6. STOCHASTIC DIFFERENTIAL EQUATIONS

Let

- a  $d$ -dimensional Brownian motion  $W$
- $\mu : [0, \infty) \times \mathbb{R}^n \rightarrow \mathbb{R}^n$
- $\sigma : [0, \infty) \times \mathbb{R}^n \rightarrow \mathbb{R}^{n \times d}$
- $x_0 \in \mathbb{R}^n$

be given. A *stochastic differential equation* is an equation at the form

$$\begin{cases} dX_t = \mu(t, X_t)dt + \sigma(t, X_t)dW_t \\ X_0 = x_0 \end{cases} \quad (1)$$

Or, equivalently,

$$X_t = x_0 + \int_0^t \mu(s, X_s)ds + \int_0^t \sigma(s, X_s)dW_s$$

**Sats 6.5**

Assume

$$\|\mu(t, x) - \mu(t, y)\| + \|\sigma(t, x) - \sigma(t, y)\| \leq K \|x - y\|$$

and  $\|\mu(t, x)\| + \|\sigma(t, x)\| \leq K \|x\|$  for some  $K$

Then there exists a unique solution  $X_t$  to the SDE (1). Moreover,

1.  $X$  is  $\mathcal{F}^W$ -adapted
2.  $X_t$  has continuous trajectories
3.  $X$  is a Markov process

## 7. GEOMETRIC BROWNIAN MOTION

Consider

$$\begin{cases} dX_t = \alpha X_t dt + \sigma X_t dW_t & \alpha, \sigma \text{ constants} \\ X_0 = x \end{cases}$$

**Anmärkning:**

If  $\sigma = 0$ , then  $dX_t = \alpha X_t dt$  so  $X_t = x_0 e^{\alpha t}$

Let  $Z_t = \ln(X_t)$ . Then

$$dZ_t \stackrel{\text{Ito}}{=} \frac{1}{X_t} dX_t - \frac{1}{2} \frac{1}{X_t^2} (dX_t)^2 = \left( \alpha - \frac{\sigma^2}{2} \right) dt + \sigma dW_t$$

so  $Z_t = \ln(x_0) + \left( \alpha - \frac{\sigma^2}{2} \right) t + \sigma W_t$  and  $X_t = e^{Z_t} = x_0 e^{\left( \alpha - \frac{\sigma^2}{2} \right) t + \sigma W_t}$

Moreover,

$$\mathbb{E}(X_t) = x_0 + \mathbb{E} \left[ \int_0^t \alpha X_s ds \right] + \underbrace{\mathbb{E} \left[ \int_0^t \sigma X_s dW_s \right]}_{=0}$$

So if  $m(t) = \mathbb{E}(X_t)$ , we find  $\begin{cases} \frac{dm}{dt} = \alpha m(t) \\ m(0) = x_0 \end{cases}$

Thus  $m(t) = x_0 e^{\alpha t}$

**Results:**

The solution of  $\begin{cases} dX_t = \alpha X_t dt + \sigma X_t dW_t \\ X_0 = x_0 \end{cases}$  is  $X_t = x_0 \exp \left\{ \left( \alpha - \frac{\sigma^2}{2} \right) t + \sigma W_t \right\}$

Moreover,  $\mathbb{E}(X_t) = x_0 e^{\alpha t}$

**Example:**

Consider the SDE  $\begin{cases} dX_t = -X_t dt + dW_t \\ X_0 = x \end{cases}$  (this is a mean-reverting Ornstein-Uhlenbeck process)

The trick here is to let  $Y_t = e^t X_t$ . Then

$$\begin{aligned} dY_t &= e^t X_t dt + e^t dX_t = e^t dW_t \\ \Rightarrow Y_t &= x + \int_0^t e^s dW_s \end{aligned}$$

Thus  $X_t = e^{-t} Y_t = x e^{-t} + e^{-t} \int_0^t e^s dW_s$   
Moreover  $\mathbb{E}(X_t) = x e^{-t}$

### Definition 7.9 Diffusion process

The solution  $X$  of an SDE

$$\begin{cases} dX_t = \mu(t, X_t) dt + \sigma(t, X_t) dW \\ X_0 = x_0 \end{cases}$$

is called a *diffusion process*.

$\mu$  is called the *drift* and  $\sigma$  is the *diffusion coefficient*

## 8. PARTIAL DIFFERENTIAL EQUATIONS

Consider the following *terminal value problem*:

Given function  $\sigma, \mu, \phi$ , find a function  $F(t, x)$  such that

$$\begin{cases} \frac{\partial F}{\partial t}(t, x) + \frac{\sigma^2(t, x)}{2} \frac{\partial^2 F}{\partial x^2}(t, x) + \mu(t, x) \frac{\partial F}{\partial x}(t, x) = 0 \\ F(T, x) = \phi(x) \end{cases} \quad (2)$$

If  $F(t, x)$  satisfies (2), define  $X_s$  by  $\begin{cases} dX_s = \mu(s, X_s) ds + \sigma(s, X_s) dW_s \\ X_t = x \end{cases}$  and let  $Z_s = F(s, X_s)$ . Then

$$\begin{aligned} dZ_s &\stackrel{\text{Ito}}{=} \frac{\partial F}{\partial s} ds + \frac{\partial F}{\partial x} dX_s + \frac{1}{2} \frac{\partial^2 F}{\partial x^2} (dX_s)^2 \\ &= \underbrace{\left( \frac{\partial F}{\partial s} + \mu \frac{\partial F}{\partial x} + \frac{\sigma^2}{2} \frac{\partial^2 F}{\partial x^2} \right)}_{=0} ds + \sigma \frac{\partial F}{\partial x} dW_s \\ &= \sigma \frac{\partial F}{\partial x} dW_s \end{aligned}$$

Integrate:

$$Z_T = Z_t + \int_t^T \sigma(s, X_s) \frac{\partial F}{\partial x}(s, X_s) dW_s$$

Take expectation:

$$\mathbb{E}(Z_T) = Z_t = F(t, x) = \mathbb{E}(F(T, X_T)) \stackrel{*}{=} \mathbb{E}(\phi(X_T))$$

We write  $F(t, x) = \mathbb{E}_{t,x}(\phi(X_T))$  (to indicate that  $X_t = x$ )

We have thus proved the following:

### Sats 8.6: Feynman-Kac

If  $F(t, x)$  satisfies

$$\begin{cases} \frac{\partial F}{\partial t} + \frac{\sigma^2(t, x)}{2} \frac{\partial^2 F}{\partial x^2} + \mu(t, x) \frac{\partial F}{\partial x} = 0 & (t < T) \\ F(t, x) = \phi(x) \end{cases}$$

then  $F(t, x) = \mathbb{E}_{t,x}(\phi(X_T))$  where  $\begin{cases} dX_s = \mu(s, X_s) ds + \sigma(s, X_s) dW_s \\ X_t = x \end{cases}$

**Example:**

Solve the PDE 
$$\begin{cases} \frac{\partial F}{\partial t} + \frac{\sigma^2}{2} \frac{\partial^2 F}{\partial x^2} = 0 \\ F(T, x) = x^2 \end{cases}$$

**Solution:**

Let  $X_s$  be the solution of 
$$\begin{cases} dX_s = \sigma dW_s \\ X_t = x \end{cases} \quad \text{i.e } X_s = x + \sigma(W_s - W_t)$$

By Feynman-Kac:

$$\begin{aligned} F(t, x) &= \mathbb{E}_{t,x}(X_T^2) = \mathbb{E}((x + \sigma(W_T - W_t))^2) \\ &= x^2 + 2x\sigma\mathbb{E}(W_T - W_t) + \sigma^2\mathbb{E}((W_T - W_t)^2) \\ &= x^2 + \sigma^2(T - t) \end{aligned}$$

$$F(t, x) = x^2 + \sigma^2(T - t)$$

### Sats 8.7: Feynman-Kac in higher dimensions + discounting

Assume that  $F : [0, T] \times \mathbb{R}^n \rightarrow \mathbb{R}$  satisfies

$$\begin{cases} \frac{\partial F}{\partial t} + \frac{1}{2} \sum_{i,j=1}^n C_{i,j}(t, x) \frac{\partial^2 F}{\partial x_i \partial x_j} + \sum_{i=1}^n \mu_i(t, x) \frac{\partial F}{\partial x_i} - rF(t, x) = 0 \\ F(T, x) = \phi(x) \end{cases}$$

Where  $C(t, x) = \sigma(t, x)\sigma^*(t, x)$  for some matrix  $\sigma$  ( $n \times d$ )

Then  $F(t, x) = e^{-r(T-t)} \mathbb{E}_{t,x}(\phi(X_T))$  where

$$\begin{cases} dX_s = \mu(s, X_s)ds + \sigma(s, X_s)dW_s \\ X_t = x \end{cases}$$

### Bevis 8.1

Let  $Z_s = e^{-r(s-t)} F(s, X_s)$ . Then

$$dZ_s \stackrel{\text{Ito}}{=} e^{-r(s-t)} \underbrace{\left( \frac{\partial F}{\partial s} + \frac{1}{2} \sum_{i,j=1}^n C_{ij} \frac{\partial^2 F}{\partial x_i \partial x_j} + \sum_{i=1}^n \mu_i \frac{\partial F}{\partial x_i} - rF \right)}_{=0} ds + e^{-r(s-t)} \sum_{i=1}^n \frac{\partial F}{\partial x_i} \sigma_i dW_s$$

So

$$Z_T = \underbrace{Z_t}_{F(t,x)} + \int_t^T \dots dW_s = e^{-r(T-t)} \phi(X_T)$$

Thus  $F(t, x) = e^{-r(T-t)} \mathbb{E}(\phi(X_T))$  □

**Example:**

Solve the PDE 
$$\begin{cases} \frac{\partial F}{\partial t} + \frac{\sigma^2}{2} \frac{\partial^2 F}{\partial x^2} + \frac{\delta^2}{2} \frac{\partial^2 F}{\partial y^2} - rF = 0 \\ F(T, x, y) = xy \end{cases}$$

**Solution:**

Here  $C = \begin{bmatrix} \sigma^2 & 0 \\ 0 & \delta^2 \end{bmatrix}$  so  $\sigma = \begin{bmatrix} \sigma & 0 \\ 0 & \delta \end{bmatrix}$  satisfies  $C = \sigma\sigma^*$

$$d \begin{bmatrix} X_t \\ Y_t \end{bmatrix} = \begin{bmatrix} \sigma & 0 \\ 0 & \delta \end{bmatrix} \begin{bmatrix} dW_t^1 \\ dW_t^2 \end{bmatrix} \Rightarrow \begin{cases} X_t = x + \sigma(W_T^1 - W_t^1) \\ Y_t = y + \delta(W_T^2 - W_t^2) \end{cases}$$



Feynman-Kac gives

$$F(t, x, y) = \mathbb{E}_{t, x, y} \left( e^{-r(T-t)} X_T Y_T \right) = e^{-r(T-t)} \mathbb{E} \left( (x + \sigma(W_T^1 - W_t^1)) (y + \delta(W_T^2 - W_t^2)) \right) \\ \stackrel{\text{indep}}{=} e^{-r(T-t)} \mathbb{E} (x + \sigma(W_T^1 - W_t^1)) \mathbb{E} (y + \delta(W_T^2 - W_t^2)) = e^{-r(T-t)} xy$$

par Answer is therefore  $F(t, x, y) = e^{-r(T-t)} xy$

### Definition 8.10 Infinitesimal Operator

The differential operator

$$\mathcal{A} = \frac{1}{2} \sum_{i,j=1}^n C_{ij} \frac{\partial^2}{\partial x_i \partial x_j} + \sum_{i=1}^n \mu_i \frac{\partial}{\partial x_i}$$

is called the *infinitesimal operator* of  $X$

**Itos formula:**

If  $Z_t = f(t, X_t)$ , then  $dZ_t = \left( \frac{\partial f}{\partial t} + \mathcal{A}f \right) dt + \sum_{i=1}^n \frac{\partial f}{\partial x_i} \sigma_i dW_t$

## 9. PORTFOLIO DYNAMICS

Let the time axis be discrete

**Definition 9.11**

- $N$  = the number of different assets
- $S_n^i$  = the price of one unit of asset  $i$  at time  $n$
- $h_n^i$  = the number of units of asset  $i$  bought at time  $n$
- $h_n = (h_n^1, h_n^2, \dots, h_n^N)$  is a *portfolio*
- $V_n$  = the value of a portfolio  $h_n$  at time  $n = \sum_{i=1}^N h_n^i S_n^i = h_n \cdot S_n$

The interpretation:

- At time  $n-$  we have an old portfolio  $h_{n-1}$  from the previous period
- At time  $n$ ,  $S_n$  becomes observable
- At time  $n$ , after observing  $S_n$ , we chose  $h_n$

**Definition 9.12 Budget equation**

$$h_n \cdot S_{n+1} = h_{n+1} \cdot S_{n+1}$$

**Notation:** If  $\{x_n\}_{n=0}^\infty$  is a sequence of real numbers, let  $\Delta x_n = x_{n+1} - x_n$ .  
The budget equation becomes  $S_{n+1} \cdot \Delta h_n = 0$

Recall  $Y_n = h_n \cdot S_n$

Since  $\Delta V_n = h_{n+1} \cdot S_{n+1} - h_n \cdot S_n = h_{n+1} \cdot S_{n+1} - h_n \cdot S_{n+1} + h_n \cdot S_{n+1} - h_n \cdot S_n$   
 $= S_{n+1} \cdot \Delta h_n + h_n \cdot \Delta S_n$

we have  $\Delta V_n = h_n \cdot \Delta S_n$  if the budget equation is fulfilled.

Below we use this relation to *define* what is meant by a self-financing portfolio in continuous time.

**Definition 9.13**

Let  $\{S_t \mid t \geq 0\}$  be an  $N$ -dimensional process

- A *portfolio*  $h$  is an  $\mathcal{F}^s$ -adapted  $N$ -dimensional process
- $h$  is *Markovian* if  $h_t = h(t, S_t)$  for some function  $h$
- The *value process*  $V^h$  of  $h$  is

$$V_t^h = \sum_{i=1}^N h_t^i S_t^i = h_t \cdot S_t$$

- A portfolio  $h$  is *self-financing* if

$$dV_t^h = h_t \cdot dS_t$$

- For a given portfolio  $h$ , the corresponding *relative portfolio*  $w$  is

$$w_t^i = \frac{h_t^i S_t^i}{V_t^h} \quad i = 1, \dots, N$$

Note that  $\sum_{i=1}^N w_t^i = 1$ .

Also,  $h$  is self-financing if and only if  $dV_t^h = V_t^h \sum_{i=1}^N \frac{\partial w_t^i}{\partial S_t^i} dS_t^i$

## 10. ARBITRAGE PRICING

In this chapter,  $N = 2$  (two assets):

$$dB_t = rB_t dt$$

This is a risk-free asset, think bank account and  $r$  is a constant interest rate, and

$$dS_t = \mu(t, S_t)S_t dt + \sigma(t, S_t)S_t dW_t$$

is a risky asset, think stock price

**Remarks:**

1.  $B_t = B_0 e^{rt}$
2.  $\mu$  (local mean rate of return) and  $\sigma$  (volatility) are functions of  $t$  and current stock price
3. In the Black-Scholes model,  $\mu$  and  $\sigma$  are constants

The aim is to find a "fair" value of options written on  $S$

Options are also called *financial derivatives*

**Definition 10.14 European Call Option**

A *European call option* with strike price  $K$  and maturity date  $T$  on the underlying asset  $S$  is a contract such that the holder (owner) at time  $T$  has the right, but not the obligation to buy one share of  $S$  at price  $K$  from the option writer (seller)

**Remarks:**

- A *European put option* gives the right (but not the obligation) to *sell* one share of  $S$  at time  $T$  at price  $K$
- An *American call/put* gives the right to buy/sell at *any* time before  $T$

**Definition 10.15**

A *contingent claim with maturity  $T$*  (or a  *$T$ -claim*) is a random variable  $X \in \mathcal{F}_T^S$   
A contingent claim is *simple* is  $X = \phi(S_T)$  for some *contract function* (or payoff function)  $\phi$

**Example:**

For a European call option,  $\phi(x) = (x - K)^+ = \max\{x - K, 0\}$

Indeed, if  $S_T \geq K$ , then buy at price  $K$  and make profit  $S_T - K$ . If  $S_T < K$ , do not exercise the option.

For a European put option  $\phi(x) = (K - x)^+$

We will determine the price  $\pi(t, X)$  of a  $T$ -claim  $X$  at time  $t$  by requiring the market to be *arbitrage-free*.

**Definition 10.16**

A self-financing portfolio  $h$  is an *arbitrage* if 
$$\begin{cases} V_0^h = 0 \\ \mathbb{P}(V_T^h \geq 0) = 1 \\ \mathbb{P}(V_T^h > 0) > 0 \end{cases}$$

The market is *arbitrage-free* if no arbitrage exists.

**Example:**

$$\begin{cases} dS_t^1 = dt + dW_t \\ dS_t^2 = dW_t \\ dB_t = 0 \end{cases} \quad \text{is not arbitrage free}$$

$$\begin{cases} dS_t^1 = dt + dW_t^1 \\ dS_t^2 = dW_t^2 \\ dB_t = 0 \end{cases} \quad \text{is arbitrage free (first two lines indep)}$$

*Assumption:* The price process  $\Pi_t(X)$  is such that  $(B_t, S_t, \Pi_t(X))$  is arbitrage-free.

We also assume that all assets (including the option) can be sold/bought with no market frictions (no transaction costs, no liquidity constraints)

*Idea:* Create a self-financing portfolio of options and the stock such that its value process is locally risk-free (has no  $dW$ -term). The drift of the value must then coincide with the interest rate (otherwise arbitrage). This will give a condition on the price of the option.

Assume  $X = \phi(S_T)$  (simple  $T$ -claim) and that  $\Pi_t(X) = F(t, S_t)$  for some function  $F$ .

*New Notation:*  $F_t = \frac{\partial F}{\partial t}$ ,  $F_s = \frac{\partial F}{\partial s}$ ,  $F_{ss} = \frac{\partial^2 F}{\partial s^2}$

Then

$$\begin{aligned} dF(t, S_t) &\stackrel{\text{Ito}}{=} F_t dt + F_s dS_t + \frac{1}{2} F_{ss} (dS_t)^2 \\ &= \underbrace{\left( F_t + \frac{\sigma^2 S_t^2}{2} F_{ss} + \mu S_t F_s \right)}_{= \mu^F F} F(t, S_t) dt + \underbrace{\frac{\sigma S_t F_s}{F}}_{= \sigma^F} F dW_t \\ &= \mu^F F dt + \sigma^F F dW_t \end{aligned}$$

Let  $(w^S, w^F)$  be a self financing relative portfolio of stocks and options ( $w^S + w^F = 1$ ), and let  $V$  be its value process. Then

$$\begin{aligned} dV_t &= V_t \left( \frac{w^S}{S_t} dS_t + \frac{w^F}{F} dF_t \right) \\ &= (\mu w^S + \mu^F w^F) V_t dt + (\sigma w^S + \sigma^F w^F) V_t dW_t \end{aligned}$$

Let  $(w^S, w^F)$  be defined by

$$\left. \begin{aligned} w^S + w^F &= 1 \\ \sigma w^S + \sigma^F w^F &= 0 \end{aligned} \right\} \Leftrightarrow \begin{cases} w^S = \frac{\sigma^F}{\sigma^F - \sigma} \\ w^F = \frac{-\sigma}{\sigma^F - \sigma} \end{cases}$$

Then  $dV_t = \frac{\mu \sigma^F - \mu^F \sigma}{\sigma^F - \sigma} V_t dt$

By a no-arbitrage argument, we must have  $r = \frac{\mu \sigma^F - \mu^F \sigma}{\sigma^F - \sigma}$

$$\begin{aligned} \text{Here } \underbrace{r \sigma^F - r \sigma}_{= \frac{r \sigma S_t F_s}{F} - r \sigma} &= \underbrace{\mu \sigma^F - \mu^F \sigma}_{= \frac{\mu \sigma S_t F_s}{F} - \frac{\sigma(F_t + \mu S_t F_s) + \frac{-2 S_t^2}{2} F_{ss}}{F}} \\ r S_t F_s - r F &= \mu S_t F_s - F_t - \mu S_t F_s + \frac{\sigma^2}{2} S_t^2 F_{ss} \\ &= -F_t + \frac{\sigma^2}{2} S_t^2 F_{ss} \\ F_t + \frac{\sigma^2 S_t^2}{2} F_{ss} + r S_t F_s - r F &= 0 \end{aligned}$$

Since  $S_t$  can take any value,  $F$  must satisfy the PDE

$$F_t(t, s) + \frac{\sigma^2(t, s)}{2} s^2 F_{ss} + r s F_s(t, s) - r F(t, s) = 0$$

Also,  $\Pi_T(X) = F(T, S_T) = \phi(S_T)$ , so we also have  $F(T, S) = \phi(S_T)$

### Sats 10.8: Black-Sholes equation

$$\text{In the market } \begin{cases} dB_t = rB_t dt \\ dS_t = \mu(t, S_t)S_t dt + \sigma(t, S_t)S_t dW_t \end{cases}, \text{ the only arbitrage-free price of a } T\text{-claim } X = \phi(S_T) \text{ is } F(t, S_t), \text{ where } F(t, s) \text{ solves}$$

$$\begin{cases} F_t(t, s) + \frac{\sigma^2(t, s)}{2} s^2 F_{ss}(t, s) + r s F_s(t, s) - r F(t, s) = 0 \\ F(T, s) = \phi(s) \end{cases}$$

The solution to the BS-equation is by Feynman-Kac

$$F(t, s) = \mathbb{E}_{t,s} (\exp \{-r(T-t)\phi(S_T)\})$$

where

$$\begin{aligned} dS_u &= rS_u du + \sigma(u, S_u)S_u dW_u \\ S_t &= s \end{aligned} \tag{3}$$

we refer to

$$\begin{cases} dS_u = \mu(u, S_u)S_u du + \sigma(u, S_u)S_u dW_u \\ S_t = s \end{cases} \tag{4}$$

as the *P-dynamics* of  $S$  (the specification of  $S$  under the "physical measure"  $P$ ). (3) is referred to as the *Q-dynamics* of  $S$  ( $Q$  is the *pricing measure*, or the *martingale measure*)

### Sats 10.9

The arbitrage-free price of a simple  $T$ -claim  $X = \phi(S_T)$  is  $F(t, S_t)$  where

$$F(t, s) = \mathbb{E}_{t,s}^Q (\exp \{-r(T-t)\phi(S_T)\})$$

and the  $Q$ -dynamics of  $S$  are as in (3)

### Example:

In the standard BS-model (i.e constant  $\sigma$ ), what is the arbitrage-free price of the  $T$ -claim  $X = S_T^2$ ?

By risk-neutral valuation,  $F(t, s) = \exp \{-r(T-t)\} \mathbb{E}_{t,s}^Q (S_T^2)$

Let  $Y_u = S_u^2$ , then

$$dY_u = 2S_u dS_u + (dS_u)^2 \stackrel{dS_u = rS_u du + \sigma S_u dW_u}{=} (2r + \sigma^2)Y_u du + 2\sigma Y_u dW_u$$

$Y$  is a gBm and thus

$$\mathbb{E}_{t,s}^Q (S_T^2) = \mathbb{E}^Q (Y_T) = s^2 \exp \{(2r + \sigma^2)(T-t)\}$$

Which is the price of  $X$  at time  $t$

### Example:

What is the price of  $X = S_t$ ?

By risk-neutral valuation

$$F(t, s) = \exp \{-r(T-t)\} \mathbb{E}_{t,s}^Q (S_T) = s$$

So the price at time  $t$  is  $S_t$

### Remark:

In time-homogenous models (such as the BS-model), the relevant quantity is time  $T-t$  left to maturity.

### Example: Binary option

In the standard BS-model, find the value of  $X = \phi(S_T)$  where  $\phi(x) = \begin{cases} 1 & \text{if } x \geq K \\ 0 & \text{if } x < K \end{cases}$

$$\begin{aligned}
F(0, s) &= \exp \{-rT\} \mathbb{E}_{0,s}^Q (I_{\{S_T \geq K\}}) = \exp \{-rT\} Q(S_T \geq K) \\
&= \exp \{-rT\} Q(\text{sexp} \left\{ \left(r - \frac{\sigma^2}{2}\right)T + \sigma W_T \right\} \geq K) \\
&= \exp \{-rT\} Q \left( \frac{1}{\sqrt{T}} W_T \geq \frac{\ln \left( \frac{K}{S} \right) - \left(r - \frac{\sigma^2}{2}\right)T}{\sigma \sqrt{T}} \right) \\
&= \exp \{-rT\} Q \left( \frac{1}{\sqrt{T}} W_t \leq \frac{\ln \left( \frac{S}{K} \right) + \left(r - \frac{\sigma^2}{2}\right)T}{\sigma \sqrt{T}} \right) \\
&= \exp \{-rT\} N \left( \frac{\ln \left( \frac{S}{K} \right) + \left(r - \frac{\sigma^2}{2}\right)T}{\sigma \sqrt{T}} \right)
\end{aligned}$$

Where  $N(x) \sim N(0, 1)$ , and the last line is the price at time  $t$

**Example:**

What is the price of a European call option  $X = (S_T - K)^+$ ? In the standard BS-model

$$\begin{aligned}
F(0, s) &= \exp \{-rT\} \mathbb{E}_{0,s}^Q ((S_T - K)^+) = \exp \{-rT\} \mathbb{E}^Q \left( \left( \text{sexp} \left\{ \left(r - \frac{\sigma^2}{2}\right)T + \sigma W_T \right\} - K \right)^+ \right) \\
&= \exp \{-rT\} \int_a^\infty \left( \text{sexp} \left\{ \left(r - \frac{\sigma^2}{2}\right)T + \sigma \sqrt{T}x \right\} - K \right) \frac{1}{\sqrt{2\pi}} \exp \left\{ -\frac{x^2}{2} \right\} dx \quad a = \frac{\ln \left( \frac{K}{S} \right) - \left(r - \frac{\sigma^2}{2}\right)T}{\sigma \sqrt{T}} \\
&\quad s \int_a^\infty \frac{1}{\sqrt{2\pi}} \exp \left\{ -\frac{(x - \sigma \sqrt{T})^2}{2} \right\} dx - K \exp \{-rT\} N(-a) \\
&= s \int_{a - \sigma \sqrt{T}}^\infty \frac{1}{\sqrt{2\pi}} \exp \left\{ -\frac{x^2}{2} \right\} dx - K \exp \{-rT\} N(-a) \\
&= sN(\sigma \sqrt{T} - a) - K \exp \{-rT\} N(-a)
\end{aligned}$$

Here we used the fact that the normal-distribution has symmetric tails

**Sats 10.10: Black-Scholes formula**

In the standard BS-model, the price of a European call option is  $F(t, S_t)$ , where

$$F(t, s) = sN(d_1) - K \exp \{-r(T - t)\} N(d_2)$$

and

$$\begin{cases} d_1 = \frac{\ln \left( \frac{S}{K} \right) + \left(r + \frac{\sigma^2}{2}\right)(T - t)}{\sigma \sqrt{T - t}} \\ d_2 = d_1 - \sigma \sqrt{T - t} \end{cases}$$

Consider  $F(0, s) = sN(d_1) - K \exp \{-rT\} N(d_2)$  as above, then we have

$$F(0, s) = \mathbb{E}_{0,s}^Q (\exp \{-rT\} (S_T - K)^+) \leq \mathbb{E}_{0,s}^Q (\exp \{-rT\} (S_T)) = s$$

and

$$F(0, s) = \mathbb{E}_{0,s}^Q (\exp \{-rT\} (S_T - K)^+) \geq \mathbb{E}_{0,s}^Q (\exp \{-rT\} (S_T - K)) = s - K \exp \{-rT\}$$

We shall see below that  $F(0, s) = F(0, s; \sigma)$  is increasing in  $\sigma$

**Remark:**

What about the put option?

$$\mathbb{E}_{0,s}^Q (\exp \{-rT\} (K - S_T)^+) = \text{similar to above}$$

Alternatively,  $(K - s)^+ = K - s + (s - K)^+$ . We have priced  $(s - K)^+$ , and  $s$ , so  $p(0, s) = K \exp \{-rT\} - s + c(0, s)$  where  $p$  is the put price and  $c$  is the call price. This relation is called the *put-call parity*. Thus,

$$\begin{aligned} p(0, s) &= K \exp \{-rT\} - s + sN(d_1) - K \exp \{-rT\} N(d_2) \\ &= K \exp \{-rT\} \underbrace{(1 - N(d_2))}_{=N(-d_2)} - s \underbrace{(1 - N(d_1))}_{=N(-d_1)} \end{aligned}$$

### Sats 10.11

Let  $F(t, s)$  be the pricing function of a simple  $T$ -claim  $X = \phi(S_T)$  in the standard BS-model.

If  $\phi$  is convex, then:

1.  $F(t, s)$  is convex in  $s$
2.  $F(t, s)$  is increasing in  $\sigma$

### Bevis 10.1

$$F(0, s) = \exp \{-rT\} \int_{\mathbb{R}} \phi \left( \exp \left\{ \left( r - \frac{\sigma^2}{2} \right) T + \sigma \sqrt{T} x \right\} \right) \frac{1}{\sqrt{2\pi}} \exp \left\{ -\frac{x^2}{2} \right\} dx$$

1.

$$F_{ss} = \exp \{-rT\} \int_{\mathbb{R}} \phi'' \left( \exp \left\{ \left( r - \frac{\sigma^2}{2} \right) T + \sigma \sqrt{T} x \right\} \right) \exp 2 \left\{ \left( r - \frac{\sigma^2}{2} \right) T + \sigma \sqrt{T} x \right\} \frac{1}{\sqrt{2\pi}} \exp \left\{ -\frac{x^2}{2} \right\} dx \geq 0$$

2.

$$\begin{aligned} \frac{\partial F}{\partial \sigma} &= \int_{\mathbb{R}} \phi' \left( \exp \left\{ \left( r - \frac{\sigma^2}{2} \right) T + \sigma \sqrt{T} x \right\} \right) \exp \left\{ -\frac{\sigma^2 T}{2} + \sigma \sqrt{T} x \right\} \sqrt{T} (x - \sigma \sqrt{T}) \frac{1}{\sqrt{2\pi}} \exp \left\{ -\frac{x^2}{2} \right\} dx \\ &= s \sqrt{T} \int_{\mathbb{R}} \phi' \left( \exp \left\{ \left( r - \frac{\sigma^2}{2} \right) T + \sigma \sqrt{T} x \right\} \right) (x - \sigma \sqrt{T}) \exp \left\{ -\frac{(x - \sigma \sqrt{T})^2}{2} \right\} \frac{1}{\sqrt{2\pi}} dx \\ &\stackrel{\text{parts.}}{=} s \sqrt{T} \int_{\mathbb{R}} \phi'' \left( \exp \left\{ \left( r - \frac{\sigma^2}{2} \right) T + \sigma \sqrt{T} x \right\} \right) \sigma \sqrt{T} \exp \left\{ -\frac{(x - \sigma \sqrt{T})^2}{2} \right\} \frac{1}{\sqrt{2\pi}} dx \geq 0 \end{aligned}$$

□

### 10.1. Drift estimation.

Assume  $X_t = \mu t + \sigma W_t$  and we want a confidence interval for  $\mu$ . An estimate for  $\mu$  is  $\hat{\mu} = \frac{X_t}{t} \in N\left(\mu, \frac{\sigma}{\sqrt{t}}\right)$  and a confidence interval is

$$\left(\hat{\mu} - \frac{\sigma}{\sqrt{t}} \cdot 1.96, \hat{\mu} + \frac{\sigma}{\sqrt{t}} \cdot 1.96\right)$$

If one wants a certain precision  $\Delta\mu$  so that  $\mathbb{P}(\mu \in (\hat{\mu} - \Delta\mu, \hat{\mu} + \Delta\mu)) = 0.95$ , one needs

$$\frac{2\sigma}{\sqrt{t}} = \Delta\mu \quad \Leftrightarrow \quad t = \frac{4\sigma^2}{(\Delta\mu)^2}$$

Plug in reasonable values  $\left. \begin{array}{l} \sigma = 0.3 \\ \Delta\mu = 0.06 \end{array} \right\} \Rightarrow t = 100 \text{ years!}$

#### Remark:

When pricing options, the drift of the stock needs not be estimated (since under the pricing measure  $Q$ , the drift is  $r$ )

## 11. VOLATILITY

In the BS-formula,  $s, r, t$  are observable,  $T, K$  are specified in the contract and  $\sigma$  is not directly observable. All are needed.

There are 2 approaches, one using *historic volatility* and one using *implied volatility*.

### 11.1. Historic volatility.

If  $dS_t = \mu S_t dt + \sigma S_t dW_t$ , then sample  $S$  at  $n + 1$  time points and let

$$\xi_i = \ln\left(\frac{S_{t_i}}{S_{t_{i-1}}}\right) = \left(\mu - \frac{\sigma^2}{2}\right)\Delta t + \sigma(W_{t_i} - W_{t_{i-1}}) \sim N\left(\left(\mu - \frac{\sigma^2}{2}\right)\Delta t, \sigma\sqrt{\Delta t}\right)$$

An estimate of  $\sigma^2$  is then  $S^2 = \frac{\sum_{i=1}^n (\xi_i - \bar{\xi})^2}{(n-1)\Delta t}$  where  $\bar{\xi} = \frac{1}{n} \sum_{i=1}^n \xi_i$

### 11.2. Implied volatility.

Let  $p$  be the price in the market of a certain call option (maturity  $T$ , with strike price  $K$ ). Find  $\sigma$  such that  $p = \text{BS}(s, t, T, r, \sigma, K)$  where BS denotes the Black-Scholes formula

This  $\sigma$  is called *implied volatility*

#### Remark:

Recall that the BS-formula is increasing in  $\sigma$

If gBm is the correct model (i.e option prices are calculated using the BS-formula), then the *same* implied volatility would be obtained for different  $K$  and  $T$

## 12. COMPLETENESS AND HEDGING

### Definition 12.17

A  $T$ -claim  $X$  can be *replicated* if there exists a self-financing portfolio  $h$  with  $\mathbb{P}(V_T^h = X) = 1$ .  
If every  $T$ -claim can be replicated then the market is *complete*

### Sats 12.12

Assume that a  $T$ -claim  $X$  can be replicated using  $h$ . Then the only possible arbitrage-free price of  $X$  is  $\Pi_t(X) = V_t^h$



**Bevis 12.1**

If for example  $\Pi_t(X) < V_t^h$  for some  $t$ ; sell the portfolio and buy the claim  $\Rightarrow$  arbitrage  $\square$

We now specialize to the model

$$\begin{cases} dB_t = rB_t dt \\ dS_t = \mu(t, S_t)S_t dt + \sigma(t, S_t)S_t dW_t \end{cases} \quad (5)$$

with  $\sigma(t, s) > 0$

**Sats 12.13**

The model (5) is complete

We will prove a simpler result, namely that all *simple*  $T$ -claims can be replicated.

Recall that the value  $\Pi_t(X)$  of a simple  $T$ -claim  $X = \phi(S_T)$  is  $F(t, S_t)$  where  $F(t, s)$  is the pricing function. Thus

$$\begin{aligned} d\Pi_t &= F_t dt + F_s dS_t + \frac{1}{2} F_{ss} (dS_t)^2 \\ &= \left( F_t + \frac{\sigma^2}{2} S_t^2 F_{ss} \right) dt + F_s dS_t \end{aligned}$$

Moreover, a portfolio  $h = (h^B, h^S)$  is self-financing if  $dV_t^h = h_t^B dB_t + h_t^S dS_t$ . Choose  $h_t^S = F_s(t, S_t)$

**Sats 12.14**

Let  $X = \phi(S_T)$  and define  $F(t, s)$  by

$$\begin{cases} F_t + \frac{\sigma^2 S^2}{2} F_{ss} + r s F_s - r F = 0 \\ F(T, s) \phi(s) \end{cases}$$

Define  $h = (h^B, h^S)$  by

$$\begin{cases} h_t^B = \frac{F(t, S_t) - S_t F_s(t, S_t)}{B_t} \\ h_t^S = F_s(t, S_t) \end{cases}$$

Then  $h$  replicates  $X$  and  $\Pi_t(X) = V_t^h = F(t, S_t)$

**Bevis 12.2**

$V_t^h = h_t^B B_t + h_t^S S_t = F(t, S_t)$ , so

$$\begin{aligned} dV_t^h &= F_t dt + F_s dS_t + \frac{1}{2} F_{ss} (dS_t)^2 \\ &= \left( F_t + \frac{\sigma^2}{2} S_t^2 F_{ss} \right) dt + F_s dS_t \\ &\stackrel{\text{BS PDE}}{=} r(F - S_t F_s) dt + F_s dS_t = h_t^B dB_t + h_t^S dS_t \end{aligned}$$

Thus  $h$  is self-financing. Since  $V_T^h = F(T, S_T) = \phi(S_T) = X$ ,  $h$  replicates  $X$ .

By no-arbitrage  $\Pi_t(X) = V_t^h = F(t, S_t)$   $\square$

**Example:**

If  $X = S_T$ , then  $F(t, s) = s$ , so  $h_t^S = F_s = 1$

**Example:**

For a call option (in the standard BS-model),  $F(0, s) = sN(d_1) - K \exp\{-rT\} N(d_2)$ , thus

$$F_S(0, s) = N(d_1) + \frac{1}{\sqrt{2\pi}} \left( s \exp\left\{-\frac{d_1^2}{2}\right\} - K \exp\{-rT\} \exp\left\{-\frac{d_2^2}{2}\right\} \right) \frac{\partial d_1}{\partial s}$$

Moreover,

$$s \exp\left\{-\frac{d_1^2}{2}\right\} - K \exp\{-rT\} \exp\left\{-\frac{d_2^2}{2}\right\} = \exp\left\{-\frac{d^2}{2}\right\} \left( s - K \exp\{-rT\} \exp\left\{-\frac{\sigma^2 T}{2}\right\} \exp\left\{\sigma\sqrt{T}d_1\right\} \right) = 0$$

so  $F_s(0, s) = N(d_1)$

**Remark:**

The derivative  $\Delta = F_s$  is called the *delta*.

In a replicating portfolio one should hold  $\Delta$  shares of  $S$  at each time.

If the pricing function is convex in  $S$ , then in order to replicate it then  $\Delta$  goes up then buy more stock. Conversely, sell off if the opposite.

**Example:**

For a call option in the standard BS-model

$$F(0, s) = sN(d_1) - K \exp\{-rT\} N(d_2)$$

Where 
$$\begin{cases} d_1 = \frac{\ln\left(\frac{s}{K}\right) + (r + \frac{\sigma^2}{2})T}{\sigma\sqrt{T}} \\ d_2 = \frac{\ln\left(\frac{s}{K}\right) + (r - \frac{\sigma^2}{2})T}{\sigma\sqrt{T}} \end{cases}$$

Thus

$$\begin{aligned} \Delta = F_s(0, s) &= N(d_1) + s\varphi(d_1) \frac{1}{s\sigma\sqrt{T}} - K \exp\{-rT\} \varphi(d_2) \frac{1}{s\sigma\sqrt{T}} \\ &= N(d_1) + \frac{1}{\sigma\sqrt{T}} \left( \varphi(d_1) - \frac{K}{s} \exp\{-rT\} \varphi(d_2) \right) \end{aligned}$$

Where

$$\begin{aligned} N(x) &= \int_{-\infty}^x \varphi(z) dz \\ \varphi(z) &= \frac{1}{\sqrt{2\pi}} \exp\left\{-\frac{z^2}{2}\right\} \end{aligned}$$

The claim is that we are left with 0 on the second term, we check:

$$\begin{aligned} &\frac{1}{\sqrt{2\pi}} \frac{\varphi(d_1) - \frac{K}{s} \exp\{-rT\} \varphi(d_2)}{s} \Big|_{d_2=d_1-\sigma\sqrt{T}} \exp\left\{-\frac{d_1^2}{2}\right\} - \frac{K}{s} \exp\{-rT\} \exp\left\{-\frac{(d_1 - \sigma\sqrt{T})^2}{2}\right\} \\ &= \exp\left\{-\frac{d_1^2}{2}\right\} \left( 1 - \frac{K}{s} \exp\{-rT\} \exp\left\{-\frac{\sigma^2 T}{2}\right\} \exp\left\{d_1 \sigma\sqrt{T}\right\} \right) \\ &= \exp\left\{-\frac{d_1^2}{2}\right\} \left( 1 - \frac{K}{s} \underbrace{\exp\{-rT\} \exp\left\{-\frac{\sigma^2 T}{2}\right\} \exp\left\{\ln\left(\frac{s}{K}\right) + (r + \sigma^2/2)T\right\}}_{\frac{s}{K}} \right) = 0 \\ &\Rightarrow N(d_1) + \frac{1}{\sigma\sqrt{T}} \left( \varphi(d_1) - \frac{K}{s} \exp\{-rT\} \varphi(d_2) \right) = N(d_1) \end{aligned}$$

The  $\Delta$  is simply the first derivative of the pricing function.

## 13. VOLATILITY MIS-SPECIFICATION

Assume that a trader believes in

$$dS_t = \mu(t, S_t)S_t dt + \sigma(t, S_t)S_t dW_t$$

whereas the stock actually follows

$$d\tilde{S}_t = \tilde{\mu}(t, \tilde{S}_t)\tilde{S}_t dt + \tilde{\sigma}(t, \tilde{S}_t)d\tilde{W}_t$$

What happens if the trader tries to replicate a simple  $T$ -claim  $x = \phi(\tilde{S}_T)$ ?

The trader solves 
$$\begin{cases} F_t + \frac{\sigma^2}{2} S_t^2 F_{ss} + rS_t F_s - rF = 0 \\ F(T, s) = \phi(s) \end{cases}$$
 and constructs a portfolio  $h = (h^B, h^S)$  with initial

value  $V_0^h = F(0, s)$  containing  $F_s(t, \tilde{S}_t)$  shares of  $\tilde{S}$  at each time (and  $V_t^h - \tilde{S}_t F_s(t, S_t)$  in the bank account.

The *tracking error*  $Y_t = V_t^h - F(t, \tilde{S}_t)$  satisfies  $Y_0 = 0$  and

$$\begin{aligned} dY_t &= r(V_t^h - \tilde{S}_t F_s)dt + F_s d\tilde{S}_t - \left( F_t dt + F_s d\tilde{S}_t + \frac{1}{2} \tilde{\sigma}^2 \tilde{S}_t^2 F_{ss} dt \right) \\ &= rV_t^h dt - \underbrace{\left( F_t + \frac{1}{2} \sigma^2 \tilde{S}_t^2 F_{ss} + r\tilde{S}_t F_s \right)}_{rF} dt + \frac{\sigma^2 - \tilde{\sigma}^2}{2} \tilde{S}_t^2 F_{ss} dt \\ &= rY_t dt + \frac{\sigma^2 - \tilde{\sigma}^2}{2} \tilde{S}_t^2 F_{ss} dt \end{aligned}$$

Thus, if  $\sigma^2 \geq \tilde{\sigma}^2$  and  $F_{ss} \geq 0$ , then  $Y(T) = V(T) - \phi(\tilde{S}_T) \geq 0$

A trader who overestimates volatility and who uses a model with a convex price will superreplicate the claim!

## 14. ASIAN OPTIONS

Asian options are option on the *average* of  $S$ .

An Asian call option pays  $\chi = \left( \frac{1}{T} \int_0^T S_t dt - K \right)^+$  at  $T$ .

Note, it is not a simple  $T$ -claim!

**Sats 14.15**

Let  $\chi = \phi(S_T, Z_T)$ , where  $Z_t = \int_0^t g(u, S_u) du$  for some function  $g$ .

Let  $F(t, s, z)$  solve

$$\begin{cases} F_t + \frac{\sigma^2 s^2}{2} F_{ss} + rsF_s + g(t, s)F_z - rF = 0 \\ F(T, s, z) = \phi(s, Z) \end{cases}$$

and let  $\begin{cases} h_t^B = \frac{F(t, S_t, Z_t) - S_t F_s(t, S_t, Z_t)}{B_t} \\ h_t^S = F_s(t, S_t, Z_t) \end{cases}$

Then  $h$  is self-financing and it replicates  $\chi$ , with

$$\Pi_t(\chi) = V_t^h = F(t, S_t, Z_t)$$

Moreover,  $F(t, s, Z) = \exp\{-r(T-t)\} \mathbb{E}_{t,s,z}^Q[\phi(S_T, Z_T)]$

where the  $Q$ -dynamics are

$$\begin{cases} dS_u = rS_u du + \sigma(u, S_u)S_u dW_u^Q \\ S_t = s \\ dZ_u = g(u, S_u) du \\ Z_t = z \end{cases}$$

**Bevis 14.1**

$$V_t^h = h_t^B B_t + h_t^S S_t = F(t, S_t, Z_t)$$

In particular,  $V_T^h = F(T, S_T, Z_T) = \phi(S_T, Z_T) = \chi$

Moreover,

$$\begin{aligned} dV_t^h &\stackrel{\text{Ito}}{=} F_t dt + F_s dS_t + \underbrace{F_z dZ_t}_{g dt} + \frac{1}{2} F_{ss} (dS_t)^2 + \underbrace{\frac{1}{2} F_{zz} (dZ)^2}_{=0} + F_{sz} \underbrace{dS dZ}_{=0} \\ &= \underbrace{\left( F_t + \frac{\sigma^2}{2} S_t^2 F_{ss} + g(t, S_t) F_z \right)}_{=r(F - S_t F_s) \text{ by BS PDE}} dt + F_s dS_t \\ &= r(F - S_t F_s) dt + F_s dS_t = h_t^B dB_t + h_t^S dS_t \end{aligned}$$

So  $h$  is self-financing and replicates  $\chi$

Therefore, by no arbitrage,  $\Pi_t(\chi) = V_t^h = F(t, S_t, Z_t)$

Finally, the stochastic representation follows from Feynman-Kac □

**Example:**

$\chi = \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} S_u du$  paid at  $T_2$

What is the value of the  $T_2$ -claim  $\chi$  at time 0?

$$\begin{aligned} \mathbb{E}_{t,s}^Q \left[ \exp\{-r(T_2 - t)\} \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} S_u du \right] &= \frac{\exp\{-r(T_2 - t)\}}{T_2 - T_1} \int_{T_1}^{T_2} \underbrace{\mathbb{E}_{t,s}^Q[S_u]}_{\text{sexp}\{r(u-t)\}} du \\ &= \frac{\exp\{-r(T_2 - t)\}}{T_2 - T_1} \frac{s}{r} (\exp\{r(T_2 - t)\} - \exp\{r(T_1 - t)\}) \\ &= \frac{s}{r(T_2 - T_1)} (1 - \exp\{-r(T_2 - T_1)\}) \end{aligned}$$

Which yields the answer, i.e the price is  $\frac{S_t}{r(T_2 - T_1)} (1 - \exp\{-r(T_2 - T_1)\})$

**Remark:**

All  $T$ -claims  $\chi$  are priced as  $\mathbb{E}^Q[\exp\{-rT\}\chi]$  (not only simple  $T$ -claims and Asian options)

**Remark:**

What is the value of  $\chi$  in the previous exercise at  $t \in [T_1, T_2]$ ?

$$\chi = \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} S_u du = \underbrace{\frac{1}{T_2 - T_1} \int_{T_1}^t S_u du}_{\text{known at } t} + \underbrace{\frac{1}{T_2 - T_1} \int_t^{T_2} S_u du}_y$$

Price of  $y$ :

$$\begin{aligned} \mathbb{E}_{t,s}^Q \left[ \exp \{ -r(T_2 - t) \} \frac{1}{T_2 - T_1} \int_t^{T_2} S_u du \right] \\ = \frac{\exp \{ -r(T_2 - t) \}}{T_2 - T_1} \int_t^{T_2} s \exp \{ r(u - t) \} du \\ = \frac{s}{r(T_2 - T_1)} (1 - \exp \{ -r(T_2 - t) \}) \end{aligned}$$

The answer is  $\frac{1}{T_2 - T_1} \left( \exp \{ -r(T_2 - t) \} \int_{T_1}^t S_u du + \frac{S_t}{r} (1 - \exp \{ -r(T_2 - t) \}) \right)$

**14.1. Completeness vs Absence of Arbitrage.**

1. The BS-model  $\begin{cases} dB_t = rB_t dt \\ dS_t = \mu S_t dt + \sigma S_t dW_t \end{cases}$  is arbitrage-free and complete

2. The model

$$\begin{aligned} dB_t &= rB_t dt \\ dS_t^1 &= \mu_1 S_t^1 dt + \sigma_1 S_t^1 dW_t \\ dS_t^2 &= \mu_2 S_t^1 dt + \sigma_2 S_t^2 dW_t \end{aligned}$$

is complete, but (typically) *not* arbitrage free since one may construct a portfolio in  $S^1, S^2$  with no  $dW$  term and with local mean rate of return  $\neq r$

3. The model

$$\begin{aligned} dB_t &= rB_t dt \\ dS_t &= \mu S_t dt + \sigma_1 S_t dW_t^1 + \sigma_2 S_t dW_t^2 \end{aligned}$$

is arbitrage-free but *not* complete since  $\chi = W_T^1$  cannot be replicated

**Sats 14.16: Meta-theorem**

Let  $M$  = the number of traded assets excluding  $B$  and  $R$  = the number random sources (BMs, Poisson processes) etc. Then:

- Absence of arbitrage  $\Leftrightarrow M \leq R$
- Completeness  $\Leftrightarrow M \geq R$
- Absence of arbitrage and completeness  $\Leftrightarrow M = R$

## 15. PARITY RELATIONS

To replicate a  $T$ -claim in the BS-model, we need *continuous* rebalancing of our portfolio. In reality, this is expensive (due to transaction costs). There are two approaches to this:

1. Static hedging
2. Delta and gamma hedging

## 15.1. Static Hedging.

A put option can be replicated with a *static* portfolio of stocks, bonds and call options

**Remark:** A *bond* (or a *zero-coupon  $T$ -bond*) pays its owner a pre-determined fixed amount  $K$  at time  $T$ .

If the interest rate is constant, the price of a  $T$ -bond is  $K \exp\{-r(T-t)\}$  where  $K$  is called the *face value* of the bond.

**Lemma 15.1: Put-call parity**

If  $p(t, s)$  is the price at  $t$  of a put option (strike price  $K$ , maturity date  $T$ ) and similarly  $c(t, s)$  is the price of a call option, then

$$p(t, s) = K \exp\{-r(T-t)\} - s + c(t, s)$$

Moreover, the put can be replicated by a static portfolio consisting of a call, a short position in the stock, and a zero-coupon bond with face value  $K$

**Example:**

What is the pricing formula for a put option in the standard BS-model?

*Alternative 1:*

$$\begin{aligned} p(t, s) &= \mathbb{E}_{t,s}^Q [\exp\{-r(T-t)(K - S_T)^+\}] \\ &= \exp\{-r(T-t)\} \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}} \exp\{-x^2/2\} \left( K - s \exp\left\{\left(r - \frac{\sigma^2}{2}\right)(T-t) + \sigma\sqrt{T-t}x\right\} \right) dx \\ &= \dots \end{aligned}$$

*Alternative 2:* Put-call parity yields

$$\begin{aligned} p(t, s) &= K \exp\{-r(T-t)\} - s + c(t, s) = K \exp\{-r(T-t)\} - s + sN(d_1) - K \exp\{-r(T-t)\} N(d_2) \\ &= KN(-d_2) - sN(d_1) \end{aligned}$$

where

$$\begin{cases} d_1 = \frac{\ln\left(\frac{s}{K}\right) + \left(r + \frac{\sigma^2}{2}\right)(T-t)}{\sigma\sqrt{T-t}} \\ d_2 = d_1 - \sigma\sqrt{T-t} \end{cases}$$

**Example:**

$$\chi = \begin{cases} K & \text{if } S_T \leq A \\ K + A - S_T & \text{if } A < S_T \leq K + A \\ 0 & \text{if } K + A < S_T \end{cases}$$

Determine a static portfolio of stocks, bonds, and call options that replicates  $\chi$

Here,  $\chi$  can be graphed as the constant function  $K$  minus the linear function starting at  $A$  plus the linear function starting at  $K + A$ , so the portfolio consisting of:

- One zero-coupon bond with face value  $K$
- One short position in a call with strike  $A$
- One long position in a call with strike  $K + A$

can be used to replicate  $\chi$

### 15.2. The Greeks.

Let  $F(t, s)$  be the pricing function of a simple  $T$ -claim in the standard BS-model.

#### Definition 15.18

$$\Delta = \frac{\partial F}{\partial s} \quad \Gamma = \frac{\partial^2 F}{\partial s^2} \quad \rho = \frac{\partial F}{\partial r} \quad \theta = \frac{\partial F}{\partial t} \quad \nu = \frac{\partial F}{\partial \sigma}$$

### 15.3. Delta and Gamma Hedging.

The seller of an option would often try to replicate it to reduce risk. In discrete time, the seller does as follows:

1. At  $t = 0$ : Sell the option, buy  $F_s(0, S_0)$  shares of  $S$ , deposit  $F(0, S_0) - F_s(0, S_0)S_0$  in the bank
2. At  $t = \Delta t$ : Adjust stock holdings to  $F_s(\Delta t, S_{\Delta t})$  shares (in a self-financing way, i.e. adjust bank holdings accordingly)
3. At  $t = k\Delta t$ : Repeat until  $T$

The  $\Delta$  of the whole portfolio (option, stocks, bank account) is close to 0. If  $\Gamma = \frac{\partial \Delta}{\partial s}$  is small, then changing in  $\Delta$  is small and then rebalancing can be made less frequently!

Let  $G$  be the pricing function of another claim  $\chi_G$  on the same stock  $S$ . Modify the strategy as follows:

- Buy  $x_G$  units of  $\chi_G$  (where  $\frac{\partial^2 F}{\partial s^2} = x_G \frac{\partial^2 G}{\partial s^2}$ )
- Buy  $x_s$  shares of  $S$  (where  $\frac{\partial F}{\partial s} = x_s + x_G \frac{\partial G}{\partial s}$ )
- Deposit  $F(0, S_0) - x_G G(0, S_0) - x_s S_0$  in the bank account.

This portfolio is  $\Delta$ -neutral and  $\Gamma$ -neutral. Rebalancing can be made less frequently!

## 16. MULTI-DIMENSIONAL MODELS

**Definition 16.19 Multi Dimensional Model**

A model  $\begin{cases} dB_t = rB_t dt \\ dS_t^i = \mu_i S_t^i dt + S_t^i \sum_{j=1}^n \sigma_{ij} dW_t^j \end{cases}$  where  $r, \mu_i, \sigma_{ij}$  are constants and  $\begin{pmatrix} \sigma_{11} & \cdots & \sigma_{1n} \\ \vdots & \ddots & \vdots \\ \sigma_{n1} & \cdots & \sigma_{nn} \end{pmatrix}$  is a non-singular matrix is a *multi-dimensional* model

**Remark:**

In the meta-theorem,  $R = M = n$ , so we expect the market to be arbitrage-free and complete.

The question becomes, what is the arbitrage-free price of a simple  $T$ -claim  $\chi = \phi(S_T)$ ?

The idea is that we could construct a portfolio of  $S^1, S^2, \dots, S^n, \Pi(\chi)$  which is locally risk-free (no  $dW$ -terms). Then, to avoid arbitrage, the drift of the portfolio must be  $r$ . This will yield a PDE for the price.

Instead, we will take the following route. We *guess* that the price is  $\Pi_t(\chi) = F(t, S_t^1, \dots, S_t^n)$  where  $F(t, S_1, \dots, S_n)$  satisfies

$$\begin{cases} F_t + \frac{1}{2} \sum_{i,j=1}^n S_i S_j C_{ij} F_{s_i s_j} + r \sum_{i=1}^n S_i F_{S_i} - rF = 0 \\ F(T, S_1, \dots, S_n) = \phi(S_1, \dots, S_n) \end{cases} \quad (6)$$

where  $C = \sigma \sigma^*$

To show that the guess is correct, we give a replication argument.

**Sats 16.17**

To avoid arbitrage, the price of  $\chi = \phi(S_T)$  has to be  $F(t, S_t)$  where  $F(t, s)$  is given by (6) above. Moreover,  $\chi$  is replicated by  $h = (h^B, h^1, \dots, h^n)$  where

$$\begin{cases} h_t^B = \frac{F(t, S_t) - \sum_{i=1}^n S_t^i F_{S_i}(t, S_t)}{B_t} \\ h_t^i = F_{S_i}(t, S_t) \quad (i = 1, \dots, n) \end{cases}$$

**Bevis 16.1**

$$V_t^h = h_t^B B_t + \sum_{i=1}^n h_t^i S_t^i = F(t, S_t)$$

So  $V_T^h = F(T, S_T) = \phi(S_T) = \chi$  which is the correct terminal value.

We have

$$\begin{aligned} dV_t^h &\stackrel{\text{Ito}}{=} F_t dt + \sum_{i=1}^n F_{S_i} dS_t^i + \frac{1}{2} \sum_{i,j=1}^n F_{S_i S_j} (dS_t^i)(dS_t^j) \\ &= \left( F_t + \frac{1}{2} \sum_{i,j=1}^n S_t^i S_t^j C_{ij} F_{S_i S_j} \right) dt + \sum_{i=1}^n F_{S_i} dS_t^i \\ &\stackrel{(6)}{=} \left( rF - r \sum_{i=1}^n S_t^i F_{S_i} \right) dt + \sum_{i=1}^n F_{S_i} dS_t^i \\ &= h_t^B dB_t + \sum_{i=1}^n h_t^i dS_t^i \end{aligned}$$

Thus  $h$  is self-financing and it replicates  $\chi$ .

Any price different from  $V_t^h = F(t, S_t)$  would lead to an arbitrage □



**Sats 16.18: Risk Neutral Valuation**

The pricing function has the representation

$$F(t, s) = \mathbb{E}_{t,s}^Q [\exp \{-r(T-t)\} \phi(S_T)]$$

Where the  $Q$ -dynamics of  $S$  are 
$$\begin{cases} dS_u^i = rS_u^i du + S_u^i \sum_{j=1}^n \sigma_{ij} dW_u^j \\ S_t^i = S_i \end{cases}$$

**16.1. Reducing the state space.**

Let  $n = 2$ , and assume that  $\phi(kS_1, kS_2) = k\phi(S_1, S_2)$  for  $k > 0$ .

Then  $\phi(S_1, S_2) = S_2 \phi\left(\frac{S_1}{S_2}, 1\right)$

**Ansatz:**

$$F(t, S_1, S_2) = S_2 G\left(t, \frac{S_1}{S_2}\right)$$

For some function  $G(t, z)$

The terminal condition  $F(T, S_1, S_2) = \phi(S_1, S_2)$  translates into  $G(T, z) = \phi(z, 1)$

We now translate all derivatives in the BS-equation:

$$F_t + \frac{1}{2} S_1^2 C_{11} F_{S_1 S_1} + \frac{1}{2} S_2^2 C_{22} F_{S_2 S_2} + S_1 S_2 C_{12} F_{S_1 S_2} + r S_1 F_{S_1} + r S_2 F_{S_2} - r F = 0$$

Into derivatives of  $G$  :

$$\begin{aligned} F_t &= S_2 G_t & F_{S_1 S_1} &= \frac{1}{S_2} G_{zz} \\ F_{S_1} &= G_z & F_{S_1 S_2} &= \frac{-S_1}{S_2^2} G_{zz} \\ F_{S_2} &= G - \frac{S_1}{S_2} G_z & F_{S_2 S_2} &= \frac{S_1^2}{S_2^3} G_{zz} \end{aligned}$$

We get:

$$S_2 G_t + \frac{1}{2} \frac{S_1^2}{S_2} C_{11} G_{zz} + \frac{1}{2} \frac{S_1^2}{S_2} C_{22} G_{zz} - \frac{S_1^2}{S_2} C_{12} G_{zz} + r S_1 G_z + r S_2 G - r S_1 G_z - r S_2 G = 0$$

which simplifies to

$$G_t + \frac{1}{2} \frac{S_1^2}{S_2^2} (C_{11} + C_{22} - 2C_{12}) G_{zz} = 0$$

Since the argument of  $G$  and its derivatives is  $\left(t, \frac{S_1}{S_2}\right)$ , we have the following:

**Lemma 16.1**

Assume  $\phi(kS_1, kS_2) = k\phi(S_1, S_2)$ , then  $F(t, S_1, S_2) = S_2 G\left(t, \frac{S_1}{S_2}\right)$  where  $G(t, z)$  solves

$$\begin{cases} G_t + \frac{1}{2} (C_{11} + C_{22} - 2C_{12}) z^2 G_{zz} = 0 \\ G(T, z) = \phi(z, 1) \end{cases}$$

**Example:**

$$\begin{cases} dS_t^1 = \mu_1 S_t^1 dt + \sigma_1 S_t^1 dW_t^1 \\ dS_t^2 = \mu_2 S_t^2 dt + \sigma_2 S_t^2 dW_t^2 \\ dB_t = r B_t dt \end{cases}$$

Let  $\chi = (S_T^1 - S_T^2)^+$ . This is an *exchange option*. It gives the right to exchange one share of  $S^2$  for one share of  $S^1$

We have  $\phi(S_1, S_2) = (S_1 - S_2)^+$  so  $\phi(kS_1, kS_2) = k\phi(S_1, S_2)$

By our recipe,  $F(t, S_1, S_2) = S_2 G\left(t, \frac{S_1}{S_2}\right)$  where  $G(t, z)$  solves

$$\begin{cases} G_t + \frac{1}{2}(\sigma_1^2 + \sigma_2^2) z^2 G_{zz} = 0 \\ G(T, z) = (z - 1)^+ \end{cases}$$

Using the BS-formula,  $G(t, z) = zN(d_1) - N(d_2)$  so

$$F(t, S_1, S_2) = S_2 G\left(t, \frac{S_1}{S_2}\right) = S_1 N(d_1) - S_2 N(d_2)$$

Where

$$\begin{cases} d_1 = \frac{\ln\left(\frac{S_1}{S_2}\right) + \frac{1}{2}(\sigma_1^2 + \sigma_2^2)(T - t)}{\sqrt{\sigma_1^2 + \sigma_2^2}\sqrt{T - t}} \\ d_2 = d_1 - \sqrt{(\sigma_1^2 + \sigma_2^2)(T - t)} \end{cases}$$

**Example:**

In the market  $\begin{cases} dB_t = rB_t dt \\ dS_t^1 = \mu S_t^1 dt + \sigma_1 S_t^1 dW_t^1 \\ dS_t^2 = \mu_2 S_t^2 dt + \sigma_2 S_t^2 (\rho dW_t^1 + \sqrt{1 - \rho^2} dW_t^2) \end{cases}$

Find the price at  $t = 0$  of the  $T$ -claim  $\chi = \frac{(S_T^1)^2}{S_T^2}$

To answer this, note that  $\phi(S_1, S_2) = \frac{S_1^2}{S_2}$ , to  $\phi(kS_1, kS_2) = k\phi(S_1, S_2)$

Thus,  $F(t, S_1, S_2) = S_2 G\left(t, \frac{S_1}{S_2}\right)$  where

$$\begin{cases} G_t + \frac{1}{2}z^2(\sigma_1^2 + \sigma_2^2 - 2\rho\sigma_1\sigma_2) G_{zz} = 0 \\ G(T, z) = z^2 \end{cases}$$

par Let  $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 - 2\rho\sigma_1\sigma_2}$ , we have

$$G(0, z) = \mathbb{E}_{0,z}[Z_T^2] \quad dZ_t = \sigma Z_t dW_t$$

Let  $Y_t = Z_t^2$ , then

$$dY_t = 2Z_t dZ_t + (dZ_t)^2 = \sigma^2 Y_t dt + 2\sigma Y_t dW_t$$

so  $G(0, z) = \mathbb{E}[Z_T^2] = z^2 \exp\{\sigma^2 T\}$

*Answer:*  $F(0, S_1, S_2) = S_2 G\left(0, \frac{S_1}{S_2}\right) = \frac{S_1^2}{S_2} \exp\{(\sigma_1^2 + \sigma_2^2 - 2\rho\sigma_1\sigma_2) T\}$

**Example:**

$$\begin{cases} dS_t^1 = \mu_1 S_t^1 dt + \sigma_1 S_t^1 dW_t^1 \\ dS_t^2 = \mu_2 S_t^2 dt + \sigma_2 S_t^2 dW_t^2 \\ dB_t = rB_t dt \end{cases}$$

Here  $dW^1 dW^2 = \rho dt$ . Let  $\chi = (S_T^1 - S_T^2)^+$ .

By our recipe  $F(t, S_1, S_2) = S_2 G\left(t, \frac{S_1}{S_2}\right)$  where  $G(t, z)$  satisfies

$$\begin{cases} G_t + \frac{1}{2}(\sigma_1^2 + \sigma_2^2 - 2\rho\sigma_1\sigma_2) z^2 G_{zz} = 0 \\ G(T, z) = (z - 1)^+ \end{cases}$$

Using the BS formula

$$G(t, z) = zN(d_1) - N(d_2)$$

where

$$\begin{cases} d_1 = \frac{\ln(z) + \frac{(\sigma_1^2 + \sigma_2^2 - 2\rho\sigma_1\sigma_2)}{2}(T-t)}{\sigma\sqrt{T-t}} \\ d_2 = \frac{\ln(z) - \frac{\sigma^2}{2}(T-t)}{\sigma\sqrt{T-t}} \end{cases}$$

Thus, the pricing function  $F$  is

$$\begin{aligned} F(t, S_1, S_2) &= S_2 G\left(t, \frac{S_1}{S_2}\right) = S_2 \left( \frac{S_1}{S_2} N(d_1) - N(d_2) \right) \\ &= S_1 N(d_1) - S_2 N(d_2) \end{aligned}$$

Where  $d_1, d_2$  are now equal to

$$\begin{cases} d_1 = \frac{\ln\left(\frac{S_1}{S_2}\right) + \frac{\sigma^2}{2}(T-t)}{\sigma\sqrt{T-t}} \\ d_2 = \frac{\ln\left(\frac{S_1}{S_2}\right) - \frac{\sigma^2}{2}(T-t)}{\sigma\sqrt{T-t}} \end{cases}$$

**Remark:**

In general, the payoff function  $\phi$  could be something like  $\min\{S_1(T), S_2(T)\}$ , then according to the recipe we should plug in for the terminal condition  $\min\{z, 1\} = \phi(z, 1)$ .

This is a linear function minus a call option, so it is solvable. For the linear function the one-dimensional BS PDE is easy to solve.

## 17. INCOMPLETE MARKETS

**Assumption:** Two objects are given:

- A risk-free asset  $dB_t = rB_t dt$
- A stochastic process  $X$  which is *not* assumed to be the price of a traded assets, with

$$dX_t = \mu(t, X_t)dt + \sigma(t, X_t)dW_t$$

Consider a  $T$ -claim  $y = \phi(X_T)$ , what is the price  $\Pi_t(y)$  at  $t < T$ ?

**Example:**

$X_t$  is the temperature in Brighton at time  $t$

$$\phi(x) = \begin{cases} 100 & \text{if } x \leq 20 \\ 0 & \text{if } x > 20 \end{cases}$$

The holder of the  $T$ -claim receives 100 if the temperature is below 20, 0 otherwise

**Our expectations:** In the meta-theorem,  $R = 1$ ,  $M = 0$  so the market is incomplete. The price of  $y$  is *not* uniquely determined. If the price of a benchmark derivative is given, however, then all other derivatives will have unique prices. Certain consistency relations between prices should hold!

Assume  $y$  and  $Z$  have price processes

$$\begin{aligned} \Pi_t(y) &= F(t, X_t) & \Pi_t(Z) &= G(t, X_t) \\ d\pi_t(y) &= \mu_F F dt + \sigma_F F dW_t & \begin{cases} \mu_F = \frac{F_t + \frac{\sigma^2}{2} F_{xx} + \mu F_x}{F} \\ \sigma_F = \frac{\sigma F_x}{F} \\ d\Pi_t(Z) = \alpha_G G dt + \sigma_G G dW_t \end{cases} \end{aligned}$$

Let  $w = (w^F, w^G)$  be a self-financing relative portfolio in  $F$  and  $G$

$$\begin{aligned} dV_t^w &= V_t^w w^F \frac{dF}{F} + V_t^w w^G \frac{dG}{G} \\ &= (\mu_F w^F + \mu_G w^G) V_t^w dt + (\sigma_F w^F + \sigma_G w^G) V_t^w dW_t \end{aligned}$$

Chose  $w^F, w^G$  so that

$$\left. \begin{aligned} w^F + w^G &= 1 \\ \sigma_F w^F + \sigma_G w^G &= 0 \end{aligned} \right\} \Leftrightarrow \begin{cases} w^F = \frac{-\sigma_G}{\sigma_F - \sigma_G} \\ w^G = \frac{\sigma_F}{\sigma_F - \sigma_G} \end{cases}$$

$$\text{Then } dV_t^w = \frac{\sigma_F \mu_G - \sigma_G \mu_F}{\sigma_F - \sigma_G} V_t^w dt$$

By the no-arbitrage assumption, we must have  $\frac{\sigma_F \mu_G - \sigma_G \mu_F}{\sigma_F - \sigma_G} = r$

Thus

$$\begin{aligned} \sigma_F \mu_G - \sigma_G \mu_F &= r \sigma_F - r \sigma_G \\ \Leftrightarrow \frac{\mu_F - r}{\sigma_F} &= \frac{\mu_G - r}{\sigma_G} \end{aligned}$$

Note that the LHS does not involve  $G$  and the RHS does not involve  $F$

### Lemma 17.1

Assume the market for derivatives is arbitrage-free. Then there exists a process  $\lambda$  such that  $\lambda(t, X_t) = \frac{\mu_F(t, X_t) - r}{\sigma_F(t, X_t)}$  for any pricing function  $F$

**Terminology:**  $\lambda_t$  is called the *market price of risk*

$$\text{We have } \lambda = \frac{\mu_F - r}{\sigma_F} = \frac{F_t + \frac{\sigma^2}{2} F_{xx} + \mu F_x - rF}{\sigma F_x}$$

**Lemma 17.2**

The price of a  $T$ -claim  $\phi(X_T)$  is  $F(t, X_t)$  where  $F(t, x)$  solves

$$\begin{cases} F_t + \frac{\sigma^2}{2} F_{xx} + (\mu - \sigma\lambda)F_x - rF = 0 \\ F(T, x) = \phi(x) \end{cases}$$

Moreover,  $F(t, x) = \mathbb{E}_{t,x}^Q [\exp \{-r(T-t)\} \phi(X_T)]$

$$\text{where } \begin{cases} dX_s = (\mu(s, X_s) - \lambda(s, X_s)\sigma(s, X_s)) ds + \sigma(s, X_s) dW_s^Q \\ X_t = x \end{cases} \quad \text{under } Q$$

**Remark:**

$\lambda(t, x)$  is *not* specified within the model. If we take the price of one derivative as given with price process  $\Pi_t = G(t, X_t)$ , then  $\lambda(t, x) = \frac{\mu_G(t, x) - r}{\sigma_G(t, x)}$  can be calculated. This  $\lambda$  can then be used to price other derivatives.

**Special Case:**

Assume that  $X$  is in fact a traded asset. The claim  $\bar{Z} = X_T$  then has price  $G(t, X_t) = X_t$ , so

$$\lambda(t, x) = \frac{\mu_F - r}{\sigma_G} = \frac{G_t + \frac{\sigma^2}{2} G_{xx} + \mu G_x - rG}{\sigma G_x} \stackrel{G(t,x)=x}{=} \frac{\mu - rx}{\sigma}$$

The factor  $\mu - \lambda\sigma$  is then  $\mu - \lambda\sigma = rx$

Thus the usual BS-equation is recovered!

## 18. DISCRETE DIVIDENDS

Consider a stock  $S$  that pays dividends at times  $T_1, \dots, T_K$  where  $0 < T_1 < T_2 \dots T_K < T$ .  
 In addition to  $S$ , there is also a bank account  $dB_t = rB_t dt$   
 Between dividend dates,  $S$  follows the geometric Brownian motion

$$dS_t = \mu S_t dt + \sigma S_t dW_t$$

At each  $t = T_i$ , a dividend  $\delta(S_{T_i})$  is paid out.

Here  $\delta : [0, \infty) \rightarrow [0, \infty)$  is a continuous function with  $\delta(S) \leq S$

To avoid arbitrage, we must have  $S_{T_i} = S_{T_i} - \delta(S_{T_i})$

**Question:** What is the price of a  $T$ -claim  $\chi = \phi(S_T)$ ?

**Answer:** For  $t \in [T_i, T_{i+1}]$  we have  $\Pi_t(\chi) = F^i(t, S_t)$  where  $F^i(t, s)$  is constructed as follows:

- Up to  $T_{K-1}$

$$\begin{cases} F_t^{K-2} + \frac{\sigma^2}{2} S^2 F_{ss}^{K-2} r S F_s^{K-2} - r F^{K-2} = 0 \\ F^{K-2}(T, S) = F^{K-1}(F, S - \delta(S)) \end{cases}$$

- Up to  $T_K$

$$\begin{cases} F_t^{K-1} + \frac{\sigma^2}{2} S^2 F_{ss}^{K-1} + r S F_s^{K-1} = r F^{K-1} \\ F^{K-1}(T_K, S) = F^K(T_K, S - \delta(S)) \end{cases}$$

- Up to  $T$

$$\begin{cases} F_T^K + \frac{\sigma^2}{2} S^2 F_{ss}^K + r S F_s^K = r F^K \\ F^K(T, S) = \phi(S) \end{cases}$$

**Lemma 18.1: Risk-neutral valuation**

The arbitrage-free price of a simple  $T$ -claim  $\chi = \phi(S_T)$  in the presence of discrete dividends is  $F(t, S_t)$  where

$$F(t, s) = \exp \{-r(T-t)\} \mathbb{E}_{t,s}^Q [\phi(S_T)]$$

Here, the following is under  $Q$ :

$$\begin{cases} dS_u = r S_u du + \sigma S_u dW_u^Q \\ S_t = s \\ S_{T_i} = S_{T_i} - \delta(S_{T_i}) \end{cases}$$

**Important special case:**

$$\delta(S) = \underbrace{\delta}_{\delta \in (0,1)} S$$

Then

$$\begin{aligned} S_T &= S_{T_K} \exp \left\{ \left( r - \frac{\sigma^2}{2} \right) (T - T_K) + \sigma (W_T^Q - W_{T_K}^Q) \right\} \\ &= (1 - \delta) S_{T_K}^- \exp \left\{ \left( r - \frac{\sigma^2}{2} \right) (T - T_K) + \sigma (W_T^Q - W_{T_K}^Q) \right\} \\ &= (1 - \delta) S_{T_{K-1}} \exp \left\{ \left( r - \frac{\sigma^2}{2} \right) (T - T_{K-1}) + \sigma (W_T^Q - W_{T_{K-1}}^Q) \right\} \\ &= (1 - \delta)^2 S_{T_{K-1}^-} \exp \left\{ \left( r - \frac{\sigma^2}{2} \right) (T - T_{K-1}) + \sigma (W_T^Q - W_{T_{K-1}}^Q) \right\} \\ &= \dots = (1 - \delta)^n S \exp \left\{ \left( r - \frac{\sigma^2}{2} \right) (T - t) + \sigma (W_T^Q - W_t^Q) \right\} \end{aligned}$$

Where  $n$  is the number of dividends times in  $[t, T]$

Therefore  $F^\delta(t, s) = F^0(t, S(1 - \delta)^n)$ , i.e pricing function in presence of dividends = pricing function with no dividends.

**Example:**

Assume  $\delta(S) = \delta S$ . What is the price of a call option  $\chi = (S_T - K)^+$ ?

*Answer:*

$$F^\delta(t, s) = F^0(t, S(1 - \delta)^n) = (1 - \delta)^n SN(d_1)_K \exp\{r(T - t)\} N(d_2)$$

$$\begin{cases} d_1 = \frac{\ln\left(\frac{S(1 - \delta)^n}{K}\right) + \left(r + \frac{\sigma^2}{2}\right)(T - t)}{\sigma\sqrt{T - t}} \\ d_2 = d_1 - \sigma\sqrt{T - t} \end{cases}$$

**Example:**

Find a replicating strategy for  $\chi = S_T$  (assume  $n$  remaining dividends)

*Answer:*

The value of  $\chi$  is  $F^\delta(0, S) = F^0(0, S(1 - \delta)^n) = S(1 - \delta)^n$

At  $t = 0$ , buy  $(1 - \delta)^n$  shares of  $S$

At  $t = T_1$ , receive  $(1 - \delta)^n \delta S_{T_1^-}$  in dividends.

New stock price is  $S_{T_1} = (1 - \delta)S_{T_1^-}$ ; so we can buy  $\frac{(1 - \delta)^n \delta S_{T_1^-}}{(1 - \delta)S_{T_1^-}}$  new shares. Total holdings of

$$(1 - \delta)^n + \delta(1 - \delta)^{n-1} = (1 - \delta)^{n-1}$$

Continue similarly at  $T_2, \dots, T_n$ . After  $T_k$ ; we have  $(1 - \delta)^{n-k}$  shares, so at  $t = T$  we have  $(1 - \delta)^{n-n} = 1$  shares of  $S$

Thus  $\chi$  is replicated!

## 19. CONTINUOUS DIVIDENDS

The market admits the same model as previously, i.e

$$\begin{cases} dB_t = rB_t dt \\ dS_t = \mu S_t dt + \sigma S_t dW_t \end{cases}$$

**Dividend structure:**  $dD_t = \delta(S_t)S_t dt$  where  $\delta$  is some continuous function

**Interpretation:**

During an interval  $[t_1, t_2]$ , the holder of one share of  $S$  receives the amount

$$\int_{t_1}^{t_2} \delta(S_u) S_u du$$

To price a  $T$ -claim  $\chi = \phi(S_T)$ , we follow our usual approach.

Assume  $\Pi_t(\chi) = F(t, S_t)$  and let  $(w^S, w^F)$  be a self-financing relative portfolio of  $S$  and  $F$

$$\begin{aligned} dV_t^{w \text{ self-fin}} &\stackrel{\text{def}}{=} V_t^w w^S \frac{dS_t + dD_t}{S_t} + V_t^w w^F \frac{dF_t}{F_t} \\ &= V_t^w (w^S(\mu + \delta) + w^F \mu_F) dt + V_t^w (w^S \sigma + w^F \sigma_F) dW_t \end{aligned}$$

Where

$$\begin{cases} \mu_F = \frac{F_t + \mu S F_s + \frac{\sigma^2 S^2}{2} F_{ss}}{F} \\ \sigma_F = \frac{\sigma S F_s}{F} \end{cases}$$

Choose  $(w^S, w^F)$  such that

$$\left. \begin{aligned} w^S + w^F &= 1 \\ \sigma w^S + \sigma_F w^F &= 0 \end{aligned} \right\} \Leftrightarrow \begin{cases} w^S = \frac{-\sigma_F}{\sigma - \sigma_F} \\ w^F = \frac{\sigma}{\sigma - \sigma_F} \end{cases}$$

Comparing with the bank account to avoid arbitrage, we must have

$$w^S(\mu + \delta) + w^F \mu_F = r$$

Thus

$$\begin{aligned}
 -\sigma_F(\mu + \delta) + \mu_F \sigma &= r(\sigma - \sigma_F) - SF_s(\mu + \delta) + F_t + \mu SF_S + \frac{\sigma^2 S^2}{2} F_{ss} \\
 &= rF - rSF_s \\
 F_t + \frac{\sigma^2 S^2}{2} F_{ss} + (r - \delta) S F_s - rF &= 0
 \end{aligned}$$

Since  $S_t$  can take any value, the PDE must hold at all points  $(t, s)$

**Lemma 19.1**

The pricing function  $F(t, s)$  of  $\chi = \phi(S_T)$  solves

$$\begin{cases} F_t + \frac{1}{2} \sigma^2 S^2 F_{ss} + (r - \delta) S F_s - rF = 0 \\ F(T, S) = \phi(S) \end{cases}$$

Moreover,  $F(t, s) = \mathbb{E}_{t,s}^Q [\exp \{-r(T-t)\} \phi(S_T)]$  where

$$\begin{cases} dS_u = (r - \delta) S_u dt + \sigma S_u dW_u^Q \\ S_t = s \end{cases}$$

under  $Q$

**Remark:**

If  $\delta(s) = \delta$  (i.e constant), then

$$\begin{aligned}
 S_T &= \text{sexp} \left\{ \left( r - \delta - \frac{\sigma^2}{2} \right) (T-t) + \sigma (W_T - W_t) \right\} \\
 &= \text{sexp} \{-\delta(T-t)\} \exp \left\{ \left( r - \frac{\sigma^2}{2} \right) (T-t) + \sigma (W_T - W_t) \right\}
 \end{aligned}$$

Thus  $F^\delta(t, s) = F^0(t, \text{sexp} \{-\delta(T-t)\})$

I.e the pricing function with continuous dividends is the same as the pricing function with no dividends

**Example:**

What is the price of  $\chi S_T$  if continuous dividends are paid (at a constant proportional to the rate  $\delta$ )?

$$F^\delta(0, s) = F^0(0, \text{sexp} \{-\delta T\}) = \text{sexp} \{-\delta T\}$$

Can we find a replicating strategy?

At  $t = 0$ ; buy  $\exp \{-\delta T\}$  shares of  $S$ . Use all dividends to buy new shares. If  $f(t)$  shares are held at time  $t$ , then  $\delta f(t) dt$  new shares can be bought during  $(t, t + dt)$

Thus

$$\begin{cases} \frac{df(t)}{dt} = \delta f(t) \\ f(0) = \exp \{-\delta T\} \end{cases}$$

So  $f(t) = \exp \{-\delta(T-t)\}$ . In particular,  $f(T) = 1$  so  $\chi$  is replicated!