

Fys4150

Project 5

Peter Killingstad and Karl Jacobsen

<https://github.com/kaaaja/fys4150>

November 22, 2017

Note to instructors regarding Github repository

If the above Github-link does not work, it is either because you have not yet accepted our invite to the repository, or you have not yet provided us with an e-mail address available at Github so that we can invite you. The Github user you will be invited from is "kaaaja". If the latter applies to you, please send us an e-mail with an e-mail address available in Github or your Github username so that we can send you an invite. Our e-mail addresses: peter.killingstad@hotmail.com, karljaco@gmail.com.

1 5a

1.1 Derivation of schemes with truncation errors

All the schemes will be derived from Taylor series expansions, and the truncation error will be related to the remainder in the Taylor-series expansions. This remainder is the error we get when truncating the series by leaving out the remainder.

1.1.1 Forward Euler

For the time derivative, we expand $u(x, t + \Delta t)$ around t

$$u(x, t + \Delta t) = u(x, t) + u_t(x, t)\Delta t + \mathcal{O}(\Delta t^2) \quad (1a)$$

$$\rightarrow u_t(x, t) = \frac{u(x, t + \Delta t) - u(x, t)}{\Delta t} + \mathcal{O}(\Delta t) \quad (1b)$$

The space derivative, which is a 2nd derivative, we derive by combining two Taylor series'

$$u(x + \Delta x, t) = u(x, t) + u_x(x, t)\Delta x + \frac{u_{xx}(x, t)\Delta x^2}{2} + \frac{u_{xxx}(x, t)\Delta x^3}{6} + \mathcal{O}(\Delta x^4) \quad (2a)$$

$$u(x - \Delta x, t) = u(x, t) - u_x(x, t)\Delta x + \frac{u_{xx}(x, t)\Delta x^2}{2} - \frac{u_{xxx}(x, t)\Delta x^3}{6} + \mathcal{O}(\Delta x^4) \quad (2b)$$

Now we add (2a) and (2b) and solve for $u_{xx}(x, t)$

$$\begin{aligned} (u(x + \Delta x, t) + u(x - \Delta x, t)) &= (u(x, t) + u(x, t)) \\ &+ (u_x(x, t)\Delta x + (-u_x(x, t)\Delta x)) \\ &+ \left(\frac{u_{xx}(x, t)\Delta x^2}{2} + \frac{u_{xx}(x, t)\Delta x^2}{2}\right) \end{aligned} \quad (3a)$$

$$\begin{aligned} &+ \left(\frac{u_{xxx}(x, t)\Delta x^3}{6} + (-\frac{u_{xxx}(x, t)\Delta x^3}{6})\right) \\ &+ (\mathcal{O}(\Delta x^4) + \mathcal{O}(\Delta x^4)) \\ &= 2u(x, t) + u_{xx}(x, t)\Delta x^2 + \mathcal{O}(\Delta x^4) \end{aligned} \quad (3b)$$

$$\rightarrow u_{xx}(x, t) = \frac{u(x - \Delta x, t) - 2u(x, t) + u(x + \Delta x, t)}{\Delta x^2} + \mathcal{O}(\Delta x^2) \quad (3c)$$

Combining (1b) and (3c) we get the Forward Euler scheme

$$u_t(x, t) = u_{xx}(x, t) \quad (4a)$$

$$\frac{u(x, t + \Delta t) - u(x, t)}{\Delta t} + \mathcal{O}(\Delta t) = \frac{u(x - \Delta x, t) - 2u(x, t) + u(x + \Delta x, t)}{\Delta x^2} + \mathcal{O}(\Delta x^2) \quad (4b)$$

From (4b) we see that the scheme has a truncation error that goes like $\mathcal{O}(\Delta t)$ in time and $\mathcal{O}(\Delta x^2)$ in space.

We will now analyze the stability of the Forward Euler scheme (4b) by applying Neuman stability analyzis. From the analytical solution of the problem, we know that the particular solutions are on the form $u = e^{-(k\pi)^2 t} e^{ik\pi x}$, where k is an integer greater than one. We observe that the solutions are stable in t , meaning that the solutions do not blow up as t increaes. Based on the analytical particular solution, we make the numerical ansatz

$$u = a_k^n e^{ik\pi x_j} \quad (5)$$

For the numerical ansatz (5) to reproduce the characteristics of the analytical particular solution, with stability in t , we observe that $|a_k^n| < 1$ in necessary. We now plug in the ansatz (5) into the (4b) and derive an equation for $|a_k^n|$:

$$\frac{u(x, t + \Delta t) - u(x, t)}{\Delta t} = \frac{u(x - \Delta x, t) - 2u(x, t) + u(x + \Delta x, t)}{\Delta x^2} \quad (6a)$$

$$\frac{a_k^{n+1} e^{ik\pi(j+1)\Delta x} - a_k^n e^{ik\pi j\Delta x}}{\Delta t} = \frac{a_k^n e^{ik\pi(j-1)\Delta x} - 2a_k^n e^{ik\pi j\Delta x} + a_k^n e^{ik\pi(j+1)\Delta x}}{\Delta x^2} \quad (6b)$$

$$a_k^n e^{ik\pi j\Delta x} \frac{a_k - 1}{\Delta t} = a_k^n e^{ik\pi j\Delta x} \frac{e^{-ik\pi\Delta x} - 2 + e^{ik\pi\Delta x}}{\Delta x^2} \quad (6c)$$

$$\frac{a_k - 1}{\Delta t} = \frac{e^{-ik\pi\Delta x} - 2 + e^{ik\pi\Delta x}}{\Delta x^2} \quad (6d)$$

$$a_k = 1 + \frac{\Delta t}{\Delta x^2} (e^{-ik\pi\Delta x} - 2 + e^{ik\pi\Delta x}) \quad (6e)$$

$$= 1 + \frac{\Delta t}{\Delta x^2} (2 \cos(k\pi\Delta x) - 2) \quad (6f)$$

$$= 1 + 2 \frac{\Delta t}{\Delta x^2} (\cos(k\pi\Delta x) - 1) \quad (6g)$$

$$= 1 + 2 \frac{\Delta t}{\Delta x^2} \left(-2 \sin^2\left(\frac{k\pi\Delta x}{2}\right)\right) \quad (6h)$$

$$= 1 - 4 \frac{\Delta t}{\Delta x^2} \sin^2\left(\frac{k\pi\Delta x}{2}\right) \quad (6i)$$

$$|a_k| = \left|1 - 4 \frac{\Delta t}{\Delta x^2} \sin^2\left(\frac{k\pi\Delta x}{2}\right)\right| \quad (6j)$$

From (6j) we get

$$|a_k| < 1 \text{ if } ||1 - 4\frac{\Delta t}{\Delta x^2} \sin^2(\frac{k\pi\Delta x}{2})|| < 1 \quad (7a)$$

$$\rightarrow |1 - 4\frac{\Delta t}{\Delta x^2}| < 1 \rightarrow |a_k| < 1 \text{ (Since } \sin^2(k\pi\Delta x/2)_{max} = 1) \quad (7b)$$

$$\rightarrow 1 - 4\frac{\Delta t}{\Delta x^2} > -1 \quad (7c)$$

$$\rightarrow \frac{\Delta t}{\Delta x^2} < \frac{1}{2} \quad (7d)$$

(7d) gives that the Forward Euler scheme is conditionally stable, and the condition that ensures stability.

1.2 Backward Euler

Here we will do the same as we did for Forward Euler above: Derive the scheme, including truncation errors, and analyze stability.

The only change compared to Forward Euler, is the time discretization, which now becomes

$$u(x, t - \Delta t) = u(x, t) + u_t(x, t)\Delta t - \mathcal{O}(\Delta t^2) \quad (8a)$$

$$\rightarrow u_t(x, t) = \frac{u(x, t) - u(x, t - \Delta t)}{\Delta t} + \mathcal{O}(\Delta t) \quad (8b)$$

The space discretization is the same as for Forward Euler, (3c). Combining the space discretization (3c) and (8b) gives

$$\frac{u(x, t) - u(x, t - \Delta t)}{\Delta t} + \mathcal{O}(\Delta t) = \frac{u(x - \Delta x, t) - 2u(x, t) + u(x + \Delta x, t)}{\Delta x^2} + \mathcal{O}(\Delta x^2) \quad (9a)$$

We note that the truncation errors have the same asymptotic behavior as for the Forward Euler scheme.

Now lets check the stability of the Backward Euler scheme. We apply the same method as we did for Forward Euler, and insert the ansatz (5) into (9a) to get

$$\frac{u(x, t) - u(x, t - \Delta t)}{\Delta t} = \frac{u(x - \Delta x, t) - 2u(x, t) + u(x + \Delta x, t)}{\Delta x^2} \quad (10a)$$

$$\frac{a_k^n e^{ik\pi j \Delta x} - a_k^{n-1} e^{ik\pi j \Delta x}}{\Delta t} = \frac{a_k^n e^{ik\pi(j-1)\Delta x} - 2a_k^n e^{ik\pi j \Delta x} + a_k^n e^{ik\pi(1+j)\Delta x}}{\Delta x^2} \quad (10b)$$

$$a_k^n e^{ik\pi j \Delta x} \frac{1 - a_k^{-1}}{\Delta t} = a_k^n e^{ik\pi j \Delta x} \frac{e^{-ik\pi \Delta x} - 2 + e^{ik\pi \Delta x}}{\Delta x^2} \quad (10c)$$

$$\frac{1 - a_k^{-1}}{\Delta t} = \frac{e^{-ik\pi \Delta x} - 2 + e^{ik\pi \Delta x}}{\Delta x^2} \quad (10d)$$

$$a_k^{-1} = 1 - \frac{\Delta t}{\Delta x^2} (e^{-ik\pi \Delta x} - 2 + e^{ik\pi \Delta x}) \quad (10e)$$

$$a_k = \frac{1}{1 - \frac{\Delta t}{\Delta x^2} (e^{-ik\pi \Delta x} - 2 + e^{ik\pi \Delta x})} \quad (10f)$$

$$\stackrel{(6)}{=} \frac{1}{1 + 4\frac{\Delta t}{\Delta x^2} \sin^2(\frac{k\pi\Delta x}{2})} \quad (10g)$$

$$|a_k| = \left| \frac{1}{1 + 4\frac{\Delta t}{\Delta x^2} \sin^2(\frac{k\pi\Delta x}{2})} \right| < 1. \quad (10h)$$

$$(10i)$$

From (10h) we see that, in contrast to the Forward Euler scheme, the Backward Euler scheme is unconditionally stable.

(9a) reveals another difference between the Backward Euler scheme and the Forward Euler scheme: (9a) is implicit in $u(x, t)$, meaning that we cannot solve (9a) directly for $u(x, t)$, as we did in the Forward Euler scheme. However, we can find $u(x, t)$ from (9a) by recognizing that (9a) can be rewritten as a linear system:

$$\frac{u(x, t) - u(x, t - \Delta t)}{\Delta t} = \frac{u(x - \Delta x, t) - 2u(x, t) + u(x + \Delta x, t)}{\Delta x^2} \quad (11a)$$

$$\frac{u_i^n - u_i^{n-1}}{\Delta t} = \frac{u_{i-1}^n - 2u_i^n + u_{i+1}^n}{\Delta x^2} \quad (11b)$$

$$\frac{\Delta x^2}{\Delta t} (u_i^n - u_i^{n-1}) = u_{i-1}^n - 2u_i^n + u_{i+1}^n \quad (11c)$$

$$-\left(u_{i-1}^n - \left(2 + \frac{\Delta x^2}{\Delta t}\right)u_i^n + u_{i+1}^n\right) = \frac{\Delta x^2}{\Delta t} u_i^{n-1} \quad (11d)$$

$$\left(-u_{i-1}^n + \left(2 + \frac{\Delta x^2}{\Delta t}\right)u_i^n - u_{i+1}^n\right) = \frac{\Delta x^2}{\Delta t} u_i^{n-1} \quad (11e)$$

$$\underbrace{\begin{bmatrix} 2 + \frac{\Delta x^2}{\Delta t} & -1 & \cdots & 0 \\ -1 & 2 + \frac{\Delta x^2}{\Delta t} & -1 & \vdots \\ \vdots & & \ddots & \vdots \\ 0 & \cdots & -1 & 2 + \frac{\Delta x^2}{\Delta t} \end{bmatrix}}_{\mathbf{A}} \underbrace{\begin{bmatrix} u_1^n \\ u_2^n \\ \vdots \\ u_N^n \end{bmatrix}}_{\mathbf{U}} = \frac{\Delta x^2}{\Delta t} \underbrace{\begin{bmatrix} u_0^{n-1} \\ u_1^{n-1} \\ \vdots \\ u_N^{n-1} \end{bmatrix}}_{\tilde{\mathbf{b}}} \quad (11f)$$

We see from (11f) that solving Backward Euler corresponds to solving a linear system $AU = \tilde{b}$, where A is a tridiagonal matrix.

1.3 Crank-Nicolson

Here we Taylor expand $u(x + \Delta x, t + \Delta t)$ and $u(x - \Delta x, t + \Delta t)$ around $t' = t + \Delta t/2$ to get

$$\begin{aligned} u(x + \Delta x, t + \Delta t) &= u(x, t') + \frac{\partial u(x, t')}{\partial x} \Delta x + \frac{\partial u(x, t')}{\partial t} \frac{\Delta t}{2} + \frac{\partial^2 u(x, t')}{2\partial x^2} \Delta x^2 + \frac{\partial^2 u(x, t')}{2\partial t^2} \frac{\Delta t^2}{4} \\ &\quad + \frac{\partial^2 u(x, t')}{\partial x \partial t} \frac{\Delta t}{2} \Delta x + \mathcal{O}(\Delta t^3) \end{aligned} \quad (12a)$$

$$\begin{aligned} u(x - \Delta x, t + \Delta t) &= u(x, t') - \frac{\partial u(x, t')}{\partial x} \Delta x + \frac{\partial u(x, t')}{\partial t} \frac{\Delta t}{2} + \frac{\partial^2 u(x, t')}{2\partial x^2} \Delta x^2 + \frac{\partial^2 u(x, t')}{2\partial t^2} \frac{\Delta t^2}{4} \\ &\quad - \frac{\partial^2 u(x, t')}{\partial x \partial t} \frac{\Delta t}{2} \Delta x + \mathcal{O}(\Delta t^3) \end{aligned} \quad (12b)$$

$$\begin{aligned} u(x + \Delta x, t) &= u(x, t') + \frac{\partial u(x, t')}{\partial x} \Delta x - \frac{\partial u(x, t')}{\partial t} \frac{\Delta t}{2} + \frac{\partial^2 u(x, t')}{2\partial x^2} \Delta x^2 + \frac{\partial^2 u(x, t')}{2\partial t^2} \frac{\Delta t^2}{4} \\ &\quad - \frac{\partial^2 u(x, t')}{\partial x \partial t} \frac{\Delta t}{2} \Delta x + \mathcal{O}(\Delta t^3) \end{aligned} \quad (12c)$$

$$\begin{aligned} u(x - \Delta x, t) &= u(x, t') - \frac{\partial u(x, t')}{\partial x} \Delta x - \frac{\partial u(x, t')}{\partial t} \frac{\Delta t}{2} + \frac{\partial^2 u(x, t')}{2\partial x^2} \Delta x^2 + \frac{\partial^2 u(x, t')}{2\partial t^2} \frac{\Delta t^2}{4} \\ &\quad + \frac{\partial^2 u(x, t')}{\partial x \partial t} \frac{\Delta t}{2} \Delta x + \mathcal{O}(\Delta t^3) \end{aligned} \quad (12d)$$

$$u(x, t + \Delta t) = u(x, t') + \frac{\partial u(x, t')}{\partial t} \frac{\Delta t}{2} + \frac{\partial^2 u(x, t')}{2\partial t^2} \Delta t^2 + \mathcal{O}(\Delta t^3) \quad (12e)$$

$$u(x, t) = u(x, t') - \frac{\partial u(x, t')}{\partial t} \frac{\Delta t}{2} + \frac{\partial^2 u(x, t')}{2\partial t^2} \Delta t^2 + \mathcal{O}(\Delta t^3) \quad (12f)$$

The above formulae are taken from Hjørth-Jensen's slides [2].

Combining (12e) and (12f) gives the time derivative

$$\begin{aligned} \left(u(x, t + \Delta t) - u(x, t) \right) &= \left(u(x, t') - u(x, t') \right) + \left(\frac{\partial u(x, t')}{\partial t} \frac{\Delta t}{2} - \left(-\frac{\partial u(x, t')}{\partial t} \frac{\Delta t}{2} \right) \right) \\ &+ \left(\frac{\partial^2 u(x, t')}{2\partial t^2} \Delta t^2 - \frac{\partial^2 u(x, t')}{2\partial t^2} \Delta t^2 \right) + \left(\mathcal{O}(\Delta t^3) - \mathcal{O}(\Delta t^3) \right) \end{aligned} \quad (13a)$$

$$u(x, t + \Delta t) - u(x, t) = \frac{\partial u(x, t')}{\partial t} \Delta t + \mathcal{O}(\Delta t^3) \quad (13b)$$

$$\frac{\partial u(x, t')}{\partial t} = \frac{u(x, t + \Delta t) - u(x, t)}{\Delta t} + \mathcal{O}(\Delta t^2) \quad (13c)$$

Now for the spacial derivative. First we solve (12a) and (12b) for $u_{xx}(x, t')$

$$\begin{aligned} u(x + \Delta x, t + \Delta t) + u(x - \Delta x, t + \Delta t) &= \left(u(x, t') + u(x, t') \right) + \left(\frac{\partial u(x, t')}{\partial x} \Delta x - \frac{\partial u(x, t')}{\partial x} \Delta x \right) \\ &+ \left(\frac{\partial u(x, t')}{\partial t} \frac{\Delta t}{2} + \frac{\partial u(x, t')}{\partial t} \frac{\Delta t}{2} \right) + \left(\frac{\partial^2 u(x, t')}{2\partial x^2} \Delta x^2 + \frac{\partial^2 u(x, t')}{2\partial x^2} \Delta x^2 \right) \\ &+ \left(\frac{\partial^2 u(x, t')}{2\partial t^2} \frac{\Delta t^2}{4} + \frac{\partial^2 u(x, t')}{2\partial t^2} \frac{\Delta t^2}{4} \right) + \left(\frac{\partial^2 u(x, t')}{\partial x \partial t} \frac{\Delta t}{2} \Delta x - \frac{\partial^2 u(x, t')}{\partial x \partial t} \frac{\Delta t}{2} \Delta x \right) \\ &+ \left(\mathcal{O}(\Delta t^3) + \mathcal{O}(\Delta t^3) \right) + \mathcal{O}(\Delta x^4) \end{aligned} \quad (14a)$$

$$= 2u(x, t') + \frac{\partial u(x, t')}{\partial t} \Delta t + \frac{\partial^2 u(x, t')}{\partial x^2} \Delta x^2 + \frac{\partial^2 u(x, t')}{2\partial t^2} \frac{\Delta t^2}{2} + \mathcal{O}(\Delta t^3) + \mathcal{O}(\Delta x^4) \quad (14b)$$

$$= 2u(x, t') + \frac{\partial u(x, t')}{\partial t} \Delta t + \frac{\partial^2 u(x, t')}{\partial x^2} \Delta x^2 + \mathcal{O}(\Delta t^2) + \mathcal{O}(\Delta x^4) \quad (14c)$$

$$\begin{aligned} \frac{\partial^2 u(x, t')}{\partial x^2} \Delta x^2 &= u(x + \Delta x, t + \Delta t) + u(x - \Delta x, t + \Delta t) - 2u(x, t') \\ &+ \frac{\partial u(x, t')}{\partial t} \Delta t + \mathcal{O}(\Delta t^2) + \mathcal{O}(\Delta x^4) \end{aligned} \quad (14d)$$

$$\begin{aligned} \frac{\partial^2 u(x, t')}{\partial x^2} &= \frac{u(x - \Delta x, t + \Delta t) - 2u(x, t') + u(x + \Delta x, t + \Delta t)}{\Delta x^2} \\ &+ \frac{\partial u(x, t')}{\partial t} \frac{\Delta t}{\Delta x^2} + \mathcal{O}(\Delta t^2) + \mathcal{O}(\Delta x^2) \end{aligned} \quad (14e)$$

Note that in (14e) we added $\mathcal{O}(\Delta x^4)$, since $\mathcal{O}(\Delta x^3)$ cancels out in the addition. Also note that the Δx^3 -term was not originally included in (12a) and (12b), but these would have been of equal magnitude with opposite sign, so when adding the equations we would have been left with $\mathcal{O}(\Delta x^4)$.

Doing the same as in (14e) for (12c) and (12d) we obtain

$$\begin{aligned} \frac{\partial^2 u(x, t')}{\partial x^2} &= \frac{u(x - \Delta x, t) - 2u(x, t') + u(x + \Delta x, t)}{\Delta x^2} \\ &- \frac{\partial u(x, t')}{\partial t} \frac{\Delta t}{\Delta x^2} + \mathcal{O}(\Delta t^2) + \mathcal{O}(\Delta x^2) \end{aligned} \quad (15a)$$

Now we take the mean of (14e) and (15)

$$\begin{aligned}
u_{xx}(x, t') &= \frac{1}{2} \left(\frac{u(x - \Delta x, t + \Delta t) - 2u(x, t') + u(x + \Delta x, t + \Delta t)}{\Delta x^2} + \frac{\partial u(x, t')}{\partial t} \frac{\Delta t}{\Delta x^2} + \mathcal{O}(\Delta t^2) + \mathcal{O}(\Delta x^2) \right) \\
&+ \frac{u(x - \Delta x, t) - 2u(x, t') + u(x + \Delta x, t)}{\Delta x^2} - \frac{\partial u(x, t')}{\partial t} \frac{\Delta t}{\Delta x^2} + \mathcal{O}(\Delta t^2) + \mathcal{O}(\Delta x^2) \\
&= \frac{1}{2} \left(\frac{u(x - \Delta x, t + \Delta t) - 2u(x, t') + u(x + \Delta x, t + \Delta t)}{\Delta x^2} \right. \\
&+ \left. \frac{u(x - \Delta x, t) - 2u(x, t') + u(x + \Delta x, t)}{\Delta x^2} \right) + \mathcal{O}(\Delta t^2) + \mathcal{O}(\Delta x^2) \\
u(x, t') &= \frac{u(x, t) + u(x, t + \Delta t)}{2} \\
&\frac{1}{2} \left(\frac{u(x - \Delta x, t + \Delta t) - u(x, t) + u(x, t + \Delta t) + u(x + \Delta x, t + \Delta t)}{\Delta x^2} \right. \\
&+ \left. \frac{u(x - \Delta x, t) - u(x, t) + u(x, t + \Delta t) + u(x + \Delta x, t)}{\Delta x^2} \right) + \mathcal{O}(\Delta t^2) + \mathcal{O}(\Delta x^2) \\
&= \frac{1}{2} \left(\frac{u(x - \Delta x, t + \Delta t) - 2u(x, t + \Delta t) + u(x + \Delta x, t + \Delta t)}{\Delta x^2} + \frac{u(x - \Delta x, t) - 2u(x, t) + u(x + \Delta x, t)}{\Delta x^2} \right) \\
&+ \mathcal{O}(\Delta t^2) + \mathcal{O}(\Delta x^2)
\end{aligned} \tag{16a}$$

Now combining (13c) and (16a) we get the Crank-Nicolson scheme

$$\begin{aligned}
\frac{u(x, t + \Delta t) - u(x, t)}{\Delta t} + \mathcal{O}(\Delta t^2) &= \frac{1}{2} \left(\frac{u(x - \Delta x, t + \Delta t) - 2u(x, t + \Delta t) + u(x + \Delta x, t + \Delta t)}{\Delta x^2} \right. \\
&+ \left. \frac{u(x - \Delta x, t) - 2u(x, t) + u(x + \Delta x, t)}{\Delta x^2} \right) + \mathcal{O}(\Delta x^2),
\end{aligned} \tag{17a}$$

where we have put both $\mathcal{O}(\Delta t^2)$ into a common term.

(17) shows that the Crank-Nicolson scheme is 2nd order in both time and space, implying better convergence properties for the Crank-Nicolson scheme compared to the Backward Euler scheme and the Forward Euler scheme.

Using the same method as we used for the previous schemes, we now study the stability of the Crank-Nicolson scheme. We insert the ansatz (5) into the Crank-Nicolson scheme (17) and solve for $|a_k|$:

$$\begin{aligned}
\frac{u(x, t + \Delta t) - u(x, t)}{\Delta t} &= \frac{1}{2} \left(\frac{u(x - \Delta x, t + \Delta t) - 2u(x, t + \Delta t) + u(x + \Delta x, t + \Delta t)}{\Delta x^2} \right. \\
&+ \left. \frac{u(x - \Delta x, t) - 2u(x, t) + u(x + \Delta x, t)}{\Delta x^2} \right) \\
a_k^n e^{ik\pi j \Delta x} \frac{a_k - 1}{\Delta t} &= \frac{a_k^n e^{ik\pi j \Delta x}}{2} \left(\frac{a_k e^{-ik\pi \Delta x} - 2a_k + a_k e^{ik\pi \Delta x}}{\Delta x^2} + \frac{e^{-ik\pi \Delta x} - 2 + e^{ik\pi \Delta x}}{\Delta x^2} \right) \\
\frac{a_k - 1}{\Delta t} &= \frac{1}{2} \left(\frac{a_k e^{-ik\pi \Delta x} - 2a_k + a_k e^{ik\pi \Delta x}}{\Delta x^2} + \frac{e^{-ik\pi \Delta x} - 2 + e^{ik\pi \Delta x}}{\Delta x^2} \right) \\
&= \frac{1 + a_k}{2\Delta x^2} (e^{-ik\pi \Delta x} - 2 + e^{ik\pi \Delta x}) \\
&\stackrel{(6)}{=} -4 \frac{1 + a_k}{2\Delta x^2} \sin^2\left(\frac{k\pi \Delta x}{2}\right) \\
a_k - 1 &= (1 + a_k) \left(-\frac{2\Delta t}{\Delta x^2}\right) \sin^2\left(\frac{k\pi \Delta x}{2}\right) \\
\left(1 + \frac{2\Delta t}{\Delta x^2} \sin^2\left(\frac{k\pi \Delta x}{2}\right)\right) a_k &= 1 - \frac{2\Delta t}{\Delta x^2} \sin^2\left(\frac{k\pi \Delta x}{2}\right) \\
a_k &= \frac{1 - \frac{2\Delta t}{\Delta x^2} \sin^2\left(\frac{k\pi \Delta x}{2}\right)}{1 + \frac{2\Delta t}{\Delta x^2} \sin^2\left(\frac{k\pi \Delta x}{2}\right)} < 1
\end{aligned} \tag{18a}$$

$$\tag{18b}$$

(18b) shows that the Crank-Nicolson scheme is unconditionally stable.

Based on the analysis of the different schemes, we expect the Crank-Nicolson scheme to be the best scheme with respect to convergence and stability.

1.4 θ -rule

All the schemes derived above can be derived from a more general scheme, called the θ -rule scheme. To see this, first notice that the Crank-Nicolson scheme (17) is the average of the Forward Euler scheme (4b) and the Backward Euler scheme (9a). We can think of the average, represented by the Crank-Nicolson scheme, as the special case of equals weights in a weighted average of the Backward Euler scheme and the Forward Euler scheme. Writing the weighted average of the Forward Euler and Backward Euler schemes with weights $0 \leq \theta \leq 1$, we get the θ -rule

$$(1 - \theta) \frac{u(x, t + \Delta t) - u(x, t)}{\Delta t} + \theta \frac{u(x, t + \Delta t) - u(x, t)}{\Delta t} = \theta \frac{u(x - \Delta x, t + \Delta t) - 2u(x, t + \Delta t) + u(x + \Delta x, t + \Delta t)}{\Delta x^2} + (1 - \theta) \frac{u(x - \Delta x, t) - 2u(x, t) + u(x + \Delta x, t)}{\Delta x^2} \quad (19a)$$

$$\frac{u(x, t + \Delta t) - u(x, t)}{\Delta t} = \theta \frac{u(x - \Delta x, t + \Delta t) - 2u(x, t + \Delta t) + u(x + \Delta x, t + \Delta t)}{\Delta x^2} + (1 - \theta) \frac{u(x - \Delta x, t) - 2u(x, t) + u(x + \Delta x, t)}{\Delta x^2} \quad (19b)$$

From the θ -scheme (19b) we see that $\theta = 0, 1/2, 1$ corresponds to the Forward Euler, the Crank-Nicolson and the Backward Euler scheme respectively.

When implementing the 1D-schemes, we will use the θ -scheme. Using the θ -scheme, we need only write one scheme instead of three.

1.5 Implementation of 1D problem

As mentioned in the previous paragraph, we implement the 1D schemes using the θ -scheme. We will now rewrite (19b) to a linear system, and then we will apply the Thomas algorithm to this system.

To ease the notation, we introduce

$$\alpha = \frac{\Delta t}{\Delta x^2}. \quad (20)$$

Insertion of α (20) into the θ -scheme (19b) and introducing the discretization $u(x + \Delta x, t - \Delta t) = u_{i+1}^{n-1}$ gives

$$\frac{u(x, t + \Delta t) - u(x, t)}{\Delta t} = \theta \frac{u(x - \Delta x, t + \Delta t) - 2u(x, t + \Delta t) + u(x + \Delta x, t + \Delta t)}{\Delta x^2} + (1 - \theta) \frac{u(x - \Delta x, t) - 2u(x, t) + u(x + \Delta x, t)}{\Delta x^2} \quad (21a)$$

$$u(x, t + \Delta t) - u(x, t) = \alpha \theta \left(u(x - \Delta x, t + \Delta t) - 2u(x, t + \Delta t) + u(x + \Delta x, t + \Delta t) \right) + \alpha(1 - \theta) \left(u(x - \Delta x, t) - 2u(x, t) + u(x + \Delta x, t) \right) \quad (21b)$$

$$u_i^{n+1} - u_i^n = \alpha \theta \left(u_{i-1}^{n+1} - 2u_i^{n+1} + u_{i+1}^{n+1} \right) + \alpha(1 - \theta) \left(u_{i-1}^n - 2u_i^n + u_{i+1}^n \right) \quad (21c)$$

$$u_i^n - u_i^{n-1} = \alpha \theta \left(u_{i-1}^n - 2u_i^n + u_{i+1}^n \right) + \alpha(1 - \theta) \left(u_{i-1}^{n-1} - 2u_i^{n-1} + u_{i+1}^{n-1} \right) \quad (21d)$$

$$u_i^n - \alpha \theta \left(u_{i-1}^n - 2u_i^n + u_{i+1}^n \right) = u_i^{n-1} + \alpha(1 - \theta) \left(u_{i-1}^{n-1} - 2u_i^{n-1} + u_{i+1}^{n-1} \right) \quad (21e)$$

$$- \alpha \theta u_{i-1}^n + (2\alpha\theta + 1)u_i^n - \alpha \theta u_{i+1}^n = \alpha(1 - \theta)u_{i-1}^{n-1} + \left(1 - 2\alpha(1 - \theta) \right) u_i^{n-1} + \alpha(1 - \theta)u_{i+1}^{n-1} \quad (21f)$$

$$- 2\alpha\theta u_{i-1}^n + 2(2\alpha\theta + 1)u_i^n - 2\alpha\theta u_{i+1}^n = 2\alpha(1 - \theta)u_{i-1}^{n-1} + 2 \left(1 - 2\alpha(1 - \theta) \right) u_i^{n-1} + 2\alpha(1 - \theta)u_{i+1}^{n-1} \quad (21g)$$

Now we rewrite (21g) as a matrix-vector equation $A_1 U^n = A_2 U^{n-1}$:

$$\underbrace{\begin{bmatrix} 2(2\alpha\theta + 1) & -2\alpha\theta & \cdots & 0 \\ -2\alpha\theta & 2(2\alpha\theta + 1) & -2\alpha\theta & \vdots \\ \vdots & & \ddots & -2\alpha\theta \\ 0 & \cdots & -2\alpha\theta & 2(2\alpha\theta + 1) \end{bmatrix}}_{\mathbf{A}_1} \underbrace{\begin{bmatrix} u_1^n \\ u_2^n \\ \vdots \\ u_N^n \end{bmatrix}}_{\mathbf{U}^n} = \underbrace{\begin{bmatrix} 2(1 - 2\alpha(1 - \theta)) & 2\alpha(1 - \theta) & \cdots & 0 \\ 2\alpha(1 - \theta) & 2(1 - 2\alpha(1 - \theta)) & 2\alpha(1 - \theta) & \vdots \\ \vdots & & \ddots & 2\alpha(1 - \theta) \\ 0 & \cdots & 2\alpha(1 - \theta) & 2(1 - 2\alpha(1 - \theta)) \end{bmatrix}}_{\mathbf{A}_2} \underbrace{\begin{bmatrix} u_1^{n-1} \\ u_2^{n-1} \\ \vdots \\ u_N^{n-1} \end{bmatrix}}_{\mathbf{U}^{n-1}} \quad (22a)$$

In (22a), the right hand side $\mathbf{A}_2 \mathbf{U}^{n-1}$ is known, since \mathbf{U}^{n-1} is the previous periods solution, so (22a) is a linear system of the known type $AU = b$. So in principle the above system is solved for each time step, solving it for a time step and then using this solution in the right hand side in the next time step.

We note that with $\theta = 0$ in (22a), the system reduces to the explicit Forward Euler system, which can be obtained from (4b). $\theta = 1$ gives the Backward Euler system (11f). $\theta = 1/2$ in (22a) gives the system that can be obtained by rewrtng the Crank-Nicolson scheme (17) as a linear system.

In principle the above system can be solved by calculating the inverse of A_1 and solving $U^n = A_1^{-1}(A_2 U^{n-1})$. This is a costly operation and is avoided. Instead of calculating the inverse, one often solves these systems by some kind of elimination method, e.g. Gaussian elimination or by LU. In this case, we note that we are dealing with a tridiagonal matrix. For tridiagonal systems, the Thomas algorithm gives an alterative way of solving the linear system which reduces the number of FLOPS considerably. In our case we are even more lucky. Our matrix is symmetric, and the elements are constant, so the standard Thomas algorithm can be further improved. We will now derive the algorithm that we implement.

We start with a tridiagonal symmetric linear system $Au = f$, with A being 4×4 . The following show the forward

substitution steps for this sytem

$$\begin{bmatrix} d_1 & e_1 & 0 & 0 & f_1 \\ e_2 & d_2 & e_2 & 0 & f_2 \\ 0 & e_3 & d_3 & e_3 & f_3 \\ 0 & 0 & e_4 & d_4 & f_4 \end{bmatrix} \rightarrow \begin{bmatrix} d_1 & e_1 & 0 & 0 & f_1 \\ 0 & \tilde{d}_2 & e_2 & 0 & \tilde{f}_2 \\ 0 & e_3 & d_3 & e_3 & f_3 \\ 0 & 0 & e_4 & d_4 & f_4 \end{bmatrix} \rightarrow \begin{bmatrix} d_1 & e_1 & 0 & 0 & f_1 \\ 0 & \tilde{d}_2 & e_2 & 0 & \tilde{f}_2 \\ 0 & 0 & \tilde{d}_3 & e_3 & \tilde{f}_3 \\ 0 & 0 & e_4 & d_4 & f_4 \end{bmatrix} \rightarrow \begin{bmatrix} d_1 & e_1 & 0 & 0 & f_1 \\ 0 & \tilde{d}_2 & e_2 & 0 & \tilde{f}_2 \\ 0 & 0 & \tilde{d}_3 & e_3 & \tilde{f}_3 \\ 0 & 0 & e_4 & \tilde{d}_4 & \tilde{f}_4 \end{bmatrix} \quad (23a)$$

From (22a) we have that in our case $e_1 = e_2 = \dots = e_N = -2\alpha$ and $d_1 = d_2 = \dots = d_N = 2(2\alpha\theta + 1)$. Calculating the first couple of \tilde{d} 's we quickly see that we get the following general expression for \tilde{d}_i

$$\tilde{d}_i = 2(2\alpha\theta + 1) + \frac{(2\alpha)^2}{\tilde{d}_{i-1}} \text{ for } i > 1. \quad (24)$$

Doing the same for \tilde{f} we get the general expression

$$\tilde{f}_i = f_i + \frac{2\alpha\theta}{\tilde{d}_{i-1}} \tilde{f}_{i-1} \text{ for } i > 1. \quad (25)$$

Having \tilde{d} and \tilde{f} we are ready to do the back substitution step. We have

$$\begin{bmatrix} d_1 & e_1 & 0 & 0 \\ 0 & \tilde{d}_2 & e_2 & 0 \\ 0 & 0 & \tilde{d}_3 & e_3 \\ 0 & 0 & e_4 & \tilde{d}_4 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = \begin{bmatrix} f_1 \\ \tilde{f}_2 \\ \tilde{f}_3 \\ \tilde{f}_4 \end{bmatrix} \quad (26a)$$

From (26) we get

$$u_4 = \frac{\tilde{f}_4}{\tilde{d}_4} \quad (27)$$

and

$$u_i = \frac{\tilde{f}_i + 2\alpha\theta u_{i+1}}{\tilde{d}_i} \text{ for } i > 1. \quad (28)$$

The equations (24), (25), (27) and (28) is what we need for our algorithm.

```

for time in times:
    Calculate RHS f (= A_2 U^{n-1})

    // Forward substitution
    for row in rows (Start from 1st row):
        Calculate \tilde{d}
        Calculate \tilde{f}
    end row loop

    // Backward substitution
    For row in rows (Starting from last row)
        Calculate u
    end row loop

    // Update RHS for next time step
    U^{n-1} = U^n
end time loop

```

2 Bibliography

- [1] Hjorth-Jensen, M.(2015) Computational physics. Lectures fall 2015. <https://github.com/CompPhysics/ComputationalPhysics/tree/master/doc/Lectures>
- [2] <https://github.com/CompPhysics/ComputationalPhysics/tree/master/doc/pub/pde>