

# Lab Assignments Computational Finance

## Submission guidelines

These assignments can be done in groups of two students. Reports with a *clear description of the assignment, the methods, the results and discussion* should be submitted before the deadlines. Quality is valued over quantity: aim for a report with a page count of 5-10. You are free to choose the programming language/environment in which you would like to write your computer programs. If you have questions about the assignments do not hesitate to contact the teaching assistants.

## Grading scheme

- Each of the three assignments carries equal weight of 20% and the exam is worth 40%;
- The score of the exam should be 5 points (on the scale of 1 to 10) and higher for passing the course;

Assignment 1	Assignment 2	Assignment 3	Exam
20%	20%	20%	40%

# Assignment 3: The finite difference Method

## Part I

### Background of PDE approach

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The Black-Scholes Partial Differential Equation (BS-PDE) derived for a plain vanilla option has the following form:

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

The equation can be transformed into a PDE with constant coefficients, by introducing:

$$\begin{aligned} X &= \ln(S) \\ \tau &= T - t \end{aligned}$$

A. Show that the transformed BS-PDE has the following form:

$$\frac{\partial V}{\partial \tau} = \left( r - \frac{1}{2} \sigma^2 \right) \frac{\partial V}{\partial X} + \frac{1}{2} \sigma^2 \frac{\partial^2 V}{\partial X^2} - rV \quad (2)$$

The explicit FTCS (Forward Time Centred in Space) for the transformed BS-PDE (2) can be derived by means of Taylor Expansion Techniques. Recalling that

$$V(X + \Delta X, \tau) = V(X, \tau) + \Delta X \frac{\partial V(X, \tau)}{\partial X} + \frac{1}{2!} \Delta X^2 \frac{\partial^2 V(X, \tau)}{\partial X^2} + \dots \quad (3)$$

B. Show that the discrete Finite-Difference (FD) approximation of the FTCS scheme equals:

$$\begin{aligned} V_i^{n+1} = & V_i^n + \left( r - \frac{1}{2} \sigma^2 \right) \frac{\Delta \tau}{2 \Delta X} (V_{i+1}^n - V_{i-1}^n) + \frac{1}{2} \sigma^2 \frac{\Delta \tau}{\Delta X^2} (V_{i+1}^n - 2V_i^n + V_{i-1}^n) \\ & - r \Delta \tau V_i^n, \end{aligned} \quad (4)$$

where the superscript  $n$  denotes the time point and the subscript  $i$  denotes the spatial index of  $X$ .

C. Now, show that the Crank-Nicolson scheme for equation (2) is given by:

$$\begin{aligned} V_i^{n+1} = & V_i^n + \left( r - \frac{1}{2} \sigma^2 \right) \frac{\Delta \tau}{4 \Delta X} (V_{i+1}^n - V_{i-1}^n + V_{i+1}^{n+1} - V_{i-1}^{n+1}) \\ & + \frac{1}{4} \sigma^2 \frac{\Delta \tau}{\Delta X^2} (V_{i+1}^n - 2V_i^n + V_{i-1}^n + V_{i+1}^{n+1} - 2V_i^{n+1} + V_{i-1}^{n+1}) - \frac{r \Delta \tau}{2} (V_i^n + V_i^{n+1}), \end{aligned} \quad (5)$$

and show by using Taylor series expansion that this scheme is second order in space.

## Part II

# FD-Schemes for European call

The FD-mesh for the derived schemes is drawn below. It should be noted that the cell-width is uniform over the whole computational domain. The infinite extent of  $X = \ln(S)$  in the continuous problem is approximated by the truncated interval  $[-M_1, M_2]$ , where  $M_1$  and  $M_2$  are sufficiently large chosen positive constants so that the boundary conditions at the two ends of the infinite interval can be applied with sufficient accuracy. Approximated option values are computed at grid points  $(X_{\min} + i\Delta X, n\Delta\tau)$ ,  $i = 0, 1, 2, \dots, N$  and  $n = 0, 1, \dots, N_T$ . The option values along the boundaries  $i = -1$  and  $i = N + 1$  are prescribed by boundary conditions of the option model, while initial values along  $n = 0$  are given by the terminal payoff function. The

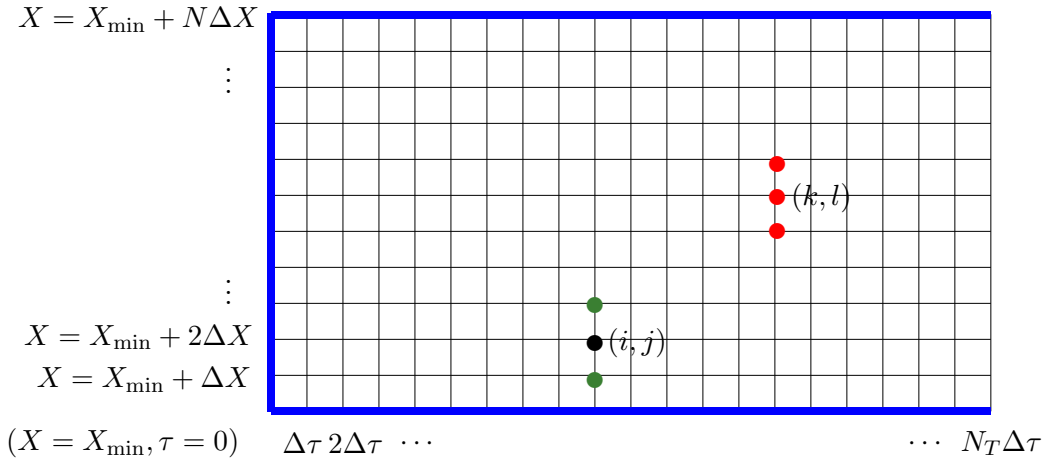


Figure 1: Schematic overview of discretized grid. The blue boundaries denote the known boundary or initial values and the green dots show the points needed for FD approximation of the first derivative at point  $(i, j)$  and the red points are the needed points for the approximation of the second derivative at point  $(k, l)$ .

FTCS and the Crank-Nicolson scheme can be represented in matrix vector notation as:

$$B\vec{V}^{n+1} = A\vec{V}^n, \quad (6)$$

where  $A$  and  $B$  is a sparse matrix (mainly zero values) with the three non-zero diagonals represented by the vectors:

$$B = \begin{pmatrix} \ddots & \ddots & \ddots & & \\ & \vec{b}_{-1} & \vec{b}_0 & \vec{b}_1 & \\ & & \ddots & \ddots & \ddots \end{pmatrix} \text{ and } A = \begin{pmatrix} \ddots & \ddots & \ddots & & \\ & \vec{a}_{-1} & \vec{a}_0 & \vec{a}_1 & \\ & & \ddots & \ddots & \ddots \end{pmatrix}$$

- A. Compute the vectors  $\vec{a}_{-1}, \vec{a}_0, \vec{a}_1, \vec{b}_{-1}, \vec{b}_0, \vec{b}_1 \in \mathbb{R}^{n \times 1}$ . for the FTCS scheme and the Crank-Nicolson scheme. Show which boundary conditions you use and how you incorporate them!

- B. Solve the above tri-diagonal system by writing a computer program in Python, Matlab or any other programming language of your choice. Do this for both the FTCS-scheme and the Crank-Nicolson scheme. Use the following market parameters for a European call:

$$\begin{aligned} r &= 4\%, \quad \text{vol} = 30\%, \quad S_0 = 100, \quad K = 110, \quad T = 1 \text{ year (in the money)} \\ r &= 4\%, \quad \text{vol} = 30\%, \quad S_0 = 110, \quad K = 110, \quad T = 1 \text{ year (at the money)} \\ r &= 4\%, \quad \text{vol} = 30\%, \quad S_0 = 120, \quad K = 110, \quad T = 1 \text{ year (out of the money)} \end{aligned}$$

and additionally present your results in graphs.

Check whether your computer program is in line with your expectations from the theoretical analysis in Part I C. (second order convergence in number of grid points in space).

Determine your own optimal mesh size. Plot the delta as function of the underlying  $S$ , i.e.

$$\Delta = \frac{\partial V}{\partial S}. \tag{7}$$

Note (!) that the Greeks are in the original variable  $S$  and not in  $X$ . Explain the graphs.

## Part III

# The COS-method

Let an asset price  $S_t$  (e.g. a stock) be modeled with a Geometric Brownian motion:

$$dS_t = rS_t dt + \sigma S_t dW_t \quad (8)$$

where  $W_t$  is a Wiener process,  $r$  the risk-free rate and  $\sigma$  the volatility. Consider a European call option written on  $S_t$  with strike  $K$  and maturity  $T$ . We apply the following transformation:

$$x = \log\left(\frac{S_0}{K}\right) \text{ and } y = \log\left(\frac{S_T}{K}\right). \quad (9)$$

A. Show that the characteristic function of  $y$  is given by

$$\phi_y(u) = e^{iu(x + (r - \frac{1}{2}\sigma^2)T) - \frac{1}{2}T\sigma^2 u^2}$$

*Hint:* You may use the fact that the characteristic function of a standard normal distribution  $Z$  is given by  $\phi_Z(u) = e^{-\frac{1}{2}u^2}$ .

B. Argue that the payoff function  $g$  for a European call option is given by

$$g(y) = K(e^y - 1)^+$$

Considering the COS-method, the  $t$ -zero option price  $V(x, 0)$  can be approximated as

$$V(x, 0) := e^{-rT} \int_{\mathbb{R}} g(y) f(y|x) dy \approx e^{-rT} \sum_{n=0}^N {}'F_n(x) G_n$$

for a suitable  $a < 0$ ,  $b > 0$ ,  $N \in \mathbb{N}$  and coefficients

$$F_n(x) = \operatorname{Re} \left\{ \phi_y\left(\frac{n\pi}{b-a}; x\right) e^{-i\frac{n\pi a}{b-a}} \right\}$$

$$G_n = \frac{2}{b-a} \int_a^b g(y) \cos\left(n\pi \frac{y-a}{b-a}\right) dy$$

where  $\sum'$  indicates that the first term in the summation is weighted by  $\frac{1}{2}$ .

C. Define the following two functions:

$$\chi_n(a, b) := \frac{e^b \cos(n\pi) - \cos\left(\frac{n\pi a}{b-a}\right) + \frac{n\pi}{b-a} \sin\left(\frac{n\pi a}{b-a}\right)}{1 + \left(\frac{n\pi}{b-a}\right)^2}$$

$$\psi_n(a, b) := \begin{cases} b & \text{if } n = 0 \\ \frac{b-a}{n\pi} \sin\left(\frac{n\pi a}{b-a}\right) & \text{if } n \neq 0 \end{cases}$$

Show that the coefficients  $G_n$  can be rewritten as

$$G_n = \frac{2K}{b-a} (\chi_n(a, b) - \psi_n(a, b))$$

D. Price a call option with the parameters from part IIB using the COS-method. Use up to  $N = 64$  terms and select suitable  $a, b \in \mathbb{R}$ . Compare your results with the Black-Scholes pricing formula and analyze the error convergence. Discuss the results.