Numerical Solution of Differential Equations I

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2020

Lecture 14

Stability of finite difference schemes

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We shall say that a finite difference scheme for the unsteady heat equation is **(practically) stable in the ℓ_2 norm**, if

$$\|U^m\|_{\ell_2} \leq \|U^0\|_{\ell_2}, \qquad m = 1, \ldots, M,$$

where

$$\|U^m\|_{\ell_2} = \left(\Delta x \sum_{j=-\infty}^{\infty} |U_j^m|^2 \right)^{1/2}.$$

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We shall use the semidiscrete Fourier transform to explore the stability of finite difference schemes.

Definition

The semidiscrete Fourier transform of a function U defined on the infinite mesh $x_j = j\Delta x$, $j = 0, \pm 1, \pm 2, \ldots$, is:

$$\hat{U}(k) = \Delta x \sum_{j=-\infty}^{\infty} U_j \, \mathrm{e}^{-\imath k x_j}, \qquad k \in [-\pi/\Delta x, \pi/\Delta x].$$

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We shall also need the inverse semidiscrete Fourier transform, as well the discrete counterpart of Parseval's identity that connect these transforms, similarly as in the case of the Fourier transform and its inverse considered earlier.

Definition

Let $\hat{U}$ be defined on the interval $[-\pi/\Delta x, \pi/\Delta x]$. The inverse semidiscrete Fourier transform of $\hat{U}$ is defined by

$$U_j := \frac{1}{2\pi} \int_{-\pi/\Delta x}^{\pi/\Delta x} \hat{U}(k)\, \mathrm{e}^{\imath k j \Delta x}\, \mathrm{d}k.$$

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We then have the following result.

Lemma (Discrete Parseval's identity)

Let

$$\|U\|_{\ell_2} = \left(\Delta x \sum_{j=-\infty}^{\infty} |U_j|^2 \right)^{1/2} \quad \text{and} \quad \|\hat{U}\|_{L_2} = \left(\int_{-\pi/\Delta x}^{\pi/\Delta x} |\hat{U}(k)|^2 \, \mathrm{d}k \right)^{1/2}.$$

If $\|U\|_{\ell_2}$ *is finite, then also* $\|\hat{U}\|_{L_2}$ *is finite, and*

$$\|U\|_{\ell_2} = \frac{1}{\sqrt{2\pi}} \|\hat{U}\|_{L_2}.$$

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$$\|U\|_{\ell_2} = \frac{1}{\sqrt{2\pi}} \|\hat{U}\|_{L_2}.$$

The proof of this is similar to that of Parseval's identity discussed earlier, and we shall therefore leave its proof as an exercise.

Stability analysis of the explicit Euler scheme

By inserting

$$U_j^m = \frac{1}{2\pi} \int_{-\pi/\Delta x}^{\pi/\Delta x} \mathrm{e}^{\imath k j \Delta x} \hat{U}^m(k) \, \mathrm{d}k$$

into the Euler scheme we deduce that

$$\frac{1}{2\pi} \int_{-\pi/\Delta x}^{\pi/\Delta x} \mathrm{e}^{\imath k j \Delta x} \frac{\hat{U}^{m+1}(k) - \hat{U}^m(k)}{\Delta t} \, \mathrm{d}k$$
$$= \frac{1}{2\pi} \int_{-\pi/\Delta x}^{\pi/\Delta x} \frac{\mathrm{e}^{\imath k (j+1) \Delta x} - 2\mathrm{e}^{\imath k j \Delta x} + \mathrm{e}^{\imath k (j-1) \Delta x}}{(\Delta x)^2} \hat{U}^m(k) \, \mathrm{d}k.$$

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By inserting

$$U_j^m = \frac{1}{2\pi}\int_{-\pi/\Delta x}^{\pi/\Delta x} \mathrm{e}^{\imath kj\Delta x}\hat{U}^m(k)\,\mathrm{d}k$$

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$$\begin{aligned}\frac{1}{2\pi}\int_{-\pi/\Delta x}^{\pi/\Delta x} \mathrm{e}^{\imath kj\Delta x}\,\frac{\hat{U}^{m+1}(k)-\hat{U}^m(k)}{\Delta t}\,\mathrm{d}k \\ = \frac{1}{2\pi}\int_{-\pi/\Delta x}^{\pi/\Delta x} \frac{\mathrm{e}^{\imath k(j+1)\Delta x}-2\mathrm{e}^{\imath kj\Delta x}+\mathrm{e}^{\imath k(j-1)\Delta x}}{(\Delta x)^2}\,\hat{U}^m(k)\,\mathrm{d}k.\end{aligned}$$

Therefore, we have that

$$\begin{aligned}\frac{1}{2\pi}\int_{-\pi/\Delta x}^{\pi/\Delta x} \mathrm{e}^{\imath kj\Delta x}\,\frac{\hat{U}^{m+1}(k)-\hat{U}^m(k)}{\Delta t}\,\mathrm{d}k \\ = \frac{1}{2\pi}\int_{-\pi/\Delta x}^{\pi/\Delta x} \mathrm{e}^{\imath kj\Delta x}\,\frac{\mathrm{e}^{\imath k\Delta x}-2+\mathrm{e}^{-\imath k\Delta x}}{(\Delta x)^2}\,\hat{U}^m(k)\,\mathrm{d}k.\end{aligned}$$

By comparing the left-hand side with the right-hand side we get

$$\hat{U}^{m+1}(k) = \hat{U}^{m}(k) + \mu(\mathrm{e}^{\imath k\Delta x} - 2 + \mathrm{e}^{-\imath k\Delta x})\hat{U}^{m}(k)$$

for all **wave numbers** $k \in [-\pi/\Delta x, \pi/\Delta x]$.

[1] After: Richard Courant, Kurt Friedrichs, and Hans Lewy (*Über die partiellen Differenzengleichungen der mathematischen Physik*. Mathematische Annalen, 100:32–74, 1928).

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for all **wave numbers** $k \in [-\pi/\Delta x, \pi/\Delta x]$. Thus we have

$$\hat{U}^{m+1}(k) = \lambda(k)\hat{U}^m(k),$$

where

$$\lambda(k) = 1 + \mu(\mathrm{e}^{\imath k \Delta x} - 2 + \mathrm{e}^{-\imath k \Delta x})$$

is the **amplification factor** and

$$\mu := \frac{\Delta t}{(\Delta x)^2}$$

is called the **CFL number**[1].

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By the discrete Parseval identity stated in Lemma 3 we have that

$$\begin{aligned}
\|U^{m+1}\|_{\ell_2} &= \frac{1}{\sqrt{2\pi}}\|\hat{U}^{m+1}\|_{L_2} \\
&= \frac{1}{\sqrt{2\pi}}\|\lambda\hat{U}^{m}\|_{L_2} \\
&\leq \frac{1}{\sqrt{2\pi}}\max_k|\lambda(k)|\;\|\hat{U}^{m}\|_{L_2} \\
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In order to mimic the L_2 norm bound, we would like to ensure that

$$\|U^{m+1}\|_{\ell_2} \leq \|U^{m}\|_{\ell_2}, \qquad m = 0, 1, \ldots, M-1.$$

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$$\|U^{m+1}\|_{\ell_2} \leq \|U^{m}\|_{\ell_2}, \qquad m = 0, 1, \ldots, M-1.$$

Thus we demand that

$$\max_k|\lambda(k)| \leq 1,$$

i.e., that

$$\max_k|1 + \mu(\mathrm{e}^{\imath k\Delta x} - 2 + \mathrm{e}^{-\imath k\Delta x})| \leq 1.$$

Using Euler's formula

$$e^{\imath\varphi} = \cos\varphi + \imath\sin\varphi$$

and the trigonometric identity

$$1 - \cos\varphi = 2\sin^2\frac{\varphi}{2}$$

we can restate this as follows:

$$\max_k \left| 1 - 4\mu \sin^2\left(\frac{k\Delta x}{2}\right) \right| \leq 1.$$

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This holds if, and only if, $\mu = \frac{\Delta t}{(\Delta x)^2} \leq \frac{1}{2}$.

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Theorem

Suppose that U_j^m is the solution of the explicit Euler scheme

$$\frac{U_j^{m+1} - U_j^m}{\Delta t} = \frac{U_{j+1}^m - 2U_j^m + U_{j-1}^m}{(\Delta x)^2}, \quad j = 0, \pm 1, \pm 2, \dots,$$

$$U_j^0 = u_0(x_j), \qquad j = 0, \pm 1, \pm 2, \dots,$$

and $\mu = \frac{\Delta t}{(\Delta x)^2} \leq \frac{1}{2}$. Then,

$$\|U^m\|_{\ell_2} \leq \|U^0\|_{\ell_2}, \qquad m = 1, 2, \dots, M. \tag{1}$$

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$$U_j^0 = u_0(x_j), \qquad j = 0, \pm 1, \pm 2, \dots,$$

and $\mu = \frac{\Delta t}{(\Delta x)^2} \leq \frac{1}{2}$. *Then,*

$$\|U^m\|_{\ell_2} \leq \|U^0\|_{\ell_2}, \qquad m = 1, 2, \dots, M. \tag{1}$$

Hence, the explicit Euler scheme is **conditionally practically stable**, the condition for stability being that $\mu = \Delta t / \Delta x^2 \leq 1/2$. One can also show that if $\mu > 1/2$, then (1) will fail.

Stability analysis of the implicit Euler scheme

We shall now perform a similar analysis for the **implicit Euler scheme** for the heat equation:

$$\frac{U_j^{m+1} - U_j^m}{\Delta t} = \frac{U_{j+1}^{m+1} - 2U_j^{m+1} + U_{j-1}^{m+1}}{(\Delta x)^2}, \quad j = 0, \pm 1, \pm 2, \ldots$$

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$$U_j^0 = u_0(x_j), \qquad j = 0, \pm 1, \pm 2, \ldots.$$

Equivalently,

$$U_j^{m+1} - \mu(U_{j+1}^{m+1} - 2U_j^{m+1} + U_{j-1}^{m+1}) = U_j^m$$

$$U_j^0 = u_0(x_j), \qquad j = 0, \pm 1, \pm 2, \ldots,$$

where, again,

$$\mu = \frac{\Delta t}{(\Delta x)^2}.$$

Using an identical argument as for the explicit Euler scheme, we find that the amplification factor is now

$$\lambda(k) = \frac{1}{1 + 4\mu \sin^2\left(\frac{k\Delta x}{2}\right)}.$$

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Clearly,

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$$U_j^0 = u_0(x_j), \qquad j = 0, \pm 1, \pm 2, \ldots.$$

Then, for all $\Delta t > 0$ and $\Delta x > 0$,

$$\|U^m\|_{\ell_2} \leq \|U^0\|_{\ell_2}, \qquad m = 1, 2, \ldots, M. \tag{2}$$

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Then, for all $\Delta t > 0$ and $\Delta x > 0$,

$$\|U^m\|_{\ell_2} \leq \|U^0\|_{\ell_2}, \qquad m = 1, 2, \ldots, M. \tag{2}$$

Thus, the implicit Euler scheme is **unconditionally practically stable**, meaning that the bound (2) holds without any restrictions on Δx and Δt.

Stability analysis of the θ-scheme

Consider the θ-scheme:

$$\frac{U_j^{m+1} - U_j^m}{\Delta t} = (1-\theta)\,\frac{U_{j+1}^m - 2U_j^m + U_{j-1}^m}{(\Delta x)^2} + \theta\,\frac{U_{j+1}^{m+1} - 2U_j^{m+1} + U_{j-1}^{m+1}}{(\Delta x)^2},$$

$$U_j^0 = u_0(x_j), \qquad j = 0, \pm 1, \pm 2, \ldots,$$

where $\theta \in [0,1]$ is a parameter.

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$$U_j^0 = u_0(x_j), \qquad j = 0, \pm 1, \pm 2, \ldots,$$

where $\theta \in [0,1]$ is a parameter.

For $\theta = 0$ it is the explicit Euler scheme, for $\theta = 1$ it is the implicit Euler scheme, and for $\theta = 1/2$ it is the arithmetic average of the two Euler schemes, and is called the **Crank–Nicolson scheme**.

Using an identical argument as in the case of the two Euler methods, we find that

$$\lambda(k) - 1 \;\; = \;\; -4(1-\theta)\,\mu\,\sin^2\left(\frac{k\Delta x}{2}\right) - 4\theta\,\mu\,\lambda(k)\sin^2\left(\frac{k\Delta x}{2}\right).$$

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Therefore,

$$\lambda(k) = \frac{1 - 4(1-\theta)\mu\sin^2\left(\frac{k\Delta x}{2}\right)}{1 + 4\theta\mu\sin^2\left(\frac{k\Delta x}{2}\right)}.$$

For practical stability, we demand that

$$|\lambda(k)| \leq 1 \qquad \forall k \in [-\pi/\Delta x, \pi/\Delta x],$$

which holds if, and only if,

$$2(1-2\theta)\mu \leq 1.$$

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which holds if, and only if,

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Thus we have shown that:

- For $\theta \in [1/2, 1]$ the θ-scheme is **unconditionally practically stable**;
- For $\theta \in [0, 1/2)$ the θ-scheme is **conditionally practically stable**, the stability condition being that

$$\mu \leq \frac{1}{2(1-2\theta)}.$$

Von Neumann stability

In certain situations, practical stability is too restrictive and we need a less demanding notion of stability.

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Definition (von Neumann stability)

We shall say that a finite difference scheme for the unsteady heat equation on the time interval $[0, T]$ is **von Neumann stable** in the ℓ_2 norm, if there exists a positive constant $C = C(T)$ such that

$$\|U^m\|_{\ell_2} \leq C\|U^0\|_{\ell_2}, \qquad m = 1, \ldots, M = \frac{T}{\Delta t},$$

where

$$\|U^m\|_{\ell_2} = \left(\Delta x \sum_{j=-\infty}^{\infty} |U_j^m|^2\right)^{1/2}.$$

Clearly, practical stability implies von Neumann stability, with stability constant $C = 1$.

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As the **stability constant** C in the definition of von Neumann stability may dependent on T, and when it does then, typically, $C(T) \to +\infty$ as $T \to +\infty$, it follows that, unlike practical stability which is meaningful for $m = 1, 2, \ldots$, von Neumann stability makes sense on finite time intervals $[0, T]$ (with $T < \infty$) and for the limited range of $0 \leq m \leq T/\Delta t$, only.

Von Neumann stability of a finite difference scheme can be easily verified by using the following result.

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Lemma

Suppose that the semidiscrete Fourier transform of the solution $\{U_j^m\}_{j=1}^{\infty}$, $m = 0, 1, \ldots, \frac{T}{\Delta t}$, *of a finite difference scheme for the heat equation satisfies*

$$\hat{U}^{m+1}(k) = \lambda(k)\hat{U}^m(k)$$

and

$$|\lambda(k)| \leq 1 + C_0 \Delta t \qquad \forall k \in [-\pi/\Delta x, \pi/\Delta x].$$

Then the scheme is von Neumann stable. In particular, if $C_0 = 0$ *then the scheme is practically stable.*

PROOF: By Parseval's identity for the semidiscrete Fourier transform

$$
\begin{aligned}
\|U^{m+1}\|_{\ell_2} &= \frac{1}{\sqrt{2\pi}}\|\hat{U}^{m+1}\|_{L_2} = \frac{1}{\sqrt{2\pi}}\,\|\lambda\hat{U}^{m}\|_{L_2} \\
&\leq \frac{1}{\sqrt{2\pi}}\max_k|\lambda(k)|\;\|\hat{U}^{m}\|_{L_2} = \max_k|\lambda(k)|\;\|U^{m}\|_{\ell_2}.
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Hence,

$$\|U^{m+1}\|_{\ell_2} \le (1 + C_0\Delta t)\|U^m\|_{\ell_2}, \qquad m = 0, 1, \dots, M-1.$$

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Hence,

$$\|U^{m+1}\|_{\ell_2} \leq (1 + C_0\Delta t)\|U^m\|_{\ell_2}, \qquad m = 0, 1, \ldots, M-1.$$

Therefore,

$$\|U^m\|_{\ell_2} \leq (1 + C_0\Delta t)^m\|U^0\|_{\ell_2}, \qquad m = 1, \ldots, M.$$

PROOF: By Parseval's identity for the semidiscrete Fourier transform

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Hence,

$$\|U^{m+1}\|_{\ell_2} \leq (1 + C_0\Delta t)\|U^m\|_{\ell_2}, \qquad m = 0, 1, \ldots, M-1.$$

Therefore,

$$\|U^{m}\|_{\ell_2} \leq (1 + C_0\Delta t)^m\|U^0\|_{\ell_2}, \qquad m = 1, \ldots, M.$$

As $(1 + C_0\Delta t)^m \leq \mathrm{e}^{C_0 m\Delta t} \leq \mathrm{e}^{C_0 T}$, it follows that

$$\|U^{m}\|_{\ell_2} \leq \mathrm{e}^{C_0 T}\|U^0\|_{\ell_2}, \qquad m = 1, 2, \ldots, M,$$

implying von Neumann stability, with $C = \mathrm{e}^{C_0 T}$. $\diamond$